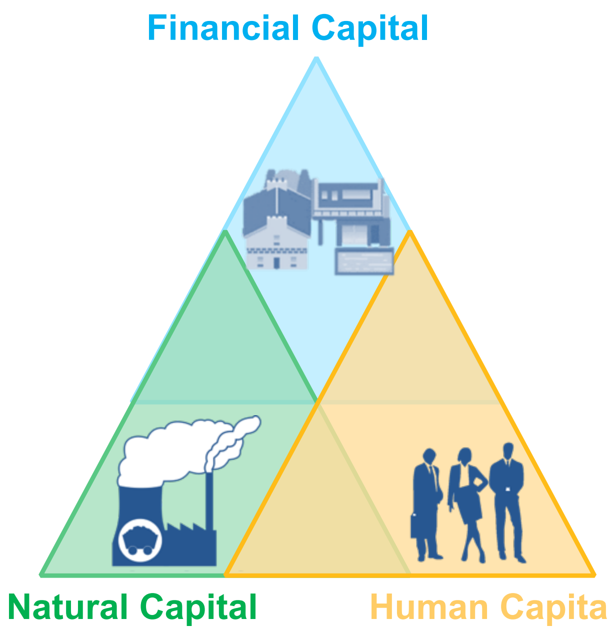
INTEGRATING FINANCIAL, ENVIRONMENTAL AND HUMAN CAPITAL
- THE TRIPLE BOTTOM LINE -
FOR HIGH PERFORMANCE INVESTMENTS IN THE BUILT ENVIRONMENT



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School of Architecture
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Dissertation

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TITLE:

Integrating Financial, Environmental and Human Capital – *the Triple Bottom Line* - for High Performance Investments in the Built Environment

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To my parents.

Abstract

Residential and commercial buildings account for almost 40 % of total U.S. energy consumption and U.S. carbon dioxide emissions (Pew Center, 2009). Nearly all of the greenhouse gas (GHG) emissions from the residential and commercial sectors can be attributed to energy use in buildings, making high performance energy efficient buildings central to addressing diminishing resources and transitioning to a green economy. However, energy efficiency in buildings receives inadequate attention because first least cost decision-making as opposed to life cycle cost analysis (Romm, 1999). When life cycle analysis is used, it typically captures only the 'hard' financial cost benefits of operational energy and maintenance savings, but rarely includes environmental capital or human capital savings. This thesis proposes an empirical approach to triple bottom line calculations that integrates the economic, environmental and human cost benefits to accelerate investments in high performance building technologies. The development of a new methodology for capital expenditures in investments in the built environment can provide compelling arguments for decision makers and encourage the widespread adoption of high performance building technologies.

In the first bottom line, this research quantifies the 'financial' or capital costs and benefits of high performance building investments, by broadening the category of associated benefits beyond energy savings from an investment (Birkenfeld et al., 2011). Traditionally, building investment decisions are made using a value engineering approach, which is driven by the agenda of cost reduction rather than valuing the benefit of different alternatives. Using net present value (NPV) and return on investment (ROI) indices, well-known in financial practices, the first bottom line calculation in this thesis moves away from a 'first least cost' to a life cycle approach to account for multiple non-energy financial benefits that can directly be quantified for the building decision maker.

To advance a second bottom line that can be translated into Corporate Sustainability Reporting, the thesis provides a methodology for capturing the environmental benefits of reducing electricity demand related to carbon, air quality and water resources. These calculations are based on three levels of information - electricity fuel sources and power plant quality, the respective air pollution and water consumption consequences, and emerging valuation incentives for pollution reduction. The methodology focuses on critical greenhouse gases CO_2, CH_4; SO_x, NO_x, as well as particulates and water use, for three global scenarios – an emerging economy such as India, a country with mid-level sustainability goals such as the US, and a leading economy with low carbon growth goals such as the EU - in order to represent the range of environmental impacts of electric energy use. The capital saved by avoiding the environmental impacts of electricity use based on fuel source and mix can thus be added to each kilowatt-hour of electricity saved in a second bottom line calculation.

To advance the third bottom line, this thesis engages a methodology for measuring and quantifying human benefits from building investments based on ongoing development of CMU CBPD's BIDS toolkit. The methodology is built on the field and laboratory research findings that link high performance building design decisions to human health and individual and organizational productivity. This thesis advances an approach to handling the third bottom line calculations, including an approach to establishing baselines, applying a broad base of laboratory and field findings.

Given first cost data from vendors, first bottom line simple paybacks for 12 energy retrofit measures ranges from 2-20 years - with energy and facility management savings. When the environmental benefits are included, simple paybacks were accelerated to 1.5-18 years. Most strikingly, when human benefits are included - from reduced headaches and absenteeism to improved task performance or productivity - paybacks for investments in energy efficiency in US offices are often less than 1 year.

To support the validity and reliability of results, both quantitative and qualitative methods were used to validate how Triple Bottom Line (TBL) cost benefits might impact and shift decision-making patterns from a least-first-cost approach to an approach that includes TBL information. Field testing of the potential influence on decision makers to move beyond first-cost decision-making to support investments in high performance, energy efficient technologies revealed the positive impact of Triple Bottom Line accounting for decision makers ($p<0.05$). The introduction of triple bottom line accounting for decision-makers in the built environment may be the most critical catalyst for investments in building energy improvements.

Acknowledgements

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Table of Contents

Acronyms

LEED – Leadership in Energy and Environmental Design

U.S. – United States

C- Celsius

CAP – Criteria Air Pollutants

CH_4 – Methane

CO – Carbon Monoxide

CO_2- Carbon Dioxide

C2C – Cradle to Cradle

DOE – U.S. Department of Energy

eGRID – Emissions and Generation Resource Integrated Database

EIA – U.S. Energy Information Administration

EPA – U.S. Environmental Protection Agency

GHG – Greenhouse Gas

HAP – Hazardous air pollutant

IPCC – Intergovernmental Panel on Climate Change

kWh – Kilowatt-hour

lbs – Pounds

NO2 – Nitrous Oxide

NOx- Nitrogen Oxide

PM2.5- Fine Particulate Matter

PM10 – Course Particulate Matter

ppm – Parts per million

SCC – Social Cost of Carbon

TBL – Triple Bottom Line

TTL – Triple Top Line

USD - U.S. Dollars

VOC – Volatile Organic Compounds

Glossary

Abatement Cost: The engineering and resource costs required to capture a specified abatement option. The costs include all capital, operations and maintenance costs and exclude all social, welfare and regulatory costs associated with realizing that opportunity. Where expressed as per-ton cost, the net discounted cost (including benefits) is divided by the total emissions reduction.

Allowance: An authorization for the holder to emit a specified amount of a pollutant into the atmosphere as set forth in the Clean Air Act Amendments, i.e. one SO2 allowance permits one ton of SO2 emissions.

Anthracite has the highest carbon content (between 86% and 98%), and a heat value of about 15,000 BTUs. Anthracite coal is a small part of the electric power market.

Avoided Costs: The incremental costs of energy and/or capacity, except for the purchase from a qualifying facility, that a utility would incur in the generation of the energy or its purchase from another source.

Absenteeism: frequent or habitual absence from work

Asset: A resource with economic value that an individual, corporation or country owns or controls with the expectation that it will provide future benefit.

Bituminous coal has a carbon content ranging from 45% to 86%, and a heat value between 10,500 British Thermal Units (BTUs) and 15,500 BTUs per pound.

Corporate Social Responsibility (CSR): The inclusion of environmental and social concerns within an organization's activities, corporate decision making and relationship with stakeholders.

Cradle-to-Grave: A procedure in which hazardous wastes are identified as they are produced and are followed through further treatment, transportation, and disposal by a series of permanent linkable, descriptive documents.

Damage Function Approach: A step-by-step approach to valuing environmental damages, starting from emissions, to concentrations, to impacts, to damage.

Damages: Following legal terminology, damages are the monetized value of detrimental impacts which accrue to society from the activities of producers and consumers. A related term, benefit, refers to the monetary value of positive impacts.

Daylight Harvesting: The term used in the building controls industry for a control system that reduces electric light in building interiors when daylight is available, in order to reduce energy consumption

Daylight Sensor: A device that reads available light and sends a signal to the control system. Daylight Sensor = Photo Cell = Photo Sensor

Depreciation: The decrease in the market value of an asset over time due to use or obsolescence.

Electric Utility: A corporation, person, agency, authority, or other legal entity or instrumentality that owns and/or operates facilities within the U.S., its territories, or Puerto Rico for the generation, transmission, distribution, or sale of electric energy primarily for use by the public and files forms listed in the Code of Federal Regulations, Title 18, Part 141. Facilities that qualify as cogenerators or small power producers under the Public Utility Regulatory Policies Act (PURPA) are not considered electric utilities.

Emissions Trading: With an emissions trading system, a regulatory agency specifies an overall level of pollution that will be tolerated—a cap—and then uses allowances to develop a market to allocate the pollution among sources of pollution under that cap. Emissions permits or allowances become the currency of the market, as pollution sources are free to buy, sell, or otherwise trade permits based on their own marginal costs of control and the price of the permits. In no case can the total emissions exceed the cap.

Energy Star: Am energy performance rating system for commercial, institutional and industrial buildings developed by the US Environmental Protection Agency.

Externality: The environmental impacts or damages caused by pollutant emissions are often labeled environmental "externalities" and are the benefits or costs resulting as an unintended byproduct of an economic activity (EIA, 1995).

Financial Return: The gain or loss of a security in a particular period. The return consists of the income and the capital gains relative on an investment.

Fossil Fuel: Any naturally occurring organic fuel, such as petroleum, coal, and natural gas.

Global Warming: The scientific hypothesis which states that the earth's temperature is rising as a result of the increasing concentration of certain gases, known as greenhouse gases, in the atmosphere, trapping heat that would otherwise radiate into space.

Greenhouse Effect: A popular term used to describe the roles of water vapor, carbon dioxide, and other trace gases in keeping the Earth's surface warmer than it would be otherwise. These radiatively active gases are relatively transparent to incoming shortwave radiation but are relatively opaque to outgoing longwave radiation. The latter radiation, which would otherwise escape to space, is trapped by these gases within the lower levels of the atmosphere. The sub- sequent reradiation of some of the energy back to the Earth maintains surface temperatures higher than they would be if the gases were absent. There is concern that increasing concentrations of greenhouse gases, including carbon dioxide, methane, and manmade chlorofluorocarbons, may enhance the greenhouse effect and cause global warming.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, tropospheric ozone, nitrous oxide, and methane, that are transparent to solar radiation but opaque to longwave radiation. Their action is similar to that of glass in a greenhouse.

Green Lease: A lease that has additional provision within it whereby the landlord and the tenant undertake specific responsibilities/ obligations with regards to the sustainable operation of a property.

Green Portfolio: An investment portfolio which invests solely in assets that display positive environmental, social and governance (ESG) practices.

Hard Costs: Relate to the tangible items that need to be procured to complete the building, including the cost of acquiring the site, the building structure, finishes, material and landscaping.

High performance/ Green / Sustainable buildings: Buildings that deliver more than energy efficiency, improved indoor environmental quality by using resources like energy, water, materials and land more efficiently compared to buildings built to code.

Human Capital: A measure of the economic value of an employee's skill set. The concept of human capital recognizes that by investing in employees the quality of work and labor can be improved.

Integrated Resource Planning: In the case of an electric utility, a planning and selection process for new energy resources that evaluates the full range of alternatives, including new generating capacity, power purchases, energy conservation and efficiency, cogeneration and district heating and cooling applications, and renewable energy resources, in order to provide adequate and reliable service to its electrical customers at the lowest system cost. Often used interchangeably with least-cost planning.

Internalizing Externalities: This expression means to create social conditions where the damages (or benefits) from production and consumption are taken into account by those who produce these effects. These Social conditions can be created by government regulation, a tort system, bargaining between private parties, or other policy and institutional arrangements. Benefits and damages can exist even when all externalities have been internalized.

Internal rate of return: The internal rate of return (IRR) is the discount rate established by an organization as the threshold for which an investment is considered economically viable. It is calculated using the value of future cash flows in an investment where the net present value is greater than or equal to zero. It can also be thought of as the annual compounded rate of return one can expect on an initial investment.

Lignite has the lowest carbon content of the four types of coal generally used for electric power generation, averaging between 25% and 35%, and a high moisture and ash content. It also has the lowest heat value, ranging between 4,000 BTUs and 8,300 BTUs.

Net present value: The net present value (NPV) of an investment is the sum of all future cash flows from an investment discounted back to the time of the initial investment. The discount rate should be equal to the rate of return that could be achieved in an alternate investment with similar risk characteristics.

Presenteeism: the practice of coming to work despite illness. Injury, anxiety often resulting in reduced productivity.

Productivity: Productivity generally measures quantity - how much work is performed and delivered into goods and services (inputs and outputs) and how efficiently. Quality of work is also important and can include easily-tracked outcomes such as errors, number of do-overs, and work completed on time.

Public Utility: An enterprise providing essential public services, such as electric, gas, telephone, water and sewer, under legally established monopoly conditions.

Sick Building Syndrome: The sick building syndrome (SBS) is used to describe a situation in which the occupants of a building experience acute health- or comfort-related effects that seem to be linked directly to the time spent in the building.

Simple payback period: The simple payback period of an investment is the amount of time that the returns from the investment take to pay back the initial cost of the investment. A basic example would be a $100 (US dollars) investment that pays $25 (US dollars) per year. In this case, the simple payback period is 4 years, and the discounted payback period would be slightly less since the value of future cash flows is discounted using a market discount rate.

Smog: Air pollution associated with oxidants.

Social or Societal Cost: The term social cost is often used interchangeably with the cost of externalities, but actually refers to the sum of private costs and the costs of externalities.

Soft costs: relate to items or services that do not form part of the finished buildings but, are necessary components of development process. These include costs associated with architectural and design fees, inspection fee and permits, legal and valuation fee, environmental certification fee, loan generated interest, accounting fee, insurance, taxes, marketing and project management costs.

Subbituminous coal has a carbon content of between 35% and 45%, and a heat value of between 8,300 BTUs and 13,000 BTUs. Subbituminous coal generally has a lower sulfur content than other types of coal.

Triple Bottom Line: A term coined by John Elkington (1997) to measure an organization's performance and success against economic, environmental and social consideration.

Utility: Investor-owned companies and public agencies engaged in the generation, transmission, or distribution of electric power for public use. Public agencies include municipal electric utilities, Federal power projects, rural electrification, cooperatives, power districts, and State power authorities and projects.

Whole Life Cost: The total cost of ownership over the life of an asset, through planning, acquisition or development, operation, maintenance and refurbishment and ultimately replacement and disposal (RICS, 2010).

Chapter 1

The Need for Life Cycle Decision-Making in the Built Environment

Constructing and operating buildings is extremely resource intensive, incurring financial capital expenses and engendering environmental costs. In both developed and developing countries, buildings are responsible for more than 40 percent of the global energy used, 12 percent of global freshwater use, and more than 30 percent of landfill waste (United Nations Environment Programme, 2011). Along with the financial costs from high energy and resource use, buildings generate about 19% of the global greenhouse gas emissions (UNEP, 2009). In addition to financial and environmental costs, one frequently overlooked cost of building operations is the cost of inadequate built environments on human capital. Employers spend the largest faction of the "cost of doing business" on their employees, often 10 times more than they spend on energy and water utilities (Kershaw & Lash, 2013)(Terrapin, 2012). Investments that improve indoor environmental conditions can impact occupant health and productivity and thus impact the organization's bottom line (Loftness et al., 2005)(Terrapin, 2012). Yet the environmental and human impacts from a building investment are rarely considered in the decision-making process for new buildings or retrofit investments (figure 1.1).

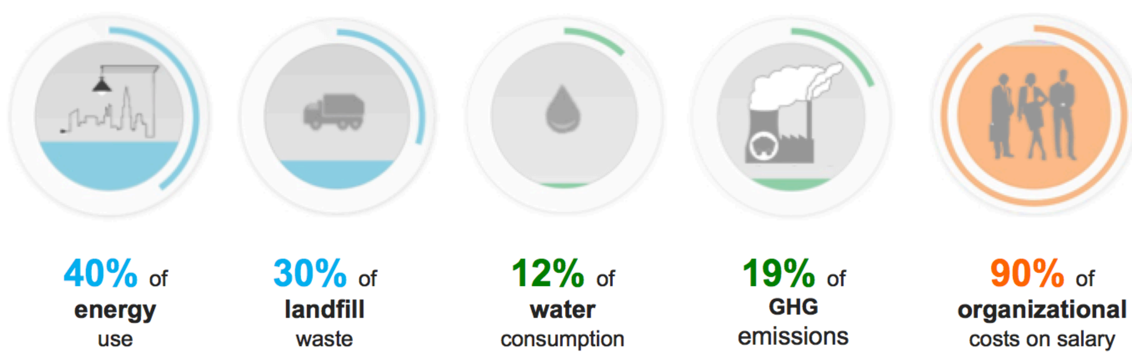


Figure 1.1: Constructing and operating buildings is extremely resource intensive

1.1 First least cost decision making in the built environment

Environmental and human goals for new buildings and major retrofits are typically driven by client and market demands, as well as by building codes (World Green Building Council, 2013), but not typically quantified as economic goals in first cost additions or cost/square foot. Owners or property managers making capital expenditure decisions often have the same goal - to "improve the value of the property as an asset" (BOMI, 2016). However, the perception of investment value is unique to individual or organizational stakeholder groups - from owners, to investors, to the occupants of the building. Investment levels could be set by comparable metrics in the building industry, by either the "financial resale worth of the property, the net operating income enabled through smooth and healthy business operations of a tenant" (BOMI, 2016), or by commitments to sustainability and carbon footprint goals, amongst others. While strong progress has been made to incorporate these values in the decision making process, the real estate industry still struggles to quantify and articulate the value of investing in high performance building technologies and systems (Muldavin, 2010a).

The standard practice for designing, constructing, managing and occupying buildings is to control upfront costs (Newton et al., 2009). Using a 'least first cost approach,' developers and builders can achieve short-term financial gains. While this approach accounts for design and construction costs, it typically ignores life cycle expenses which are equally significant for the owner and investor (Builder's Association, 2013).

Existing approaches to the investment decision process typically rely on preset financial capital expenditures, a first-least-cost approach, with possible use of simple payback or simple return on investment (ROI) calculations when considering increased investments for potential operational savings (UNEP, 2009). Projects that exceed the preset capital budgets have little or no potential for weighing investments for operational savings. Instead, 'value engineering' often eliminates investments included for operational gains, to ensure the project does not exceed available investment capital. Originally developed for the manufacturing industry, value engineering is actively used in the construction industry (Dell'Isola,1988) and could be expanded to identify opportunities to reduce construction costs while optimizing performance, reducing operating expenses, and shortening building delivery time without sacrificing functionality (Bazjanac et al. 2014). In its current form, value engineering has become a systematic procedure that is directed towards the achievement of the required functions at the least cost (Jensen & Maslesa, 2015).

The actual focus on cost reduction is problematic because the externalities related to building activities are often ignored when investment decisions are made. The design team is frequently rewarded for their "ability to minimize the initial costs of a building, as opposed to its life cycle costs" (Romm,1998). In addition, environmental impacts related to the ecological degradation from use of energy and natural resources, often described as externalities, are not quantified. With respect to the human capital impacts, "most investors and many tenants today understand that sustainable properties can generate health and productivity benefits, recruiting and retention advantages, and reduce risks, but struggle to integrate benefits beyond cost savings into their valuations and underwriting" (Muldavin, 2010a). In other words, equity investors, developers, corporate real estate executives and other real estate decision makers may believe in the health and productivity benefits of high performance buildings, including worker retention, but they find it difficult to integrate these benefits in their decision-making process.

By excluding the life cycle operating costs, environmental externalities and human benefits from value engineering, decision makers ignore the opportunity to integrate these benefits into valuations and underwritings that can help overcome the 'first least cost' barrier and provide convincing justifications in favor of quality in building investments. High performance investments impact core business operations through improving efficiency and minimizing or eliminating waste (a first bottom line), protecting and enhancing the natural environment (a second bottom line), and by improving the quality of life and health of building occupants (a third bottom line). It is imperative that an accounting method be developed and demonstrated that integrates all the benefits from such investments.

1.2 Emerging shifts from first least cost

While first cost limits are preferred by most building decision-makers, leaders in the building industry use different sustainability frameworks and tools to meet the growing demand for accountability (figure 1.2) and transparency in reporting the financial, natural and the human value of their actions. By addressing these issues, organizations are able to evaluate consequences of their investment decisions and provide a long-term perspective on sustainability initiatives for the shareholder. Developer-Owners such as LendLease , Stockland, Holcim Ltd, Cemex, Skanska, and Obayashi, amongst others, issue Corporate Sustainability Reports (CSR) and have adopted sustainability frameworks to evaluate their performance and report environmental and social actions taken to their investors (Savitz & Weber, 2007; Musikanski, 2012; Lamprinidi & Ringland, 2008). However, CSR reporting still lacks metrics to reflect the environmental and human impacts (Slaper & Hall, 2011).

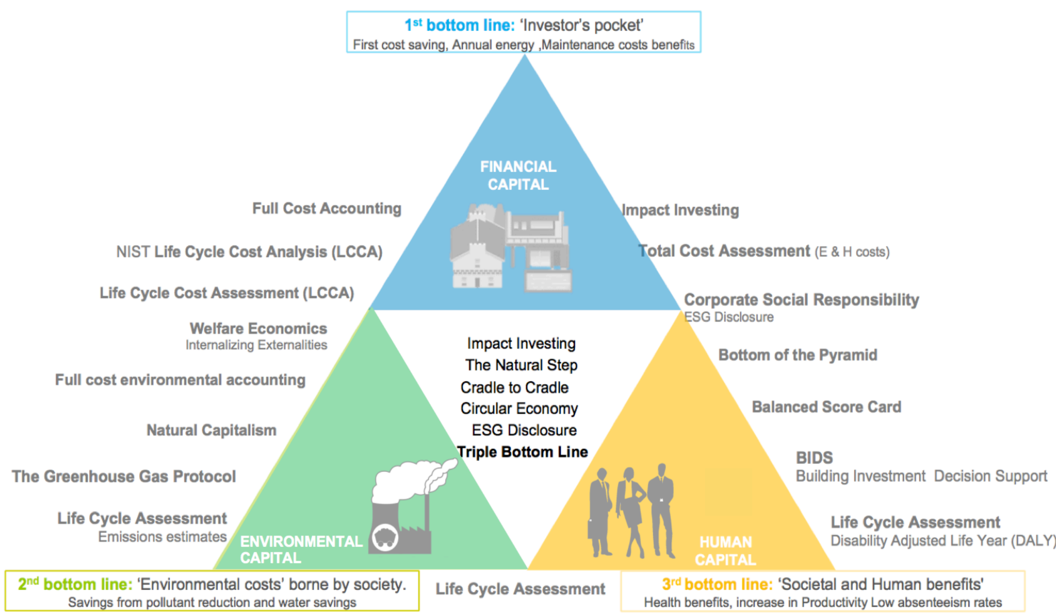


Figure 1.2: Sustainability frameworks, tools and processes reviewed

This thesis builds upon a range of quantification tools that are beginning to capture the economic, environmental and human benefits of quality built environments, a literature review that will be further described.

1.2.1 First bottom line: Financial NPV

The valuation criteria for property includes "financial considerations that go into purchasing or leasing real estate" and the associated "facilities management of existing buildings" (BOMI International, 2011). Since building investments require some level of capital commitments of capital by the owner, inflation, taxation and uncertainty in the market often influence decisions to invest. The standard financial evaluation techniques typically applied to investment decisions include – return on investment, break even analysis, payback analysis, net present value analysis and internal rate of return.

Return on investment (ROI) accounts for financing and can represent component level savings. ROI for high performance investments are defined as the annual rate of savings earned on an investment, expressed as a percentage (BOMI International, 2011). To calculate a project's ROI, the total annual savings are divided by the net investment cost. ROI has a limitation as it does not "capture lifecycle impacts of an investment as it is concerned only with the period of time it takes to recover the cost of an investment through the resulting annual savings from the investment" (BOMI, 2016).

Another way of looking at these returns is to translate ROIs into simple payback periods. For example, an investment with a 50% ROI will take 2 years to recover the cost of the investment through the savings it will provide. The payback analysis evaluates the length of time required to pay back the capital input. This time is called the payback period, and it must be shorter than the life of the investment. Once this point is reached, the investment is said to produce positive net cash flows (Investopedia, 2017). This approach again ignores the time value of money for a long-term investment and is often used for small investments that do not require in depth study or analysis (BOMI International, 2011).

Break even analysis is another evaluation used by decision makers. Break even analysis states that if a project contributes any greater return than its variable costs, the project is worth investing in (Investopedia,2015). This approach ignores capital investments and the time value of money. Cost benefit analysis is a form of break-even analysis that addresses concerns as to whether the benefits of a project are worth the costs. It is especially useful for projects requiring improvement in tenant spaces that do not affect the market or asset value of the property (BOMI International, 2011).

Net Present Value (NPV) analysis evaluates an investment in terms of the difference between the cost of an initial investment and its future cash flow stream (Kats & Capital, 2003). Typically, the future cash flow stream is converted into present value by applying a discount rate representing the investor's cost of capital or opportunity rate (BOMI International, 2011). The initial cost of the investment is then subtracted from the value of the future cash flow stream to determine the NPV (BOMI, 2016). Theoretically, if the NPV is positive, the investment return is greater than the investor's cost of capital and/or the return that could be obtained from an alternative investment (BOMI International, 2011).

Such an approach recognizes the long- term character of investment real estate, as well as the decreasing utility of money over time.

Internal rate of return (IRR) takes NPV analysis one step further as it evaluates the return generated by the net income stream from the investment as compared to the minimum acceptable rate of return to the investor. IRR is the "discount rate at which the present value of project savings is equal to the present value of project costs" (BOMI, 2016). For an investment to be selected, it must meet or exceed this minimum rate of return. The rate varies from company to company and is substantially influenced by alternative investment options. The hurdle rate "may be based on the investor's cost of capital, or may also factor in other variables such as allowance for investment risk or the interest rate earned on cash reserves in a savings account"(BOMI, 2016)

A final approach of significance for this thesis is life cycle cost analysis (LCC or LCCA) that help design teams to not only consider the 'first costs,' but also the long term costs, including utilities, operation and maintenance (Gluch & Baumann, 2004). The LCCA approach evaluates the economic performance of building investments over their entire life and is defined as the sum of all recurring and non -recurring costs over the full life span or a study period of a good, service, structure or system (Fuller, 2008). It often includes purchase price, installation cost, operating cost, maintenance and upgrade costs, as well as salvage values at the end of ownership or useful life. The emphasis is on cost effectiveness as the LCC method is used to evaluate alternatives which compete on the basis of costs (Ruegg & Marshall, 1990). LCC is suitable for evaluation of "building design alternatives that satisfy a required level of building performance - including safety, adherence to building codes and engineering standards, system reliability and even aesthetic considerations - but may have: different initial investment costs; different operating, maintenance and repair costs; and possibly different periods of longevity (Fuller & Petersen, 1995). For example, when evaluating the choice of exterior wall construction, LCC requires the inclusion of building energy costs, if they are affected by the choice, and subtracting any positive cash flows such as salvage or resale values. LCC has an important role because of the influence of total cost of ownership rather than the initial costs of ownership.

When completing LCCA, the traditional way of thinking about energy efficient investments has been that as more energy is saved, the marginal unit cost rises steeply for every additional unit of energy that is saved. However, just accounting for the energy savings from high performance building investments overlooks the potential for avoided capital expenses. Actual design and engineering practices reveal this possibility of "tunneling through the cost barrier" (see figure 1.3). For example, investment in super insulated walls and roofs, in combination with high performance and airtight windows, can eliminate the need for a furnace, saving construction capital that can be even greater than the first cost of the high-performance investments. Hawken and Lovins (1999) introduced this 'whole system engineering' approach as a 'more for less' way of thinking for design and engineering solutions. This method integrates the design of an entire system so that all accompanying benefits are accounted for, and the sequencing of the design interventions is done in a way that each measure achieves multiple benefits. This whole system life cycle costing, in which all benefits are properly accounted for in the first bottom line, is a widely accepted principle but often ignored in practice.

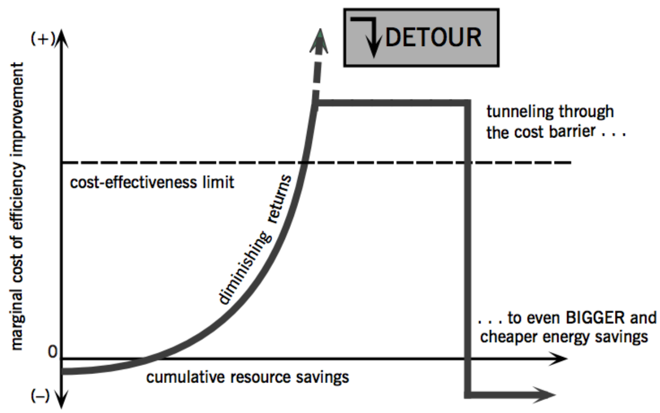


Figure 1.3: Tunneling through the cost barrier (Hawkens and Lovins,1999)

The first bottom line approach of this thesis, described in detail in chapter 2, builds on the LCCA approach to expand on the set of first bottom line savings to include all operational benefits and the potential for tunneling through the cost barrier.

1.2.2 Second bottom line: Environmental NPV

Corporate Social Responsibility (CSR) and emerging sustainability challenges have led organizations to begin tracking several performance indices that target environmental outcomes of a corporation's actions. As part the environmental aspect of CSR, companies have begun to reduce the impact of their operations on the environment by investing in green buildings, eliminating waste, reducing carbon and other GHG emissions and maximizing the efficiency and productivity of resources (Mazurkiewicz, 2004). However, this thesis contends that organizations still do not adequately address the full 2nd bottom line impact of investments in the organization's built environment (Bennett et al., 2013).

To specifically measure and manage GHG emissions the Climate Registry, Carbon Disclosure Project and the Global Real Estate Sustainability Benchmark (GRESB) offer programs that assist organizations in benchmarking environmental sustainability performance (Makower, 2014;CDP, 2009). Structured reporting instruments like the Global Reporting Initiative (GRI), Carbon Disclosure project (CDP) or the business's own CSR reporting strategy and communications further disclose environmental sustainability performance (Deloitte, 2014) (Muldavin, 2010b). Yet these programs often assist organizations in reporting only on reductions in carbon and water consumption.

While there are approaches to account for the reductions in air pollutants and GHG emissions, they are not specifically tailored to the building sector. Guidelines from the Intergovernmental Panel on Climate Change (Garg et al., 2006), include a Greenhouse Gas Protocol for reporting Scope 1, 2 and 3 emissions (WRI, 2015). ICLEI's GHG Protocol also provides general guidelines to corporations on how to account for GHG emissions from their operations and activities. Explicitly for the building sector, DOE's Building GHG Mitigation Estimator Worksheet (DOE, n.d.) and the Carbon Disclosure Project (CDP) measure, account and manage the amount of emissions. The outstanding challenge is to translate the savings from reduced emissions into values that could be useful during building capital expenditure decisions.

Life Cycle Assessment (LCA) offers another tool to assess and measure the implications of industrial or operational activities, from the raw material value chain, through product use, to end of life impacts. LCA provides an instrument for environmental decision support (UNEP, 1999), as it evaluates the potential environmental impacts throughout a product's or a system's life (Hendrickson et al., 2006). LCA enables accounting for all the upstream and downstream costs of an activity, using a detailed life cycle inventory and impact assessment of the resources used and emissions linked through its lifecycle (Kats & Capital, 2003). The impacts are measured by the amount of resources used to manufacture, operate and dispose of the product or service and the associated environmental impacts through its lifecycle. The assessment can be an influential factor in the building investment selection process when an organization has sustainability and environmental stewardship as the focus of their market growth.

There are additional 2nd bottom line environmental theories and tools that go beyond sustainability reporting to define how the design and operations of a business overlap with environmental interests. 'Full cost environmental accounting' and 'Natural Capitalism' promote advances in environmental sustainability by allocating direct and indirect environmental costs to a product or product line (Gluch & Baumann, 2004) (Pojasek et al., 1993) (Lovins et al., 1999). Natural Capitalism guides businesses to value the ecosystem services and to treat these natural resources as a 'capital' to make them a part of the balance sheet (Greenwood, 2001). This approach proposes protecting environmental resources while improving profits and competitiveness of the organization (Hawken et al, 1999). By assigning a financial cost to the use, maintenance, abuse, or depletion of natural resources and ecosystems, the value created by firms can change, and the resources and the systems in which they operate can become more efficient (Hawken et al., 2008). One pioneering example of this approach is Interface carpet. For a monthly tax deductible operating lease, Interface offers services to replace worn out square of carpet tile every month. In the process, Interface "produced a fifth as much carpet" thereby preserving natural resources, while providing better service at a lower cost (Anderson, 2009) . This model has been instrumental in reimagining operations and even the supply chains for many organizations.

Similarly, Cradle to Cradle™ is described as a "holistic economic, industrial and social framework," that seeks to create systems that are regenerative, eco-efficient and eco-effective (William. McDonough & Braungart, 2002). C2C argues that all specified products and systems should be conceived as industrial or agricultural nutrients, eliminating the concept of waste such that cradle to grave analysis is replaced by cradle to cradle. The most recent version of LEED v4 for new construction rewards projects for using Cradle to Cradle Certified products under its new *Materials and Resources Credit 4*. The most recent treatise 'Upcycle' takes the material and product sustainability to a higher level and towards ensuring continuous "reuse and at the highest level" (McDonough & Braungart, 2013). Upcycle™ urges industry to do better than "do no harm" and think of "every component of design as being borrowed", needing to be returned to the biosphere "in as good a condition as you found it" (McDonough & Braungart, 2013). These frameworks provide ecological guidelines for eliminating waste and harmful substances during the design phase.

Beyond corporate sustainability reporting, international treaties including the 2015 Paris climate agreement have led to the emergence of carbon markets to establish a market value for reducing emissions (Gold Standard, 2017). A carbon market allows organizations to quantify the benefits of reducing GHG emissions by establishing carbon taxes, emissions trading schemes, offsets and result based financing (Kerr, 2017). A large number of countries already have a trading platform (figure 1.4) with pricing instruments for CO2 specifically, and these could be used to monetize reductions in other GHG emissions to support investing in high performance building systems.

Figure 1.4: Natural capital calculations could use carbon pricing instruments to monetize benefits as large number of countries already have a trading platform (World Bank Group, 2014).

Both CSR and international carbon markets are possible vehicles for the building sector to quantify and monetize the reduction in GHG and pollutant emissions. The building industry has embraced environmental sustainability through programs such as the U.S. Green Building Council's Leadership in Energy and Environmental Design®, the Living

Building Challenge, and the Architecture 2030 challenge. In adopting these goals, designers are beginning to use carbon calculations, as well as life cycle impact assessments of building materials, as critical factors for design decisions and selection of materials.

The second bottom line approach engages the GHG protocol and includes additional emissions and pollutants in the calculations to capture the environmental benefits of reducing electricity demand in the built environment. This new methodology is further described in chapter 3 and will help decision makers select investments with the lowest environmental impact and corporate sustainability reporting gains.

1.2.3 Third Bottom line: Human NPV

The majority of the cost of doing business is for employees. Investments that improve occupant productivity or health will accelerate payback if the organizational benefits can be quantified (Loftness et al., 2005). Given the changing nature of work, measuring productivity of the knowledge worker is difficult given the complexities of human cognitive activities, skill sets and job profiles (Bluyssen, 2010; Rasmussen, 1990). However, there are a range of metrics that might be collected to assist decision makers in justifying building investments that impact the performance and health of building occupants, ranging from absenteeism to attraction-retention to performance at task (Loftness et al., 2005).

LEED, Living Building Challenge, Cradle to Cradle, and the more recent WELL standard each promote quality indoor environments as critical to the health and productivity of building occupants. The Rocky Mountain Institute, Carnegie Mellon's Center for Building Performance, GRESB, and the Global Reporting Initiative offer methodologies and tools that help quantify this impact of the indoor environment on the building occupant's health and productivity.

The Rocky Mountain Institute offers a model for owner and occupants "to calculate and present property specific deep retrofit value, focusing on the value beyond energy cost savings" (Bendewald et al., 2014). The guide "breaks down the non-energy aspects of deep retrofits into nine discrete value elements" – developments costs; non energy property operating costs, risk mitigation, health costs, employee costs, promotion and marketing costs, customer access and sales, property derived revenues and enterprise risk management. (Bendewald et al., 2014) For each of the nine elements, information is included on the rationale, the research on how value is created, as well as a guidance on how to calculate the present value to support investment capital decisions.

Carnegie Mellon University's Center for Building Performance and Diagnostics's developed an economic value added calculation in their long-term development of the Building Investment Decision Support Tool (BIDS). Focused on "identifying published health, productivity, and organizational benefits of high performance buildings, BIDS is a life cycle decision support tool for evaluating the cost-benefits of high performance building systems and technologies" (Loftness et al., 2005). The tool gathers field case studies, laboratory studies, simulation, and other research that clearly demonstrate the relationship of quality building investments to human health and performance factors (see figure 1.5). Over 500 studies have been quantified in seven categories of investment - air, temperature control, lighting control, network access, privacy and interaction, ergonomics and access to environment and ten categories of economic value to the decisionmaker - first cost; operation & maintenance, energy, organizational and technological churn, Individual productivity, organizational productivity, health, attraction/retention, taxes, litigation, codes and salvage,waste (Loftness et al., 2005; Loftness & Snyder, 2013; Loftness & Srivastava, 2014). The BIDS tool translates the linkages into life cycle calculations that can help promote investments in building components and system that enhance the quality of the workplace (CBPD,2008).

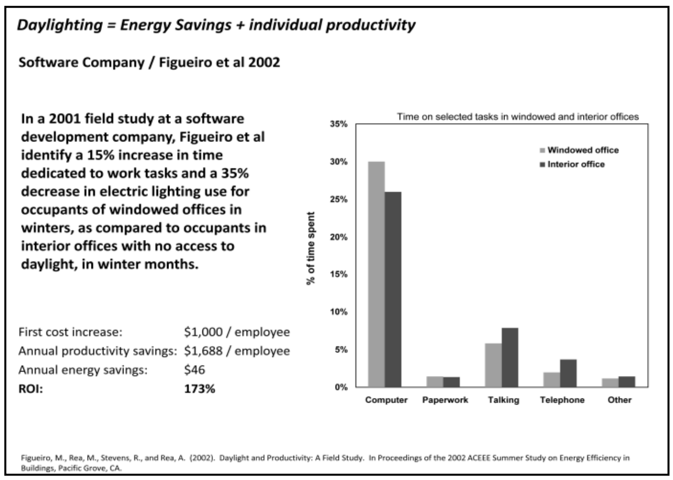


Figure 1.5: Research summaries that link lighting investments to human health and productivity

A third approach is GRESB's real estate data and analytic tool that benchmarks environmental, social and governance (ESG) performance of real estate institutions and retail investors. GRESB validates, scores and benchmarks the ESG performance , to communicate the sustainability message of the organization and help " determine the actions that will produce the greatest returns" (GRESB, 2017). In its *Health and Well-being module*, GRESB tracks 10 indicators addressing leadership, policy, needs assessment, implementation action and performance monitoring related to health and well-being. The first part of the module addresses efforts to promote the health and well-being of employees, with emphasis on operational costs and performance. The purpose is to understand the actions that provide specific health and well-being benefits (e.g., employee retention and productivity), while avoiding risks and costs (e.g., absenteeism or excessive health care costs). The second part of the module addresses efforts to provide products and services that promote the health & well-being of tenants and/or customers. This may include efforts to enhance the "value of leased space through health-promoting features or supporting services, such as green cleaning, workplace design (e.g. providing access to daylight, views, and superior indoor air quality) or community development (e.g., improvements in access to medical care or healthy food)"(GRESB, 2017) .

A fourth approach to capturing the human capital benefits is the Global Reporting Initiative (GRI). The GRI reporting structure requires organizations to identify material aspects that reflect their significant economic, environmental and social impacts. For example, one of the aspects that organizations can report on is the occupational health and safety. The social category reporting requirement includes tracking data on labor employment, labor/management relations, occupational health and safety which includes related sick leaves, training and education, diversity and equal opportunity, equal remuneration for women and men, labor practices, human rights, anti- corruption, public policy, compliance, amongst others aspects (Global Reporting Initiative, 2014). But these may or may not be attributed to the physical environment (Global Reporting Initiative, 2014).

Each of these methodologies and tools that help quantify this impact of the indoor environment on the building occupant's health and productivity support financial analyses to reflect the human benefits accrued from investments in high performance building systems. The third bottom line approach developed as part of this thesis, is further described in chapter 5.

1.2.4 Shift to an Integrated Bottom line

Traditional financial accounting techniques rarely stress the unification of the financial, natural and the social impact of design decisions (Mcdonough & Braungart, 2002) (Gluch & Baumann, 2004). However, the greater need for transparency and accountability in business operations has made accounting of all three benefits a viable mainstream business approach. The "Triple Bottom Line" was introduced by John Elkington in 1997 to incorporate sustainability goals in corporate accountability. The triple bottom line is a strategic design tool that guides organizations to center not only on economic performance, but on the natural (environmental) and human (social) performance as well (Elkington, 1997). He argues that the first, financial bottom line must be inclusive of the physical capital invested and the financial capital needed for operations and maintenance as well as updates and waste (Elkington, 1997). The second bottom line is the organization's "planet" account that measures how "environmentally responsive the company is relative to our collective natural capital" (Slaper, 2011). Lastly, the third bottom line is the organization's "people" account which measures the social value created by the operations of the company and its facilities (Gong, 2013). Social capital includes the value of human capital in an organization, in the form of health and performance (Elkington, 1997). The Triple Bottom Line (TBL) framework enables the quantification of environmental and human costs and gains within conventional accounting systems to offer new ways of valuation (Henriques & Richardson, 2004).

The TBL has been a useful tool for integrating sustainability into the business agenda. One variation is the 'Triple Top Line' (TTL) approach, which "moves accountability to the beginning of the design process, assigning value to a multiplicity of economic, ecological and social questions that enhance product value" (William McDonough & Braungart, 2002).

Through concepts like eco-efficiency, zero emissions and eco-effectiveness, designers are encouraged to "discover opportunities in honoring the needs of all three value systems" while creating products and industrial systems (Braungart, McDonough, & Bollinger, 2007). Triple top line thinking "energized the Ford company's decision-making process" when the company undertook restoration of Ford Motor Company's Rouge River plant in Dearborn, Michigan. Ford leaders and the design team used TTL accounting to justify a daylit facility with a living roof that would create habitat, connect employees to their surroundings and have porous surfaces, wetlands and swales to manage on site storm water, while eliminating the need for expensive technical controls (William McDonough & Braungart, 2002).

The more recent entry into multi-outcome accounting approaches is the 'Integrated bottom line' developed in 2010 with the launch of the International Integrated Reporting Committee to "create a globally accepted framework for accounting sustainability" (Eccles & Armbrester, 2011). Integrated Bottom Lines (IBL) present a similar construct to TBL, enabling companies to provide information on financial and nonfinancial performance in a single document (Alliance for Sustainable Colorado, 2013). It allows for 'value' based decision making that integrates environmental, social, governance and financial cost savings into a single balance sheet and income statement as captured in figure 1.6.

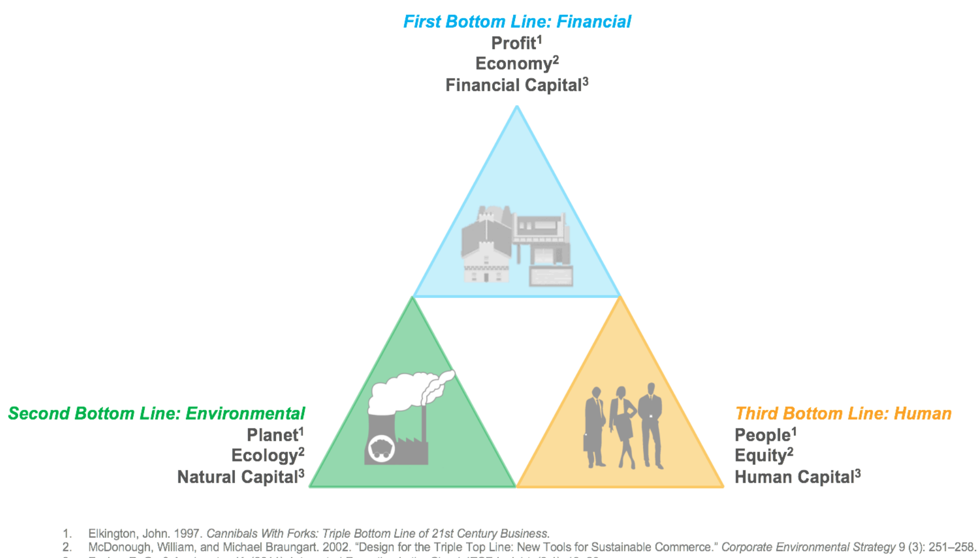


Figure 1.6: The three bottom lines as defined by Triple Bottom Line, Triple Top Line and the Integrated Bottom Line framework and reporting structure

Each of these frameworks and reporting structures for sustainable decision-making need further advances to fully monetize natural and human capital impacts. The ability of decision makers to more fully integrate these approaches in decision making hinge on the availability and utilization of environmental and human impact assessment tools and data.

1.3 Integrative approach for building investments

The triple bottom line (TBL) reporting framework and the more recent Integrated Bottom Line (IBL) encompass all three dimensions of sustainability – financial, natural and human capital. Yet their applicability in building investments is not well defined. The challenge for TBL calculations for the building industry is in the quantification of the environmental gains, including reduced emissions in power production, and of the human gains, including occupant health, productivity, and organizational performance.

First, accounting and reporting approaches for capturing the reductions in water, air pollutants and GHG emissions of power production need to be translated into values that could be useful during building capital expenditure decisions. Then, approaches to capturing human capital savings need to be translated into values relevant to capital expenditures as well. With companies spending as much as 100 times the resources on employee salaries than what they spend on building operations and maintenance, investments in the built environment can provide substantial human capital gains.

To increase investments in sustainable commercial building technologies, a triple bottom line budgetary approach is required that moves away from the least-first-cost decision making to one that accounts for the financial, environmental and human life cycle costs and savings. An accounting method that integrates all these benefits can assist organizations to select investments that improve the physical, psychological, social and financial health of individuals while improving the organization's bottom line. The literature described in this chapter has been instrumental in the development of a new integrated bottom line accounting method that is the focus of this thesis (Table 1.3 and Appendix A1) .

Table 1.3: Review of seminal literature related to this thesis

	Performance Indicators						
	Financial		Natural		Human		
	Energy	Non - Energy	GHG	Others emissions	Health	Productivity	Others
The Natural Step (2000)		•	•	•	•		
Cradle to Cradle Braungart, et al. (2007)		•	•	•			•
Natural Capitalism Lovins et al. (1999)		•	•	•			
TTL McDonough & Braungart (2002)		•		•			•
TBL Elkington (1997)		•		•			•
ESG Disclosure (2013)	•	•	•	•			•
LCA Life cycle assessment (1994)	•		•	•	•		
LCC Life Cycle Costing (1999)	•		•				
CMU **BIDS** (2008)	•	•			•	•	•
RMI Deep retrofit value (2014)	•	•			•	•	
TBL Decision Support Methodology (2018)	•	•	•	•	•	•	•

Traditionally, the term ‘capital’ is used to infer the costs on a balance sheet. Expanding the term capital, to be inclusive of financial capital, natural capital and human capital is critical to address the urgency in treating environmental degradation as a cost to the society and treating human benefits as a potential benefit of direct value to the employee and the employer.

1.3.1 Thesis Objective and Hypotheses

Building capital expenditure decisions are often least-first-cost driven and decision makers do not have data on the range of financial, environmental and human benefits from high performance building investments. Even if they inherently understand the benefits, there is no set method for quantifying the triple bottom line benefits for decision makers. This thesis engages a life cycle approach to capture the financial, environmental and human benefits from building investments to assist decision makers in selecting investments that can improve the organization’s bottom line. This thesis also tests the quantitative set of calculation with key users to identify the impacts on the decision-making patterns when triple bottom line calculations are completed.

The development of a new methodology for investments in the built environment that integrates the financial, environmental and human benefits in relation to capital expenditures can provide compelling arguments for decision makers and encourage the widespread adoption of high performance building technologies and systems.

The thesis research addresses four hypotheses:

Hypothesis 1: First bottom line benefits of building investments can be evaluated using a Life Cycle calculation approach to capture the hard ‘financial cost-benefits’ from a high-performance technology over time.

Hypothesis 2: Second bottom line benefits of building investments can be evaluated using a Life Cycle calculation approach to capture the hard ‘environmental cost-benefits’ of GHG emissions, air pollutants, and reduced use of water for electricity production, each related to energy savings.

Hypothesis 3: Third bottom line benefits of building investments can be evaluated using a Life Cycle calculation approach to capture the hard ‘human cost-benefits’ of improved health, productivity and organizational performance.

Hypothesis 4: Triple bottom line information on the financial, natural and human benefits of building investments, when provided to decision makers would impact and shift the way decisions for high performance investments are made from a first least cost approach to one that relies on TBL information.

1.3.2 Thesis Approach

To develop a new methodology that integrates financial, natural and human capital, this thesis uses a sequential mixed method design approach. In sequential mixed method designs, there is a separate quantitative and qualitative research phase (see figure 1.7). The approach allows for the possibility of triangulation, which uses several methods and data sources to examine the same phenomenon (Denzin, 1978). The multimethod, or "triangulation" approach is based on the assumption that any bias inherent in particular data sources, investigators, and methods would be neutralized when used in conjunction with other data sources, investigators and methods (Jick, 1979).

Quantitative approaches were used to measure and quantify the financial, environmental and human cost benefits that could be subsequently incorporated in building capital expenditure decisions. Common economic metrics were used to develop the new approach for evaluating investments given integrated financial, natural, and human benefits. The future benefit values are discounted to their present values and included in iterative and cumulative net present value (NPV), return on investment (ROI) and simple payback calculations.

> *Net Present Value* (NPV) reflects a stream of current and future benefits and costs and results in a value in today's dollars that represents the present value of an investment's future financial benefits minus any initial investment. To properly compare future cash flows with the initial investment, the time value of money can be factored into the comparison.
>
> $$Net\ Present\ Value\ \ (NPV) = \frac{Sum\ of\ Cash\ Flows}{(1\ +\ discount\ rate)^t}$$
>
> *Return on investment (ROI)* is an analytical tool for examining the cost to implement a project and the expected financial outcomes to determine if there is a positive or negative result over the life of the investment. To calculate ROI, revenue (or cost savings) is divided by the investment amount. ROI can be calculated for any period of time, but annualized ROI is a common metric familiar to finance professionals.
>
> $$Return\ on\ Investment\ (ROI) = \frac{return}{investment}$$
>
> *Simple payback* calculates the amount of time it will take for an investment to pay for itself. This tool is a simple formula that helps decision makers quickly predict how long it will take for revenue (or cost savings) to match the investment amount. For projects funded by operating expenses, this period of time is preferably 12 months or less. To calculate simple payback, divide the investment amount by the revenue or savings per month.
>
> $$Simple\ Payback = \frac{Investment\ (\$)}{savings\ per\ month\ (\$/time)}$$

Qualitative measures were engaged to evaluate the impact of the developed methodology on key users. This was done using user surveys that recorded responses on how building investment decisions were affected when TBL information was provided. The TBL calculations were completed for selected high impact building investments within the categories of lighting and day lighting retrofits, façade and HVAC to illustrate the viability of the new methodology and provide examples for how future building capital expenditure decisions can be evaluated.

This thesis introduces a methodology and exemplary databases that demonstrates that financial, natural and human cost-benefits can be quantified for building decision makers to move beyond first- least-cost decision-making. Based on TBL framework is adapted to the built environment to capture the energy related environmental and human capital cost savings. The results from these calculations was evaluated with key users to measure how the TBL approach can change decision-making patterns. Five tasks describe the approach taken for this thesis, illustrated in figure 1.7 and appendix A2.

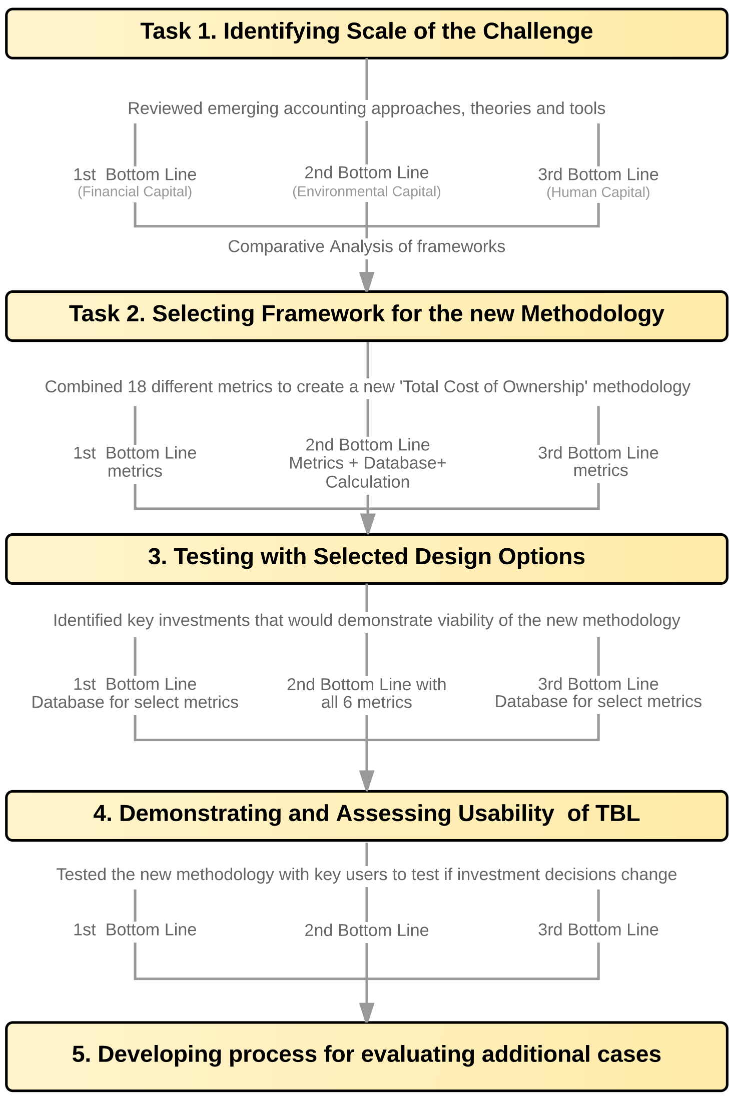


Figure 1.7: Thesis Methodology

1.3.3 Research Deliverables

In response to the four hypotheses, this thesis has the following deliverables:

Provide TBL databases and calculations for a select set of building investments with financial, natural and human capital cost-benefits. Test the impact of Triple Bottom Line calculations on decision-making priorities.

Provide a methodology for completing the first bottom line calculations using a life cycle calculation approach that captures the financial capital cost savings for select lighting and day lighting, façade and HVAC technologies. The methodology expands on the existing LCC capabilities by including more benefit categories into the calculations.

Provide a methodology and data base for completing second bottom line calculations that reflect the natural capital cost benefits of electricity savings from investments in high performance building technologies and systems.

Provide a methodology and data base for completing third bottom line calculations that reflect the human capital cost benefits, building on the CMU BIDS™ tool by adding new case studies, baselines, and calculation approaches.

1.4 Chapter outline

This section provides an overview of the organization of this dissertation.

Chapter 1: The Need for Life Cycle Decision Making in the Built Environment

The first chapter provides an introduction to the research and the rationale behind moving from a least-first-cost approach to an approach based on the triple bottom line that integrates financial, environmental and human cost benefits. The existing gaps under each bottom line are discussed to illustrate the need for further research.

Chapter 2: Financial Capital: The 1st Bottom Line

The second chapter identifies the need for the first bottom line to move beyond first cost decision-making and reviews existing literature to make the case for accounting for first bottom line savings from high performance building investments. Existing 1st bottom line approaches and the modified financial capital calculation model developed as part of this thesis is introduced. Twelve building investments are also introduced to support the iterative calculations central to the TBL decision support methodology.

Chapter 3: Environmental Capital: The 2nd Bottom Line

The third chapter identifies the need for the second bottom line to move beyond traditional financial decision-making, and reviews existing literature to identify the measurable environmental outcomes of electricity generation. The environmental capital calculation model is developed, and the critical datasets on fuel sources and mix for power generation in three economies are introduced.

Chapter 4: Human Capital: The 3rd Bottom Line

The fourth chapter identifies the need for the third bottom line and reviews existing literature to identify the measurable human benefits from high performance building investments. Existing 3rd bottom line approaches and human capital calculations are illustrated.

Chapter 5: Generating Triple Bottom Line Proof Sets

This chapter presents the results from testing the TBL framework and decision support methodology on twelve selected building investments, selected to utilize the breadth of performance benefits defined in Chapter 2,3 and 4. Results show that the TBL methodology for evaluating life cycle costs in iterative and additive steps for selected energy efficient building investments expedites the payback periods and increases the ROI and NPV.

Chapter 6: Proving the Value of TBL Calculations

This chapter presents the stakeholder response to TBL accounting through surveys that 'tested' thresholds for investing in high performance building systems given TBL calculations. Decision maker response to the Triple Bottom Line calculation, tested during this effort, confirms that when TBL information is provided, decisions to invest shifts in favor of high performance, energy efficient technologies.

Chapter 7: Conclusions, Limitations and Future Research

The final chapter highlights the contributions, limitations and future directions for this research. The main contribution is the development of a Triple Bottom Line decision support methodology, with a framework for calculations and communication that can effectively shift decision maker commitments to invest in high performance technologies and systems.

Chapter 2

Financial capital: The 1st Bottom line

2.1 The need for the 1st Bottom line

Commercial real estate is an investment undertaken for economic benefit. Traditionally, an owner or developer seeking capital for a project needs to consider the property risk and address concerns of capital decision makers (Ruegg & Marshall, 1990). When doing this, the real estate project must show a return on investment and positive financial impact (the 1st bottom line) to make it worth the owner's or investor's risk (Stone, 1983; Ruegg & Marshall, 1990). Owners, developers use total first costs or costs per square foot as the 'currency' for making design decision and this metric often binds the full set of design and delivery stakeholders.

In addition to total first cost, investors have been found to limit their investments to those "that can be paid back through energy savings in approximately 3.5 years on average" (Institute for Building Efficiency, 2012). Which is a very short time frame to justify investment using energy savings alone. The proposed 1st Bottom Line, asks decision makers to move beyond first cost to consider a life cycle cost over a set time period. The time period could be three years or a hundred years as set by the owner or developer or limited to the life of the technology or system in discussion. The 1st Bottom Line accounting approach is based on simple payback or return on investment (ROI) calculations, as well as net present value calculations (NPV).

The first bottom line has to account for the value of the project while balancing concerns around budgets, overspending, and uncertainty. Because of these concerns, projects are often value engineered. Originally developed for the manufacturing industry, the methodology has been consistently used in the construction industry (Dell'Isola, 1988) to identify opportunities to reduce construction costs, optimize performance, reduce operating expenses, and shorten building delivery time, without sacrificing functionality (Bazjanac et al., 2014). In its current form, value engineering has become a systematic procedure that is directed towards the achievement of the required functions without cost overruns (Jensen & Maslesa, 2015). Too often the focus of value engineering is on cost cutting alone (Green, 1994). This intent to trim project budgets increasingly results in last minute design changes which can have adverse and unintended impacts on building performance, energy use, and the health and productivity of occupants (Mills et al., 2004).

The financial impacts of design choices over time, over any time period from albeit 3 years or 100, would by necessity need to include: utility costs, maintenance and repair costs, replacement costs, churn costs, insurance and litigation risk costs, tax costs, and future business cost-benefits. The first cost of a building project undoubtedly becomes a carrying cost which needs to be balanced against each of these additional carrying costs. The most limiting cap on this annual carrying cost analysis is the availability of initial investment dollars and the depreciation of the built assets. The years of the loan establish a project investment life cycle. However, buildings are treated as assets that have a declining value when their systems and materials age and require replacement or repair. The declining paper value offsets the income the building generates and triggers the opportunity to renovate buildings to improve performance (Gelfand & Duncan, 2012).

Many opportunities for improving the economic performance of buildings can be enhanced through 1st bottom line, life cycle calculations. The carrying cost savings from investing in high performance building technologies and system can be taken into bottom line decision making to favor those investments. This creates value for the property owner and developer, lowers life cycle maintenance and operating costs, and improves the net operating income.

2.2 Identifying measurable financial outcomes for 1st bottom line

Research shows that stakeholders receive many compelling benefits from high performance building investments throughout the life cycle of a building. Some of these benefits can be quantified within a lifecycle calculation now available to decision makers when they are making capital expenditure decisions.

2.2.1 Financial outcomes that can be quantified across investment categories

Energy and non-energy operating costs can be a critical part of building's bottom line savings. Investments in high performance can reduce net operating costs for owners by including savings from lower energy and water use costs, maintenance costs, insurance premiums and churn rate. There is ample evidence on energy and water savings from investing in energy efficiency, but there is limited set of data available on the other benefits. The following section discusses eight different financial benefits and the available data that could influence a decision. These benefits are rarely taken into consideration and research in this area can help real estate, construction, engineering, developers, and architect's decision-making capabilities in favor of high performance building technologies and systems.

Utility Benefits: energy and water savings

The most widely accepted and recognized benefit from high performance green buildings is reduced energy costs from lower demand for heating, cooling, lighting and ventilation and water consumption. There are three types of energy savings in green buildings – 1) direct energy savings which are due to the use of efficient building technologies that use less energy; 2) indirect, economy wise energy savings that are due to drop in overall demand for energy, that may reduce the overall market price for energy and 3) "embodied energy" savings from reduction in the amount of energy used in materials and building construction (Kats, 2010).

Buildings with high performance systems and technologies are often cheaper to own and operate, making them extremely attractive in regions where energy and water costs are major considerations (Wiley et al., 2010). For example, investments in lighting upgrades, heating improvements, occupancy controls and envelop improvements yield immediate benefits in energy consumption and reduced operational costs (Gelfand & Duncan, 2012). As energy prices escalate, operational energy efficiency will become one of the key considerations for building investors.

Even more energy savings in high performance buildings are possible when other factors such as location, building design and building management that influence performance are considered. Compared to a code compliant building, high performance LEED rated buildings in the United States, save energy in the range from 25%-30% (World Green Building Council, 2013;Kats & Capital, 2003;Fullbrook & Jackson, 2006). The energy savings for retrofits is not as high. In a post retrofit study of a set of buildings in Singapore, energy savings of 17% are reported for retrofitted buildings (Yu et al., 2011). Another real estate firm in the U.S. reports typical savings of 3% - 15% in utility bills on properties that have undergone a retrofit (Bernstein & Russo, 2011)

Beyond energy, high performing green buildings offer other utility cost savings such as reduced water use. With concerns regarding scarcity of new and existing water resources and the increasing per capita water consumption, water and sewer rates, there is growing recognition of water saving initiatives that result in water, energy, and operation and maintenance savings (WBDG,2010). In a 2010 study by Kats, a 39% water consumption savings in high performance buildings are reported over comparable conventional buildings when water saving strategies such as water reuse and water efficient plumbing fixtures, are implemented (Kats, 2010).

Water conservation can be in different forms, from a reduction in outdoor water use for landscape and irrigation needs, to use of more efficient appliances and leak control indoors. The direct financial benefit of water conservation strategies is the reduced expenditure for the provision of water and disposal of waste charges. The indirect benefits include savings for the state in form of reduced costs for facilities construction and expansion and preventing potential environmental damage (Kats & Capital, 2003). Through rainwater harvesting, permeable surfaces high performance buildings reduce storm water runoff. This yield benefits in areas where the waste water and storm sewer systems are combined, and excessive runoff during storms results in sewage overflow. In regions that charge individual building owners for storm water runoff that leaves their site, high performance green buildings can reduce this charge and add to building owner's bottom line (CBPD, 2008). Even though water costs are usually a small part of the operating budgets, water conservation strategies can go a long way in areas with high water rates and scarcity of water.

Energy and water cost savings from high performance technology investments "typically exceed any design and construction cost premiums within a reasonable payback" ((World Green Building Council, 2013). There is however, caveats to achieving the predicted performance and savings from high performance green buildings. Robust commissioning, effective management and collaboration between owners and occupiers (Bendewald etal., 2014) can help achieve the optimum performance. Other uncertainties that impact the financial value of lower future energy consumption include the type of building investments, life span of the technology and future energy costs.

Peak energy benefits: Demand Side Management for peak price savings

High performance building system help reduce peak loads. For much of the United States, especially the South and Midwest, air conditioning is the dominant energy use during peak load, and high- performance lighting and façade interventions can reduce this load. Designers can downsize building systems, particularly air conditioning and lighting loads while maintaining a comfortable indoor environment (Kats & Capital, 2003). Other examples of lighting and façade investments that can reduce peak energy are high performance lighting systems, providing task lights, using sensors to turn off unnecessary lighting, using daylighting as much as possible and utilizing plenum below a raised floor to deliver conditioned air building. In hot weather, reducing peak loads has the advantage of reducing cooling loads and the subsequent need for air conditioning during peak hours.

The value of peak reduction also includes avoided purchase of electricity, or paying a higher cost for the incremental units of electricity consumed, as well as avoided capacity costs (Lovins, 2003). During periods of peak power consumption, the generation and transmission and distribution (T&D) systems may be overloaded and dirtiest and most carbon intensive power sources brought online to meet the demand (CBPD, 2008). The benefit of reduced consumption is largest during periods of peak power consumption, as it helps "avoid congestion costs, reduce power quality and reliability issues, reduce pollution and the additional capital required to expand generation and T&D infrastructure" (Lovins, 2003)(McAuliffe, 2002). Many utilities across countries have begun to provide financial incentives to customers to cut power consumption by implementing dynamic pricing policies and programs allowing for the tuning of demand to ensure that it matches the supply at times and reduces expenditure for utility (Demand Side Management). High performing building systems have the ability to reduce peak loads by permanently reducing power consumption or reducing demand at the operation level during a demand response event.

From an individual building's perspective, the impact are measurable and can seem isolated, but when this impact is aggregated at the state or national level this impact is significant when multiplied by hundreds of thousands of buildings (Lovins, 2003). A study by McKinsey & Company found the collective investment in building energy efficiency and appliances, and in industrial efficiency across the United States through 2030 could result in $300 billion savings from avoided investment in power generation (Creyts et al., 2007).

The reduction in demand driven by investment in energy efficiency can significantly shave off the peak loads.

Facility management benefits: maintenance and repair manpower & material savings

The most obvious non-energy benefit of investing in energy efficient technologies is in the savings from maintenance and manpower costs for installation (Lovins & Rocky Mountain Institute, 2011). Building maintenance includes the routine ground and janitorial maintenance manpower, processing of work orders and deferred maintenance for non-capital projects. On average, these maintenance costs for green buildings are 5-10 % less than average buildings (Bendewald etal., 2014) but includes instances where these savings are higher. For example, in U.S General Services Administration buildings, the maintenance costs of green buildings were 13 % less than the baseline buildings (Fowler & Rauch, 2008).

The other facilities management benefit is from repair manpower and material savings from fewer replacement cycles. The number and timing of capital replacement depends on the estimated life of the system and length of the service period (S. K. Fuller & Petersen, 2006). For example, investing in indirect lighting requires the light to be directed towards surfaces instead of spaces, and thus requires fewer fixtures and wiring and hence saves capital costs. Similarly, when LED lamps are installed in buildings, they last three times longer than CFLs and about 25 times longer than incandescent bulbs. A National Academy of Science study found that where lights are difficult to change, such as places that are hard to reach or where paid staff changes lamps "the value of reduced maintenance greatly exceeds the value of energy savings" (National Academy of Sciences, 2010).

Still, maintenance and repair material cost savings alone cannot be used to make the business case for higher quality building systems as "there are very incomplete records on causes of maintenance and repair costs" or the benefits of different engineering solutions (Loftness et al., 2005). There is some evidence of maintenance cost reductions in the form of reduced resources to change lighting, performing janitorial services, but not all related savings have been identified.

Replacement benefits: longevity, depreciation, waste savings

The next financial benefit reviewed as part of this study includes investing in high performance building technologies is in the replacement costs incurred when major systems and components are replaced. A typical feature of high performance buildings is the focus on the longevity and durability of systems and finishes. Durable high-performance systems need "long term less frequent replacement cycles" (World Green Building Council, 2013)(Kats & Capital, 2003) resulting in lower amounts of waste and cost savings for the owner. The cost savings could be in the form of avoided fees for disposing harmful contaminants like Polychlorinated biphenyles (PCBs) in light ballasts, mercury in lamps and the larger societal benefit of reduced cost of landfill creation and maintenance.

An important value of high performance systems to consider is the higher residual value at the time when the system is replaced or at the end of the study period. The value may be determined based on value in place, resale value, or scrap value, conversion or disposal costs. For a system at the end of its life, the residual value is small as it may have to include the cost of removal and disposal. A system that is functioning well adds significant value to the building and that value is reflected in its residual value. Value of a system with useful remaining life can be calculated using a linear depreciation prorating the initial cost model (S. K. Fuller & Petersen, 2006). Furthermore, materials that are cradle to cradle have a potential for additional income as the materials are recycled and recovered at the end of their life.

Organizational Flexibility Benefits: Churn Savings

There are significant cost-benefits of investing in high performance building systems to reduce the cost of "churn". Within buildings, churn is the cost of moving employee, either internally or externally. Churn expenses support the cost of reconfiguring working groups and individual spaces to accommodate changes in functions, densities, and work hours and changes in technologies. In 2010, the churn rates averaged 32 % for all types of facilities, while for corporations, the churn rate is around 41 % with median costs for move per person of $400 (IFMA, 2010;Bendewald etal., 2014). High performance systems often incorporate systems designed for adaptability, including raised floors and partitions, systems that allow for occupant movement and spatial reconfiguration without disruption, downtime or cost (World Green Building Council, 2013).

Studies reveal that there is on average 80 % reduction in churn costs due to high performance systems like underfloor air systems (CBPD, 2004). In the federal work sector the savings are even higher and are estimated to be 90% of reconfiguration costs and time, when reconfigurable furniture is used. An example is the Pennsylvania Department of Environmental Protection, which was able to achieve churn cost savings of up to 90% for a conventional office, by investing in a new building with raised access flooring, underfloor air, and quick disconnect manufactured power and data cabling. The measured cost per move of $2500 cost was reduced to approximately $250 per workstation (Toothacre, 2001) offering another tier of cost savings.

Real estate benefits- rental income, speed of rental, occupancy rates, public relations

Green buildings provide greater real estate value by offering better working and living environments. Multiple studies show rents and occupancy rates are higher in green high performing buildings compared to conventional buildings. An analysis of green buildings labeled under the LEED rating system or ENERGY STAR program in the U.S and Green Star rated buildings in Australia reveals that green buildings command rental premiums in the range of 0% - 17% (Wiley et al., 2010;Miller et al., 2008; Eichholtz et al., 2010). Figure 2.1, illustrates the range of rental premiums for offices in the U.S. and Australia as reported in various studies (World Green Building Council, 2013).

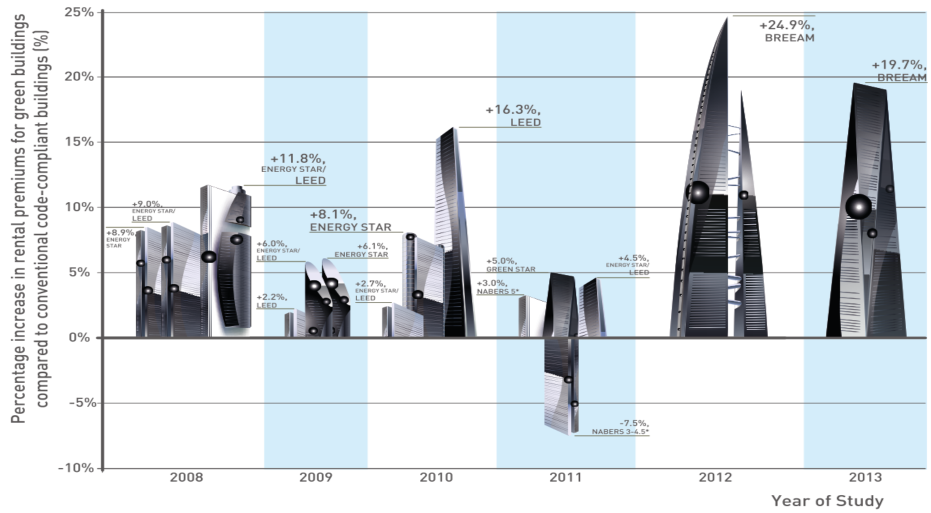


Figure 2.1: Rental rate increase in green buildings compared to conventional code compliant buildings (World Green Building Council, 2013)

A 2014 CoStar report for the California market found non-LEED or non-ENERGY STAR certified buildings in Los Angeles command an average of $2.16/ft2, but tenants were willing to pay $2.69/ft2 for ENERGY STAR certified buildings and $2.91/ft2 for LEED certified spaces respectively (Better Buildings Challenge, 2014). High performance green buildings are also correlated with rents up to 10 % higher than comparable non-green buildings (NRDC, n.d.).

There is also evidence that the reported occupancy rates increase in green buildings. In a review of recent studies that link investments in green building to an increase in real estate value, occupancy rates were found to increase on average 10% and as much as 23% (Miller et al., 2008;Fuerst & McAllister, 2010;Fuerst & McAllister, 2011; Wiley et al., 2010;Eichholtz et al., 2010;Eichholtz, Kok, & Quigley, 2010). There are examples of even the 'Lease-up rates' or the time period for newly available property to attract tenants and reach stabilized occupancy for green buildings to go up as much as 20 % above average (NRDC,2012).

A final real estate benefit includes buildings with better sustainability credentials have increased marketability. Studies indicate "green buildings being able to more easily attract tenants and command higher rents and sale prices" (World Green Building Council, 2013).Studies that compare certified green buildings to non-certified buildings in the same market, show green buildings tend to have a higher sales price. LEED and Green Star certified buildings command higher sales premiums in the range of 0-30% (World Green Building Council, 2013; Newell et al., 2014; Eichholtz et al., 2013). Studies show a relationship between green high-performance buildings and the ability to command higher sales price and rents. However, local conditions such as the location of the property, water and energy prices, comparable property rents and prices will have significant impact on the rental and occupancy rates.

Integrated first cost benefits: tunneling through the cost barrier savings

Benefits of high performance building technologies include their ability to capture multiple savings, such as savings on both energy and equipment costs. This is a more integrative benefit as it includes cascading effect of savings. Accounting for the energy cost savings as the only benefit from high performance building investments often overlooks the avoided capital expenses associated with those energy savings. These capital expense savings are achieved through the capital equipment that can be reduced or completely eliminated when investments are made in high performance technologies. Hawken and Lovins (1999) use this 'whole system engineering' approach to propose the 'more for less' way of thinking for design and engineering solutions. This method integrates the design of an entire system so that all accompanying benefits are accounted for, and the sequencing of the design interventions is done in a way that each measure achieves multiple benefits. Actual design and engineering practices reveal this possibility of saving even more energy that can often "tunnel through the cost barrier," bringing the overall cost down. An example of tunneling through the cost barrier approach is investing in thick insulation and 'heat tight' windows to eliminate the need for a furnace, which is a more capital-intensive solution than the cost of the efficiency measures.

This concept of integrated first cost savings has been exemplified in the retrofit of Empire State Building with the upgrade of 6,514 double glazed windows. The windows were remanufactured onsite into superwindows, and were able to block at least two thirds of winter heat loss and half of summer heat gain, cutting the building's peak summer cooling load by one third (Lovins & Rocky Mountain Institute, 2011). Engineers were able to renovate and reduce the existing chillers rather than replacing and enlarging the old system. By cutting the peak loads, the renewal of old interior cables was avoided. The avoided capital cost of upgrading chillers and renewing old interior cables was used to pay for the windows and other upgrades. Such whole system life cycle costing in which all benefits are properly accounted for is a widely accepted principle, but often ignored in practice.

Managing Risk: Regulatory code, market risk and tax (depreciation), and insurance savings

A less obvious benefit of high performance buildings is their ability to manage risk. With governments increasingly implementing regulations that target sustainability issues, real estate developers can be ahead by investing in high performing buildings. Mandatory disclosure, building codes and laws that ban inefficient buildings are examples of regulatory risks, that can affect an investor's revenue stream as they may risk lower incomes from their properties unless energy performance is improved (World Green Building Council, 2013Cities like New York and San Francisco, mandate public disclosure of energy use data with an intent of encouraging investors to incorporate available data into their investment decision making. By pursuing energy efficient retrofits firms can lower their operating expenses while mitigating regulatory risks and rising energy costs (Peterson & Gammill, 2010).

In addition to managing regulatory risks, high performance technologies mitigate market risks. Green buildings offer indirect benefits related to reduction in property taxes, different "cap rates to support energy efficient properties and portfolio" (LaSalle Investment Management, 2010) and even decreasing the speed of depreciation for green buildings (Parker, 2008). High performance buildings have better valuations that "reduce the risk of the building's loans going underwater when general market values decline" (Lovins & Rocky Mountain Institute, 2011). In other words, High performance building technologies offer a buffer against declining market values. Due to the multiple indirect benefits discussed above, financiers have developed tax incentives, bond financing and green leases to create pathways for financially rewarding investments in high performance technologies and systems. Certain markets where green buildings are not mainstream, there are even indications of 'brown discounts' leading buildings that are not green to sell for less (World Green Building Council, 2013).

The last type of risk that high performance systems can help manage is the insurability of buildings. With frequent extreme weather events and systematic changes in weather patterns, the key risk is the insurability of the buildings (World Green Building Council, 2013). In certain areas prone to flooding, insurers do not find it economically viable to provide flood protection cover to buildings. There are some insurance companies like Liberty Mutual Insurance, Hanover Insurance company and others that offer property owners lower premiums and improved protection against loss, especially when they implement energy efficient measures like commissioning, efficient windows and daylighting. Liberty Mutual Insurance under its Fireman's Fund, offers pricing discounts to commercial properties that are green (Mincer, 2009), while Hanover Insurance Company, gives 10 % discount on homeowner property insurance for homes with solar and energy efficient features (Mills, 2003). Real estate decision making thus need to address extreme weather events such as flooding, subsidence and ability of building skin and systems to cope with increased ambient temperatures and changing rainfall patterns. Investors will need to address the changing environment if they are not already addressing these risks in the real estate investment decision making.

2.2.2 Selected outcomes to illustrate the LCC approach

Based on a combined review of guidelines for architectural design and CSR reporting, from the longer list of benefits discussed above six financial outcomes have been identified that are frequently included in budget reporting and have an appropriate level of quantitative data necessary for the research design and methods utilized in this thesis. The six selected outcomes are included within the first bottom line calculations to illustrate the LCC approach developed as part of this research (see table 2.1 for the selected 6 outcomes).

Table 2.1: Financial benefits from high performance building investments

	Financial Capital : Economic impact of investments							
	Utility Benefits: Energy & water	Facilities Management Benefits: Maintenance & repair material and manpower	Replacement Benefits: longevity, depreciation &waste savings	Organization Flexibility Benefits: Churn savings	Real Estate Benefits: Rental income, Occupancy rate, PR	Integrated first costs benefits: tunneling through cost barrier	Peak Energy benefits: Demand side management	Managing Risk: Code, tax and insurance savings
AIA 2030	•		•		•			
LEED v4	•		•		•			
GRI	•		•					
DJSI	•		•		•			
GRESB	•		•					
RMI (2014)	•	•		•	•			•
WGBC (2013)	•	•			•	•		
Loftness et al. (2005)	•	•	•	•		•		•
Kats (2003)	•		•			•	•	•

Srivastava 2017

2.2.3 Illustrative set of investments

To quantify the first bottom line financial savings and third bottom line human health and productivity benefits, twelve energy investments in key areas: daylighting, shading, natural ventilation, mixed mode conditioning and whole building performance investments were identified. In the section below, a brief description of each of the investments is provided.

1. Install occupancy sensors for closed spaces for energy and environmental benefits.

Install occupancy sensors in all closed spaces on the occupied floor. This accounts for over 25% of the floor area in most offices. In these rooms, the occupants should turn on the lights manually, and the sensors should be set to turn off lights automatically, thus becoming ‘vacancy sensors’.

2. Add daylight dimming on perimeter lights for energy, environment and health benefits

Install daylight sensors for on/off or dimming controls of the first and second rows of lights on each building facade. Daylight sensors can be installed without full automation systems and can be introduced with wireless interfaces to existing fixtures, making them cost effective retrofits.

3. Lower ambient light & add task lights for energy, facilities, integrated first cost savings, environmental, health and productivity benefits

Modify the existing lighting system to separate ambient lighting from task by removing some of the lamps in the ceiling fixtures to reduce ambient light levels and buy LED task lights for each workstation.

 + 

4. Upgrade lighting with Individually addressable LED lamps for energy, facility, environmental, health and productivity benefits

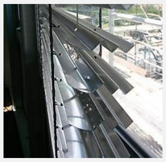
Install in digitally addressable ballasts with distributed controllers for two-way communication between occupants and building automation systems for local lighting control.

5. Replace fixtures with integrated LED lighting and dimming & IP addressable controls for energy + maintenance + waste savings, environmental and health and productivity benefits

Invest in high performance fixture upgrades that include replacement of existing 2'x4', 1'x4', or 2'x2' troffers containing between two to four T12 or T8 lamps with "vertically integrated" LED light fixtures (lamp, ballast, fixture) with add-ons for dimming and IP controlling.

6. Select blinds for light redirection, shade and glare control for energy savings, environmental and productivity benefits

Install well designed and managed blinds to ensure high levels of daylight without glare and overheating and provide critically needed views of the natural environment. Appropriate usage of blinds can even reduce heat loss on winter nights and allow for night sky cooling on summer nights.



7. Add light shelves in clerestory for energy savings, environmental and productivity benefits

Introduce light shelves or inverted blinds/louvers in the clerestory area. Light shelves distribute daylight deep into the building while providing glare control and shading. When well designed, they can ensure high levels of daylighting without glare and overheating, and even reduce heat loss on winter nights.

8. Celebrate external shading energy savings, environmental and productivity benefits

Install dynamic shading devices that can be daily or seasonally adjusted to reflect sunlight when required, while allowing effective daylight penetration and solar gain during the winter. Fixed overhangs, horizontal louvers and fins, and dynamic awnings provide shade with daylight, without diminishing our views.

9. Ensure windows are operable for natural ventilation energy, environmental, health and productivity benefits

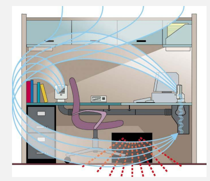
Introduce operable windows to use natural ventilation for cooling and breathing, or night ventilation for pre-cooling the building to offer hours of free cooling the next day. To avoid the possibility of rain coming in, and to ensure controlled air flow, use of awning, drop-kick, and pop-out windows are emerging in modern offices.

10. Integrate Underfloor Air and networking for energy, churn cost and integrated first cost savings, environmental and health benefits

Implement Underfloor air distribution (UFAD) system to use the plenum below a raised floor to deliver space conditioning and provide ventilation in a space. While delivering space conditioning the system cuts fan and cooling loads, while substantially lowering air conditioning load. Electrical and communications cabling are also run through this system.

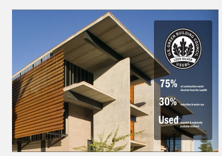
11. Engineer Individual temperature control for energy savings, environmental, health and productivity benefits

Provide thermal control for individuals through desk-based task conditioning systems for temperature, air speed and air direction. Separating ambient from task cooling conditions while saving energy increases occupant comfort and performance.



12. Invest in building performance goals for Integrated first cost savings + energy savings + real estate, environmental, human health and productivity benefits

Implement whole building design approaches such as LEED, for multiple benefits such as lower energy, waste, lower environmental and emissions costs, lower operation and maintenance costs and savings from increased productivity and health.



2.2.4 Selected Research on first bottom line benefits of energy investments

For the selected investments, financial benefits were identified from published international field and case studies (Table 2.2 and appendix for list of sources). Publications with quantitative data were reviewed on the basis of the type of study, sample size and statistical significance of results.

Table 2.2: Economic impact of selected building technologies

Financial capital: economic impact of investments						
	Energy	Facilities	Replacement	Churn cost	Real estate	Integrated cost
Install occupancy sensors	**15- 70%**[1]					
Add daylight dimming on perimeter lights	**20 - 64%**[2]					
Lower ambient light & add task lights	**13 - 40%**[3a]	**$0.05/sqft**[3b]				
Upgrade lighting with Individually addressable LED lamps	**59-87%**[4a]		**77%**[4b]			
Replace fixtures with integrated LED lighting & IP controls	**25-76%**[5a]	**80%**[5b]	**100%**[5b]			
Select blinds for light redirection, shade and glare control	**20-32%** lighting[6a] **3%** Cooling[6b]					
Add light shelves in clerestory	**30%**[7]					
Celebrate external shading	**20-25%** cooling[8a] **20-30%**[8b]					
Ensure windows are operable for natural ventilation	**50%** energy[9a] **15- 35%** cooling[9c]					
Integrate Underfloor Air & networking	**16.5%**[10a] **1.55 kWh/sqft** Milam (1992)			**90% decrease**[10b]		**$0.43 – 7.5/sqft**[10c]
Engineer Individual temperature control	**0.06-30%**[11]					
Invest in building performance goals	**33- 73%**[12a]			**66%**[12b]	**2.8-7%**[12c]	

1. EPA (1998); Maniccia et al. (1998); Mahdavi et al. (2008); Williams et al (2012)
2. Lee & Selkowitz (1998); Verderber & Rubinstein; Jennings et al. (2000); Boyce (2000) (2016);Li et al (2014)
3a. Yun Gu (2011); Linhart (2011); 3b. Knissel(1999)
4a. Energy User News (2001); Lee and Selkowitz (1998); Hedenstrőm et al. (2001); Romm & Browning (1994); b. Hedenstrőm et al. (2001)
5 Meyers (2009); **N**ewsham et al (2007); b. Meyers (2009)
6a. Lee et al. (1998);De Carli & De Giuli (2009); b. CBPD (2012)
7. Mirjam et al. (2011)
8a. DOE (2012); b. Hwang & Kim (2011)
9a. Steemer & Manchanda (2009); c. Climate Suitability tool (2007)
10a. Fisk et al (2005); b. Toothacre (2003); c. Milam (1992); Flack & Kurtz(196); Bauman et al (1992); Burt (2007) Dieckmann et al (2010)
11. Melikov et al. (2012)**;** Kaczmarczyk (2008); Makhoul et al 2012, Niu et al (2007);Shin-ichi Tanabe et al (2007); NewMancini et al (2009)
12a. Torcellini et al. (2002);Agha-Hossein et al (2013);Betterbricks (2006); Pendelberry et al. (2012); b. Pilon & Gee (2003) and c.Eichholtz et al (2010);Kok et al. (2012); Fuerst & McAllister (2011

2.3 Financial capital calculation model

2.3.1 1st BL NPV based on existing LCC model

The first bottom line, financial cost benefits, are based on a total Life Cycle Cost (LCC) approach. The scope of the life cycle cost is defined as the sum of all recurring and non - recurring costs over the full life span or a study period of a good, service, structure or system (Fuller, 2008). If often includes purchase price, installation cost, operating cost, maintenance and upgrade costs and salvage values at the end of ownership or it useful life.

LCC is a method for assessing the total cost of facility ownership and is used to make cost effective choices for a given project, facility or system (Fuller, 2016). The emphasis is on cost effectiveness as the LCC method is used to evaluate alternatives which compete on the basis of costs (Ruegg & Marshall, 1990) yet fulfill the same performance requirements. The basic LCC method is a straight forward method of accounting for present and future costs of an energy conservation project over its life-cycle. For example, in evaluating the choice of exterior wall construction, including the building energy costs if it is affected by the choice and subtract any positive cash flows such as salvage or resale values when making the decision. General formula for the LCC present value model (NIST,1995):

$$LCC = \sum_{t=0}^{N} C_t/(1+d)^t \qquad \textit{(Equation 1)}$$

Where,

LCC = Total LCC in present value dollars of a given alternative

C_t = Sum of all relevant costs, including initial and future costs, less any positive cash flows, occurring in year T

N = Number of years in the study period and

d = Discount rate used to adjust cash flows to present value

The LCC formula requires all costs are identified by year and by amount. This requires extensive calculations, especially when the study period is more than a few years long and there are annually recurring amounts. LCC has an important role because of the influence of total costs rather than the initial costs of ownership. The decision is then focused on the total cost of ownership rather than the first cost.

LCC is particularly suited for evaluating building design alternatives that satisfy a required level of building performance, but may have different initial investment costs, operating, maintenance and repair costs and life cycles (Fuller & Petersen, 2006). The evaluation criteria for an LCC analyses could be the ability of design alternatives to meet occupant comfort, safety, meeting building codes and engineering standards and or even aesthetic considerations. LCC provides a significantly better assessment of the long-term cost effectiveness of a design alternative than other economic models that rely either on first costs or short term operating costs.

NIST LCC approach

The National Institute of Standards and Technology (NIST) has developed a simplified LCC evaluation criteria for computing the energy and water savings from all investments in building energy and water conservation and renewable energy projects in federal facilities. To the extent possible, energy and some non-energy savings of energy and water conservation projects and renewable projects in federal buildings are included in the evaluation.

One of the most challenging tasks of an LCC analysis is to determine the economic effects of alternative design options and to quantify the effects and express them in dollar amount (Fuller,2016). Building related costs usually include - initial design development and capital investment and financing costs, fuel costs, operation and maintenance costs, replacement costs, alteration, refurbishing and improvement costs, salvage and retirement costs and some non-monetary benefits or costs. LCC attempts to estimate all the relevant present and future costs in the building investment to enable decision makers to select the most appropriate investment from various investment choices.

A critical aspect for an LCC is the time or the study period over which the costs and benefits related to the capital investment decision are accrued. The study period is the time over which the costs and benefits related to a capital investment decision are of the interest to the investor (Fuller & Petersen, 2006). Usually the study period begins with the base date and includes the service period or the beneficial occupancy period. There is no one correct study period for a project as investors may have different time perspectives with regards to the investment or the technology may have a set lifecycle.

While estimating capital costs, the study period can coincide with the life of the project, and/or be a different time period depending on the time horizon of the investor. When the expected life of the system is shorter than the time horizon of the investor, NIST guideline states the life of the alternative should be extended by assuming a replacement one or more times (Fuller & Petersen, 2006). Other variable costs include operational expenses for energy and other utilities that are estimated based on consumption, current rate. Energy prices are assumed to increase or decrease at a different rate than the general inflation and this price escalation should be taken into account when estimating future energy costs.

LCC analysis can be performed in constant dollar or in current dollars. Constant dollar analysis excludes the rate of general inflation and current dollar analysis includes the rate of general inflation in dollar amounts, discount rates, price escalation rates. Both types of calculation result in identical present value life cycle cost (Fuller, 2016). As per NIST guidelines for completing LCC calculations, constant dollar analysis is a consistent norm for federal projects. The constant dollar method has the advantage of not requiring an estimate of the rate of inflation for the study period.

After identifying the study period, all relevant costs and savings and discounting them to present value, they are added to the equation below to arrive at total life cycle cost:

$$LCC = I + Repl + E + W + OM\&R - Res \qquad \text{(Equation 2)}$$

Where,

LCC	= Total LCC in present value dollars of a given investment
I	= Present value investment costs
Repl	= Present value capital replacement costs
E	= Present value energy costs
W	= Present value water costs and
OM&R	= Present Value non-fueling operating, maintenance and repair costs
Res	= Present value residual value (resale, scrap or salvage value) less disposal

LCC analysis increases the likelihood of choosing a project that saves money in the long run, but there can be uncertainties associated with the LCC result. The uncertainties are with respect to the costs or the potential savings. Thus, LCC is most beneficial when performed early in the design process when estimates of costs and savings are available.

2.3.2 Equations for 1st bottom line calculations

In the proposed TBL accounting methodology, the first bottom line financial capital cost savings are calculated based on NIST's LCC evaluation criteria. The NIST equation includes only a limited set of savings and as discussed in the previous section, there is quantitative data available on other non -energy savings such as churn cost savings, real estate value benefits and integrated first cost savings.

As part of the first bottom line calculation, the NIST equation is modified to illustrate the additional financial cost savings. Water savings are still part of the equation, but none of the first bottom line calculations include the savings as energy investments described in section 2.2.3 do not have any associated water savings. The salvage savings that are part of the NIST equations are now included with the capital replacement savings. The study period is considered as 15 years to arrive at a common study length as technologies and systems used for illustrating the TBL approach have different lifecycle periods.

$$First\ bottom\ line\ savings = I + E + OM\&R + water + Repl + \boldsymbol{churn} + \boldsymbol{real\ estate} + \boldsymbol{first\ cost} \qquad \text{Equation 3}$$

Where,

I	= Investment costs
E	= Energy savings
OM&R	= Maintenance and repair cost savings
water	= Water cost savings
Repl	= Capital replacement cost saving
Churn	= Churn cost savings
Real estate	= Real estate value savings
first cost	= Integrated first cost savings

To calculate the six different types of savings following equations are used:

1. E = Energy cost savings

The calculation of energy savings is based on avoided energy consumption costs from investing in the technology. The future cost savings are automatically converted to its present value. For computing the energy saving it is critical to determine:

Energy savings from the building technology being considered. These savings can be collected from international literature, peer reviewed journal and conference papers and or manufacturer data.

Quantity of energy used at the building site by the building type and system (lighting, ventilation, heating, cooling or whole building energy). The baseline energy use differs by the building type, type of energy used and can be estimated using technical specifications, benchmarked energy use data and or computer simulations.

Current energy prices for the type of fuel used. The energy prices should be based on the utility's rate schedule.

Normalizing the savings on a per person basis, provides additional insight to illustrate the occupant as the critical unit of measurement.

$$First\ year\ energy\ savings = \%\ savings\ *\ Baseline\frac{kwh}{sqft}\ by\ system\ *\ Energy\ cost(\frac{\$}{kwh})\ *\ gross\ area$$

(Equation 4)

Energy cost escalation is important to capture in this model and reflects the increasing annual costs of energy. The calculated present value of recurring energy savings accrued over N=15 years uses the following formula:

$$Present\ Value\ of\ energy\ savings = \frac{annual\ energy\ savings}{(r-i)}\left(1-\left(\frac{1+i}{1+r}\right)^n\right)$$

(Equation 5)

Where,

r = rate per period
i = energy inflation rate
n = number of period

2. OM&R = Operation maintenance and repair cost savings

Building maintenance includes the routine ground and janitorial maintenance, processing of work orders and deferred maintenance for non-capital projects. Investing in this retrofit reduces the maintenance costs through fewer material and man hours required. For computing these savings, following data is required:

OM&R savings from the building technology being considered. Savings can be collected from international literature, peer reviewed journal and conference papers and or manufacturer data.

Baseline facility costs for maintenance. The Building Owners and Managers Association (BOMA) International, in collaboration with research firm Kingsley Associates, in its 2016 Office Experience Exchange Report (Office EER) estimate the expenses within the commercial real estate industry as seen in figure 2.2., BOMA estimates organizations spend up to $2.00 per sf on repairs and maintenance (BOMA International, 2016). With information from more than 5,200 buildings in 272 distinct markets across the United States and Canada totaling nearly 900 million square feet of space, the 2016 Office EER offers largest office sector data.

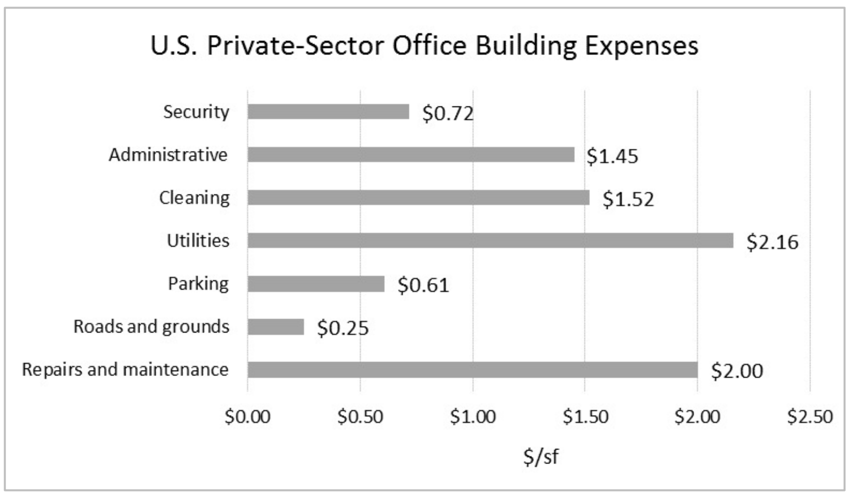


Figure 2.2: Organizational expenditure on repairs and maintenance (BOMA International, 2016).

Average facility size in square feet. For consistency in modeling, the first bottom line calculations are set at an average building size of 100,000sf.

$$First\ year\ OM\ \&\ R\ savings = \%\ of\ \ savings * \ maintencance\ cost\ per\ sqft\ \left(\frac{\$}{sqft}\right) * Square\ foot$$

(Equation 6)

Assuming these savings accrue over 15 years, the present value of the savings is:

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} OM\&\ R\ savings_t/(1+d)^t$$

(Equation 7)

Where,

N = Number of years in the study period and
d = Discount rate used to adjust cash flows to present value

3. Repl = Capital replacement cost saving

Sustainable products or systems specified for a building provide financial benefit due to fewer frequent replacement cycles and decreased cleaning and maintenance requirements. To calculate the capital replacement savings the along with the savings from investing in high performance technology the information on the replacement cost for the conventional technology is required.

Replacement savings from the building technology under consideration assembled from international literature, peer reviewed journal and conference papers and or manufacturer data.

Capital costs per replacement for a given technology. For example, if calculating savings from replacing T-8 or T-5 lamps with LED lamps, then the cost per replacement for lamp replacement is required.

$$First\ year\ Replacement\ savings = \%\ of\ replacements\ savings * Cost\ per\ replacment\ (\$)$$

(Equation 8)

Assuming these savings accrue over 15 years, the present value of the savings is:

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} Replacement\ savings_t / (1+d)^t$$

(Equation 9)

Where,

N = Number of years in the study period and

d = Discount rate used to adjust cash flows to present value

4. Churn = Churn cost savings

Churn is the cost of moving employee, either internally or externally. These costs support the cost of reconfiguring working groups and individual spaces to accommodate changes in functions, densities, and work hours and changes in technologies.

Decrease in churn costs from the building technology being considered. These savings can be collected from international literature, peer reviewed journal and conference papers and or manufacturer data.

Average Churn rate in organizations: IFMA tracks the churn and moves costs for different organizations. In 2010, the churn rates averaged 32 % for all types of facilities, while for corporations, the churn rate is around 41 %.

Cost per move: IFMA classifies office moves in three categories: box moves, furniture moves, and construction moves. Given the diverse mix of types of moves, the average cost per move is $809, while the median cost per move was $479.

$$First\ year\ churn\ cost\ saving = \%\ decrease\ in\ churn\ rate * \ churn\ rate\ (41\%) * \ Cost\ per\ move\ (\$)$$
(Equation 10)

Assuming these savings accrue over 15 years, then the present value of the savings is:

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} Churn\ cost\ savings_t / (1 + d)^t$$
(Equation 11)

Where,

N = Number of years in the study period and
d = Discount rate used to adjust cash flows to present value

5. Real Est = Real estate value benefits

Multiple studies show rents and occupancy rates are higher in green high performing buildings compared to conventional buildings. LEED certified buildings with higher levels of certifications indicate an average 3% higher rent and have a higher occupancy rate. The real estate value benefits are calculated based on:

Rental premium or the percentage increase in rent from international literature, peer reviewed journal and conference papers.

Prevalent market rent in $/sqft. The rental rates differ by the region, type of building and the class of building.

Average facility size in square feet. For the first bottom line calculations the average building size is 100,000sf.

$$First\ year\ real\ estate\ saving = \ \%\ \text{Rental}\ premium * \ Market\ rent\ \left(\frac{\$}{sqft}\right) * sqaure\ footage$$
(Equation 12)

Assuming these savings accrue over N years, the present value of savings is:

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} real\ estate\ savings_t / (1 + d)^t$$
(Equation 13)

Where,

N = Number of years in the study period and
d = Discount rate used to adjust cash flows to present value

6. First cost savings = Integrated first cost savings

A benefit of high performance building technologies is the ability to capture multiple savings, such as savings on energy and equipment costs. Accounting for the energy cost savings as the only benefit from high performance building investments often overlooks the avoided capital expenses associated with those energy savings. These capital expense savings are achieved through the equipment that can be reduced or completely eliminated when investments are made in high performance technologies.

Cost of the conventional or the usual technology that would be implemented. Once the cost is ascertained, cost differential between the conventional technology and the new technology can be calculated to determine the total savings.

Average facility size in square feet. For the purpose of the first bottom line calculations the average building size is considered to be 100,000sf.

$$First\ year\ churn\ cost\ saving = \text{Cost of (conventional technology} - \text{new)} * sqaure\ footage$$

(Equation 14)

Assuming these savings accrue over N years, then the present value of the stream of savings is:

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} integarted\ first\ cost\ savings_t/(1+d)^t$$

(Equation 15)

Where,

N = Number of years in the study period and

d = Discount rate used to adjust cash flows to present value

2.3.3 Assumptions and first bottom line data sources

The field studies that link high performance building systems to first bottom line cost-benefits are not limited to the US only. Given the lack of field studies, the calculations rely for now on international laboratory and field case studies to support TBL life cycle decision making.

Given the difficulty in securing energy efficient product costs by region in different regions, collection of national costs need to involve communications with manufacturers and professionals, while acknowledging that there are significant variations in the product and labor market across regions.

2.4 Limitations with modified financial model

The opportunity for improving the economic performance of buildings can be enhanced through 1st bottom line, life cycle decision making. Including carrying cost savings from investing in high performance building technologies and system into bottom line decision making can promote investments that bring value for the property owner and developer and improve the net operating income. The approach proposed as part of this thesis, encourages decision makers to move beyond the first cost decision making that has become industry practice, to one that includes the long-term life cycle financial benefits into the decision-making process (see Appendix B).

Many of the high-performance building investments have secondary and tertiary effects that cascade through the building. In the process of accounting for the life cycle benefits through traditional net present value, return on investment calculations, the long term environmental, human health and productivity benefits have been overlooked. The next chapter presents an approach for accounting for the environmental cost benefits from investing in high performance systems and technologies.

Chapter 3

Environmental capital: The 2nd Bottom Line

3.1 The need for a 2nd bottom line

Commercial and residential buildings consume 75 % of U.S. electricity use (EIA, 2017) to provide heating, cooling, lighting and operate electrical equipment. About 68% of that total electricity is generated from fossil fuels mainly coal, oil and natural gas which problematic (EIA, 2016). Combustion of these fuels to supply buildings with electricity results in emissions of greenhouse gases such as Carbon dioxide (CO_2), Methane (CH_4), Carbon monoxide (CO) and air pollutants such as Sulfur Dioxide (SO_2), Nitrogen Oxides (NOx), Particulate matter (PM) and heavy materials. With the increase in building electricity consumption, the proportion of these air pollutant emissions also rises.

GHG emissions and air pollution can cause several externalities. For instance, waste from power plants affects water quality and impacts aquatic populations and land use values (EIA, 1995). Emission of pollutants and greenhouse gases from fuel combustion affects human health, flora and fauna, and contributes to global climate change that exacerbates natural disasters and changes agricultural cycles. Scientists predict if emissions of greenhouse gases (GHG) from anthropogenic sources continues to rise, it will raise global temperatures by 2.5 to 10°F (McGregor et al., 2013). This will result in the rise of sea levels, more frequent floods and droughts and increased spread of infections.

In reaching a financial decision the developer or investor generally takes into account only those costs that he/she has to incur and often ignores other costs like the external costs which are borne by other groups or the community as a whole (Stone, 1983). To assist decision makers with capital expenditure decisions that meet financial thresholds and at the same time become part of the CSR reporting process, the approach to the second bottom line calculations values the environmental cost benefits from reducing building electric energy use. Electrical savings lead to reductions in greenhouse gases, air pollutants and water demands, and these reductions can be monetized.

While GHG and pollutant emissions pose several challenges, there are a variety of opportunities to reduce emissions associated with electricity generation, transmission, and distribution. One of the ways is to invest in energy efficient technologies to limit GHG and other pollutant emissions at the source of power generation while improving the bottom line (Kerr, 2017). Even though, there is significant reduction in emissions from investing in energy efficient technologies, these savings are typically not included in real estate capital expenditure decisions or the cost of doing business.

There are some notable exceptions, as some businesses are beginning to establish corporate sustainability initiatives which include GHG abatement plans (Creyts et al., 2007) and reporting on emission reduced from their activities. Even more environmentally minded businesses are using carbon pricing also called shadow pricing, to offset the costs and risks of greenhouse gas production (Weiss et al., 2015). Carbon pricing instruments create revenue that can further an organization's corporate sustainability goals by incentivizing investments in energy efficiency, reducing emissions, mitigating risks from future regulations (Weiss et al., 2015).

Besides corporate sustainability, international treaties like the 2015 Paris climate agreement have led to the emergence of carbon markets to establish a market value for reducing emissions (Gold Standard, 2017). A carbon market allows organizations to become more resilient to adverse impacts of GHG emissions by levying carbon taxes, emissions trading schemes, offsets and result based financing amongst others (Kerr, 2017). Both CSR and international carbon markets are possible prospects for building sector to use for reducing GHG and pollutant emissions.

There are several approaches to account and report on the reductions in air pollutants and GHG emissions, but they are not specifically tailored to the building sector. The Intergovernmental Panel on Climate Change guidelines (Garg et al., 2006), Greenhouse Gas Protocol for reporting Scope 1, 2 and 3 emissions (WRI, 2015) and ICLEI's GHG Protocol, all provide general guidelines to corporations on how to account for GHG emissions from their operations and activities. Sector specific approaches like the GREET model evaluates energy and emission impacts of advanced vehicle technologies and different transportation fuels (Argonne National Laboratory, 2017). For the building sector DOE's Buildings GHG Mitigation Estimator Worksheet (DOE, n.d.) and the Carbon Disclosure Project (CDP) measure, account and manage the amount of emissions. But these approaches do not yet translate the savings from reduced emissions into values that could be useful during building capital expenditure decisions.

To develop methodology for capturing the environmental benefits of reducing electricity demand for sustaining air and water resources, three levels of information are used. These include electricity fuel sources and power plant quality; the respective air pollution and water consumption consequences; and emerging valuation incentives for pollution reduction. A select set of greenhouse gases (GHG) and pollutants have been included in this framework that are responsible for a majority of the environmental damages and are released into the air by the burning of fossil fuels (Kats & Capital, 2003). In addition to air pollution and global warming, these pollutants cause respiratory illness, cancers, and developmental impairment as well.

The second bottom line calculation approach for this thesis does not include the environmental and societal costs or benefits of materials and assemblies installed and discarded, a calculation typically captured in life cycle assessment. This thesis is a "gate to gate" assessment of reductions in selected outcomes of power generation, which quantified to represent the environmental savings that can be attributed to energy efficient retrofits.

3.2 Identifying measurable environmental outcomes for 2nd bottom line

In the real estate sector, issues of environmental efficiency are often confounded with capital budgeting decisions that involve choices between the levels and types of initial investment to maximize investor returns. As illustrated in chapter 2, investing in building energy efficiency can save operating expenses, capital and material resources during operations, insure against future energy price escalation and simultaneously decrease air pollution and GHG emissions.

The next three sections elaborate on the three types of data required to complete the environmental cost-benefit calculation - diverse fuel type and power plant quality; the respective air pollution and water consumption consequences, and emerging valuation incentives for pollution reduction. For the purpose of this thesis and necessary calculations, aggregate baseline datasets relative to electric energy sources and environmental impacts will be used in three country contexts: (1) for an emerging economy such as India, (2) a country with mid-level sustainability goals such as the US, and (3) a leading country with low carbon growth goals such as the EU, to illustrate the possible low, medium and high range of second bottom line savings.

3.2.1 Diverse fuel type and power plant quality

Electricity is the largest energy source for buildings making them responsible for a large amount of corresponding emissions. A majority of these Scope 2 emissions occur at the point of electricity generation, and are caused by the burning of fossil fuels, industrial waste and non-renewable waste to generate electricity. The first type of data required for completing the second bottom line calculation is on what type of fuel (clean or dirty) is displaced, the quality and efficiency of the power plant.

Diverse fuel type & fuel mix (at the economy scale) in emerging, average and leading countries

The carbon content of the fuel used for electricity generation has a direct impact on amount of GHG and air pollutant emissions. Global trends in the fuels used for electricity generation reveal the ongoing dominance of coal worldwide, even though it is diminishing in the US and Europe (figure 3.1).

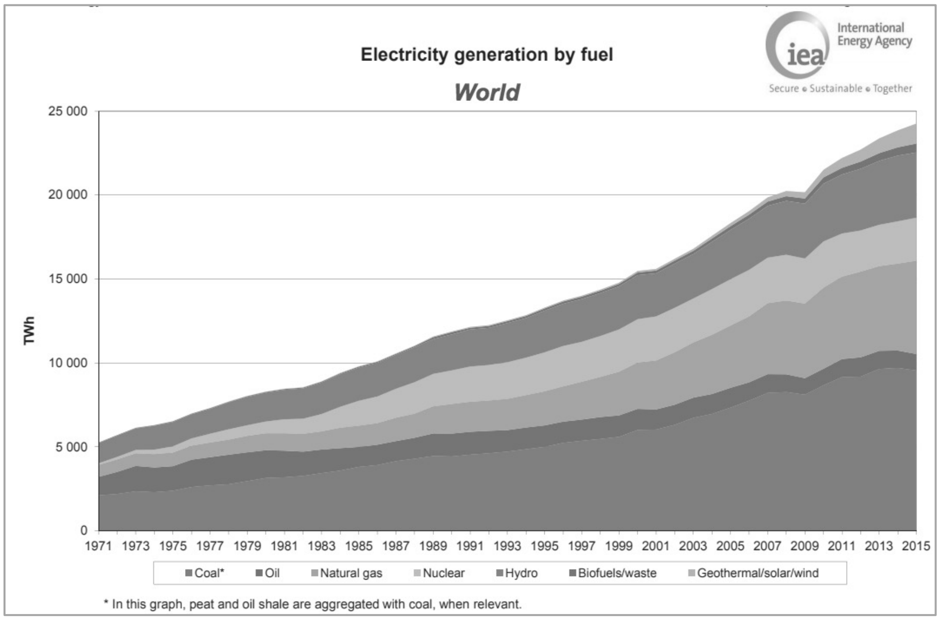


Figure 3.1 World electricity generation by fuel and the decline in use of fossil fuel for electricity generation (International Energy Agency, 2017)

In the U.S., petroleum accounts for approximately 1 % of electricity generation. The remaining generation comes from nuclear (about 19 %) and renewable sources (about 13 %), which includes hydroelectricity, biomass, wind, and solar. These sources usually release fewer greenhouse gas emissions than fossil fuel combustion (EPA, 2017b; IEA, 2011). With the availability of cleaner burning sources of energy such as natural gas and renewables, a decline in the quantity of coal for power generation is projected (figure 3.2).

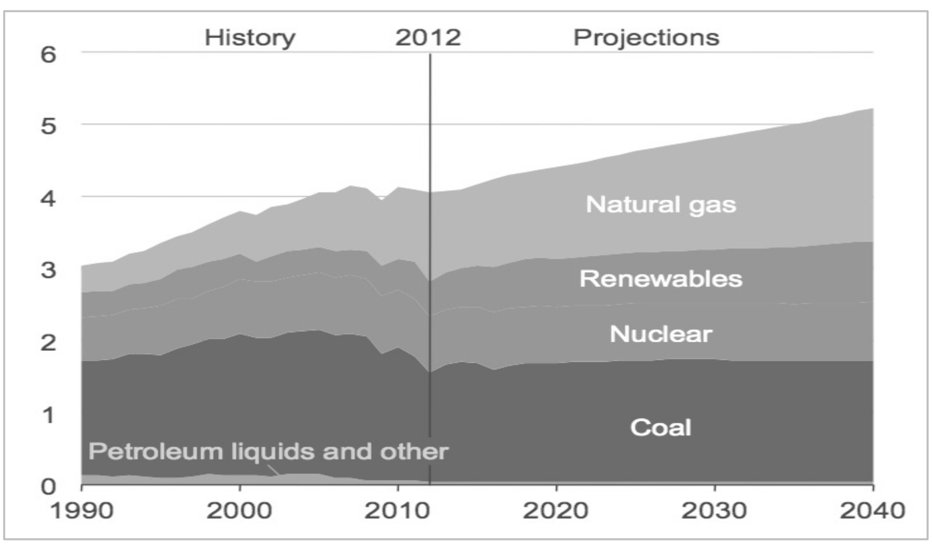


Figure 3.2: Decline in use of coal for electricity generation (U.S. Energy Information Administration, 2013)

Coal is considered to be a dirty source of energy due to its high carbon content and it is by far the largest contributor to energy related CO_2 emissions (Foster & Bedrosyan, 2014) and has the highest lifecycle GHG emissions (seen in figure 3.3). Natural gas, and to some degree oil, have lower operational GHG emissions compared to coal, but biomass, nuclear and renewable sources all have lower lifecycle GHG emission intensities compared to fossil fuel based generation (World Nuclear Association, 2011).

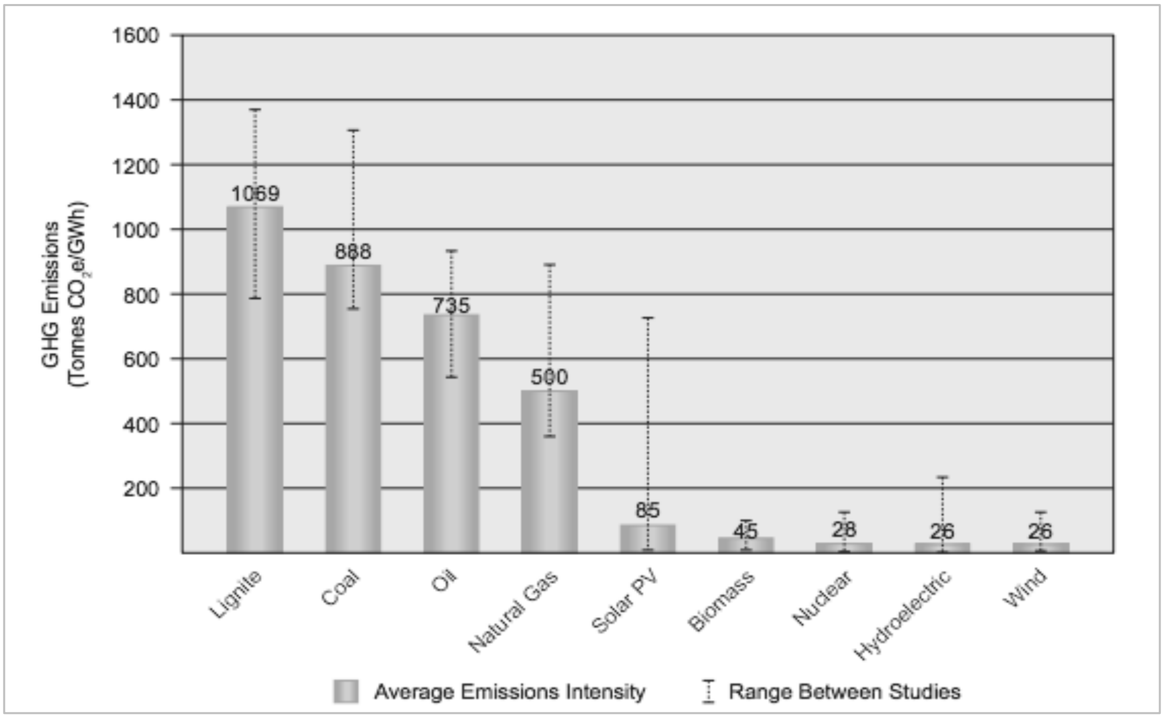


Figure 3.3: Lifecycle GHG Emissions Intensity of Electricity Generation Methods ((World Nuclear Association, 2011)

Even where a downward trend in the use of coal is projected, the type of coal burned for electricity generation can have a significant impact on the amount of emissions from the power plant (Campbell, 2013). Coal is largely composed of carbon, hydrogen and oxygen with varying amount of carbon, sulfur, ash and moisture content in the different types of coal mined (Campbell, 2013).The type of coal accounts for a significant variation in carbon content that governs power plant GHG emissions (Garg et al., 2006). There are four major types (also called 'ranks') of coal - anthracite, lignite, bituminous, subbituminous coal. The latter two are used mostly used for electric power generation.

Generally, anthracite emits the largest amount of CO_2 per million BTUs of coal burned, followed by lignite, subbituminous coal, and bituminous coal (October, 2010). CO_2 emissions from coal-fired power plants could be reduced by burning a better grade of coal, or by reducing overall coal consumption. For example, in the year 2008, US electric power generation facilities used 49.5% sub-bituminous coal, 44% bituminous, and 6.5% lignite in the total tonnage used (October, 2010). CO_2 emissions are lower when higher qualities of coal are used compared to the coal fired power plants that burn lower quality coal like lignite (figure 3.4, Cai et al., 2012).

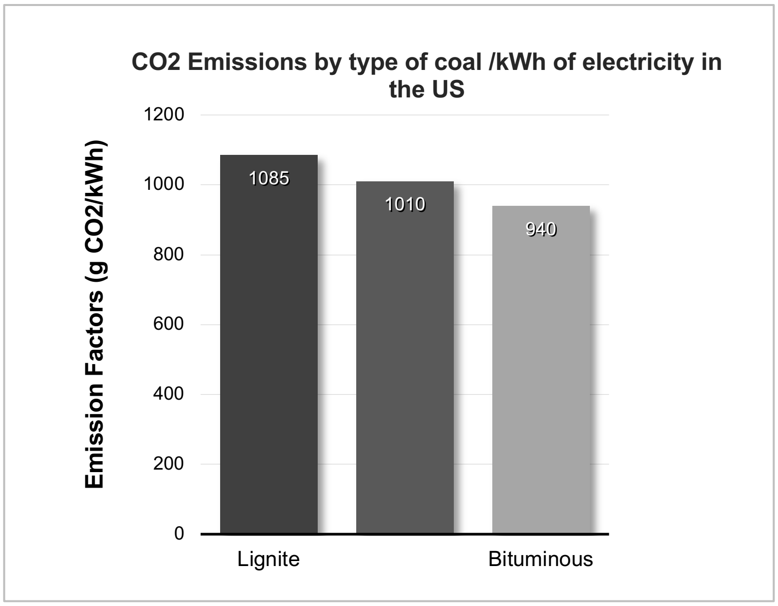


Figure 3.4: CO2 Emissions by type of coal/ kWh of electricity in the US (Cai et al,2012)

As countries rely on different types of fuel for electricity generation, to make the environmental cost benefit calculations more accurate, there needs to be a further subdivision by the fuel source and mix. This would include the percentage of coal by the different ranks of coals and their associated emissions. The fuel mix data allows for modeling emission outputs and normalize them by the fuel type for each kilowatt-hour of electricity saved and include the regional and international differences.

Each country's specific fuel mix affects their greenhouse gas (GHG) and pollutant emissions. The fuel mix in different countries reveals variability in the percentage of coal used for electricity generation (figure 4), ordered from the cleanest to the dirtiest source mix. In the case of emerging economies represented by India, 61% of the mix is dominated by coal (Kate & Ian, 2015; Vasudha Foundation, 2014) followed by a 40% for the US and 27% for the EU, seen in figure 3.5.

The EU has been in the forefront of defining medium and long-term goals relative to resource efficiency and GHG emission reduction to ensure the world does not exceed a 2°C maximum set by international agreement (Fraunhofer ISI, 2015). The resulting 2050 climate policy goals include de-carbonization of the energy supply and greater GHG emission cuts by reducing the reliance on fossil fuels (EEA, 2015). The resultant fuel mix from the EU policies provide emerging economies like India, and economies with mid-level sustainability goals, the ability to compare national and international benchmarks.

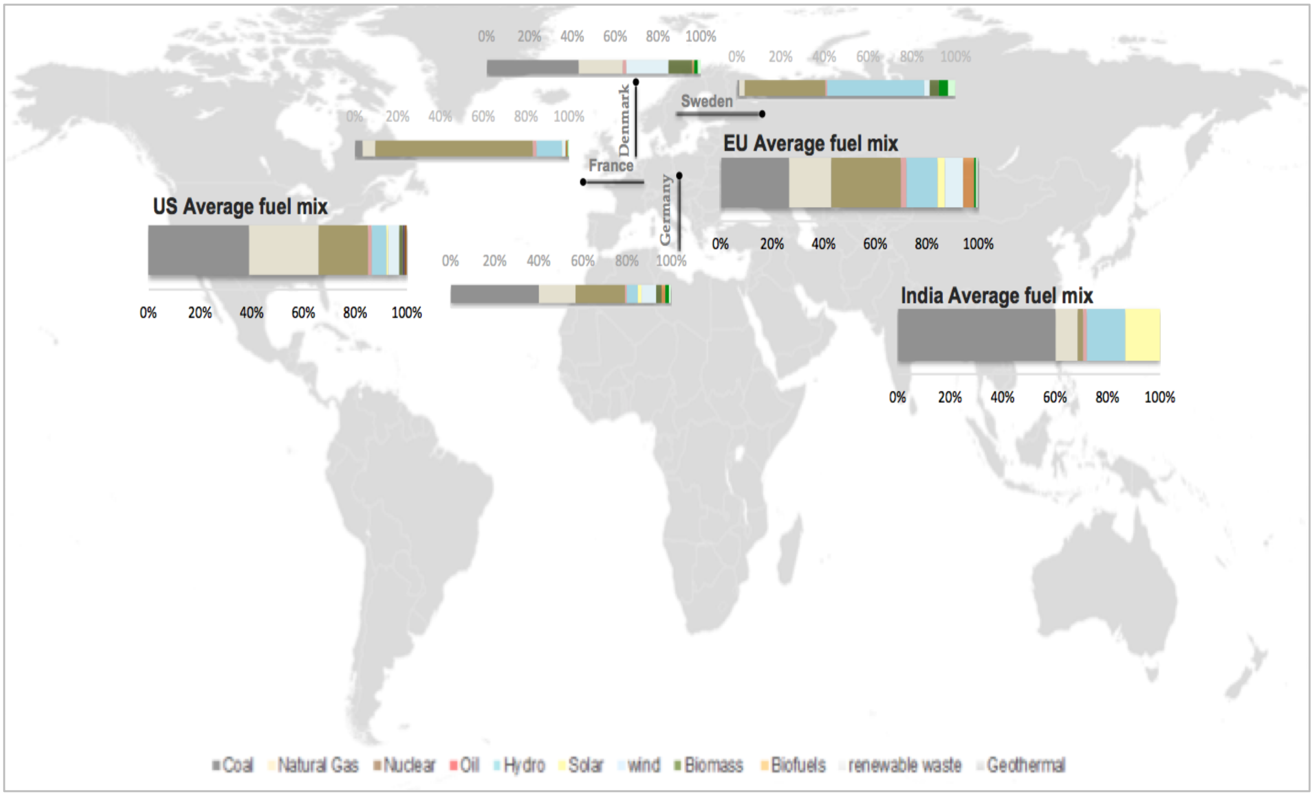


Figure 3.5 Average fuel mix (at the economy scale) in emerging, average and leading countries (Srivastava, 2016)

Power plant quality

The GHG emission and air pollutant intensity for fossil fired power generation depends not only on the share of coal in fossil power generation and fuel mix but, also on the efficiency of power production (Hussy et al., 2014). Heat rate is one way to describe the efficiency of a power plant and is typically the amount of energy used by an electrical generator or power plant to generate one kilowatt-hour of electricity. Lower heat rates are associated with more efficient power plants (EIA, 2014).

Another way of determining the efficiency of an electricity generation unit is expressing it as a fraction of the electric energy output and the fuel energy input (October, 2010). The greater the output of electric energy for a given amount of fuel energy input, higher the efficiency for the electric generation process. Figure 3.6, illustrates the variation in power plant efficiencies with different fuel sources in different countries. Coal-fired power plant efficiencies range from 27% (India) to 43% (France), while gas-fired power efficiencies range from 34% (France) to 53% (United Kingdom and Ireland). Oil-fired power generation efficiencies though not widely used range from 20% (India) to 46% (South Korea). Coal fired power plants in general have lower efficiency and require more amount of fuel to generate one kilowatt hour of electricity, thereby increasing the GHG and pollutant emissions.

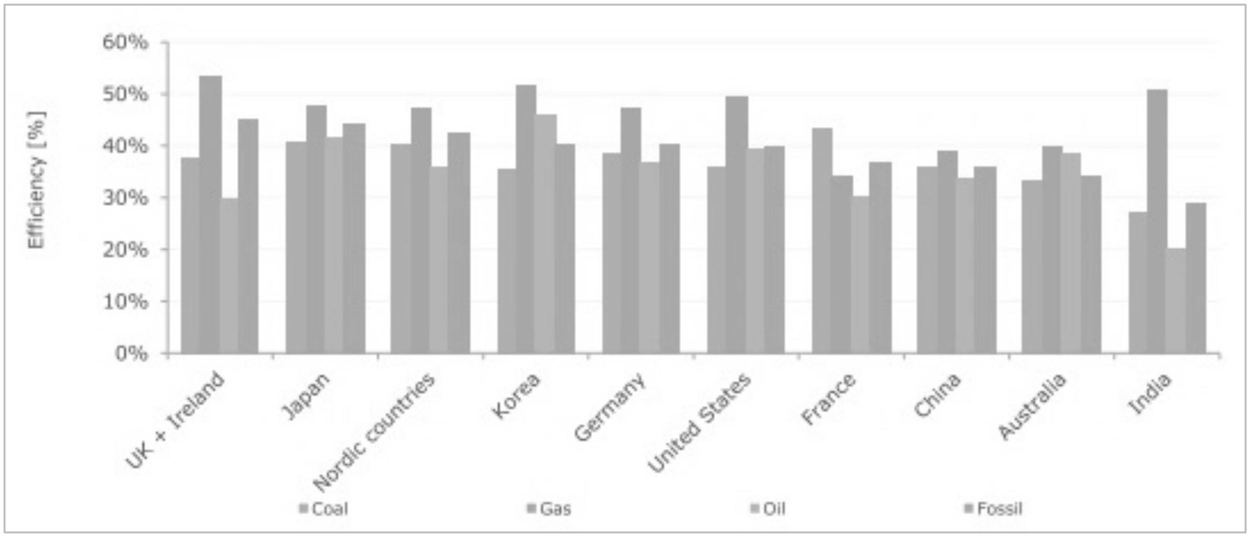


Figure 3.6: Energy Efficiency per fuel source average from 2009-2011. Source: (Hussy et al., 2014)

The overall efficiency of a power plant encompasses the efficiency of the various components of a generating unit that depends on the fuel sources. But as the efficiency of the power generation unit increases, less fuel is burned per kilowatt-hour which significantly decreases CO_2 and other pollutant emissions (Campbell, 2013). The CO_2 intensity for fossil fired power generation on average ranges from 547 g/kWh for Italy to 1,174 g/kWh for India, a difference of 100% in emissions per unit of fossil fired power generation (IEA,2013). This may be partly due to the use of unwashed coal in India that has higher ash content of 30% to 55%, and use of coal fired power plants that are used for both peak and base load power generation (Hussy et al., 2014). Hence, there is a large potential for reducing GHG emission by improving the energy efficiency of fossil power generation that vary by types of generator, and power plant emission control factors.

The combination of operating efficiency, fuel composition, coal quality and air pollution control devices in a power plant also determine other emissions beyond CO_2 (figure 3.7). The use of emission control equipment - flue gas desulfurization (FGD) scrubbers significantly reduces the SO_x emission levels (EIA, 2011). Regardless of the type of coal used, power plants that have scrubbers have substantially lower SOx emissions than coal-fired plants (figure 3.8), providing another level of pollution savings for emerging economies and economies with mid-level sustainability goals as they shift away from dirty sources of electricity generation.

In the US, coal fired power plants are the largest sources of sulfur dioxide (SO_x) emissions at a national level, whereas Indian coals have low sulfur content, hence SOx content is not very crucial in coal fired power generation (Krishnan & Nischal, 2004). Thus, there has been a greater effort to reduce SOx emissions in the US and that has even led to the emergence of SOx emission exchanges. Gas fired plants produce “negligible quantities of particulates and Sulphur oxides and the levels of nitrogen oxides are about 60% compared to plants using coal” (Krishnan & Nischal, 2004) thus the focus to date is not on reducing those emissions.

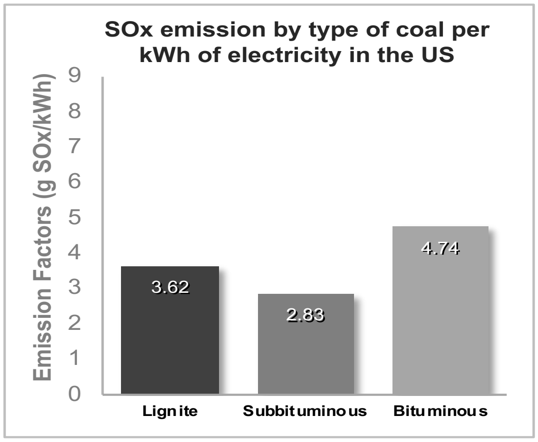


Figure 3.7: SOx Emissions by type of coal per kWh of electricity in the US

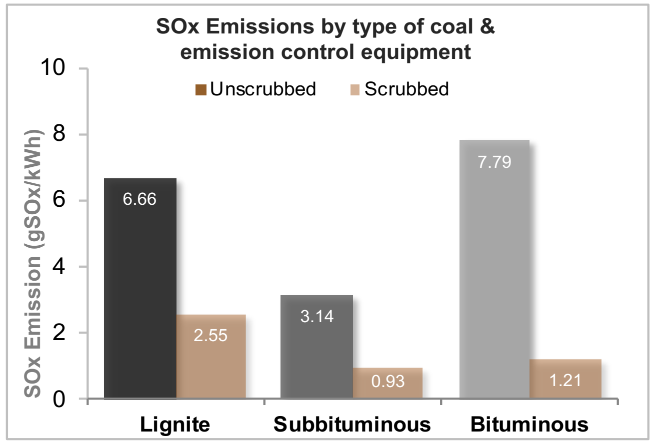


Figure 3.8: SOx Emissions by type of coal & emission control equipment (EIA, 2011)

The combination of power plant combustion efficiencies, fuel sources and the variation in the CO_2 emission outputs from the different types of fuels used for electricity generation is evident at the country level (figure 3.9). In the case of developing economy India, the highest CO_2 emission output per kilowatt-hour of electricity are due to the use of low grade low carbon content coal (Cropper et al., 2012) compared to the EU which relies on superior quality of coal for electricity generation.

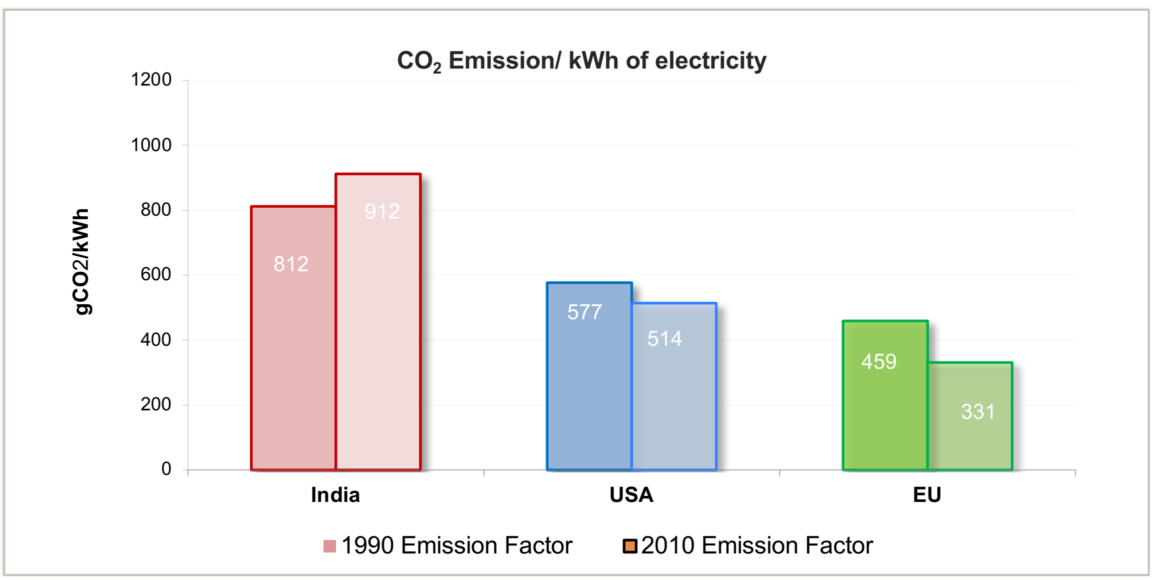


Figure 3.9: CO2 Emission / kWh of electricity given variations in coal type and generation efficiencies (IEA,2012c).

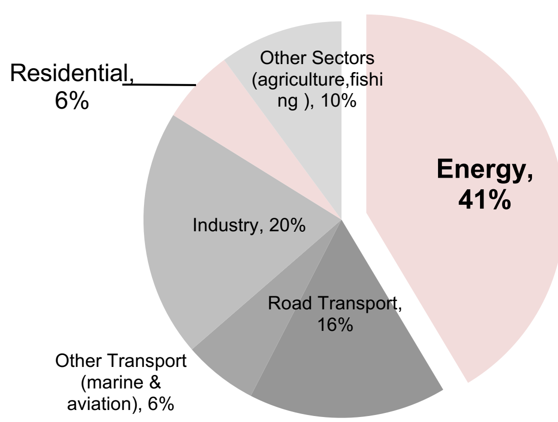
As illustrated in the figure above the amount of CO_2 emissions from electricity generating units vary by country. This variation is observed in other emissions as well since GHG and pollutant emissions vary depending on the type of coal burned, the overall efficiency of the power generation process, and the use of air pollution control device. Hence, emissions from the EU will differ from emerging economies like India, and economies with mid-level sustainability goals. The environmental benefits of shifting towards a cleaner fuel mix, high efficiency plants are lower for the EU's due to its stricter environmental standards, cleaner portfolio of fuels. But the environmental cost savings from the EU can provide emerging and economies with mid-level sustainability goals the ability to compare national and international benchmarks.

3.2.2 Measurable environmental outcomes of electricity generation

Energy generation levies a variety of costs on society. While some of these costs, are direct cost of facility construction, operation and fuel consumption that are borne by the producers and consumers. Other costs, however, are borne by society and the environment at large. Most notable among these external costs are the damages to the environment and human health. In the following section, some of the harmful emissions from electricity generation and the associated damages to the environment and human health are illustrated.

Greenhouse Gases – Carbon Dioxide and Methane

The energy supply sector, which includes fossil fuel fired electricity generating plants is the largest source of greenhouse gas (GHG) emissions, contributing to more than 40 % of the global CO_2 emissions (figure 3.10). Carbon Dioxide (CO_2) is a principal greenhouse gas and is the main product of fossil fuel combustion but, smaller amounts of methane (CH_4) and nitrous oxide (N_2O) are also emitted in the process.



3.10: CO2 emissions by sector (IEA, 2015)

CO_2 emissions in countries with emerging economies has increased very rapidly, both in relative and in absolute figures, and almost three quarters of the global CO_2 emissions come from six major economies (figure 3.11). For India, it is projected to grow even more rapidly as India is still investing in coal fired power plants to meet its electricity demands (Vasudha Foundation, 2014). For the U.S., the Environmental Protection Agency lists coal fired electric power plants as one of the largest sources of air pollution, with GHG emissions from burning fossil fuels believed to be the largest contributor to global climate change(Campbell, 2013). Since 1990 to the year 2014, U.S. greenhouse gas emissions have increased by about 7 % (U.S Environmental Protection Agency, 2010). The amount of emissions varies due to changes in the economy, fuel prices and other factors.

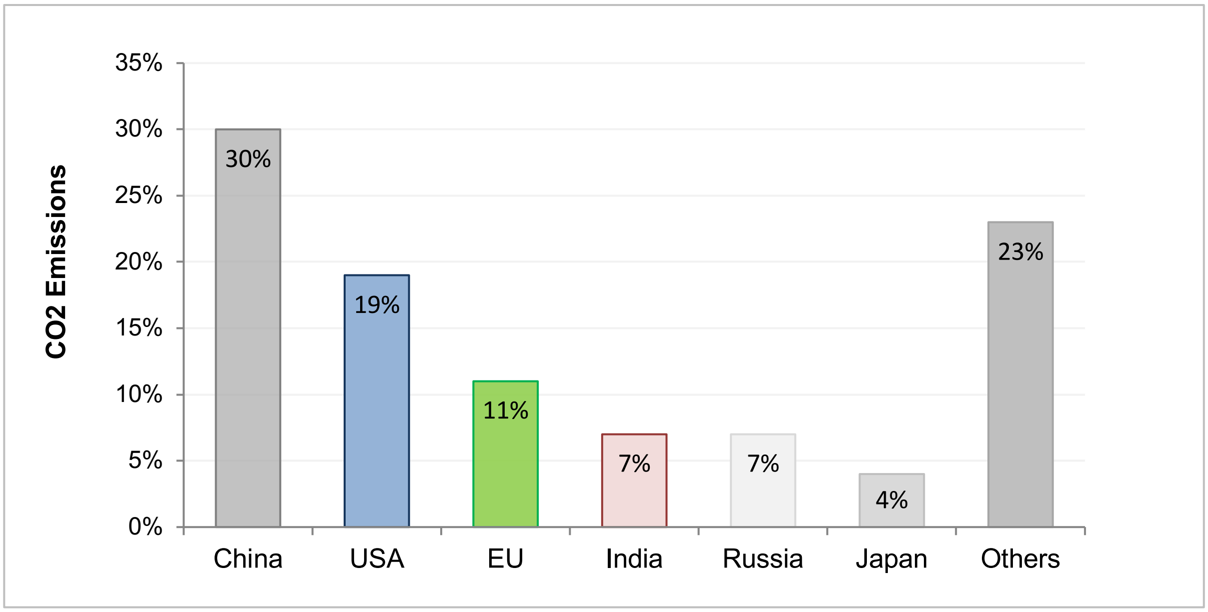


Figure 3.11: CO_2 emissions by country attributable to the energy sector (IEA, 2015)

CO_2 emissions lead to long lasting changes in the climate that can have a range of negative impacts on human health and environment around the globe (Goodkind & Polasky, 2013). Carbon emissions raise global temperatures by trapping solar radiation in the atmosphere. The Intergovernmental Panel on Climate Change estimates that carbon emissions can cause global temperatures to rise by approximately 2.5 degrees Fahrenheit (1.5 degrees Celsius) over the next 100 years (Pachauri, 2013). This change in temperature can have effects on shorelines, where rising sea levels flood buildings and roads.

Certain age groups, including children, the elderly and the poor are most vulnerable to climate related effects. Climate change related impacts include heat waves, degraded air quality and extreme weather events that are associated with potential for increased deaths, injuries and illnesses (US EPA, 2015a). Climate change can also increase ozone pollution in large metropolitan area with existing ozone problems, thereby increasing the risk of morbidity and mortality.

Increases in CO_2 can have other effects apart from global warming including ocean acidification, smog pollution, as well as changes to plant growth and nutrition levels. Broad based energy efficiency programs and taking energy consumption into consideration for buildings can reduce, lessen the impacts of CO_2, the gas responsible for intensifying the atmospheric greenhouse effect.

Methane CH_4 is another major greenhouse gas that impacts the climate leading to global warming, variation in seasonal patterns and associated health concerns such as heat strokes, impacts similar to that of CO_2 emissions.

Sulfur Dioxide (SO_x)

Sulfur Dioxide is emitted primarily by power plants that burn fossil fuels and coal plants. SO_X is usually defined to include Sulfur dioxide (SO_2), sulfur trioxide (SO_3) and gas-phase sulfuric acid (H2SO4) as well, but the latter two are not present in the atmosphere in concentrations significant for human exposures (USEPA, 2008). in the United States power plants are the leading source of SO2 pollution (USEPA, 2016). A typical uncontrolled coal plant emits close to 14,100 tons of SO2 per year. A typical coal plant with emissions controls, including flue gas desulfurization (smokestack scrubbers), emits 7,000 tons of SO2 per year (EIA, 2010).

High concentrations of SO_2 affects public health by reacting with other compounds in the air to form small acidic particulates that can penetrate into human lungs and be absorbed by the bloodstream (Kats & Capital, 2003; EPA, 2014). The increase in sulfur dioxide levels can be responsible for higher incidences of morbidity for asthmatics with asthma related emergency department visits (Jaffe, Singer et al., 2003); asthma exacerbation in the age 4–12 years and lead to acute respiratory symptoms and hospital admissions for the elderly and young children (Wilson et al.,2005; EPA, 2014; EPA, 2008). Severe exposure to SO_2 can also lead to premature mortality (Krewski et al., 2009) and respiratory effects that include airway hyper responsiveness and inflammation and impact on lung function (EPA, 2014; Lawther et al., 1970; Linn et al., 1987; Gong et al., 2001).

High concentrations of SO_2 can have serious effects on health, but it is also a precursor to the formation of particulates, that negatively impacts public health and the environment (Burtraw & Szambelan, 2009). Particulate matter affects more people and has a greater economic consequence than any other conventional air pollutant (EPA, 1998). SO_2 also dissolves in water vapor to form acid and interacts with other gases and particles in the air to form sulfates and other products and causes acid rain. Acid rain damages crops, forests, and soils, and acidifies lakes and streams (Pisupati, 2017).

Oxides of Nitrogen (NO_x)

Nitrogen oxides or NOx is a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts (Pisupati, 2017). Oxides of Nitrogen (NO_x) are a cause of smog and a contributor to the formation of ground level ozone that leads to acid rain and impacts human health (Burtraw & Szambelan, 2009). A typical uncontrolled coal plant in the U.S. emits 10,300 tons of NOx per year, while coal plant with emissions controls such as the selective catalytic reduction technology, emits 3,300 tons of NOx per year (EIA, 2014).

NOx pollution causes burning of lung tissue, exacerbates asthma, increases allergic inflammation in adults with asthma, increase heart diseases and make people more susceptible to chronic respiratory diseases (EPA, 2016; Brown, 2015; Goodman et al., 2009; Kjaergaard and Rasmussen, 1996; U.S. EPA, 2009b). NOx-related asthma attacks and asthma development have the potential to affect children’s overall well-being (EPA, 2016).

Short-term increases in ambient NOx concentrations increases respiratory-related hospital admissions and emergency Department visits (U.S. EPA, 2009b; Stieb et al., 2009; Samoli et al., 2011). Whereas, long term exposure can lead to premature mortality and other respiratory effects that include airway hyper responsiveness and inflammation, lung function (EPA, 2016).

In addition, high levels of ambient NOx levels contribute to the formation of ground-level ozone. Ground level Ozone is formed by the atmospheric mixing of NOx and volatile organic compounds (VOCs) in the presence of warm temperatures and sunlight (Burtraw & Szambelan, 2009). High ozone levels can result in chronic asthma, acute-exposure mortality, respiratory admissions, emergency room visits for asthma, and crop and timber loss (Goodkind & Polasky, 2013).

Particulates ($PM_{2.5}$) – fine particles

Particulate matter contains microscopic solids and liquid droplets that are so small that they can be inhaled and cause serious health problems (World Health Organization, 2013). The size of the particles is directly linked to their potential for causing health problems. Smaller particles less than 10 micrometers in diameters pose the greatest problem (USEPA, 2003). $PM_{2.5}$ in particular is a principal cause of respiratory illness and cancer. Fine particles are the main cause of reduced visibility (haze) and are an important contributor to smog in cities that obstruct visibility (EPA, 2009).

Epidemiological studies have found associations between short term exposure to fine particles with a broad range of respiratory illnesses, increases in cardiovascular effects such as emergency department visits, congestive heart failures and mortality (Krewski et al., 2009)(Chimonas & Gessner, 2007)(U.S. EPA, 2009b). Due to their extremely small size PM2.5 particles are able to travel deep into the respiratory tract and affect lung function and cause asthma (Vasudha Foundation, 2014). Higher particulate level exposure can cause acute and chronic bronchitis, lower and upper respiratory symptoms, strokes and cerebrovascular effects (Lisabeth et al., 2008), reproductive and development effects (Lepeule et al., 2012)(EPA, 2014).

Prolonged exposure to PM2.5 can lead to lung cancer, mutagenicity and genotoxicity effects (EIA, 2016)(Fann et al., 2014). A study by Pope et al. suggests that for every 10 µg m-3 increase in PM2.5 exposure, there is an approximately 6 % increase in the risk of premature mortality. The magnitude of this estimate has been confirmed by other studies as well, illustrating the risk from high PM levels (Krewski et al.,2009). Exposure can also lead to hospital admissions for chronic obstructive pulmonary disease (COPD) and respiratory infections (Chen et al., 2004).

Water demand for thermal power generation

Another critical environmental outcome that differs by the fuel type is the demand for water to generate electricity (IEA, 2012). Water provides cooling and meets other process related needs during power generation using coal. Washing coal and the cooling towers of power plants requires vast amounts of water. Water is used to make steam that requires large quantities of water from nearby rivers or lakes, or from local underground water aquifers (The Public Service Commission of Wisconsin, 2005). Large quantities of water are also used for carrying ash from the plants to the ash ponds or pits (Vasudha Foundation, 2014). In some cases, water is discharged from the plant after it has been used at a warmer temperature which may harm the local water body. The excessive consumption and contamination of water leads to pollution and the eventual destruction of the water table.

Hydropower facilities also use major quantities water as they need to harness the movement of water for producing electricity. Water is consumed during seepage and evaporation from the reservoir created for hydropower facilities (IEA, 2012). On average, hydropower facilities in the United States consume about 68,000 liter per MWh of electricity generated (Torcellini, Long, & Judkoff, 2003). Hydropower plants have some of the highest water consumption levels per unit of electricity generated (Torcellini et al., 2003). In moving towards a more water scarce world, substantial environmental value can be associated with systems and technologies that reduce in demand for water.

Particulates (PM 10) – coarse particles

A part of the harmful emissions from coal fired power plants are the coarse particles which have diameters between 2.5 and 10 micrometers, known as PM 10. The particles emitted from the power plants disperse over a wide area and have the potential to harm human beings by causing chronic health problems (Kats & Capital, 2003). There is evidence on the effects of short term exposure to PM10 on respiratory health , but the impact on respiratory and cardiovascular morbidity and mortality are more pronounced for PM2.5 exposure (World Health Organization, 2013). Larger particles also cause irritation to the eyes, nose and throat (Zactruba & Stonecypher, 2009).

Mercury

Coal plants are responsible for more than half of the U.S. human-caused emissions of mercury. Mercury is very volatile and can travel in the atmosphere, and be deposited and re-emitted into the atmosphere (The Public Service Commission of Wisconsin, 2005). Once mercury is deposited in lakes and rivers by rain, snow and surface runoff it changes in methylmercury, a highly toxic form (EPA, 2015). A typical uncontrolled coal plants emits approximately 170 pounds of mercury each year. Emissions of mercury are of great concern and regulated by the EPA in the U.S.

Exposure to mercury is primarily through the consumption of fish. The exposure to mercury is of concern as it causes heart problems and neurological effects through developmental delays, impaired memory behaviors (Goodkind & Polasky, 2013). If expectant mothers are exposed to excessive amounts of mercury it can have an impact on the fetuses brain and nervous system (EPA, 2001).

Coal ash

Coal ash and soot are byproducts of coal fired power generation and come with significant costs to environment and human health. Coal ash is one of the largest types of industrial waste generated in the United States. Coal ash contains contaminants like mercury, cadmium and arsenic. These pollutants are known to cause cancer, birth defects, reproductive disorders, neuro- logical damage, learning disabilities, kidney disease, and diabetes (Schaeffer & Evans, 2009). Without proper management, these contaminants can pollute waterways, ground water, drinking water, and the air. Coal ash residue and pollutants contaminate soil and are harmful to agricultural activities.

Nuclear waste

Nuclear power plants do not produce GHG or PM, SO_2, or NO_x, but they produce radioactive waste. The wastes are of two kinds - low-level radioactive waste stored at nuclear power plants until the radioactivity in the waste decays to a level where it can be disposed of as ordinary trash or to a low-level radioactive waste disposal site. Second type is the used nuclear fuel assemblies that are highly radioactive that is stored in specially designed pools of water or dry storage containers. Nuclear power generation has the potential for serious accidents, besides problems with mining, surface reclamation, and waste disposal (EIA, 1995).

Heavy metals

Combustion of coal for power generation also leads to emissions of heavy metals. These metals include antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), thallium (Tl), vanadium (V), and zinc (Zn). The most toxic metals for the environment and human health are Hg, As, Cd, Pb and Se. These toxic metals can cause cancer, lung damage and contribute to asthma, bronchitis and other chronic respiratory diseases, especially in children and the elderly (EPA, 2015).

3.2.3 Societal monetized values of selected emissions and pollutants

The last dataset in this thesis calculates the 'natural capital' savings is a monetary valuation for the selected air pollutants, greenhouse gases and water use for electric power generation. Different countries and international treaties set the values for this data. The total costs or damages per ton of GHG or criteria air pollutants can vary substantially depending on the location of the emitting plant but, the impacts associated with climate change are global and likely to be experienced many years in the future. Hence, monetized values for reducing GHG emissions and pollutants from different economies provides a range of mitigation costs the society is willing to accept and indicate the urgency nations impose to address the challenges of GHG emission reductions and climate change.

The valuation of environmental externality in terms of money is referred to as monetization. Various approaches have been used for valuing environmental externalities of energy use, amongst these are ordinal ranking, scoring and monetization (Bernow et al.,1990). Some of the environmental impacts can directly be valued only in qualitative terms, like the character of the land whether it is pristine, residential, commercial or industrial (Bernow et al., 1990). The value of reducing each externality is monetized by expressing terms such as $/pound of pollutant emitted or $/unit of externality (Chernick & Caverhill, 1990). The values can be added to resource costs when evaluating different investment alternatives.

There are several ways of monetizing costs of pollution associated with burning fossil fuels. One way is by estimating the direct monetary costs to property, health and environment and society from the environmental damage (Bernow et al., 1990). Often damage function approach in which most important effects of environmental pollution, on human health, damages to aquatic and terrestrial ecosystems or an externality adder approach is used to estimate the damage costs associated with pollutant emissions (Matthews & Lave, 2000). Dispersion modelling is carried out to track pollutants through the atmosphere and follow the chemical reactions to quantify effects linked to emissions (AEA Technology Environment, 2005). Economic valuation of the damage is obtained by the “willingness-to-pay” of the affected individual to avoid a negative impact resulting from energy production from an actual power plant (Rafaj & Kypreos, 2007).

Second method involves the use of abatement costs or the cost for control measures that reduce pollutant levels. These costs sometimes represent the monetary value of the different externalities to the society (Chernick & Caverhill, 1990). An example of this type of valuation could be the cost of installing flue gas scrubbing systems on utility generators that was used by utilities in the early 1990s (EIA, 1995). However, it has been argued that utilities lack the authority to regulate the impact of power generation on the environment by imposing a levy on power plant emissions.

Finally, the third way of monetizing the externalities is applicable in regions with established trading market. In these trading platforms different pollutants are assigned monetary values (Kats & Capital, 2003). A leading example of this type of valuation is the EU Emissions Trading Scheme, which has been trading GHG allowances since 2005. With the given current methods for monetizing, it is not possible to explicitly monetize all environmental impacts of electricity generation. Based on these three methods, monetary valuations for the selected emissions and pollutants has been assembled, to provide decision makers the possible range of values.

Greenhouse gases – CO_2 and CH_4

For certain GHG emissions and air pollutants such as CO_2 there is a fairly established method of monetizing the impacts - direct costs of damages to society, cost of control, to assigning a market value to pollutants via emissions trading programs. An example of first type of valuation is the social cost of carbon (SC CO_2) developed by the US EPA and other federal agencies to evaluate the climate benefits of national rulemaking. The SCC is a metric that estimates the monetary value of impacts associated with marginal changes in CO_2 emissions in a given year (US EPA, 2015b). It includes a wide range of anticipated climate impacts, such as net changes in agricultural productivity and human health, property damage from increased flood risk, and changes in energy system costs.

According to the Interagency Working Group on Social Cost of Carbon (SCC) is meant to be used as a measure of the net monetized damages associated with increases in GHG emissions (US EPA, 2015b). SCC encompass all impacts from climate change many years in the future and assigns a dollar value to these impacts, and then relate these values back to the emissions of GHG today. The dollar value represents the benefits or the value of damages avoided for a small emission reduction (EPA, 2013a; Goodkind & Polasky, 2013). As climate change is expected to cause global damages, the source of the emissions and its location will not matter thus the SCC can be used as a broad, uniform measure of the cost of GHG emissions (Goodkind & Polasky, 2013).

To guide selection of new electricity generation capacity, some states in the U.S. sought estimates of the social damage from different types of power generation plants. By including the externality adders, utilities were able to recognize the social cost of emissions. Utilities in California, Massachusetts, Nevada, and New York were one of the few to estimate externality adders.

In the 1990s public utilities like the Massachusetts Department of Public Utilities, Wisconsin Public Service Commission (PSCW) and the California Public Utility Commission and electric utility assigned monetary value to externalities. These values are assigned "as a hedge against the risk of future GHG regulations" or for use during resource planning (EIA, 1995). The externality costs included marginal cost for planting trees in effort to sequester carbon or the cost of forest protection to offset CO_2 emissions associated with a resource plan, control costs to reduce the pollutants or the amount individuals are willing to pay to avoid damage or the compensation individuals are willing to accept (EIA, 1995). The values range from a high of \$40/ton of CO_2 to nothing at all (Wisconsin Public Service Commission, 1992; Levy et al., 2009; EIA, 2009).

There are also a range of carbon pricing instruments such as carbon taxes, emissions trading schemes and crediting mechanisms to internalize the external cost of GHG emissions (World Bank Group, 2014). A prime example of this kind of a market is the EU emission trading system (EU ETS) that was established in 2005. It is the world's first major and biggest international carbon market that operates on the 'cap and trade' principle (European Commission, 2015b). A cap is set on the total amount of certain greenhouse gases that can be emitted by companies participating in the program and this cap is reduced over time in order to reduce the total e emissions (European Commission, 2017). There is a limit on the total number of allowances available to ensure that the allowances have a value. The carbon price is then set by the market through trading and a wide range of factors (European Commission, 2015a).

The EU ETS has also inspired the development of emissions trading in other countries and regions like the Regional Greenhouse Gas Initiative, California's Cap and Trade program.

RGGI is the first mandatory market-based program in the United States to reduce GHG emissions and is a cooperative effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont to cap and reduce CO2 emissions from the power sector. In its third control period CO_2 allowances were sold at a clearing price of $4.35 per short ton in 2016 (Vogel, 2017). The California cap and trade program came into effect in 2013 and is second in size only to the EU ETS based on the amount of emissions (C2ES, 2014). The California cap and trade program the first multi-sector cap and trade program in the U.S. with carbon prices in the range of $12 to $13 in 2017 (Climate Policy Initiative, 2017).

Based on the approaches discussed above the impact of CO_2 emission can been monetized and this valuation based on several sources. In the first approach, utilities multiply the monetized values for the externality by the amount of GHG emissions from the plant and apply the resulting costs to the energy-related costs of the plant and other related decisions. Whereas on a carbon trading platform, companies can receive or buy emission allowances that they can trade. Figure 3.12, presents a range of values for avoidance of CO_2 from different sources. A value of $33/ton has been used in this thesis model.

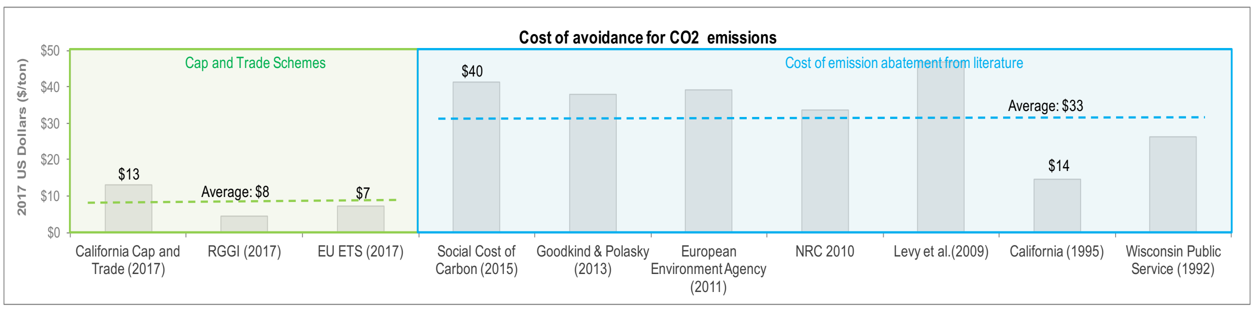


Figure 3.12: Range of environmental values for avoidance of CO_2 emissions

The amount of methane emitted as a product of fossil fuel combustion is low compared to CO_2 (Garg et al., 2006), but, its global warming potential is far more significant (EPA, 2017a). Bulk of energy related methane is emitted during fossil fuel extraction and transportation, but some emission is also produced during fossil fuel combustion in power stations (Reay, 2013). Although there is limited recent literature on the societal cost of methane emissions there are some studies that provide examples of how to monetize the environmental damages. A 1998 study by the European Commission on the ExternE program monetized the greenhouse gas damage from per tonne of methane emission from energy production as $440 to $850 (European Commission, 1998). There are some examples of utilities like the MDPU considering the warming potential relative to CO_2 and putting an externality value (EIA, 1995). The MDPU assigned $220/ton externality value for methane emissions while Wisconsin PSCW stipulated $150 per ton of emission (MDPU, 1992).

SOx and NOx

Similar to the Carbon trading platform, there are SO_2 and NO_x markets that have been active. (Burtraw & Szambelan, 2009). The first large scale application of emissions cap and trade was the SO_2 trading program initiated under Title IV of the 1990 Clean Air Act Amendments in the United States (Dudek, 1990). The amendments established the emissions allowance trading program for electric generating units. Firms that participated were able to transfer allowances for each ton of SO_2 emitted by its plants amongst facilities or to other firms or bank them for future use (Burtraw & Szambelan, 2009). Allowance prices represented the marginal cost of abatement, which were influenced by the cost of fuels and the abatement technology used. At the beginning of the program allowance prices were close to $150 per ton and fell to about $70 per ton by early 1996 (Dudek, 1990). However, by the end of 2004 prices had risen to $700, due to an increase in demand for coal-fired generation, increase in natural gas prices. In 2008 regulatory uncertainty depressed allowances prices to $65 in 2009 (Burtraw & Szambelan, 2009).

Based on the damage function approach, an EU study estimates damage per ton of SOx emissions in range of $6,000 to $10,300 (AEA Technology Environment, 2005). EPA's Office of Air Quality Planning and Standards Environmental Benefits Mapping and Analysis Program (BenMAP) provides a value in the range of $31,000 to $35,000 per ton for monetizing the benefit from reducing SO2 emissions based on the mortality risk estimate (EPA, 2013b).

In the 1990s some utilities had put a price on the externalities relating to SOx emission on the basis of the cost of installing flue gas scrubbing systems on utility generators. The values range from $1500/ton to $23,500 per ton (EIA,1995; MPUD,1992). Figure 3.13 presents the range of values gathered for the cost of avoidance of SOx emissions. The average cost based on the damage costs was found to be around $15,800, while averaging the trading costs, the value was found to be $10,000. A conservative estimate of $7,500 has been used in the model.

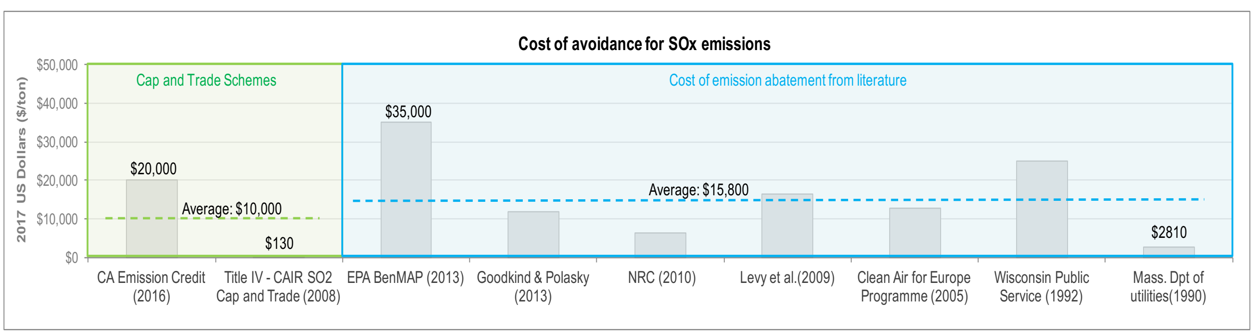


Figure 3.13: Range of environmental values for avoidance of SOx emissions

As with SOx regulatory policy, the shift towards market-based solutions for reducing NOx emissions has evolved over time. Regional Clean Air Incentives Market (RECLAIM) was the first large scale urban regional cap and trade program for NOx in the U.S. with the goal of reducing emissions by 70 % from about 390 facilities in the years from 1994 through 2003 (Burtraw & Szambelan, 2009). A single RECLAIM credit allowed the holder to emit one pound of NOx, and sell excess credits to firms that cannot or are unable to meet their limits (Information, 2013). In the first half of 2000, the price of a NOX credit rose from $1 to $30 and eventually to over $60 in 2001, as demand for allowances overtook supply (U.S. EPA, 2009a). Eventually the trading platform was suspended due to regulatory uncertainties.

In late 1997 in the U.S., EPA required states to impose restrictions NOX emission from electricity generators and industrial sources and asked them to revise their plan to meet federal ambient air quality standards. States had the flexibility to either require pollution sources to comply with the federal budget or participate in NOx Budget Training Program (U.S. EPA, 2008). Allowances were traded at high price early on in the program, but the prices lowered during rest of the period the program was in effect. In 2008 which was also the last year of the cap and trade plan, prices dropped to $592 (Burtraw & Szambelan, 2009).

As with CO_2 and SOx avoidance values, other path to monetizing reduced NOx emissions is by basing them on the direct cost to the society which includes mortality and morbidity risk estimates. EPA's office of Air Quality Planning and Standards Environmental Benefits Mapping and Analysis Program estimate the damage costs in the range of $4600 to $5200 per ton of directly emitted NOx. In early 1990s utilities had used these direct damage costs in order to internalize the costs to produce electricity. The costs ranged from $1600 per ton of emission to $6,500 which was based on installing selective catalytic reduction to reduce NOx emissions on gas turbines used to generate electricity (EIA, 1995).

Based on the two approaches, the damage cost to the society and cap and trade scheme pricing as an indirect the cost of avoidance, the average cost of avoidance for NOx emissions was found to be in the range of $5,430 to $16,100 per ton of NOx emissions (figure 3.14).

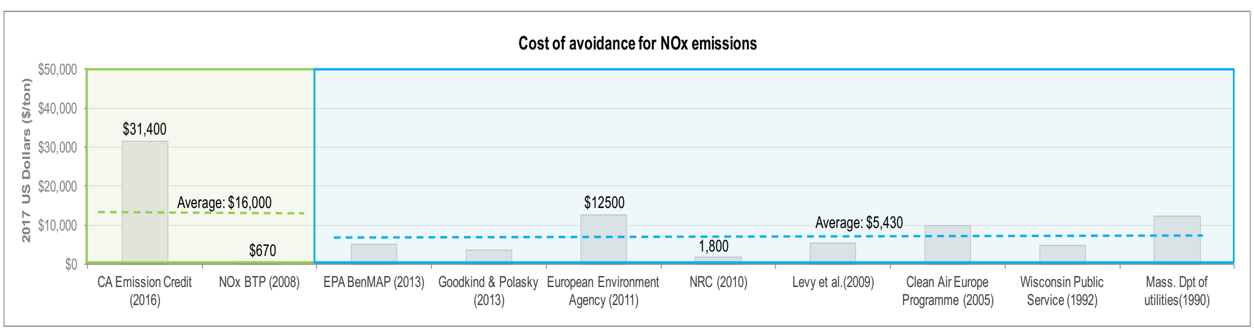


Figure 3.14: Range of environmental values for avoidance of NOx emissions

Of late the SO2 and NOx markets have been volatile, and prices have fallen. Some utilities have used the direct cost approach where they put a cost on the morbidity and mortality, but these are no longer being used as it is believed that levying a cost on emission is beyond a utilities authority.

Particulate, PM 2.5

Unlike CO2, SOx and NOx trading platforms, there are no active trading platforms that target reduction of PM levels. The two common approaches for monetizing the cost of PM emissions to the society include the direct damage cost that includes cost of mortality and morbidity costs and the cost of abatement using technology. In the former, often the impact of emissions of PM 2.5 is modelled along with other criteria air pollutants SO2, NOx and PM10 using the Air Pollution Emissions Experiments and Policy Analysis (APEEP) model. The model connects the quantities of emission to changes in concentrations and exposures of PM2.5 to changes in physical effects and valuation of these effects (Goodkind & Polasky, 2013). The marginal damages from PM2.5 are based on the impacts to human health caused by the concentrations of fine particulates.

An NRC (2010) study estimates the damage from PM2.5 in the range from $2,600 to $26,000 per ton of emissions with a mean of $9,500 per ton of emissions. These costs are based on the impact on human health in terms of premature mortality, increased morbidity and impacts to agriculture and visibility. Levy et al (2009) present a much higher external cost than NRC study. For primary emissions of PM2.5 estimates across plants in the U.S., damages are in the range of $41,000 to $180,000 per ton (5th and 95th percentile estimates, respectively), and $72,000 per ton for the median plant. The EPA's BenMAP also proposes a higher value based on the Value of a statistical life (VSL) at $130,000 per ton of PM2.5 emission. An extensive European program report calculates the air emission cost values for PM2.5 for a particular sized city and estimates a damage value of $47,800 per ton of PM2.5 emissions (Holland & Watkiss, 2002; Clean Air for Europe Program, 2005).

There are examples of avoidance values based on the cost of installing technology where the direct cost of installing technology are related to abatement in PM2.5 emissions. Massachusetts Public Utility Department allocated a value of $4,000/ton based on the cost of installing an electrostatic precipitator on a high sulfur coal plant with low resistivity fly ash that could reduce the amount of PM2.5 emitted (EIA, 1995).

As seen in figure 3.15, the cost of avoidance of PM 2.5 emissions vary from as low as $2,600 (NRC,2010) to $198,875 in the Victoria Transport Policy Institute. The latter includes costs of vehicle air pollution on human health and mortality, ecological and esthetic degradation (Victoria Transport Policy Institute, 2011).

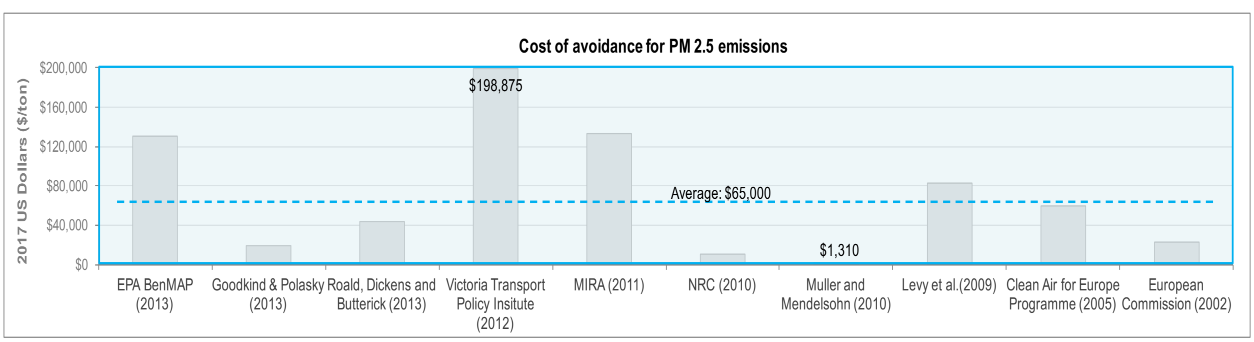


Figure 3.15: Range of environmental values for avoidance of PM2.5 emissions

Water costs

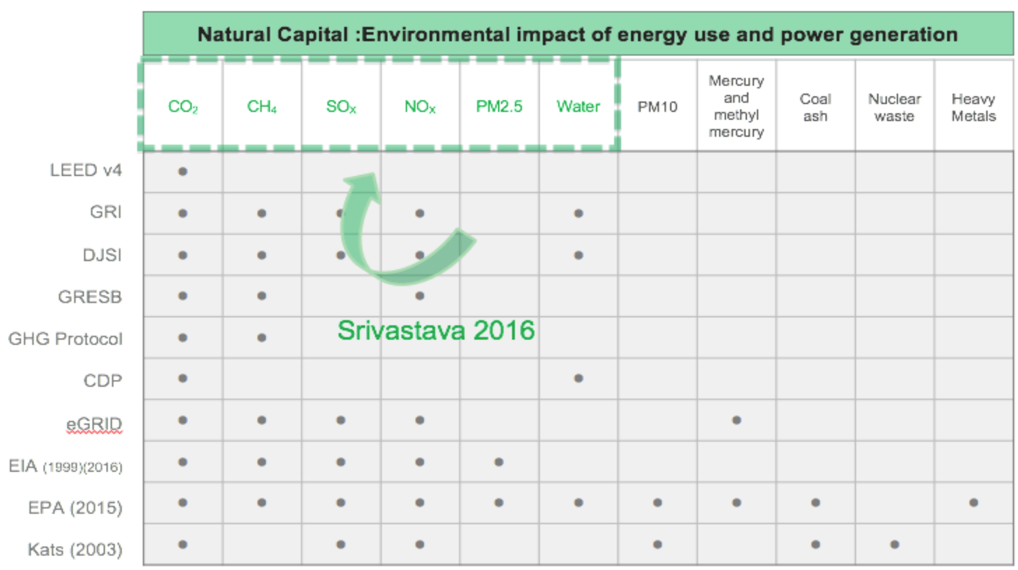
Water and energy systems are interdependent as water is used in all phases of energy production and electricity generation. Instances of water scarcity, variability and uncertainty are leading to vulnerabilities in the energy system (The California Urban Water Conservation Council, 2006) and an increase in water prices. In 2012 severe drought affected more than third of the United States and the limited water availability constrained the operation of some power plants and other energy production activities (U.S. Department of Energy, 2012).

The cost of a gallon of tap water varies, as the cost of water includes supply costs, transmission and distribution costs, and treatment costs. Historically cost of water service been low and has not been a major expense for users, but that is changing. According to the National Utility Services 2000 survey of the United States, people in U.S. cities paid between .07 cents and .4 cents per gallon. A more recent 2013 survey of water and sewer costs for various residential, commercial and industrial users in the top 50 U.S. cities, estimates the typical monthly water and wastewater bill for commercial customers with 100,000 gallons billable water usage as $946.85 on average (Black and Veatch, 2013). When normalized to a per gallon rate, the cost to a commercial user is 0.9 cents per gallon.

3.2.4 Selected building investments and outcomes to illustrate the LCC approach

Based on the review of guidelines for architectural design and CSR reporting, from the longer list of outcomes discussed in section 3.2.2, six environmental outcomes of electricity generation have been identified that are frequently included in budget reporting and have a level of quantitative data necessary for the modeling required in this thesis. These six selected outcomes in table 3.1 are included in the second bottom line calculation approach.

Table 3.1: Selected environmental impacts of electricity generation based on the review of CSR reports and architectural design rating guides



	Natural Capital :Environmental impact of energy use and power generation										
	CO_2	CH_4	SO_x	NO_x	PM2.5	Water	PM10	Mercury and methyl mercury	Coal ash	Nuclear waste	Heavy Metals
LEED v4	•										
GRI	•	•	•	•		•					
DJSI	•	•	•	•		•					
GRESB	•	•		•							
GHG Protocol	•	•									
CDP	•					•					
eGRID	•	•	•	•				•			
EIA (1999)(2016)	•	•	•	•	•						
EPA (2015)	•	•	•	•	•	•	•	•	•		•
Kats (2003)	•		•	•			•		•	•	

The six pollutants highlighted in green in table 3.1, cause a majority of the environmental damages that arise from burning fossil fuels to generate electricity (Kats & Capital, 2003) and are known contributors to global warming. These pollutants are also known to cause respiratory illness, cancers, and developmental impairment, increasingly quantified by the international community (Venema and Barg, 2003).

3.3 Environmental capital calculation model

3.3.1 Existing 2nd bottom line accounting models that address selected outcomes

To quantify the impact of selected emissions from electricity generation within this research, the methodological approach from GHG protocol for accounting for indirect emissions from purchased electricity is used. The GHG protocol methodology is consistent with the norms of the Intergovernmental Panel on Climate Change (IPCC) that provides guidance on how to account for GHG emissions from fossil fuel combustion and removal (Garg et al., 2006). The GHG Protocol's methodology establishes guidelines for developing inventory; identifying emission sources and greenhouse gases that should be measured and reported. This process involves identifying emissions associated with an organization's operations, categorizing them as direct and indirect emissions, and choosing the scope of accounting and reporting for indirect emissions.

Direct emissions are GHG emissions from owned or controlled sources by the company and are reported as part of Scope 1 emissions. Indirect emissions can be quantified as Scope 2 or Scope 3 emissions. Scope 2 emissions are GHG emissions that are associated with the generation or from the purchase of electricity, while Scope 3 emissions occur along the value chain (WRI, 2015). The most common approach for calculating the indirect GHG emissions is through the application of documented emission factors for the electricity purchased. An electricity emission factor represents the amount of a pollutant released to the atmosphere with an activity associated with the release of that pollutant (Cai et al., 2012). These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (EPA, 2015). For example, emission factor for GHG's emitted per unit of electricity delivered has units of pounds of CO2 equivalent per megawatt-hour (lbs-CO2e/MWh) or grams/kWh.

As per *GHG protocol for accounting for indirect emissions*, there are two types of electricity emission factors – emission factor at generation (EFG) and emissions factor at consumption (EFC). EFG is calculated as a fraction of the CO2 emissions from generation of electricity divided by amount of electricity generated, while EFC is calculated from CO2 emissions from generation divided by amount of electricity consumed (WBCSD & WRI, 2004). To avoid double counting and ensure internal consistency while reporting scope 2 emissions the use of EFG is recommended.

$$EFG = \frac{Total\ CO2\ emissions\ from\ electricity\ generation}{Electricity\ generated} \qquad \textit{(Equation1)}$$

$$EFC = \frac{Total\ CO2\ emissions\ from\ generation}{electricity\ consumed} \qquad \textit{(Equation 2)}$$

To calculate the environmental cost savings in the second bottom line calculations the EFG approach, illustrated as part of GHG protocol is used. The cost savings calculations not only use the GHG protocol approach to calculate the GHG emission factors but, use it for other criteria air pollutants (PM, NOx, and SOx emissions and water consumed during production of electricity).

3.3.2 Equations for second bottom line calculations

During the combustion of fossil fuels most carbon in immediately emitted as CO_2. However, some carbon is released as carbon monoxide, methane or non-methane volatile organic compounds. This is because the total CO2 emission from the combustion of fuel depends on the fuel, while the emissions of the non-CO2 gases depend on factors such as technologies, individual plant operation and maintenance (IPCC,2006). To account for these uncertainties, the approach for the second bottom line includes estimates for six selected environmental outcomes – CO_2, CH_4, SO_x, NO_x, $PM_{2.5}$ emissions and water demand for diverse fuel types and power plant quality.

To understand the capital saved by avoiding the environmental impacts of electricity use, this value is based on fuel source and mix, plant efficiencies and scrubbers for selected emissions and pollutants at the power plant, and this amount is added to each kilowatt-hour of electricity saved. The calculations are built for three country economies to illustrate the range of environmental savings possible from selecting various fuel source, mix, power plant quality and related environmental emissions and valuations (see Appendix C). Country specific emission factors for the selected outcomes differ based on the type of fuel source and mix, combustion technologies and are calculated using GHG protocol approach to include other non-CO_2 criteria air pollutants.

Calculating emission factors

The first step is to determine the emission factors for greenhouse gas, air pollutants and water consumed for producing 1 kilowatt hour using different types of fuels. The average emission factor for the select set of greenhouse gases (CO_2, CH_4), air pollutants (NOx, SOx, $PM_{2.5}$) and water consumption by the different fuel types is calculated by dividing the annual total emissions from different power plants by the annual total net electricity generated from that technology (equation below). The net electricity generation refers to the generated electricity supplied to the grid (i.e., source energy) and the electricity directly consumed by electricity generating unit is excluded. Countries where the data on the emissions is not separated by either the type of coal or the quality of the power plant, a single average value has been used.

Based on the most commonly used fuels for electricity generation, the second bottom line approach is built using a database on the 6 environmental impacts of electricity generation from 10 fuel sources - coal, natural gas, nuclear, oil, hydro, solar, wind, biomass, biofuels and waste. The emission factor for the six different environmental outcomes for different fuel sources is calculated as the fraction of the GHG or pollutant emission from electricity using a specific fuel (in grams) by the amount of electricity generated (kW) using that fuel.

For example, the emission factor for CO_2 emissions from coal fired power plants can be calculated using the first equation below.

$$EFG_{GHG} = \frac{\sum Total\ GHG\ emissions\ \ from\ electricity\ generation\ using\ fuel\ f}{\sum Net\ electricity\ generation\ using\ fuel\ f} \qquad (Equation\ 3)$$

$$EFG_{pollutant\ emission} = \frac{\sum Total\ pollutant\ emissions\ \ from\ electricity\ generation\ using\ fuel\ f}{\sum Net\ electricity\ generation\ using\ fuel\ f}$$

$$EFG_{water\ consumption} = \frac{\sum Total\ water\ used\ \ for\ electricity\ generation\ using\ fuel\ f}{\sum Net\ electricity\ generation\ using\ fuel\ f}$$

As each building project's specific fuel mix and power plant efficiencies will impact the GHG, pollutant emissions and water demand, the environmental impacts will also vary based on the fuel mix. The environmental benefits of reducing the select set of greenhouse gases, air pollutants and water consumption are computed using a product of the weighted emission factor, estimated using equation 3. The calculations completed for three economies each use the respective economy's fuel mix and power plant efficiencies.

$$EF_{weighted} = \sum_{j=1}^{n} Fuel\ mix_j * \ EFG_j \qquad (Equation\ 4)$$

Where

Fuel mix_j= fuel sources j from 1 to n based on country level fuel mix

EFG_j = average emission factor for fuel source j for selected GHG, pollutant or water use

Assigning monetary values to emissions

Finally, the monetary valuations for the specific environmental outcomes need to be set by each country in accordance with its national goals and international treaties (see section 3.2.3 for an illustrative set of valuations), to be used in equation 5 to calculate the annual 2nd bottom line savings.

$$Annual\ Second\ bottom\ line\ savings_{per\ pollutant} = \ EFC_{weighted,p} * \ MV_p \qquad (Equation\ 5)$$

Where,

$EFC_{weighted,p}$ = weighted averaged emission factor for greenhouse gas (CO_2, CH_4), pollutant (SOx, NOx, PM2.5) and water consumption p. Expressed in ton/kWh for emission and gallon/kWh.

MV_p = cost of avoidance for the selected greenhouse gas (CO_2, CH_4), pollutant (SOx, NOx, PM2.5) and water consumption p set by different countries. Expressed in \$/ton

The total annual second bottom line savings for each pollutant are calculated by multiplying the energy savings from investing in energy efficient technologies with the emission reduction per kWh. Assuming the accrual of savings over 15 years, the present value of the stream of savings is calculated using the traditional net present value formula.

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} S_t/(1+d)^t \qquad (Equation\ 6)$$

Where,

S = Environmental cost savings
N = Number of years in the study period and
d = Discount rate used to adjust cash flows to present value

3.4 Second bottom line calculation

The second bottom line savings summate the environmental value of energy savings per kilowatt-hour of electricity based on the given fuel source, fuel mix, generation efficiencies and power plant management in relation to CO_2, CH_4, SO_x, NO_X, $PM_{2.5}$ and water cost-benefits for three global scenarios. The three economies scenarios illustrate the highest possible, medium level and the low-end range of environmental cost savings possible based on the dirtiest to cleanest source of electricity.

For comparative purposes, an average of US and International valuations for CO_2, SO_x, NO_x, $PM2_{.5}$ pollution reductions and water benefits have been used to demonstrate the cost-benefit of each kwh saved through energy efficiency in the three economies (figure 3.16). The estimates are presented in a common measure of cents/kWh, broken down by the type of pollutant.

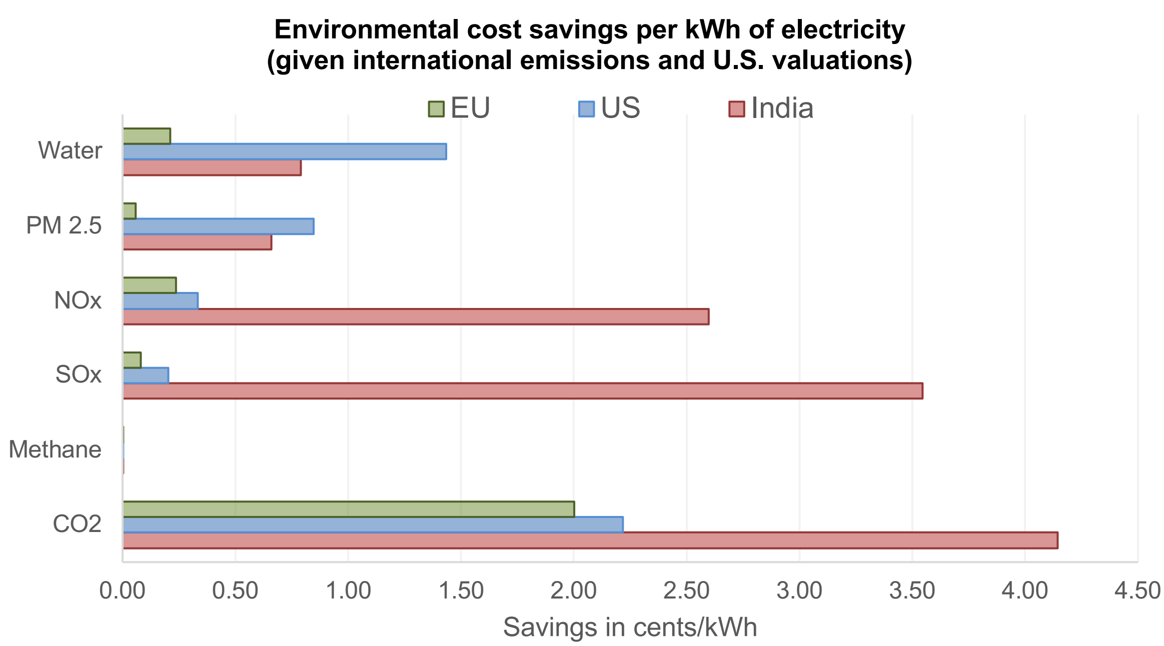


Figure 3.16: Range of environmental values for avoidance of selected outcomes for three global scenarios – an emerging economy (India), economies with mid-level sustainability goals (US), and economies in the forefront of defining climate change policies (EU) (Srivastava,2016).

In view of the lack of environmental values for avoidance of selected greenhouse gas and pollutant emissions, specifically the dollar per ton values that are required for monetizing the reduction in CO_2, SOx, NOx and PM emissions for India, international costs for pollutants reduction have been relied on. The costs are linked to the outcomes to calculate the environmental value per kWh of electricity. It is hypothesized that an extremely low value is suitable for emerging economies that does not put a price on the externalities associated with power generation, whereas a high valuation is indicative of a country's such as EU's commitment to reduction in GHG emissions. This new methodology will help decision makers select investments with the lowest environmental impact for corporate sustainability reporting.

3.4.1 Assumptions

In a second bottom line calculation, the capital saved by avoiding the environmental impacts of electricity use, based on fuel source and mix, plant efficiencies and scrubbers, for selected emissions and pollutants at the power plant are added to each kilowatt-hour of electricity saved. As part of the calculations, not all the environmental outcomes are included, only six have can be used to illustrate the approach outlined in this thesis.

The environmental cost saving per kWh of electricity are based on the available U.S. and E.U data on the cost of avoidance. In some economies, the emissions data on the fuel source and type of coal was not available, hence a single value is used for the calculation. For example, for EU and India, due to the lack of information on the difference in SOx emissions by the different coal types, a single value is used.

3.4.2 Data sources

The methods for estimating the impact of emissions from electricity generation uses techniques for estimating energy use of several fuel types using the best available data sources. These accurately reflect national data published by the countries. When national averages were not available, values from published reports and peer-reviewed articles is used.

After reviewing emission sources and values from last 10 years, and where recent figures for the emissions and cost of avoidance were not available, older sources have been considered. For example, due to the lack of recent literature on the cost of avoidance for methane emissions, 1998 cost has been used for calculating the per kWh cost savings.

3.4.3 Limitations

At present, emerging economies place no value on the externalities associated with power generation, whereas EU's commitment to reduction in GHG emissions may place a much higher value than shown on the US normalized chart 3.16 above.

For emerging economies, information on some of emissions from electricity generation is not available. As more data becomes available in the future, these calculations should be updated and automated to reflect the variation in fuel mix and plant efficiency. These updates will provide future research opportunities in this growing field of model and decision analysis involving investments in the built environment.

The second bottom line calculations do not include the environmental costs or benefits of the materials and assemblies installed and discarded, captured in life cycle assessment, which should be considered in future work and larger scale, cradle to grave environmental assessments.

3.5 Problems and limitations of financial and environmental model

The building industry has been in the forefront of embracing sustainability through green building certifications like the U.S. Green Building Council's Leadership in Energy and Environmental Design®, the Living Building Challenge, and the Architecture 2030 challenge, that requires new buildings, developments, and major renovations to be carbon neutral by 2030 (Architecture2030, 2015). However, the definitions of design for comfort, health, and well-being of the building occupant is often driven by market demands and building codes (World Green Building Council, 2013). But, workers spend more than 40 hours a week in the workplace in the U.S., where the minimum thermal (temperature, humidity levels), lighting (light levels on the work surface, in shared spaces), air (acceptable CO_2 and other contaminant levels), acoustic and spatial requirements for the operation of the space, are mostly prescribed by building codes (Muldavin, 2010a;Bendewald et al., 2014). With companies spending as much as 100 times the resources on employee salaries than what they spend on building operations and maintenance, any investment that improves the indoor environmental conditions, and increases occupant health and productivity, will impact the organization's bottom line (Loftness et al., 2005; Terrapin, 2012). Facilities operation cost is only part of the operating budget, majority of the cost is on employee salaries. Hence a more comprehensive cost benefit analysis which includes the human costs is required.

Chapter 4

Human capital: The 3rd Bottom Line

4.1 The need for 3rd Bottom line

While there is growing body of research and empirical evidence linking building design to health, well-being and productivity, the results have not been deeply integrated into building design decisions as the outcomes have not been fully linked to financial metrics. Energy and facility costs are only a small fraction of the operating cost of a business, and environmental cost-benefits are a fraction of these. Not surprisingly, however, the employee costs including salaries and benefits comprise 90 % of the cost of running most businesses (Loftness et al., 2005). As a result, any improvements made for energy efficiency that also improve indoor environment quality (IEQ) impacting occupant health or productivity will have financial implications for employers.

Quantifying human capital costs and benefits is becoming more relevant as the corporate real estate industry strives to integrate wellness features (McArthur et al., 2015) and to adopt voluntary sustainability standards to promote occupant well-being and gain competitive edge. Since a company's reputation and brand are critical to its profitability, investments in high performance building systems can help shape their branding story and contribute to a company's sustainability reputation and leadership (World Green Building Council, 2013).

Some corporations are also tracking the impact of their operations as part of Corporate Social Responsibility initiatives and sustainability reporting. In most cases, however, the metrics do not directly relate to the impact of the built environment on occupants. Investments in high performance building technologies can positively impact employees, further contributing to the accelerating sustainability compliance requirements for businesses and governments (Bendewald et al., 2014). By quantifying the human capital costs and benefits, organizations can present the savings as part of their CSR and sustainability efforts.

One of the barriers to integrating the health and productivity benefits into real estate decisions has been the ambiguity around what to measure and how to quantify savings. This is in part due to the often qualitative evidence of the impact of the built environment on occupant's health and well-being, with limited economic data that can be used by the decision maker (Bennett, Schaltegger, & Zvezdov, 2013). Clear guidance on the key performance metrics to track and a greater set of evidence of impact will be critical to move our investments in the built environment away from the first-least-cost to maximizing employee health and productivity. In the third bottom line calculations, advanced as part of this research, a new set of indices/metrics specific to the built environment are identified and the outcomes are quantified so that the information can be used during building capital expenditure decisions. An approach to handling third bottom line calculations has been developed based on establishing baseline cost-benefits for employee health and productivity and applying multi-method (portfolio data analysis, laboratory and field based) research findings to quantify human capital savings.

There are some established tools and methodologies that offer approaches to capturing human capital savings, but their application is still limited. Greg Kats, in 'The Costs and Financial Benefits of Green', quantifies the health and productivity benefits of investing in LEED buildings (Kats & Capital, 2003), although not disaggregated to the building technology or system level. Rocky Mountain Institute in '*How to calculate and present deep retrofit value'* offers a comprehensive guide for corporate and building professionals to incorporate the benefits of deep retrofits in their decision making (Bendewald et al., 2014). Yet, it does not provide average or default benefit values for completing the calculations that can help decision maker make decisions more efficiently. Carnegie Mellon's Center for Building Performance and Diagnostics 'Building Investment Decision Support' (BIDS) tool is one of most relevant tools and underpins the third bottom line calculations in this thesis. The BIDS tool establishes baseline human costs and benefits for different building types and aggregates research studies that link improved building environmental quality to human and financial life cycle cost-benefits (Loftness et al., 2005). This thesis advances the BIDS process with more built environment related metrics, modified baseline information, and aggregated benefit values for decision makers to quickly quantify the human capital cost savings.

4.2 Identifying measurable human capital outcomes for 3rd bottom line

Research shows that investments in high performance, green design materials, assemblies and building systems can improve worker productivity and occupant health and well-being, resulting in bottom line benefits for businesses. Despite the evidence of its impact, investments towards improving buildings and indoor environmental quality has not been a priority in building design and construction, and "resistance remains to incorporating it into financial decision-making" (World Green Building Council, 2013). With the availability of more quantitative studies on the link of IEQ and its impact on occupants, a stronger financial case for investing in better indoor environments can be made, which would ultimately lead to better returns on the company's greatest assets - its employees.

4.2.1 Measurable human outcomes to be quantified across investment categories

The human capital savings from investing in high performance building technologies that improve indoor environmental quality can be quantified by occupant health, well-being and productivity. Several measurable human outcomes are described below, along with the available quantitative datasets for the twelve selected investments described in chapter 2 to illustrate the TBL calculation methodology developed within this thesis.

Individual Productivity benefits: improved task performance

A majority of the cost of running a business is for employee salaries. Any investment that can increase productivity even by a small percentage can help pay back the costs for investing in the building improvement. There is evidence that deep energy or sustainability retrofits improve productivity of the occupant, as well as enhance employee satisfaction, by offering better thermal comfort, indoor air quality, and visual quality (Bendewald et al., 2014).

Leaman & Bordass (1998) estimate the potential impact of best and worst buildings on overall productivity is an increase by as much as 12.5 % in the highest performing buildings, and a decrease by as much as 17.5 % in the worst performing buildings – a range of 30% difference in productivity. Indeed, approximately 85% of the company's whole life cycle costs can be reduced through health and productivity cost savings (Issa et al., 2010). When aggregated at a national level, the benefits can be staggering. ASHRAE reports the loss to American businesses of approximately $60 billion due to diminished productivity associated with poor IEQ (1999).

Yet, measuring productivity is difficult as it is measured differently for skill based, rule based and knowledge based jobs (Loftness et al., 2005). Productivity is usually quantified as the ability of people to increase the quantity and quality of goods and services they deliver (Leaman & Bordass, 1999). In blue collar skilled manual jobs, the quantity and quality of work is measured in work completed without errors or do-overs (World Green Building Council, 2013;Loftness et al., 2005). In rule-based jobs such as call centers, productivity is often measured with a range of indices that reflect speed, accuracy, customer satisfaction, and customer longevity. In assessing white-collar, knowledge based work, productivity has more recently been measured using standardized suites of cognitive tests which may include memory, attention, reading, pattern recognition and math tasks (Rasmussen & Pejtersen, 1990). Still newer test methods are emerging to capture the strategic thinking, decision-making, communication and collaborative abilities of 'gold collar' workers - indices most difficult to measure (Bunk, 1999).

Improvement in productivity can be an extremely powerful argument for investing in workplace quality when the performance at task can be quantified. A range productivity studies have emerged in the past decade linking improvements in IEQ, lighting, and access to the nature, to an increase of 6-26% in "occupant performance" in learning of students in schools, white collar workers in commercial offices, or spending of consumers in retail venues (Muldavin, 2010a).

Researchers around the world have used controlled experiments and intervention studies to demonstrate that: increasing ventilation rates improves performance in normal office tasks (Wargocki et al,, 2000); controlling indoor air pollution sources improves cognitive function, overall health and reduces absenteeism (Feige et al., 2013; Wyon,2004; Singh,1996); integrating views and access to nature improves performance in schools (Heschong Mahone

Group, 1999). In hospitals, access to daylight and views for patients can result in shorter hospital stays and faster recovery (Choi et al., 2012).

Despite these measured gains in occupant performance through high performance building investments, productivity and task performance are not regularly quantified in deciding financial investments towards improving the work environment (Feige et al., 2013).

Organizational productivity benefits

Individual productivity can be an indicator for some job descriptions, but other knowledge based jobs need to be evaluated through measures of organization productivity that reflect the performance of team or even all employees (Charles et al., 2004 ; Loftness et al., 2005). Time to market, profit margins as well as present and future stock values are indices that can be measured to cost justify investments in high performance building systems and components (Loftness et al., 2005). Other measures include customer attraction, satisfaction and retention.

High performance quality work environments can enhance workflow by motivating and reducing employee stress which can measurably improve workflow, quantified in increased output per unit of time or company value. In addition, the collaborative, multi-disciplinary communication and creativity of the 'gold collar' workers have led to an interest in team retention indices.

None of the 12 investments used to illustrate the TBL decision support methodology have measured organizational productivity benefits.

Absenteeism savings

A second metric, often tracked by organizations, that impacts worker productivity and indirectly health, is absenteeism. Absenteeism is calculated differently by each organization, but typically reflects the number of days or hours that an employee is absent, due to illness or personal reasons, from the total working days per year. Clearly, an absent worker is not productive for the organization (World Green Building Council, 2013).

The average rate of absenteeism varies widely internationally. The U.S. Department of Labor reports the annual US absenteeism rate as 3% per employee in the private sector — or 62.4 hours per year per employee lost (World Green Building Council, 2014). The reported average absentee rate for the public sector is 4%, with over 83 hours lost to absences per year (US Department of Labor, 2010). In a large organization, this translates to millions of dollars lost to absenteeism. In all sectors, efforts to reduce absenteeism by even a fraction of a % through building design can yield substantial financial benefits. Since organizations "on average spend 112 times the amount of money on people as on energy costs, any building related investments that reduces absenteeism is highly valuable" (Bendewald et al., 2014).

There is definite evidence that investing in high quality indoor environments, including improving the indoor air quality and investing in adequate and proper lighting conditions can reduce absenteeism rates by 15 to 40 % (Bendewald et al., 2014 ; World Green Building Council, 2014). A Canadian study found that approximately one- third of employees' sick leave can be attributed to symptoms caused by poor indoor air quality (Charles et al., 2004). The same study found that improved communication and social support enabled by open office plans were also strong contributors to lowered absenteeism. A case study by the Rocky Mountain Institute identifies a 15-25 % reduction in absenteeism with better lighting and HVAC systems (Romm & Browning, 1998). A 39 % reduction in absenteeism rate was recorded in a before and after study of a Melbourne office that achieved 5 Green Star office design rating (Dunckley, 2007).

Eight summaries of relevance to the TBL proof sets in chapter 5 are included below.

Daylighting = Reduced Absenteeism + Energy Savings
In a 1995 building case study of Lockheed Building 157 in Sunnyvale, California, Thayer identifies 50% savings in lighting, cooling and ventilation energy and 15% reduced absenteeism due to the daylighting design, which integrates layout, orientation, window placement, type of glazing, light shelves, and ceilings.

Daylighting = Energy savings + individual productivity
In a 2001 field study at a software development company, Figueiro et al. identify a 15% increase in time dedicated to work tasks and a 35% decrease in electric lighting use for occupants of windowed offices as compared to occupants in interior offices with no access to daylight, in winter months.

Additional localized lighting = Individual Productivity
In 2007 study, Juslen et al identified average of 3% improvement on productivity by measuring machine repairing time localized task lighting in shift work in a Finland chocolate factory package room with 16 subjects. Although some important factors varied during the test period, short-term and long-term absenteeism were each reduced by 4% and 17% compared with the situation before the addition of lighting installation.

Lighting Control = Individual Productivity + Energy Savings
In a 1994 before and after building case study of the Pennsylvania Power and Light office in Allentown, PA, Romm and Browning identify a 13.2% increase in productivity, a 25% reduction in absenteeism and 69% lighting energy savings following a lighting retrofit introducing high-efficiency ballasts, T-8 fluorescent lamps and parabolic louver fixtures.

LEED Office Buildings = Health + Absenteeism Savings + Productivity
In a 2011 multi-building case study, Singh et al. investigated the effects of improved indoor environmental quality (IEQ) on perceived health and productivity of occupants

who moved from conventional to green buildings. The study determined that the improved IEQ contributes to 1.75 additional work hours per year for each employee due to perceived improvements in asthma and respiratory allergies, and 2.02 additional work hours per year for each employee due to perceived improvements in depression or stress, along with an additional 38.98 work hours per year due to perceived productivity improvement.

Indoor Environmental Quality = Employee Health + Productivity
In a 2009 before and after study of 2 companies with a total of 263 employees that moved from conventional offices to LEED Platinum and Gold buildings in Michigan, Grady et al. identify an approximately 50% reduction in self-reported asthma, respiratory allergies, and depression or stress related absenteeism. The study also identifies reductions in affected work hours that ranged between 6 and 10 hours per month for occupants with reported symptoms, as well as a 2.8% perceived productivity increase for general occupants. These outcomes were determined to be due to higher indoor environmental quality.

Whole Building = Individual Productivity + Energy Savings
In a 1998 field case study of expanded facilities for VeriFone Inc. in Costa Mesa, CA, Pape identifies a 40% reduction in absenteeism, 5% improved productivity, and 50% energy savings in a new office building with skylights, high performance glazing, 60% more insulation than code, increased outside air with energy efficient air handlers, a natural gas fired cooling system, and smart lighting with occupancy sensors, as compared to an older Verifone office building.

High performance building = Energy savings + individual productivity
In a 1992 building case study of ING Bank in Amsterdam, Bill Browning of Rocky Mountain Institute identifies a 92% reduction in primary energy consumption and a 15% reduction in employee absenteeism compared to the bank's former headquarters, due to high performance design strategies including daylight, a narrow floor plan that allows landscaped views for every occupant, passive solar conditioning, co-generation, and the use of heat exchangers.

Staff attraction/ retention benefit

Another benefit of investing in high performance buildings is the ability to attract and keep the best workers, often expressed in the staff attraction or turnover rate. Staff attraction/turnover is defined as the percentage of regular, full time employees leaving employment in a given year. Recruiting and retaining employees is costly for businesses and hiring new staff requires significant time for recruiting, interviewing and training new employees (Bendewald et al., 2014). A generally accepted figure is that replacing an existing employees costs in total, about 1.5 to 2 times that lost employee's salary (World Green Building Council, 2013). The inability to attract or retain employees is a significant cost center for employers: with average private sector turnover at over 14% (Society of Human Resource Management, 2012) over $4,000 is lost per employee each year.

Since employee turnover is so costly, reducing this cost through high performance, sustainable work environments can be a good business strategy. And in highly competitive organizations, a positive work environment and satisfaction can attract talent as well as improve retention of key staff. Attracting and retaining the best employees can be linked to the quality of the benefits they receive, including the physical, environmental and technological workplace (Loftness et al., 2005 ; World Green Building Council, 2014).

High performance building technologies can reduce the costs associated with employee compensation and benefits and other efforts by creating attractive and healthy work environments that improve employee satisfaction with the organization. In a survey by the real estate firm CBRE of 1,065 tenants in 156 buildings, 34 % of office tenants agreed that green office space is important to recruiting. Additionally, 62 % of office tenants agreed that green office space created a positive public image for firm's owners and stakeholders and helped attract talent (CBRE, CoStar, 2011).

None of the 12 investments used to illustrate the TBL decision support methodology have measured staff attraction/retention benefits.

Health cost savings

If salaries related to the productivity of workers is the most substantial investment of an organization, benefits are the second major investment, including medical and insurance costs, as well as workman's compensation, that can be significantly linked to the quality of the workplace environment (Loftness et al., 2005). Exposure to indoor stressors in offices including poor lighting, moisture, mold, noise, particulates and more, with increasing evidence of both short term and long-term effects on the nervous system, the immune system and the endocrine system (Bluyssen, 2012).

The list of health impacts of the built environment is an emerging and critical area of study. From the early days of the Cornell Medical Index to the current WELL™ goals, the importance of capturing and quantifying the health and associated productivity benefits of high quality built environments is central to the third bottom line (Weill Cornell Medicine Samuel J. Wood Library, n.d. ;International WELL Building Institute, 2017). Building on the Cornell Medical Index of 1948 and the WELL goals, 12 indices (Table 4.1) are used for evaluating the importance of design construction and operation decisions on human health.

Table 4.1: Qualities of human health integral with sustainable design

1 **Respiratory health** - asthma/allergies and cold/flus
2 Digestive health
3 **Visual health**
4 Aural health
5 **Skin/dermal health** (integumentary system)

6 **Musculoskeletal health**
7 Cardiovascular health
8 Nervous system health
9 Genito-urinary (including reproductive) health
10 **Endocrine system health** including fatigue, sleep
11 Immune system health
12 **Mental health -** stress, depression

Health costs include medical insurance costs, medication and medical treatment as well as impaired work performance. Recent studies have also found that IEQ may be associated with mental health effects (Houtman et al, 2007), as well as illnesses that take longer to manifest such as cardiovascular disease (Babisch, 2008; Lewtas, 2007), asthma (Fisk, Lei-Gomez, & Mendell, 2007) and obesity (Bonnefoy et al., 2004). There are expenses associated with providing medical care and medical insurance to employees annually to overcome these illnesses. Several studies show that high performance buildings can lower incidence and severity of asthma symptoms, respiratory illnesses, depression, anxiety and even chronic pulmonary disease (Bendewald et al., 2014), thereby lowering the medical costs for the employer.

Beyond direct medical costs, researchers in the medical and occupational health fields have begun to identify the indirect costs of health conditions to employers. The "days at work limited in performing job tasks because of health" (Mitchell & Bates, 2011), often referred to as 'presenteeism', can significantly impact the bottom line. The indirect costs for health conditions are reflected in reduced effectiveness on the job, especially when an employee comes to work with a cold or continues working with a headache. Mitchell and Bates (2011) combine productivity costs and medical costs for different conditions to estimate the losses for an average size employer. Their analysis showed that for every dollar of medical costs, there were 0.4 dollars of productivity cost (Figure 4.1).

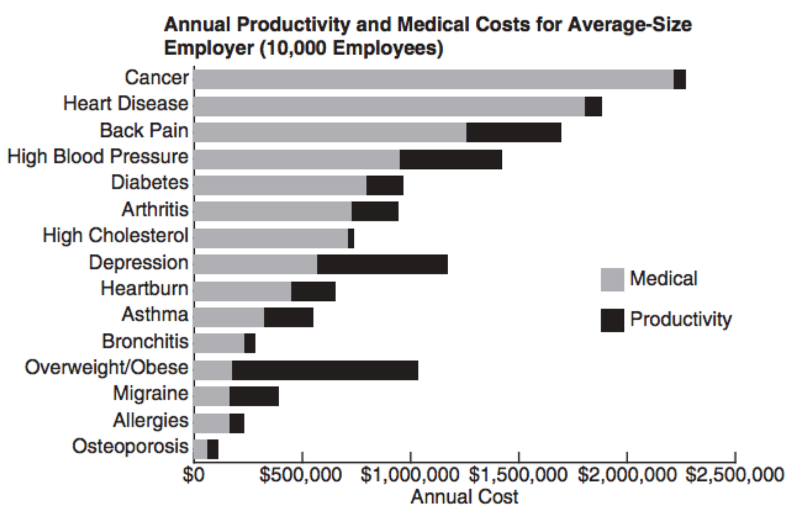


Figure 4.1: Annual productivity and medical costs for average sized employer with 10,000 employees (Mitchell & Bates, 2011)

Improved employee health can reduce the frequency and the length of illness, improving the health profile of the organization, and reducing expenses with health insurance and medical providers If high performance buildings demonstrate measured reductions in health costs and associated productivity, they will present new opportunities for investment in better quality built environments (Bluyssen, 2009).

There are twelve human systems that are impacted by the built environment, out of which some have substantial research. There is considerable evidence of this link in "six primary clusters of health issues related to the built environment: respiratory (chest, wheeze, allergies, asthma, colds, flu); mucosal (eye, nose, throat); dermal (face, hand, skin); neuro-physiological (headache, migraine, dizziness, heavy headedness); musculoskeletal; and psychological (SAD, bipolar disorder)"(Loftness et al., 2006). In this thesis, four health issues have been included in the TBL calculations and the relevant lab and field studies used in the calculation are presented below.

1. Headache cost savings

Headache and migraines are serious disorders in the workplace. It is estimated that approximately 11% of adult Americans suffer from migraine. The estimated economic burden of headaches and migraines is $14 billion, out of which $ 1 billion is in direct medical care and $13 billion in indirect costs related to lost productivity (Hawkins et al., 2008). Based on estimates by U.S EPA, per capita direct cost of headaches is $73 per year (EPA, 2007). There is also an annual indirect cost of 2.5 workdays (1% baseline workdays) due to absence from work and reduced work effectiveness attributed to headaches (Schwartz et al., 1997)(Raak & Raak, 2003).

Lighting conditions are a major driver for headaches, especially when there is direct or indirect glare, aging ballasts and lamps, or inappropriate light levels for the task (Wilkins et al.,1989; Aaras.1998, Cakir and Cakir.,1998; Viola et al., 2008). Glare specially the discomfort glare, which causes difficulty in seeing, can result in eyestrain and headaches (World Green Building Council, 2014 ; IWBI, 2017). Fluctuations in light output from lamps, specifically at low frequencies (15 Hz to 50 Hz) can cause headaches among workers who are susceptible to getting headaches (Boyce,2003) (Wilkins et al., 1989). Fewer headaches are also reported in brightly daylit offices when compared to offices with poor lighting quality (Thayer et al., 2010).

Other causes include exposure to poor indoor air with pollutants like VOCs, combustion products, dust and airborne particulate matter and high indoor temperatures (Menzies et al., 1997 ; Hedge et al., 1995 ; Bakke et al., 2008 ; Kroeling,1998 ; Apte & Erdmann, 2000; Witterseh et al.,2004). Mold spores that often grows on cooling coils in HVAC systems due to moisture condensation and enters the building's indoor air can also cause headaches, allergies and other respiratory system disorders (Kolari et al., 2005; IWBI, 2017).

Following references were valuable in developing the triple bottom line proof sets for the 12 selected investments:

Lighting Control = Health

In a 1998 multiple building study in Germany, Cakir and Cakir identify a 19% reduction in headaches for workers with separate task and ambient lighting, as compared to workers with ceiling only combined task and ambient lighting.

Adjustable LED task lighting = Health + Energy Savings

In a 2014 intervention study involving 95 office employees, 48 subjects were provided adjustable 7-watt LED task lights to replace fluorescent underbin and CFL desk lamps, with overhead lighting level of 200-500 lux. Joines et al. identify a 9.2% reduction in headaches ($p = 0.0118$) while reading or doing close work as the result of 6 months of LED task-light use, as compared to no reduction in headaches in the control group.

Lighting Control = Health

In a 1998 controlled experiment, Aaras et al identify a 27% reduction in the frequency of headaches in computer workers when conventional down lighting is replaced by user-controlled suspended indirect- direct lighting (75/25) and venetian blinds are added to windows.

Lighting control = Individual productivity + Health

In a 1989 controlled field experiment at a government legal office in the UK, Wilkins et al identify a 74% reduction in the incidence of headaches among office workers when magnetic ballasts are replaced by high frequency electronic ballasts.

Access to Operable Windows = Reduction in Sick Building Syndromes

In winter 1988 - 1989 cross sectional study of 61 buildings with 7,043 workers in Netherlands, Zweers T. et al identified percentage reduction in Sick Building Syndromes for fever (45%), skin irritations (49%), nasal (39%), eye irritations (45%) and headaches (51%) in a population of 2,806 workers due to presence of operable windows compared to buildings with air cooling systems only.

Natural Ventilation = Improved Health + Productivity

In a 1987 cross sectional study of 42 buildings (4373 office workers) in the UK, Burge et al. identify a reduction in self-perceived work-related symptoms- headaches (9.3%), dry eyes (41.9%), itchy Eyes (29%), runny nose (9.5%), blocked nose (11.1%), dry throat (21.7%), Lethargy (10.7%), flu (40%), difficulty in breathing (33.3%) and chest tightness (25%) in naturally ventilated buildings as compared to buildings that support other modes of ventilation for an average reduction of 23.11%.

Wargocki et al in a 2000 study, identify a 1.1% productivity increase for every 10% reduction in SBS complaints, suggesting a 2.54% gain in productivity gain due to natural ventilation.

Operable Windows + Indoor Plants = Health + Individual Productivity

In a 2012 cross sectional study of 30 office buildings in Hong Kong (n = 469), Zhonghua and Siu-Yu identify a reduction in Sick Building Syndrome Symptoms (SBS) with the presence of indoor plants and operable windows, resulting in an average reduction of 42.50% of sinus conditions (p = 0.025), a 47.33% reduction in skin irritation (p = 0.025), a 16.3% reduction of headaches (only significant with the presence of operable windows, p = 0.027), and a 63.60% reduction in eye irritation (only significant with the presence of indoor plants, p = 0.040).

Thermal Comfort = Health + Individual Productivity

In a 2000 field experiment of 30 subjects clothed for thermal neutrality at 22°C in an office laboratory at the Technical University of Denmark, Witterseh et al identify an average 32.7% decrease in eye irritation, 37.0% decrease in nose irritation, 30.6% decrease in throat irritation, 44.9% decrease in headache intensity, and a 7.5% increase in self-estimated productivity among subjects in work environments with thermal acceptability (22°C), as compared to those in warm thermal work environments (26°C).

Individual Ventilation Control = Individual Productivity + Health

In a 1997 controlled experiment, Menzies et al identify an 11% increase in perceived productivity and a 20% decrease in work- or indoor air quality-related headache symptoms following the installation of individual ventilation controls, as compared to the previous automatically-controlled, conventional VAV system.

2. Respiratory illnesses - colds and flus cost savings

Respiratory tract infections which include colds and flus are the most common illness in humans. The direct cost of a cold episode to an American employer is $68 per employee per year, which includes the cost of over the counter and prescription medications and doctor visits (Fendrick et al.;, 2003). Additionally, there are also indirect costs from the 1.1 days per employee per year productivity loss on the job, due to absence from work and reduced work performance (Bramley et al., 2002).

Many indoor pollutants including exposure to VOCs and particulate matter from paints, finishes and other coatings, cleaning products, air fresheners and other material brought into the building can cause discomfort and trigger nose, throat and eye irritation and asthma (IWBI, 2017). Mitigation of molds and microbes in buildings reduces the incidences of infections and allergic reactions (National Academies Press, 2004). Higher ventilation rates, reduced space sharing, reduced occupant density, or irradiation of air with ultraviolet light can also reduce instances of respiratory illnesses by 23% to 76% amongst occupants (Olli et al.,2002; Rios, 2003; Zweers, 1989; Kroeling,1988;Burge, 1987; Fisk & Kumar, 2002; Menzies et al.2000; Harrison, 1989; Jaakkola & Heinonen,1995 ; Pilotto et al., 1997).

For generating the twelve Triple Bottom Line proof sets in chapter 5, following references were valuable.

Natural Ventilation = Health

In a 2003 cross sectional study of 3,686 office workers in 2 office buildings in downtown Rio De Janeiro, Brazil, Rios et al. identified a lower prevalence of self-reported work-related symptoms including eye dryness by 18.6%, runny nose by 16.1%, dry throat by 14.3%, and lethargy by 13.7% in workers in the naturally ventilated building compared to workers in the sealed office building, despite high levels of RH, PM and VOCs in the naturally ventilated building.

Access to Operable Windows = Reduction in Sick Building Syndrome

In winter 1988 - 1989 cross sectional study of 61 buildings with 7,043 workers in Netherlands, Zweers et al identified percentage reduction in Sick Building Syndromes for fever (45%), skin irritations (49%), nasal (39%), eye irritations (45%) and headaches (51%) in a population of 2,806 workers due to presence of operable windows compared to buildings with air cooling systems only.

Ventilation = Health + Individual Productivity

In a 1988 multiple building study in Berlin and Heidelberg, Kroeling identifies a 33% reduction in reported headaches, a 28% reduction in reported frequency of colds and a 31% reduction in reported circulation problems in naturally ventilated office buildings, as compared to air-conditioned office buildings.

Natural Ventilation = Improved Health + Productivity

In a 1987 cross sectional study of 42 buildings (4373 office workers) in the UK, Burge et al. identify a reduction in self-perceived work-related symptoms- headaches (9.3%), dry eyes (41.9%), itchy eyes (29%), runny nose (9.5%), blocked nose (11.1%), dry throat (21.7%), lethargy (10.7%), flu (40%), difficulty in breathing (33.3%) and chest tightness (25%) in naturally ventilated buildings as compared to buildings that support other modes of ventilation for an average reduction of 23.11%.

Wargocki et al in a 2000 study, identify a 1.1% productivity increase for every 10% reduction in SBS complaints, suggesting a 2.54% gain in productivity gain due to natural ventilation.

Natural Ventilation = Reduced SBS symptoms

In a 2002 meta-analysis of 12 studies (467 office buildings and n = 24,000 subjects) across 6 European countries and the USA, Olli et al. identify a 23-67% decrease in SBS symptoms in naturally ventilated offices as compared to air-conditioned offices in 16 assessments within the 12 studies that spanned four locations. In these studies, the common SBS symptoms that were evaluated across all studies can be grouped as eye symptoms, upper respiratory, lower respiratory and central nervous system.

In a 2000 study, Wargocki et al. (2000) identified a 1.1% productivity increase for every 10% reduction in SBS complaints suggesting a 3.3% - 22% productivity gain due to natural ventilation.

Thermal Comfort = Health + Individual Productivity

In a 2000 field experiment of 30 subjects clothed for thermal neutrality at 22°C in an office laboratory at the Technical University of Denmark, Witterseh et al identify an average 32.7% decrease in eye irritation, 37.0% decrease in nose irritation, 30.6% decrease in throat irritation, 44.9% decrease in headache intensity, and a 7.5% increase in self-estimated productivity among subjects in work environments with thermal acceptability (22°C), as compared to those in warm thermal work environments (26°C).

Green Building = Health + Productivity

In a 2009 building case study of an office environment in Lansing, Michigan, Singh et al. identify a 2.6% increase in employee productivity, an 18.3% decrease in employee absenteeism, and a 4.82% decrease in perceived asthma and respiratory allergies, due to green buildings.

3. Skin irritation cost savings

Skin irritation costs the American employer $86 per employee per year, which includes cost of allergy diagnosis and treatment. Indoor air pollutants, exposure to VOC, formaldehyde, airborne particles and contaminants and harmful ingredients in cleaning products can cause facial skin irritation and dryness of the skin, irritation of mucosal membranes (Bluyssen, 2012; IWBI, 2017; Wolkoff et al., 2003). Extremely low humidity is also known to be a source of dryness and irritation of the skin and eye (IWBI, 2017). Additionally, cold, damp indoor environmental conditions or presence of mold and other agents in damp conditions have been statistically linked to instances of skin irritation or skin symptoms (National Academies Press, 2004). Control of air contaminants, produced either inside the building or entering from outside, and maintaining optimal IAQ can reduce instances of skin irritation (Reinikainen & Jaakkola, 2003;Bakke et al., 2008 ;Hedge et al., 1993; Zweers et al.,1989).

Two summaries of relevance to the triple bottom line proof sets in chapter 5 are included below.

Access to Operable Windows = Reduction in Sick Building Syndrome

In winter 1988 - 1989 cross sectional study of 61 buildings with 7,043 workers in Netherlands, Zweers et al., identified percentage reduction in Sick Building Syndromes for fever (45%), skin irritations (49%), nasal (39%), eye irritations (45%) and headaches (51%) in a population of 2,806 workers due to presence of operable windows compared to buildings with air cooling systems only.

Operable Windows + Indoor Plants = Health + Individual Productivity

In a 2012 cross sectional study of 30 office buildings in Hong Kong (n = 469), Zhonghua and Siu-Yu identify a reduction in Sick Building Syndrome Symptoms (SBS) with the presence of indoor plants and operable windows, resulting in an average reduction of 42.50% of sinus conditions ($p = 0.025$), a 47.33% reduction in skin irritation ($p = 0.025$), a 16.3% reduction of headaches (only significant with the presence of operable windows, p = 0.027), and a 63.60% reduction in eye irritation (only significant with the presence of indoor plants, p = 0.040).

4. Eye irritation cost savings

The annual average cost for a patient with eye irritation is $97.27 which includes the cost for anticipated diagnosis and treatment services (EPA, 2007). Given the average eye irritation prevalence rate in office workers of 18.6% and annual median health costs of $97.27, eye irritation costs the American employer $18 per employee per year (Apte & Erdmann, 2000 ; EPA, 2007).

Investing in adequate and proper lighting conditions can reduce visual discomfort that leads to eyestrain, irritation of the eyes (Stone, 2009). Poor visibility, glare, flicker and lack of control over the visual environment can affect task performance and lead to eyestrain (World Green Building Council, 2014; Wilkins et al.,1989). Exposure to certain indoor air pollutants like VOCs in cleaning products, from building operations and maintenance, airborne particles and excessively strong or distinct odors can also trigger eye irritation (Bluyssen, 2012; IWBI, 2017; Wolkoff et al., 2003 ; Šeduikyte & Bliūdžius, 2005 ; Rios,2003; Toftum,2009).

Six summaries of relevance to the triple bottom line proof sets in chapter 5 are presented below.

Natural Ventilation + Occupant Control = Health

In a 2004-2008 cross sectional study of 24 Danish office buildings and 1,272 occupants, Toftum identified a lower prevalence of building related symptoms and higher occupant satisfaction in the naturally ventilated offices as compared to in sealed offices. Additionally, out of 6 building related symptoms, Toftum identified a 9% lower prevalence of eye irritation in the naturally ventilated buildings as compared to the sealed buildings, thus reinforcing the findings of Hummelgaard et al (2007).

Natural Ventilation = Health + Productivity

In a 2007 study of 9 office buildings in Copenhagen, Denmark, Hummelgaard et al. identified 31% less prevalence of SBS symptoms and 49-86% less self-reported eye itching as an SBS symptom among workers in naturally ventilated buildings compared to workers in mechanically ventilated buildings.

Natural Ventilation = Health

In a 2003 cross sectional study of 3,686 office workers in 2 office buildings in downtown Rio De Janeiro, Brazil, Rios et al. identified a lower prevalence of self-reported work-related symptoms including eye dryness (by 18.6%), runny nose (by 16.1%), dry throat (by 14.3%), and lethargy (by 13.7%) of workers in the naturally ventilated building compared to workers in the sealed office building, despite high levels of RH, PM and VOCs in the naturally ventilated building.

Natural Ventilation = Improved Health + Productivity

In a 1987 cross sectional study of 42 buildings (4373 office workers) in the UK, Burge et al. identify a reduction in self-perceived work-related symptoms- headaches (9.3%), dry eyes (41.9%), itchy eyes (29%), runny nose (9.5%), blocked nose (11.1%), dry throat (21.7%), lethargy (10.7%), flu (40%), difficulty in breathing (33.3%) and chest tightness (25%) in naturally ventilated buildings as compared to buildings that support other modes of ventilation for an average reduction of 23.11%.

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In a 2000 field experiment of 30 subjects clothed for thermal neutrality at 22°C in an office laboratory at the Technical University of Denmark, Witterseh et al identify an average 32.7% decrease in eye irritation, 37.0% decrease in nose irritation, 30.6% decrease in throat irritation, 44.9% decrease in headache intensity, and a 7.5% increase in self-estimated productivity among subjects in work environments with thermal acceptability (22°C), as compared to those in warm thermal work environments (26°C).

5. Asthma and allergies cost savings

Allergies and asthma cost the American employer anywhere from $95 to $350 per employee per year (Nunes et al., 2017; EPA, 2007; Cisternas et al., 2003). Additionally, there are indirect costs from loss of productivity due to asthma and asthma associated activity limitations. Given the estimated asthma prevalence rate of 11.3% in adults of 18 to 64 years, indirect costs from working day absenteeism amount to 0.28 to 0.63 days per employee per year (Nunes et al., 2017;Mannino et al., 2002; Blackwell et al., 2012).

Poor indoor air quality with the presence of VOCs, airborne particulate matter, pests and dust mites, moisture and mold problems can lead to increased allergies and asthma (Fisk & Kumar, 2002; IWBI, 2017; Wieslander et al., 1997; Cox-Ganser et al., 2005). In residential buildings up to 100 % increase in asthma and lower respiratory symptoms can be attributed to mold or moisture problems (Milton et al., 2000 ; Norbäck et al., 1995). Ambient outdoor air is often better quality and natural ventilation through operable doors and windows and general building infiltration can improve the indoor air quality unless the external air parameters are poor (IWBI, 2017). High performance buildings also provide significant protection against potentially toxic chemicals, allergens and other pollutants (Grady et al., 2009; Singh et al., 2011).

Two summaries of relevance to the TBL proof sets in chapter 5 are presented below.

> *Indoor Environmental Quality = Employee Health + Productivity*
>
> In a 2009 before and after study of 2 companies with a total of 263 employees that moved from conventional offices to LEED Platinum and Gold buildings in Michigan, Grady et al. identify an approximately 50% reduction in self-reported asthma, respiratory allergies, and depression or stress related absenteeism. The study also identifies reductions in affected work hours that ranged between 6 and 10 hours per month for occupants with reported symptoms, as well as a 2.8% perceived productivity increase for general occupants. These outcomes were determined to be due to higher indoor environmental quality.
>
> *LEED Office Buildings = Health + Absenteeism Savings + Productivity*
>
> In a 2011 multi-building case study, Singh et al. investigated the effects of improved indoor environmental quality (IEQ) on perceived health and productivity of occupants who moved from conventional to green buildings. The study determined that the improved IEQ contributes to 1.75 additional work hours per year for each employee due to perceived improvements in asthma and respiratory allergies, and 2.02 additional work hours per year for each employee due to perceived improvements in depression or stress, along with an additional 38.98 work hours per year due to perceived productivity improvement.

6. Sick Building Syndrome (SBS) symptoms cost savings

The U.S. EPA defines Sick Building Syndrome (SBS) as “situations in which building occupants experience health and comfort effects that appear to be linked to time spent in the building and which lessen after leaving the building. Symptoms typically include headache, eye, nose or throat irritation, dry cough, dry or itchy skin, dizziness and nausea, difficulty in concentrating, fatigue and sensitivity to odors. Estimating the costs of SBS related costs is difficult as no comprehensive data is available on the costs of SBS remediation or litigation (Fisk & Kumar, 2002), but there are few studies that have measured small decrease in worker performance linked to SBS symptoms.

In a survey of 100 U.S. offices, 23% of office workers (64 million workers) frequently experienced two or more SBS symptoms at work (Fisk & Kumar, 2002). The “estimated productivity decrement caused by SBS symptoms in the office worker population was 2%, with an annual cost of $60 billion (Fisk & Kumar, 2002)” therefore, even a 10-20% reduction in SBS symptoms, would yield large economic benefits.

Several studies have linked Sick building syndrome symptoms to the physical environment (Burge et al., 1987). The factors that contribute to SBS symptoms include lower ventilation rates, presence of moisture in HVAC systems, higher indoor air temperature, presence of carpets and fabrics and increased chemical and microbiological pollutants in the air (Kats & Capital, 2003;LBNL Indoor Environment Group, 2016; Wargocki,2000).

None of the 12 investments used to illustrate the TBL decision support methodology have measured SBS symptoms cost savings benefits.

7. Other physical complaints – muscular skeletal disorders (MSD) cost savings

Another easily identified health cost-savings linked to high-performance ergonomic systems is muscular skeletal disorders (MSD). For instance, in the State of Washington, workers' compensation claims for muscular skeletal disorders average over 43,000 per year with an average 1.84 workdays lost per employee (eBIDS,2008). Given average claim rates of 3.6 % per workforce and median MSD cost of $470, the average MSD cost per employee per year is $17, which can be substantially offset (over 80 %) through ergonomic furniture and employee training (CBPD,2008).

None of the 12 investments used to illustrate the TBL decision support methodology have measured muscular skeletal disorder cost savings.

Lower Fatigue, Stress and depression cost savings

Workers can be physically present in a work but may not feel 'well' due to fatigue, stress and at times may feel depressed in the workplace. Depression can drastically impair the abilities of an individual. It is estimated that employees with self-reported depression can have upto 10% lower productivity compared to employees who do not suffer from depression (Stewart et al.,2002). For a 52-week work-year, employees who suffer from depression lose 291 hours of effective productivity at work (Stewart et al.,2002).

There are some design features such as workspaces with daylight, visual access to the outdoors and good air quality that can improve the general well-being, stress and mood of the occupant (Thayer et al., 2010 ; Ulrich, 1993; Heerwagen, 1998) . The improvement in mood can impact occupant's satisfaction with the job, work motivation and even lower absenteeism.

None of the 12 investments used to illustrate the TBL decision support methodology have measured fatigue, stress and depression cost savings.

Higher job satisfaction benefit

Organizations as well as individuals may benefit from higher job satisfaction among employees. Higher job satisfaction has been correlated with greater customer loyalty, lower employee turnover and higher profitability for the organization (Harter et al.,2012). There are examples of the direct relationship between physical workplace environment and occupant comfort, satisfaction and behavior (Newsham et al., 2009; World Green Building

Council, 2014). But, the relationship between workplace environment satisfaction and job satisfaction is indirect. High performance green buildings can increase job satisfaction amongst employees, create value for clients and stakeholders and ultimately contribute towards organizational productivity (Newsham et al., 2017).

None of the 12 investments used to illustrate the TBL decision support methodology have quantitative job satisfaction benefits.

4.2.2 Selected outcomes included in the third bottom line

Six human cost benefit outcomes were identified, from the longer list of benefits discussed above, based on a review of design budgeting and CSR reporting and a critical level of available quantitative data Table 4.2. Four health costs-benefits – reduced headaches, cold and flus, skin and eye irritation, and asthma and allergies – are combined with task performance or productivity benefits and absenteeism benefits to complete the third bottom line calculation.

Table 4.2: Select human capital outcomes for 3rd bottom line NPV calculations

	Human capital: Employee Impacts										
			Health costs								
	Task performance & Productivity	Absenteeism	Headache	Cold & Flu	Skin & Eye irritation	Asthma & Allergies	Sick Building Syndrome	Other physical complaints, MSD	Fatigue, Stress & Depression	Staff attraction /retention	Job Satisfaction
BIDS	•	•	•	•	•	•	•	•		•	
LEED v4	•		•	•	•	•	•	•	•		
WELL		•	outcomes could be tracked as part of occupant health , wellness								
GRI Dow Jones			outcomes could be tracked as part of occupant health, wellness							•	•
GRESB			outcomes could be tracked as part of occupant health, wellness								
RMI (2014)	•	•	•	•	•	•		•		•	
WGBC (2013)(2015)	•	•	•	•	•	•	•	•	•	•	
Kats (2003)	•	•	•	•	•	•	•	•			

Srivastava 2018

4.2.3 Third bottom line benefits of the 12 investments

The human capital benefits for the selected investments (discussed previously in chapter 2) were identified from published international field studies and literature from university research databases and Carnegie Mellon's Center for Building Performance and Diagnostics' BIDS tool (see appendix D for list of sources). Publications with quantitative data for the selected set of building investments were selected based on the type of study, sample size and statistical significance of the findings. A summary of findings that link investments in the 12 building technologies to health and productivity is summarized in table 4.3.

Table 4.3: Human capital savings from selected set of building investments

Human capital: impact of investments on employer's pocket						
	Productivity	Absenteeism	Headache	Cold & Flu	Skin & eye	Asthma & Allergies
Install occupancy sensors	No human capital savings					
Add daylight dimming on perimeter lights	**15 %**[2a]	**15%**[2b]				
Lower ambient light & add task lights	**3 - 11%**[3a]	**1 - 25%**[3b]	**9 – 19%**[3c]			
Upgrade lighting with Individually addressable LED lamps	**2 – 13%**[4a]		**27- 74%**[4b]			
Replace fixtures with integrated LED lighting & IP controls	**1 - 19%**[5a]					
Select blinds for light redirection, shade and glare control	**3 - 6.7%**[6a]	**25%**[6b]				
Add light shelves in clerestory	**4%**[7a] on evening tasks	**15%**[7b]				
Celebrate external shading	**19%**[8]					
Ensure windows are operable for natural ventilation	**2.5 - 76%**[9a]		**9 – 40%**[9b]	**9 - 42%**[9c]	**23 – 67%**[9d]	
Integrate Underfloor Air & networking	**0.7 - 26%**[10a]					
Engineer Individual temperature control	**4.5 - 13%**[11]					
Invest in building performance goals	**2.6 - 85%**[12a] **4 - 42%**[12b]	**15 - 40%**[12c]		**4.8%**[12d]		**50%**[12e]

2a. Figueiro et al. (2002); b Thayer (1995)
3a. Kuang-Sheng Liu et al (2010); Juslen (2007); Linhart (2011); Nishihara et al. (2006) b. Schwartz et al (1997) Juslen et al. (2007) Romm & Browning (1994); c. Joines et al. (2014); Çakir & Çakir (1998)
4a. Newsham et al. (2004), Juslen et al. (2007); National Lighting Bureau (1988); Romm & Browning (1994); b. Aaras et al. (1998); Wilkins et al. (1989)
5a. Iskra-Golec et al. (2012); Kuang-Sheng Liu et al. (2010); Anderson et al. (2009); Jaen et al. (2005); Hoffmann et al. (2012); Hawes et al. (2012); Marmot et al. (2006); Mott et al. (2012)
6a. Zhang & Altan and Osterhaus & Bailey (2011); Heschong et al. (2003); b. Romm & Browning (1994)
7a. Mirjam et al. (2011) and Zhang & Altan and Osterhaus & Bailey (2011); b. Thayer (1995)
8. Hua et al. (2011)
9a. Wargocki et al. (2000); Seppanen (2003); Lee and Guerin (2009); b. Burge et al. (1987); Harrison et al. (1992); Zhounghua et al (2012); Olli & Fisk (2002); Teeuw et al (1994); Kroeling (1998); c. Burge et al. (1987); Harrison et al. (1992); Olli & Fisk (2002); Teeuw et al (1994); Kroeling (1998); Zhounghua et al (2012); d. Burge et al. (1987); Teeuw et al (1994); Zweers et al. (1989); Olli & Fisk (2002)
10a. Fitzner (1985); EPA 1989; Huizenga et al. (2006); Mariusz (2014);
11a. Boerstra et al (2015); Shin-ichi Tanabe et al (2007); Kaczmarczyk (2008); Melikov et al. (2012); Bogdan et al. (2012)
12a. Singh et al (2009); Zhang et al (2010); Clausen and Wyon et al (2004); Rosekind et al (2010); Agha-Hossein et al (2013); Mac & Lui (2011) b. Allen et al. (2012); Newsham (2013) / Clement et al. (2000); c. Browning (1992); Singh et al (2009); Verrifone/Pape (1998); d. Singh et al (2009) e. Grady et al (2010)

4.3 Human capital cost savings model

4.3.1 3rd Bottom Line Net Present Value based on existing BIDS tool

To advance a 3rd bottom line, this research builds on precedent methodologies and tools, and engages a method for measuring and quantifying human benefits from building investments based on the ongoing development of Building Investment Decision Support (BIDS™) toolkit. Carnegie Mellon's Center for Building Performance and Diagnostics BIDS™ tool is a life cycle decision support tool for evaluating the cost-benefits of high performance building systems" (Loftness et al., 2005). Over 500 studies have been quantified in seven categories of investment - *air, temperature control, lighting control, network access, privacy and interaction, ergonomics, and access to the environment* - in ten cost-saving categories of economic value to the decisionmaker - first cost; energy; operation & maintenance; individual productivity; organizational productivity; health; organizational & technological churn; attraction/ retention; taxes, litigation, and codes; as well as salvage and waste cost-savings (figure 4.2 from Loftness et al., 2005; Loftness & Snyder, 2013; Loftness & Srivastava, 2014).

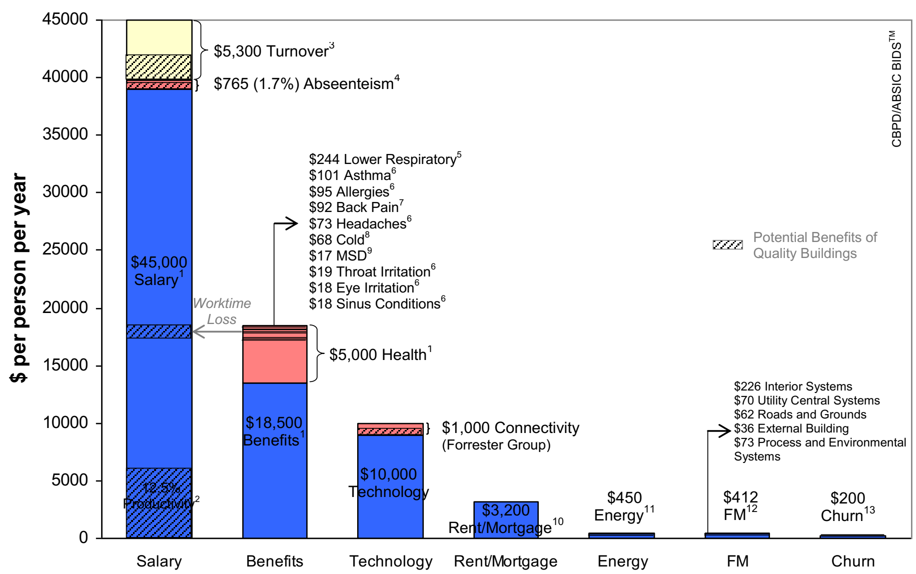


Figure 4.2: CMU BIDS™ tool monetizes human capital in the 'cost of doing business'

4.3.2 Equations for 3rd bottom line calculations

To complete BIDS 3rd bottom line calculations for the 12 energy retrofit measures identified, an extensive literature review was undertaken to identify laboratory and field studies that link the physical attributes of buildings to human health and productivity benefits. The selection of six key benefits – headaches, colds & flu, skin & eye irritation, asthma, productivity, absenteeism was dependent on the availability on epidemiological studies that statistically link health outcomes to building IEQ and quantifications of the human costs of inaction by the employer (BIDS baselines). Illustrated in equation 1, the third bottom line savings are a summation of the improvements in productivity, health cost savings and the impact of reduced absenteeism.

$$\textbf{Third bottom line savings} = \textbf{Productivity}_{\textbf{savings}} + \textbf{Health}_{\textbf{savings}} + \textbf{Absenteeism}_{\textbf{savings}}$$

(Equation 1)

Productivity, health and absenteeism savings are calculated using the equations below. Four equations for health savings were developed to estimate the medical cost savings from reduced headaches, cold and flus, skin and eye irritation, asthma and allergies.

Productivity savings

To calculate the value from worker productivity, the savings are defined as a function of:

Average salary cost C_{salary}, within the office context. A high percentage of business costs are employee salaries resulting in a high financial benefit to organizations who can improve the productivity of their staff.

The percentage positive effect on productivity, $improvement_{productivity}$ in table 4.3. The change in productivity is assembled from published literature that provides evidence of the relationship between selected building investments and worker productivity.

Time at task, a scaling factor from zero to 100 %. Increases in overall productivity is rare, compared to increase in a specific task, hence an understanding of the specific tasks in an average work day or week is critical. The scaling factor is included to address the fraction of work hours spent on the task for which the effect on productivity is being considered. The time spent on different task breakdown is based on a survey by researchers at Carnegie Mellon University of 97 employees, on the time spent on processing emails, reading, writing, on research and on planned meeting among other various tasks (See figure 4.3).

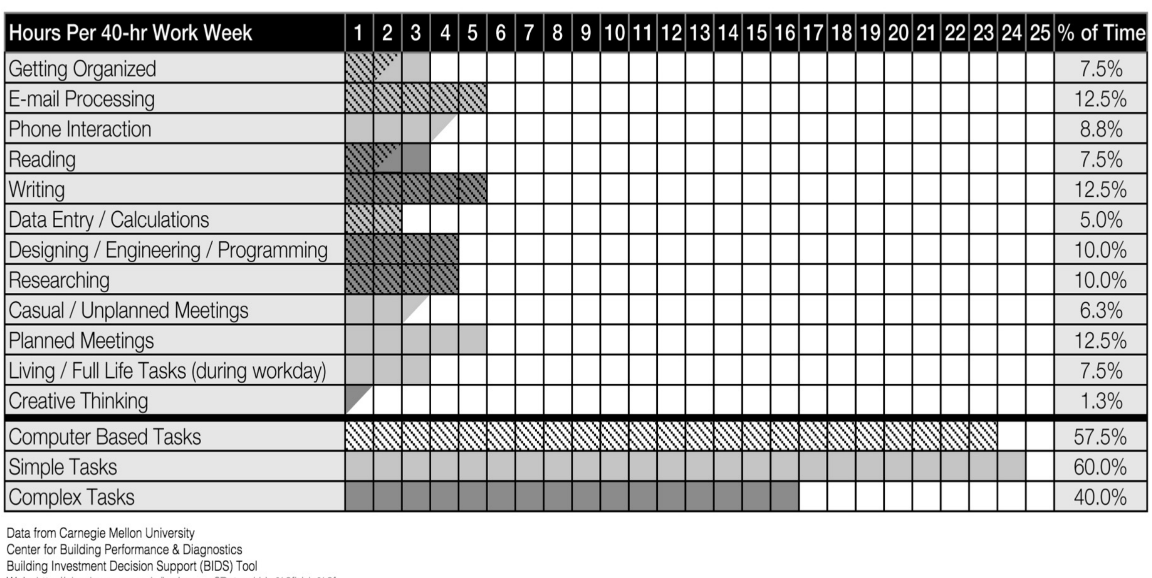


Figure 4.3: Time spent on different task in a typical workplace

$$Productivity_{savings} = cost_{salary} * \sum(improvement_{productivity} * time_{\,at\,task}) \qquad \text{(Equation 2)}$$

Assuming the accrual of savings over 15 years, the net present value of the stream of savings is calculated by the following equation.

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} Productivity\ savings_t/(1+d)^t$$

(Equation 3)

Where,

N = Number of years in the study period and

d = Discount rate used to adjust cash flows to present value

Health cost savings

To calculate the health benefits, it is critical to articulate how the specific high-performance building technology and system generates improved air quality, thermal comfort, or ventilation rates that can be linked to improved health. Once the mechanism is established, the medical health cost savings can be calculated using the following information.

Average health costs for the employees in the retrofitted space. Annual health care costs per employee is $5,026. Average worker's compensation costs vary by state and industry but are typically in the range of $500 per employee. The U.S. EPA provides the medical cost of illness, which includes the cost for doctor visits, medication and other related expenses (EPA, 2007). The costs for the four health symptoms - headaches, cold and flus, skin and eye irritation and asthma and allergies are from the EPA's Cost of Illness handbook.

Percentage reduction in the health outcome from the investment. The percentage change in health outcomes is gathered from the most relevant published literature that provides evidence of the relationship between high performance building investments and its impact on worker health. The health impacts are presented in table 8.

Population suffering from the specific health ailment when the data is available for the specific ailment.

$$Health\ cost_{savings} = cost_{illness} * \%\ improvement_{\ health} * population_{\ rate}$$

(Equation 4)

Assuming thee accrual of savings over 15 years, the present value of the stream of savings:

$$Present\ Value\ of\ savings\ = = \sum_{t=0}^{N} Health\ cost\ savings_t/(1+d)^t$$

(Equation 5)

Where,

N = Number of years in the study period and

d = Discount rate used to adjust cash flows to present value

Absenteeism

The formula for calculating savings from building related reduced absenteeism is based on the product of the following:

Average salary cost C_{salary}, within the office context.

The number or the percentage of reduced absenteeism linked to investments in high performance building systems and technologies.

Average absenteeism rate, as reported by the U.S. Department of Labor at 3% per private sector employee—or 62.4 hours per year per employee lost, and 4% per public sector employee – or 83 hours lost to absences per year (US Department of Labor, 2010).

$$Absenteeism\ reduction_{savings} = cost_{salary} * reduced_{absenteeism} * absenteeism_{rate}$$

(Equation 6)

Assuming the accrual of savings over 15 years, the present value of the stream of savings is calculated as follows:

$$Present\ Value\ of\ savings = = \sum_{t=0}^{N} Absenteeism\ reduction\ savings_t/(1+d)^t$$

(Equation 7)

Where,

N = Number of years in the study period and

d = Discount rate used to adjust cash flows to present value

4.3.3 Assumptions and notes about data sources

The third bottom line calculations are built for 6 outcomes from the range of human capital benefits illustrated in table 8. The calculations are based on U.S. salary costs, healthcare costs and absenteeism rates. The health savings are based on the available epidemiological studies that statistically link health outcomes to building IEQ. Some of these studies may be from the early 1990s and 2000s, but these impacts remain relevant even today.

For few of the investments selected to illustrate the TBL methodology, there are not enough number of studies to illustrate the link between human health and productivity and the selected technology. For example, third bottom line savings for awnings, overhangs and light shelves are based on the findings of a single study. When multiple studies are available. Otherwise, an average value from different studies and articles has been calculated and used for estimating the third bottom line savings.

4.3.4 Limitations of the Third Bottom Line Calculations

There is a range of baseline assumptions built into these calculations, including property size, age, location, and existing system conditions. The calculations assume US baselines for health, absenteeism and productivity costs to the employer, and US assumptions about time at various tasks that are central to the original research findings. Future research and development of decision analysis modeling should include updating and modifying these assumptions to customize the savings for an individual organization outside the U.S.

The third bottom line calculations completed include a limited set of outcomes only, and there are other human cost benefits that could be included in future iterations of the calculation. Decision makers can follow the same approach and find the most relevant costs if they wish to include additional benefits in the calculation.

4.4 Integrated approach to decision making

NPV, ROI and Payback times are important focal points for decision makers. These financial performance metrics can now be reviewed with additional environmental and social cost savings. Taking an integrated approach to including these cost savings can change the decision from a “no” to a “yes” when stakeholders take this additional information into consideration.

The 1st bottom line is an important starting point for decision makers. Due to current low energy costs, however, savings from reduced energy may not be enough to pay back the additional investment (Wallbaum and Meins,2009). Other first bottom line savings like tax reductions or subsidies, capital and rental value premiums, higher occupancy rates are available for owners and can reduce the payback further. But the 2^{nd} and 3^{rd} bottom lines can enable more informed decisions to move forward with high performance buildings.

Chapters 3 and 4 demonstrate how the physical office environment has an impact on the environment, health, wellbeing and productivity of staff. The literature review, model development and analysis in this thesis contribute to the field of research by making cost savings from real estate investments relevant for individual organizations. Using the methodology developed as part of this thesis, an integrated bottom line (Sroufe, 2017) business case can be made for the individual organizations. The cost benefit analyses for 12 building investments using the developed TBL approach presented in the next chapter provides decision maker compelling arguments for inspiring investment in energy retrofits that will improve the quality of the indoor environment for workers. These illustrations will enable decision makers to apply TBL calculations to their own circumstances using their own operating costs, and to calculate the impact that a diverse set of retrofit projects and small improvements will have.

With the ever increasing interest of clients and professionals in sustainability, and their commitment towards achieving high levels of energy and environmental standards in new and retrofit projects, the investment community has a choice to move beyond first cost decision making. In the end, most investment decision are made based on financial understandings. The importance of introducing environmental and human health and productivity considerations into the financial bottom line can no longer be ignored. When these considerations are translated into an integrated approach to financial decision making, decision makers will be able to overcome the first-least-cost hurdle.

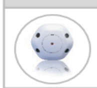
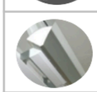
Chapter 5

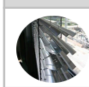
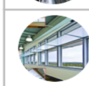
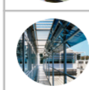
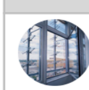
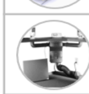
Generating Triple Bottom Line Proof Sets

Moving beyond first-least-cost decision making to embrace, at the very least, the life-cycle costs from operational energy to facility management and waste costs, can be decisive for energy efficient decision-making in new construction projects and low-cost retrofits. However, in retrofit projects that include façade, HVAC, and lighting upgrades with moderate to high cost implications, the added calculations of environmental and human cost benefits may be critical, especially in existing buildings where the benefits of only justifying cost differentials cannot play a role.

With Triple Bottom Line (TBL) accounting, the three successive NPV calculations of operational, environmental and human benefits can support customized evaluation of high performance energy efficient building technologies and systems. A focus of this thesis has been on developing a TBL cost-benefit framework and decision-support methodology and evaluate its usefulness relative to a selection of energy efficient technologies and systems for building projects. This chapter presents the results from testing the TBL framework and decision support methodology on 12 building investments selected to utilize the breadth of performance benefits defined in Chapter 2,3 and 5. Outlined in table 5.1, these twelve energy and environmental quality investments will be used to illustrate how environmental and human cost benefits increase net present value and shorten payback periods.

Table 5.1: Selected lighting, enclosure, HVAC response and whole building performance investments

Lighting Investments	
	Occupancy sensors for closed spaces
	Daylight dimming for perimeter lights
	Lower ambient light & add task lights
	Individually addressable LED lamps
	Integrated LED fixtures w IP controls
Whole Building Performance Investments	
	Building performance goals

Enclosure Investments	
	Blinds for light redirection, shade, glare control
	Internal light shelves in clerestory
	External shading/awning for shading
HVAC Response Investments	
	Operable windows for natural ventilation
	Underfloor air and networking
	Individual temperature control

5.1 Steps to Triple Bottom Line Calculations

The first task in TBL calculations is to gather the first cost for the selected range of component and system investments, including labor and installation costs. For the 12 lighting, enclosure, HVAC response and whole building performance investments outline in Table 5.1, average technology and labor costs were collected for a medium size office of 100,000 square feet, of three to five floors, with 500 employees. The costs were collected from both literature and direct communications with manufacturers and professionals specifying components and systems. Costs can vary significantly based on the condition of the existing technology in the building, variations in the product, and labor markets.

While cost data is typically available per square foot of building, the TBL methodology explicitly includes the human impacts related to health and productivity, suggesting that costs should be normalized per person or employee instead. The length of the life-cycle of interest to the owner or occupant must also be set, with a 15-year life-cycle chosen for the set of 12 investments to follow. Finally, a significant number of operational, health and productivity studies must be assembled to complete the triple bottom line. Given the growing body of international research linking the quality of the built environment to human outcomes, it should be possible to assemble a modest robust body of studies. With all assumptions clearly stated, it is possible to modify first costs, life cycle periods, and even expected benefits when completing the triple bottom line calculation.

The CMU Center for Building Performance & Diagnostics team has focused on calculating the life cycle benefits of building investments in three iterative calculations to offer a triple bottom line: 'hard' financial cost benefits in the first bottom line; environmental cost-benefits of energy savings (that may be legislated or incentivized in the future) in the second bottom line; and the human cost-benefits that should drive standards and investments in buildings in the third bottom line.

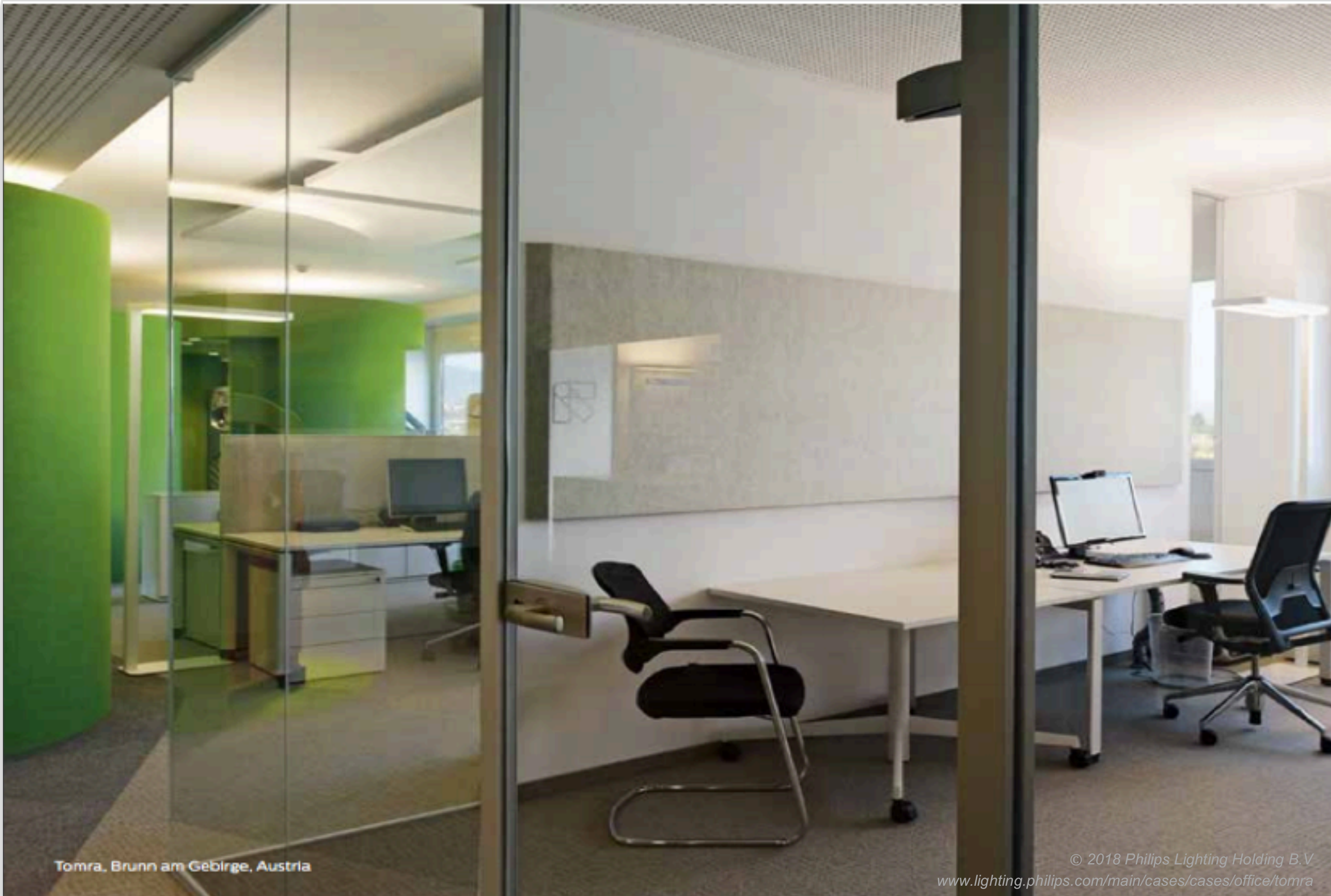
The first bottom line calculations capture the 'hard' **financial** cost-benefits of energy, facility management savings, replacement savings, churn cost savings and real estate premiums from the building investment. The economic benefits of the recommendations have been calculated or drawn from the literature. The cost of energy was set at $0.103/kwh, the average all-inclusive commercial fixed rate in the US (EIA, 2016). Energy saving calculations are based on CBECS averages of 6.8 kWh/sqft of annual lighting energy use, 2.4 kWh/sqft of annual cooling energy, 10.1 kWh/sqft of annual heating energy, and 1.5 kWh/sqft of annual ventilation energy use for a total of 24.9 kWh/sqft (CBPD, 2012).

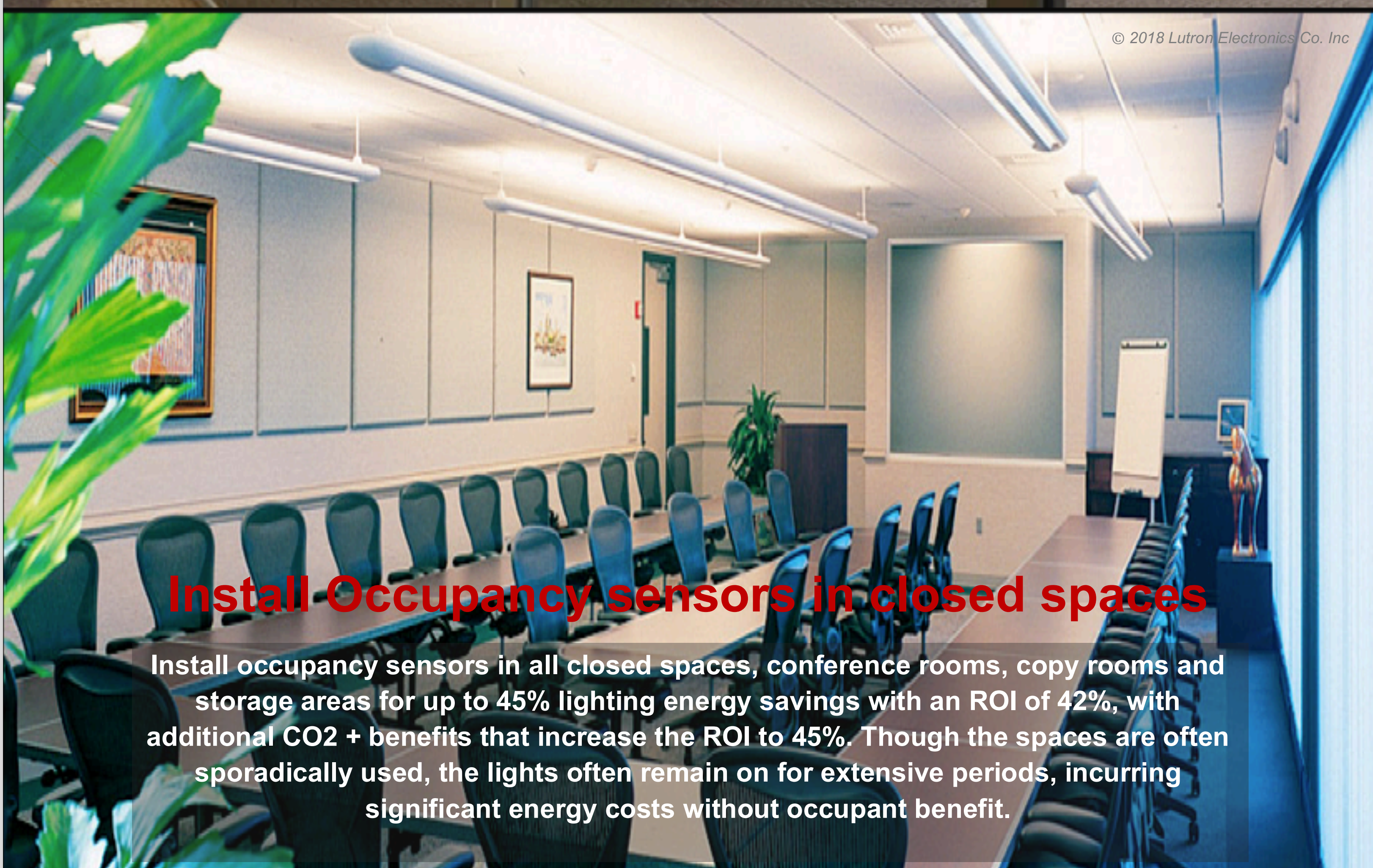
The second bottom line calculations capture the **environmental** cost-benefits to quantify the economic value of reduction in CO_2, CH_4, SO_X, NO_X, particulates, and water demands that are directly linked to electric energy savings. Three types of data were assembled for the environmental cost benefit calculations: electricity fuel sources and plant quality, their respective pollution consequences, and relative values for pollution reduction. The environmental costs of the six environmental challenges were assigned for each kilowatt-hour of electricity saved, based on US 2016 values for pollution avoidance.

The third bottom line relates to the **human** cost-benefits that are directly linked to improved IEQ. The human benefits associated with each recommendation have been drawn from the ongoing work of the Center for Building Performance and Diagnostics to aggregate research linking the quality of buildings to health and productivity outcomes in Building Investment Decision Support (BIDS) Tool (CBPD, 2008).

5.2 TBL value sets for 12 Building Energy Investments

The following pages offer completed Triple Bottom Line calculations for 12 distinct investments that improve the energy performance of buildings as well as offering other economic, environmental or human benefits. Each investment is described and illustrated, costs and benefits summarized and concludes with a one-page TBL calculation. The bottom lines include the Return on Investment (ROI), Payback in months or years, and 15-year Net Present Values for the Investment. The critical literature for the second bottom line was outlined in Chapter 3. The critical literature for each of third bottom lines is cited in the text and summarized in Appendix D. These twelve investments and their TBL calculations are illustrative of the potential of triple bottom line accounting to shift financial decision-making. They are not intended to be definitive or comprehensive as a set of investments, but each are significant relative to improving building energy performance and indoor environmental quality.





Install Occupancy sensors in closed spaces

Install occupancy sensors in all closed spaces, conference rooms, copy rooms and storage areas for up to 45% lighting energy savings with an ROI of 42%, with additional CO_2 + benefits that increase the ROI to 45%. Though the spaces are often sporadically used, the lights often remain on for extensive periods, incurring significant energy costs without occupant benefit.

Occupancy driven lighting controls, whether wired or wireless, are cost effective in locations that are used intermittently.

The newest generation of occupancy sensors combine acoustic and thermal information to communicate with lighting fixtures. These sensors are often tied to manual controls that enable the occupant to customize the preferred occupancy line of sight, duration, and even light level thresholds to meet local functional requirements (EBN, 2003). California has restated the energy saving goal by mandating 'vacancy sensors'. Instead of installing 'occupancy sensors' in conference rooms and closed offices, occupants should turn on the lights manually, whenever daylight is inadequate. However, 'vacancy' sensors should be set to turn off the lights automatically when the occupant leaves the space, to ensure the highest level of sustained energy savings and user satisfaction. Vacancy sensors and switches can be installed without full automation systems, making them cost effective retrofits for all closed spaces with sporadic use or available daylighting.

Wall mounted Ultrasonic (US) and Passive Infrared (PIR) sensors support manual or automatic turning on of lights and turn off lights automatically when no one is present *(Image source – Eaton. (2013) NeoSwitch sensor).*

Figure 5.1: Example of occupancy sensors with critical attributes for occupant satisfaction

Occupancy sensors offers substantial energy savings with a 2.5 years payback

The material and labor costs for introducing switches that incorporate occupancy sensors (set to vacancy operation) in each closed space are roughly $150 per room. The initial investment cost assumes that occupancy sensors are installed in the 25% of the 100,000 sq. foot office building that are typically dedicated to meeting rooms, closed offices, and service spaces (CBPD, 2009). Given the average number of conference rooms and closed spaces per 100,000 square foot building, first costs are set at 0.75/sqft installed. The sensors must be professionally installed to ensure correct sensor settings and space coverage, so that lights do not go off inappropriately, and controls are optimum for the activities planned.

The economic benefit of investing in vacancy sensors is focused on the annual energy savings, although lamp longevity may also be positively impacted. Studies have shown that adding occupancy controls in closed spaces can reduce lighting energy use by 30% – 66% (EPA, 1998; Maniccia et al., 1998; Mahdavi et al., 2008; Williams et al., (2012) (see Figure 5.2). An average of 45% savings in the 25% closed spaces of a baseline building would translate to a 10% lighting energy savings for the baseline building. Balancing the costs and the benefits, the first bottom line calculation reveals that energy savings alone offers payback of less than 2.5 years and an ROI of 42%.

Occupancy sensors also offers environmental benefits to shorten the payback

Each kWh saved through occupancy driven lighting controls results in commensurate reductions in environmental CO_2, CH_4, SO_X, NO_X, particulates, and water (see Chapter 3). As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. Meanwhile, in the second bottom line calculation of 'vacancy' sensors, combined with the economic gains from energy savings shortens the 30-month payback to 22 months!

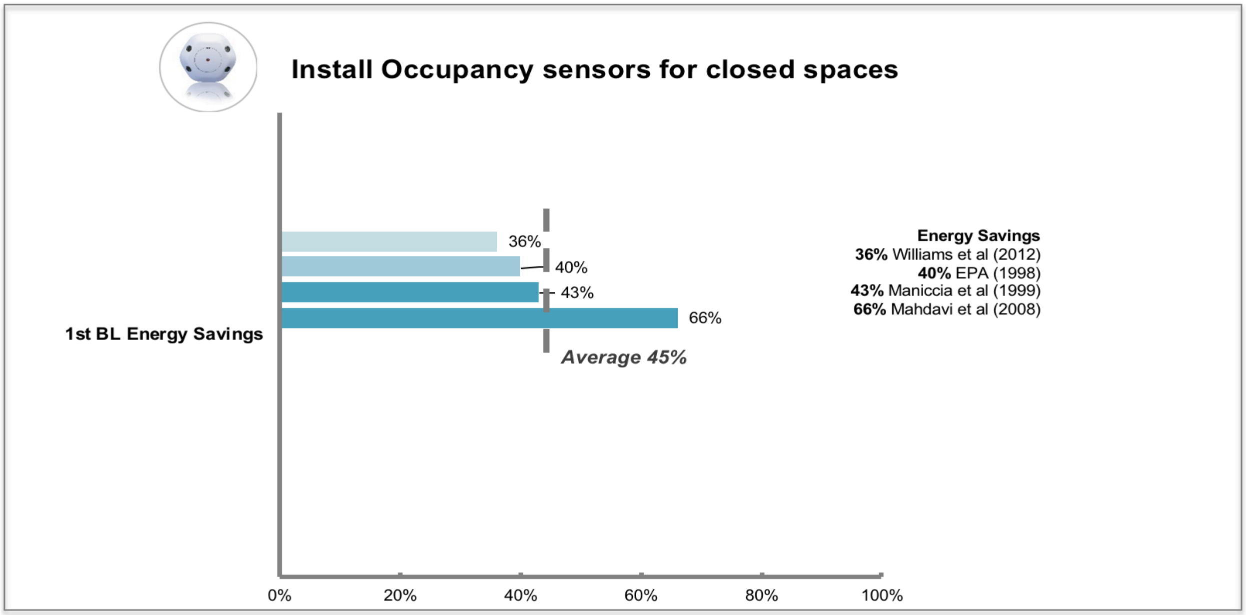


Figure 5.2: Cross sectional chart of the range of research on benefits from occupancy sensors

Turning off lights in unoccupied spaces will not improve the health or productivity of the occupants in a building. Hence, the third ROI calculation of human benefits is not included. With energy savings alone, the ROI was 42% a significant return on investment. Combining energy and environmental savings in the second bottom line resulted in a 45% ROI and will critically meet corporate and agency carbon goals or corporate sustainability reporting goals. In addition, the hardware and installation costs for robust occupancy sensors are coming down, making their utilization in all closed offices and conference rooms a high priority investment.

Table 5.2: First and Second Bottom line calculations for investing in vacancy sensors

Costs to install occupancy sensors for closed spaces

	Per sq. ft.	Per room
Cost for occupancy sensors	$0.25	$50
Cost of installation	$0.50	$100
Initial Investment costs for a 100,000sq. ft. building *(for a 25% baseline building area)*	**$18,750**	

1st Financial Capital savings

	Per sq. ft.	Per employee
Lighting Energy savings (46% in 25% space)	$0.31	$62
Annual 1st bottom line savings	**+$0.31**	**+$62**
ROI (Financial)	**42%**	
Payback Period	**2.5 years**	
15-year Net Present Value	**$ 59,450**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.85 kWh	170 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.05	$10
CO_2 reductions	$0.03	$6
Water savings	$0.01	$2.5
Annual 2nd bottom line savings	**+$0.02**	**+$18**
Cumulative ROI (Financial + Environmental)	**45%**	
Payback Period	**2 years 3 months**	
Cumulative 15-year Net Present Value	**$ 63,950**	


Add daylight dimming to perimeter lights
Install daylight sensors and controllers for dimming the first and second rows of lights on each building façade to: generate up to 35% energy savings through 'daylight harvesting' with an ROI of 22%; with additional CO2 + benefits that increase the ROI to 25%; as well as a lab or field identified 15% increase in time dedicated to visual work tasks and 15% reduction in absenteeism that increase the ROI to over 400%!
© Graylight, 2013
www.graylight.com.au/?attachment_id=236

Occupancy and daylighting sensors and controllers have dramatically improved in the last 20 years.

The second cost-effective retrofit action for lighting energy savings is the installation of daylight sensors for on/off or dimming controls of the first and second rows of lights on each building facade. The critical attributes for selection of daylight sensors include: programmable thresholds for acceptable daylight minimums, relocatable sensors to address variations in office layout, and assurance of gradual light level changes through dimming or time limited switching. Two examples are shown, with $55 - 65 hardware costs per fixture.

Acuity SensorSwitch wired sensor monitors daylight in the room and turns off the lights when sufficient natural light is present and back on when insufficient (Acuity, 2013)

Lutron Radio Powr Savr™ is a wireless daylight sensor decreases light levels to fill in when insufficient daylight is available *(Lutron, 2013).*

Figure 5.3: Example daylight sensors for occupant satisfaction and energy savings

Daylight dimming offers substantial energy savings with a 5-year payback

The material and labor costs for introducing new daylight sensors and controllers to each row of perimeter lights with independent switching is less than 0.90/sqft. Encelium, Lutron and other lighting control companies have developed wireless controls that can be added to existing ballasts in combination with well-placed daylight sensors. This lighting upgrade is a quick and low cost retrofit for the majority of buildings. A web-based controller is also available for calendar-driven or daylight-sensor-driven switching of each row.

The financial ROI is calculated using first costs divided by annual energy savings. 30%-65% lighting energy savings has been achieved in perimeter workplaces (Lee and Selkowitz 1998, Boyce 2006, Verderber & Rubinstein 1984, Jennings et al. 2000) especially when a combination of daylighting and occupancy sensors are used (Figure 5.4).

Daylight dimming offers environmental benefits to shorten the payback to 3.5 years

Each kWh saved through daylight responsive controls results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 3.5 years.

Increased daylighting ensures human benefits to shorten the payback to months

The human benefits of daylighting the workspace is measurable. The circadian variation in full spectrum light is an important factor in human health and absenteeism. A field study conducted by Figueiro et al. (2002) identifies a 15% increase in time dedicated to visual work tasks in daylit workspaces, tasks which correlate to 25-30% of time spent at work, for a potential performance improvement of 3.75%. A case study by Thayer (1995) identifies a 15% reduction in absenteeism in daylit workspaces, also contributing to the human benefits of daylighting calculated in the third bottom line. Incorporating these two benefits in the third bottom line calculation results in a Triple Bottom Line payback of 3 months. More studies are emerging each year on the productivity and health benefits of daylighting which could be added or averaged to update these calculations.

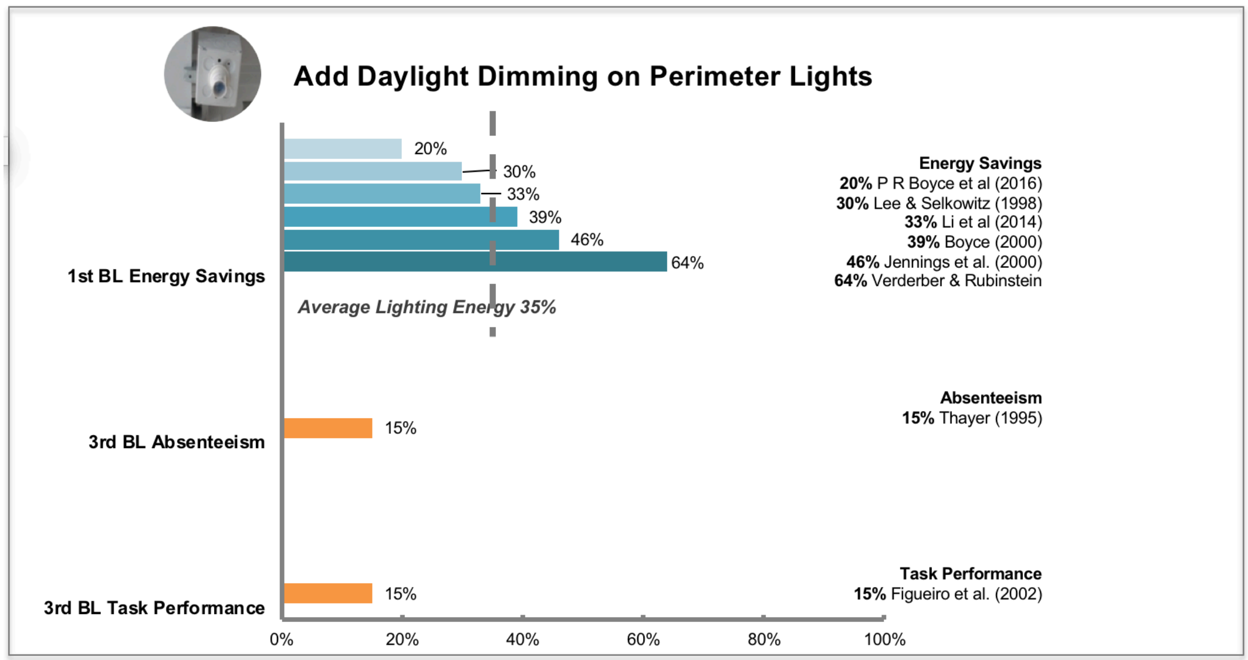


Figure 5.4: Cross sectional chart of the range of research on benefits from adding daylight dimming on perimeter lights

Table 5.3: Triple bottom line calculations for investing in daylight harvesting

Costs to install daylight harvesting for perimeter lights

	Per sq. ft.	Per employee
Cost for daylight sensors	$0.40	$26
Cost of installation and labor	$0.50	$34
First cost for the investment	$0.90	$60
Initial Investment costs for a 100,000sq. ft. building *(for 1/3 baseline building perimeter area)*	$30,000	

1st Financial Capital savings

	Per sq. ft.	Per employee
Energy savings (30%)	$0.20	$40
Annual 1st bottom line savings	**+$0.20**	**+$40**
ROI (Financial)	22%	
Payback Period	4.5 years	
15-year Net Present Value	$ 51,700	

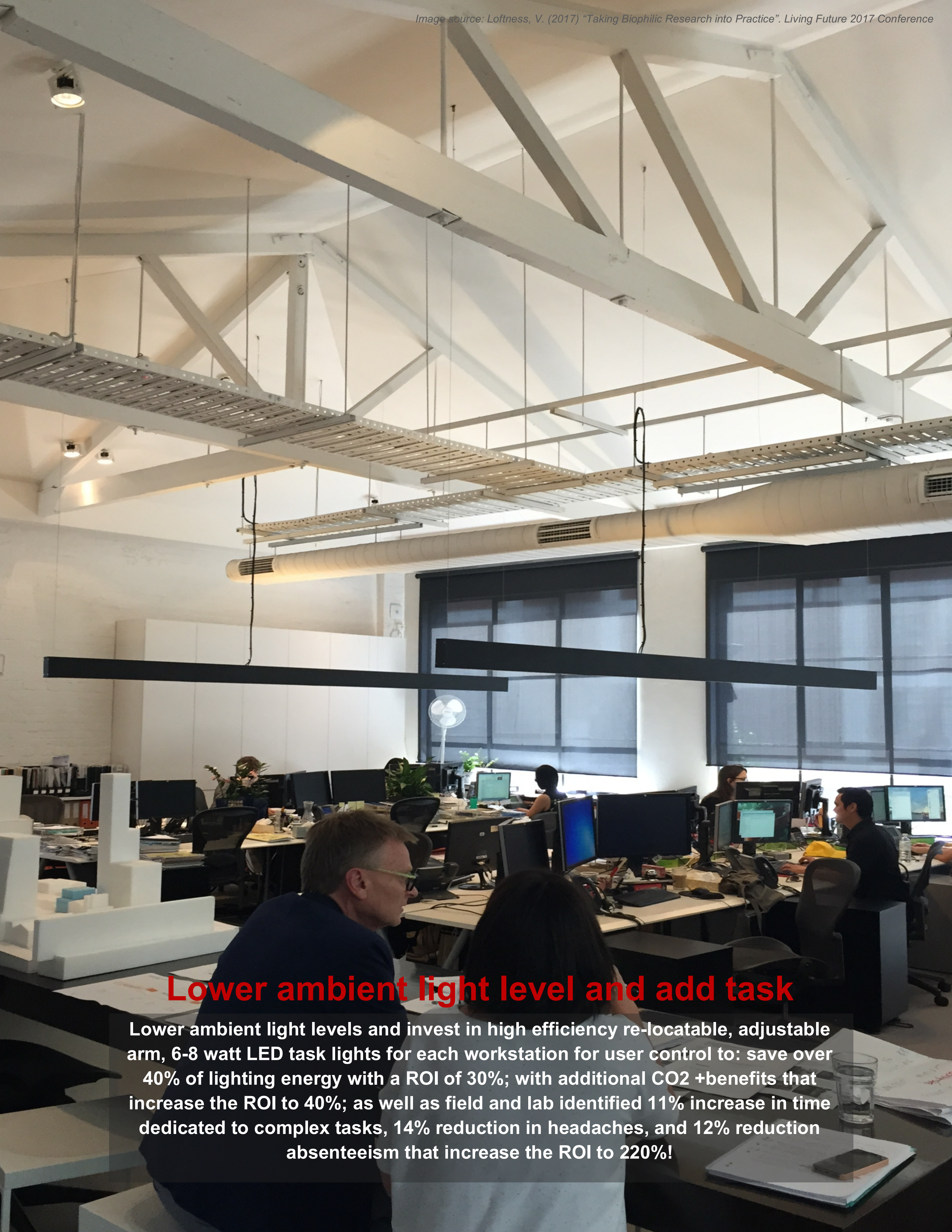
2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.61 kWh	122 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.01	$2
CO_2 reductions	$0.01	$1.2
Water savings	$0.003	$0.5
Annual 2nd bottom line savings	**+$0.02**	**+$4**
Cumulative ROI (Financial + Environmental)	25%	
Payback Period	4 years	
Cumulative 15-year Net Present Value	$ 56,380	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Absenteeism reduction (15% of 2%)	$0.68	$135
Productivity increase (3.75%)	$2.95	$590
Annual 3rd bottom line savings	**+$3.62**	**+$725**
ROI (Financial + Environment+ Human)	428%	
Payback Period	3 months	
Cumulative 15-year Net Present Value	$ 976,230	

Image source: Loftness, V. (2017) "Taking Biophilic Research into Practice". Living Future 2017 Conference



Lower ambient light level and add task

Lower ambient light levels and invest in high efficiency re-locatable, adjustable arm, 6-8 watt LED task lights for each workstation for user control to: save over 40% of lighting energy with a ROI of 30%; with additional CO_2 +benefits that increase the ROI to 40%; as well as field and lab identified 11% increase in time dedicated to complex tasks, 14% reduction in headaches, and 12% reduction absenteeism that increase the ROI to 220%!

Reducing ceiling lighting output and adding task lights provides substantial energy savings, given the 6-8-watt LED task lights available today.

The typical ceiling light fixture today has multiple 32-watt lamps that turn on simultaneously to deliver over 500 lux of task and ambient lighting, ideally but not consistently aligned with the work surface for paper based work. This results in the consumption of 64-138 watts of electricity per workstation to support the occasional paper-based work, as compared to the 6-10 watts in an LED task light that the user can position directly on the task. To better set light levels for today's predominantly computer based tasks, ceiling lighting should be lowered to 200-300 lux and task lights should be provided. These task lights should be relocatable, include adjustable arms for positioning the light on the paper task, with on-off or dimming switches. Two examples are shown, and costs range from $150 to $400 per unit.

Finelite™ Curve LED dimmable task light, delivers up to 4[illegible] Lumens/Watt, consumes just 8 watts of power *(Finelite, 2013).*

The Humanscale Element Vision LED is a flexible task light consumes just 10 watts of power *(Humanscale, 2017)*

Figure 5.5: LED Task Lamps use 6-10 watts for over 500 lux of light for paper based tasks

Lower ambient levels & adding task lights offers energy and maintenance savings

The labor cost of de-lamping fixtures throughout the workplace and purchasing at least one high performance LED task light for each workstation is approximately $200 per workstation or $1.00/sqft. If dimming ballasts already exist, there is a reduced labor cost of resetting light level output to achieve 200-300 lux for computer based tasks. Under-cabinet lighting should be removed, since it is far more energy intensive than the task lights of today and often does not illuminate the surfaces where paper tasks are set.

The financial ROI is calculated using published first costs divided by annual energy and maintenance savings. 40% lighting energy can be achieved, while lowering task-ambient light levels and adding high efficiency task lights (Gu,2011 and Linhart,2013). Maintenance savings of $0.05/sq. ft. has been reported due to fewer fixtures replacements with effective daylight design and split task and ambient lighting (Knissel, 1999). While not quantified here, there could also be spatial churn cost savings as task lighting can move with the work-surface, eliminating the need to relocate or add ceiling fixtures with changing densities of workstations. With these first bottom line benefits included, the payback for the retrofit will be 3 years.

Lowering ambient & adding task lights offers environmental benefits to shorten payback

Each kWh saved through lowering ambient light levels and adding task lights results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 2 years.

Increased user control ensures human benefits to shorten the payback to months

The human benefits of shifting to lower ambient and user controlled task lighting that have been identified in research include reduced headaches as well as greater speed and accuracy at complex tasks. In two different studies, Çakir and Çakir (1998) found a 19% and Joines (2014) a 9% reduction in headache for workers who had separate task and ambient lighting compared to workers with ceiling-only combined task and ambient lighting respectively. A study by Nishihara et al. (2006) identifies an 11% improvement on triple digit multiplication tasks (p=0.01), while a study by Linhart (2013) identifies a 25% improvement on evening office tasks when occupants could control their task lights. Incorporating these benefits in the third bottom line, and iteratively combining the three bottom lines, results in a TBL payback of 5 months.

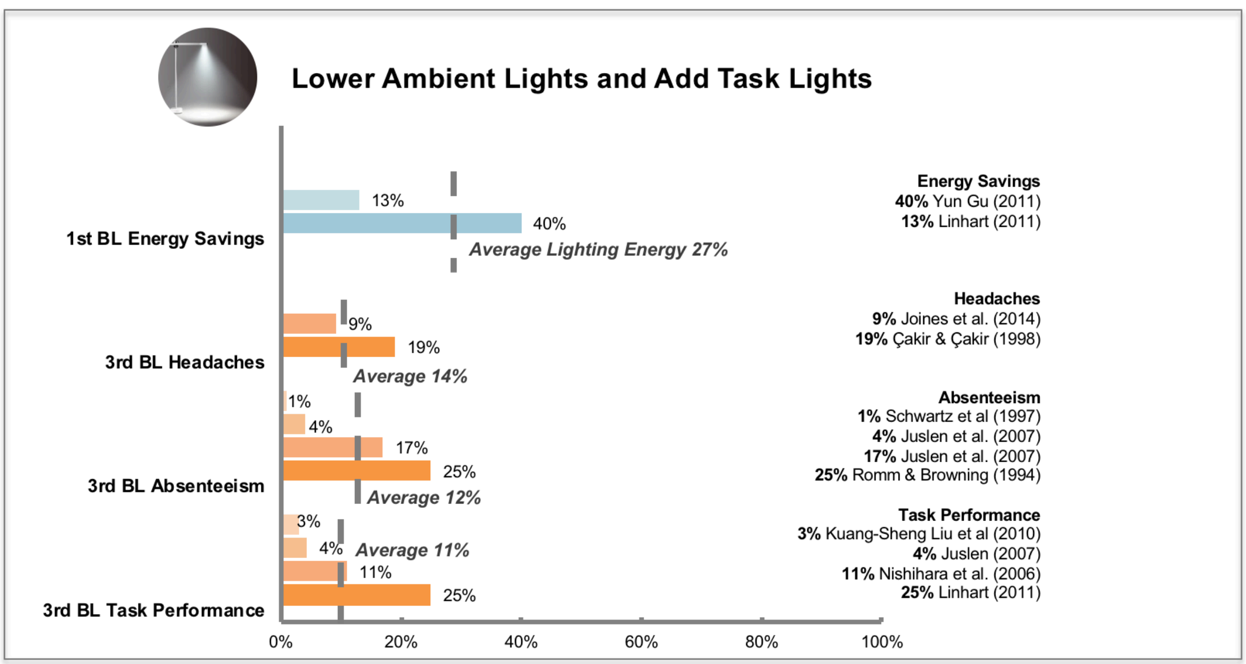


Figure 5.6: Cross sectional chart of the range of research on benefits from lower ambient lights and adding task lights for each workstation

Table 5.4: Triple bottom line calculations for lowering ambient light levels and adding task lights for each workstation

Costs to Modify Ambient Lighting and Add Task Lights

	Per sq. ft.	Per employee
Cost for reducing ambient light levels	$0.18	$36
Cost for LED desk lamp	$0.82	$164
First cost for the investment	**$1.00**	**$200**
Initial Investment costs for a 100,000 sq. ft. building	**$100,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
Energy savings (40%)	$0.27	$54
O & M Savings	$0.05	$10
Annual 1st bottom line savings	**+$0.32**	**+$64**
ROI (Financial)	**30%**	
Payback Period	**3 years**	
Cumulative 15-year Net Present Value	**$ 244,900**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	2.7 kWh	542 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.04	$8.8
CO_2 reductions	$0.03	$5
Water savings	$0.01	$2
Annual 2nd bottom line savings	**+$0.08**	**+$16**
Cumulative ROI (Financial + Environmental)	**40%**	
Payback Period	**2.5 years**	
Cumulative 15-year Net Present Value	**$ 307,000**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Headache reduction (14% of $73)	$0.05	$10
Absenteeism reduction (12% of 2% year)	$0.54	$108
Productivity increase (11% of 5%)	$1.25	$250
Annual 3rd bottom line savings	**+$1.84**	**+$368**
ROI (Financial + Environment+ Human)	**220%**	
Payback Period	**5 months**	
Cumulative 15-year Net Present Value	**$ 1,697,900**	

Upgrade to individually addressable LED lamps

Replace existing lamps with Individually addressable LED lamps to: generate up to 60% lighting energy savings and 80% maintenance costs savings with an ROI of 18%; additional CO2 + benefits that increase the ROI to 22%; as well as a lab identified 5% increase in productivity that increase the ROI to over 275%!

LED lamp upgrade warrants careful consideration with regard to lighting quality & longevity of the existing luminaire

Replace the existing CFLs and incandescent light sources (lamps) with individually addressable LED light sources while keeping the original fixtures, reflectors and lenses. LED lamp retrofit should include a replacement or bypass of the existing fluorescent ballast with a dedicated, hardwired electronic driver to support dimming. LED lamps should be selected based on lamp efficacy, measured in lumens per watt, as well as the correlated color temperature and the color rendition index (CRI). This is because the high efficiency LED lamps are often characterized by high correlated color temperatures (CCTs), above 5000K, that produce a "cold" bluish light. To achieve the warm white light that occupants prefer, the LED lamps must have lower CCT of 2600K to 3500K, which can compromise efficiency. LED lamps should be selected by the CRI. While CRI above 80 (on a 100-point scale) is acceptable for interior applications, CRI's above 90 provide excellent color quality.

2x4 Troffers (36 W, 4000 Lumens, 4000K, 93 CRI) offer up to 55% energy savings when they replace a 96W 3-lamp T8 fixture, with excellent color quality *(CREE, 2017)*

CREE 6" recessed soft white dimmable LED downlight replacement (65W, 650 Lumens, 2700K, 90CRI)

Figure 5.7: Example of LED lamp replacement with critical attributes for occupant satisfaction

LED lamp upgrade offers substantial energy savings with a 6 years payback

The hardware and labor costs for installing individually addressable LED lamps is close to $2.75/sqft. The costs per square foot and energy savings depend on the existing wiring and fixture conditions as the installation requires removing the existing fluorescent lamps and ballasts, leaving only the luminaire housing.

The financial ROI is calculated using first costs divided by annual energy and maintenance savings. 25% - 80% lighting energy savings have been achieved in lab and field studies when LED lamps are compared to fluorescent or traditional incandescent (DLC, 2003; Newsham,2007; DOE,2016). Meyers (2009) also identifies 80% savings in maintenance costs and complete elimination of mercury disposal costs by using LED sources instead of T8 fluorescent lamps. With these savings, the payback for the retrofit will be 5 years.

LED lamp upgrade offers environmental benefits to shorten the payback

Each kWh saved through LED lamp upgrade results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 4 years.

LED light quality ensures human benefits to shorten the payback to months

The human benefits relate to the value of LED light quality for productivity at task. The third tier calculations are based on field studies that demonstrate 1% to 19% improvement in occupant productivity (Iskra-Golec et al.,2012; Kuang-Sheng Liu et al.,2010; Hoffmann et al./ Braun LaTour et al.,2012; Hawes et al.,2012; Mott et al.,2012). For instance, Hawes et al. (2012) identify an 8 % improvement in work performance at visual and cognitive tasks with the introduction of LED lighting with high color temperature and adequate illuminance level, as compared to traditional fluorescent lighting. An average increase of 5% has been assumed for the calculations based on multiple studies. Incorporating the productivity benefits in the third bottom line calculation results in a TBL payback of 7 months. More studies are emerging each year on the productivity and health benefits of LED lighting which could be added or averaged to update these calculations.

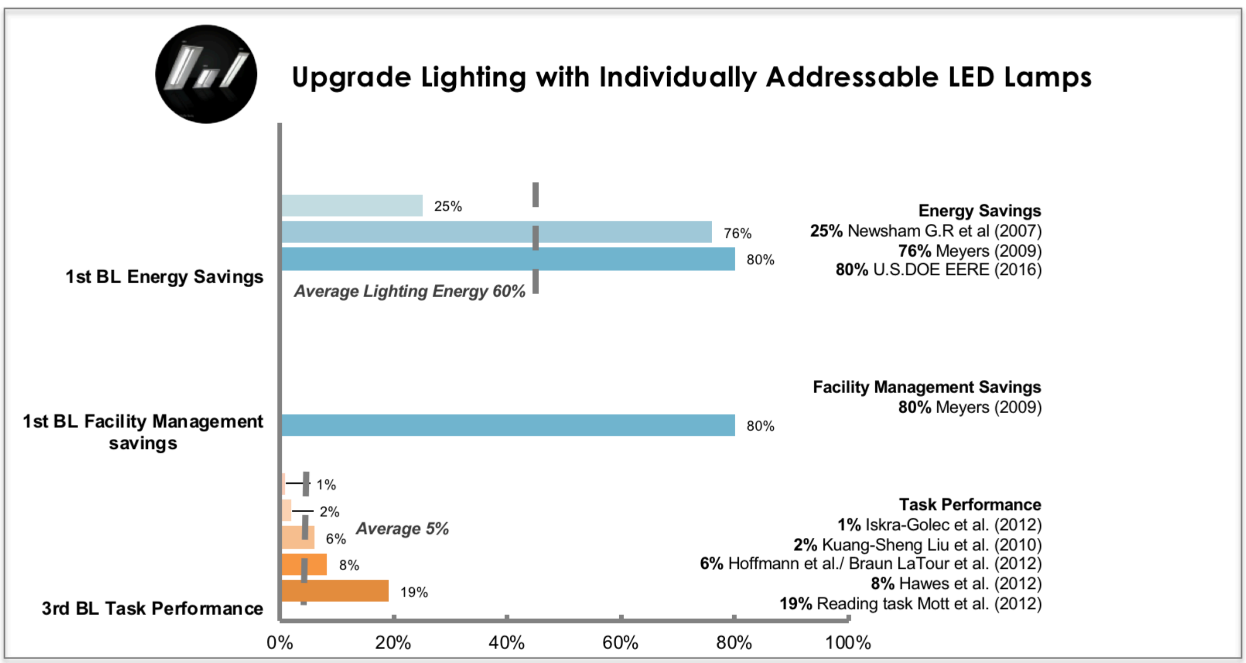


Figure 5.8: Cross sectional chart of the range of research on benefits from ugrading lighting with individually addressable LED lamps

Table 5.5: Triple bottom line calculations for upgrading to individually addressable LED lamps

Costs of upgrade lighting with individually addressable LED lamps

	Per sq. ft.	Per employee
Cost of LED lamps and lighting controls	$1.75	$350
Cost of labor + installation	$1.00	$200
First cost for the investment	$2.75	$550
Initial Investment costs for a 100,000 sq. ft. building	**$275,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
Energy savings (65%)	$0.44	$88
O & M Savings	$0.04	$8
Annual 1st bottom line savings	**+$0.48**	**+$96**
ROI (Financial)	**18%**	
Payback Period	**5 years**	
Cumulative 15-year Net Present Value	**$ 366,000**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	4.4 kWh	884 kWh
Air pollution emissions (SO_X, NO_X, PM, CH4)	$0.07	$14
CO_2 reductions	$0.05	$9
Water savings	$0.02	$4
Annual 2nd bottom line savings	**+$0.14**	**+$27**
Cumulative ROI (Financial + Environmental)	**22%**	
Payback Period	**4 years**	
Cumulative 15-year Net Present Value	**$ 467,500**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Productivity increase (5%) *(Improvement in a windowless office)*	$1.12	$2250
Annual 3rd bottom line savings	**+$11.86**	**+$2,373**
ROI (Financial + Environment+ Human)	**275%**	
Payback Period	**7 months**	
Cumulative 15-year Net Present Value	**$ 3,2551,900**	

Replace fixtures with integrated LED lighting

Install fixtures with integrated LED lighting, dimming & IP addressable controls to generate up to 80% lighting energy and 79% facility management savings with ROI of 17%; additional CO_2 + benefits that increase the ROI to 20%; as well as lab and field identified 7% increase in productivity and 50% reduction in headaches that increase the ROI to over 360%!

Integrated LED lighting offers the best opportunity for superior photometric performance, longevity and savings.

High performance fixture upgrades include replacement of existing 2’x4’, 1’x4’, or 2’x2’ troffers containing between two to four T12 or T8 lamps with "vertically integrated" LED fixtures with add-ons for dimming and IP controlling. LED light fixtures are vertically integrated, meaning that the fixture, ballast, lamp, reflector, and diffuser are integral. Given the capability of LED sources to be dimmed and locally controlled with wireless controls, it is important to specify dimming ballasts with Digital Addressable Lighting Interface (DALI) controls for local and central light level management. Replacing the ballasts, lamps and adding automated lighting controls offers the ability to bring operating lighting power densities below 1 watt per square foot, create ambient lighting levels appropriate for computer tasks while giving occupants greater control.

Osram DALI Ballasts enable up to 60% energy savings through dimming, daylight sensing, occupancy sensing, local control *(DALI,2013)*

Philips connected lighting with Cisco technology provides each fixture IP address to send & receive data, providing value to occupant & facility manager *(Philips, 2015).*

Figure 5.9: Examples of high performance ballasts and IP control for local and central lighting control

Integrated LEDs offers substantial energy savings with a payback of 6 years

The hardware and labor costs for installing LED fixtures with dimming and IP addressable ballasts is under $5/sqft. The purchase of the automation system includes installation, commissioning, and training on the use of the facility manager and user control interfaces, which are valuable to optimize energy savings. Retrofitting with an entirely new LED luminaire is likely to be the most expensive option in terms of initial project costs, but over the life of the product, the incremental cost is small compared to lamp replacement option.

The financial ROI is calculated using first costs divided by annual energy and FM savings. 74% - 87% lighting energy savings has been achieved in multiple lab and field studies (Meyers, 2009; EERE,2016; Energy User News,2001, Hedenstrom et al., 2001) with intelligent lighting fixtures and network controls. Finally, Hedenstrő́m et al. (2001) identified a 77% savings in lighting system maintenance costs due to high-performance lighting design. While not quantified here, there could be churn cost-benefit since IP addressable fixtures eliminate the need for additional resources to support layout changes.

Integrated LEDs offers environmental benefits to shorten the payback to 5 years

Each kWh saved through integrated LED lighting upgrade results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 5 years.

Lighting control ensures human benefits to shorten the payback to months

The human health and productivity benefits from replacing existing fixtures with integrated LED fixtures depend on the existing lighting condition of the building. In a controlled experiment Aaras et al. (1998) identify a 27% reduction in headaches in computer workers when conventional downlighting was replaced by user-controlled indirect-direct lighting. Multiple filed and lab studies show a 2% to 10% increase in productivity with high performance lighting upgrades (Newsham et al., 2004; Juslen et al., 2007; Hoffmann et al., 2008; Hawes et al.,2012; Anderson et al., 2009; Newsham et al., 2004). In a study Hoffmann et al. (2012) identify a 33% improvement in mood ratings due to the use of daylight simulating lighting (dimming and color modified) as compared to regular fluorescent lighting. In a 2007 study by Braun-LaTour et al., a 33% improvement in positive mood ratings translates into a 5.76% work efficiency increase. Incorporating these two benefits in the third bottom line calculations results in a TBL payback of 4 months.

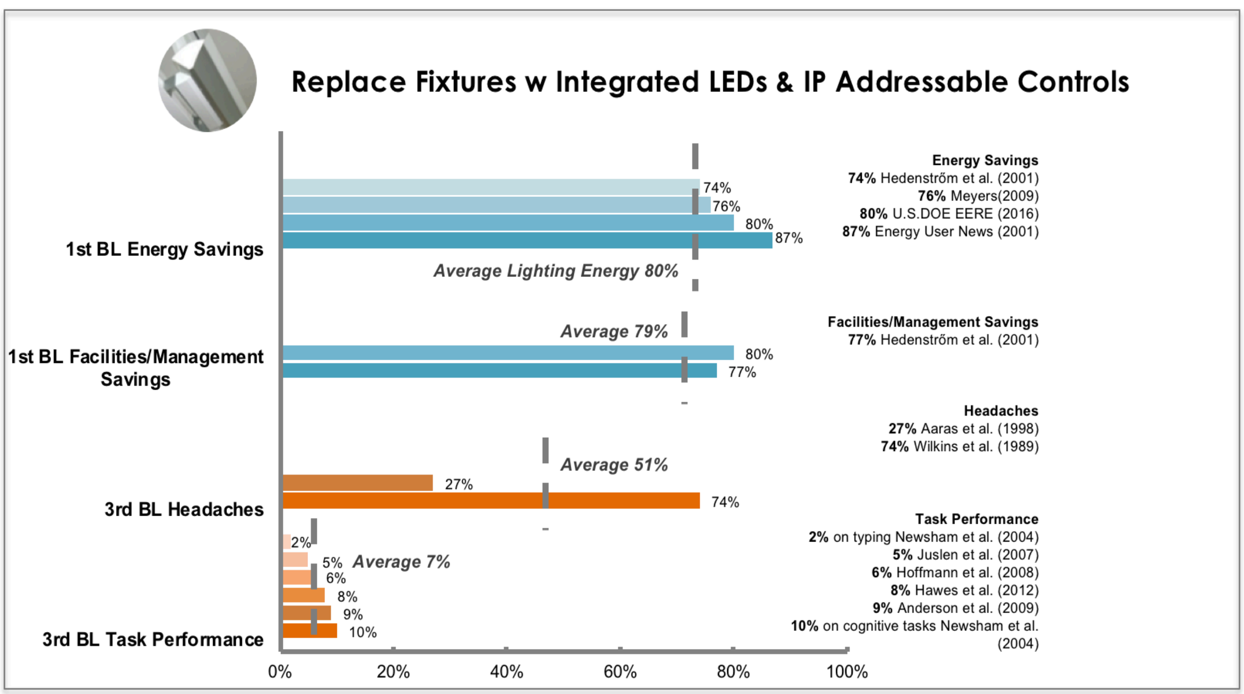


Figure 5.10: Cross sectional chart of the range of research on benefits from replacing light fixtures with integrated LEDs

Table 5.6: Triple bottom line calculations for replacing existing fixtures with integrated LED lighting

Costs of upgrading with vertically integrated LED fixtures

	Per sq. ft.	Per employee
First cost for the investment	$4.75	$950
Initial Investment costs for a 100,000 sq. ft. building	$475,000	

1st Financial Capital savings

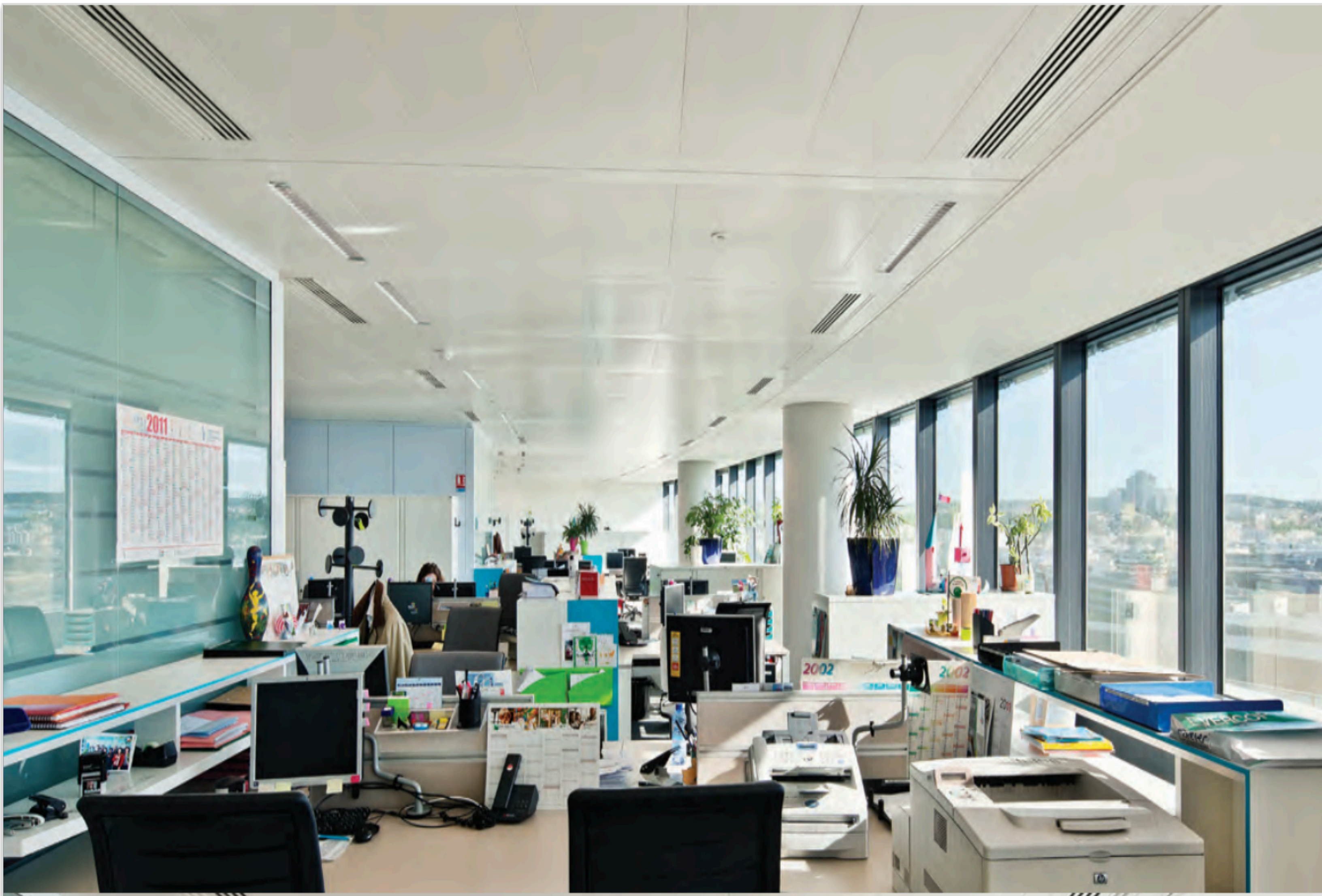
	Per sq. ft.	Per employee
Energy savings (80%)	$0.54	$108
Replacement Savings	$0.25	$50
Annual 1st bottom line savings	+$0.79	+$158
ROI (Financial)	17%	
Payback Period	6 years	
Cumulative 15-year Net Present Value	$ 603,900	

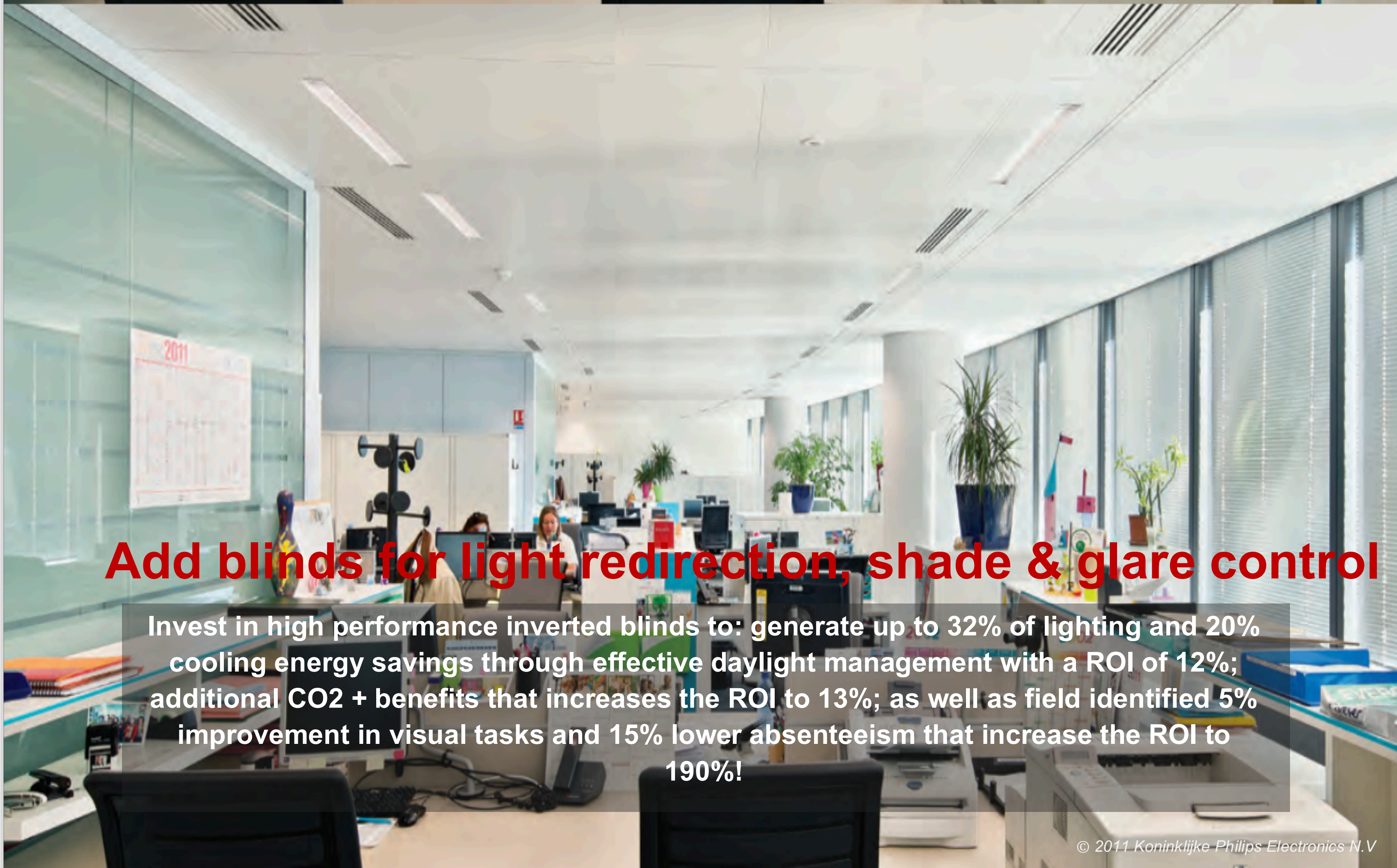
2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	5.44 kWh	1088 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.09	$18
CO_2 reductions	$0.05	$10
Water savings	$0.02	$4
Annual 2nd bottom line savings	+$0.16	+$32
Cumulative ROI (Financial + Environmental)	20%	
Payback Period	5 years	
Cumulative 15-year Net Present Value	$ 728,185	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Headache reduction (51% of $73)	$0.26	$52
Productivity increase (7%) *(Improvement in a windowless office)*	$11.3	$3,150
Annual 3rd bottom line savings	+$15.8	+$2250
ROI (Financial + Environment+ Human)	360%	
Payback Period	4 months	
Cumulative 15-year Net Present Value	$ 12,432,300	





Add blinds for light redirection, shade & glare control

Invest in high performance inverted blinds to: generate up to 32% of lighting and 20% cooling energy savings through effective daylight management with a ROI of 12%; additional CO_2 + benefits that increases the ROI to 13%; as well as field identified 5% improvement in visual tasks and 15% lower absenteeism that increase the ROI to 190%!

Blinds when well designed and well managed, ensure high levels of daylight without glare and overheating and provide critically needed views of the outside.

Blinds serve a number of critical purposes for effectively managing daylighting, thermal and glare control. Appropriate usage of blinds can even reduce heat loss on winter nights and allow for night sky cooling on summer nights. The ideal blinds to buy should be highly reflective in color and inverted (cupped facing upwards) to redistribute daylight to the ceiling plane. The inverted blinds could even have a seasonally “smart” profile that reflects high sun angles back outdoors to reduce solar gain in the cooling season and reflects low sun angles into the space to increase solar gain in the heating season (Retrosolar™ profile).

Figure 5.11: Examples of High Performance Retrosolar™ Inverted Blinds (CBPD,2012)

Inverted blinds offer substantial energy savings with a 5-year payback

The first cost for new blind purchases has been derived from Means Cost Guides and manufacturer estimates, assuming 40% of the baseline building surface area as windows to be equipped with new blinds. The cost of adding venetian blinds includes the cost of management training time and hardware costs.

The financial ROI is calculated using first costs divided by annual energy savings for both lighting and cooling energy. The lighting energy savings are estimated at 32% based on measured field results from De Carli and De Giuli (2009) in field studies with automated blinds and mixed user behavior, and measured field results in the Center for Building Performance (2012). Cooling energy savings of 20% has been achieved in a field study by Lee et al. (1998), who measured a 7-15% lighting energy savings and a 19-52% cooling energy savings with venetian blinds. With energy savings alone, the payback is 4.5 years.

Inverted blinds offer environmental benefits to shorten the payback to 3.5 years

Each kWh saved through installing venetian blinds results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 3.5 years.

Increased daylighting ensures human benefits to shorten the payback to months

The human benefits from selecting high performance blinds relate to the value of both daylighting and views for productivity and health, as well as the importance of sunshine for health in winter and shading for comfort in summer. The impact of well managed daylight for productivity include a 3% improvement in visual tasks related to reduced glare, captured in a 2006 field study by Zhang and Altan and combined with findings from Osterhaus and Bailey (2011). A field study by Heschong et al. (2003) identified an even more substantial 6.7% improvement in Average Handling Time (AHT) for call center employees with seated access to larger windows and a view with vegetation from their cubicles, as compared to employees with no view of the outdoors. Finally, absenteeism savings are calculated based on a 15% reduction in absenteeism for occupants that have access to daylight identified by Romm and Browning in a 1994 study. Incorporating these benefits in the third bottom line calculations results in a payback of 4 months.

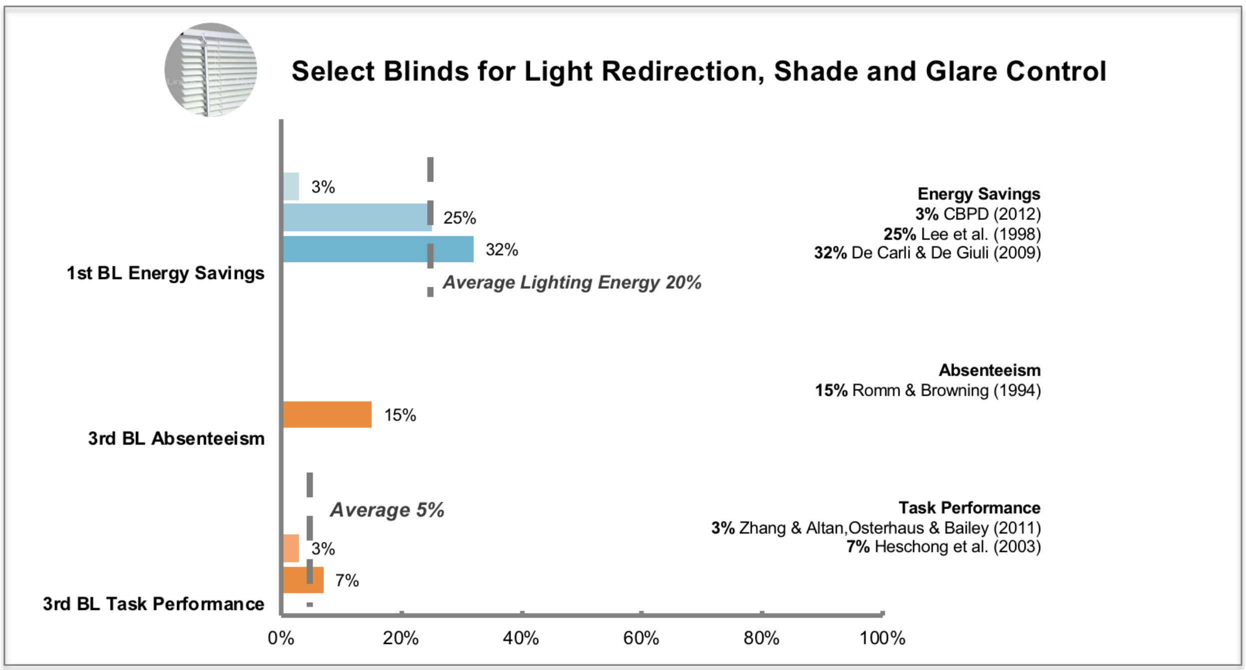


Figure 5.12: Cross sectional chart of the range of research on benefits from investing in blinds for light redirection, shade and glare control

Table 5.7: Triple bottom line calculations for buying and managing new inverted venetian blinds

Costs of buying and managing new inverted venetian blinds

	Per sq. ft.	Per employee
Cost of new inverted blinds *(for baseline building with 40% window wall ratio)*	$5.65	$300
Cost of annual FM/Training costs	$0.25	$50
First cost for the investment	$5.90	$350
Initial Investment costs for a 100,000 sq. ft. building *(for 1/3 baseline building perimeter area)*	**$180,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
Lighting Energy savings (20%)	$0.14	$28
Cooling Energy Savings (20%)	$0.45	$9
Annual 1st bottom line savings	**+$0.18**	**+$37**
ROI (Financial)	**12%**	
Payback Period	**8 years**	
Cumulative 15-year Net Present Value	**$ 46,650**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.55 kWh	110 kWh
Air pollution emissions (SO_X, NO_X, PM, CH4)	$0.01	$2
CO_2 reductions	$0.01	$1
Water savings	$0.002	$0.4
Annual 2nd bottom line savings	**+$0.02**	**+$3.4**
Cumulative ROI (Financial + Environmental)	**13%**	
Payback Period	**7.5 years**	
Cumulative 15-year Net Present Value	**$ 50,850**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Productivity increase (3%)	$2.02	$405
Annual 3rd bottom line savings	**+$2.02**	**+$405**
ROI (Financial + Environment+ Human)	**190%**	
Payback Period	**37 months**	
Cumulative 15-year Net Present Value	**$ 735,400**	

Image source: Loftness, V. (2017) "Taking Biophilic Research into Practice", Living Future 2017 Conference

Add light shelves to clerestory windows

Introduce light shelves or inverted blinds/louvers in the clerestory area to: generate up to 30% lighting energy savings through distribution of daylight deep into the building with effective glare control and shading for an ROI of 22%; additional CO2 + benefits to increase the ROI to 24%; as well as field identified 3% increase in time dedicated to visual tasks and 15% reduction in absenteeism to increase the ROI to 140%!

Light shelves can redirect daylight deep into the building, while shading and effectively reducing glare and the requirement for electric lighting and cooling.

To ensure daylight effectiveness beyond the first few feet of work area, the retrofit recommendation is to introduce light shelves or inverted blinds/louvers in the clerestory area. The ideal light shelves would be highly reflective in color. If louvers or venetian blinds are used, they should be inverted (curve upwards) to reflect daylight onto the ceiling for diffusion (see Lightlouver™ profile below). The inverted blinds can even have a seasonally "smart" W-profile that reflects high sun angles back outdoors to reduce solar gain in the cooling season and reflects low sun angles into the space to increase solar gain in the heating season. Inverted blinds and louvers in the clerestory, in combination with a highly reflective ceiling, create a daylighting system that can be used on the east, west and the south façade.

Wausau internal lighting shelf at Armstrong World Industries office in Lancaster, PA. *(Wausau, 2017)*

LightLouver units in clerestory to reflect sunlight into the ceiling *(Lightlouver, 2016).*

Figure 5.13: Example of two different light shelves for use in clerestory

Inverted blinds/louvers offer substantial energy savings with a 5-year payback

On the cost side, the most affordable solution is approximately $20 per sqft of building façade or a $2.20/sf of floor area upfront cost, based on manufacturer estimates, given 20% of the baseline building surface area as clerestory to be equipped with light shelves (Skyshade™, 2014; Lightlouver, 2015).

The financial ROI is calculated using first costs divided by annual energy savings. Given that 25-100% of workstations may be within 15 feet of a window wall in many office buildings, daylighting without glare can save up to 30% of a medium size office building's total lighting energy (Carli and Guili, 2009). With the electricity savings included in the first bottom line the payback is 4.5 years.

Inverted blinds/louvers offer environmental benefits to shorten the payback

Each kWh saved through the use of inverted blinds/lovers in the clerestory results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 3.5 years.

Increased daylighting ensures human benefits to shorten the payback to months

The human benefits of investing in light redirection/diffusion are related to the spectral quality of daylight, the management of brightness contrast by bouncing light, the improvement of views, as well as the importance of sunshine in winter and shading for comfort in summer. In a 2011 lab experiment Mirjam et al. identify a 4% increase in accuracy at early evening cognitive tasks when subjects were exposed to daylight in the afternoon using anidolic daylight system compared to those exposed to conventional fluorescent lighting system. In a 1992 laboratory experiment conducted using 26 subjects, Osterhaus and Bailey found a 3% improvement in visual tasks related to reduced glare (Osterhaus & Bailey, 1992). Together, these studies account for up to 3% increase in productivity. A case study by Thayer (1995) identifies a 15% reduction in absenteeism in daylit workspaces also contributing to the human benefits of daylighting calculated in the third bottom line. Incorporating these two benefits in the third bottom line calculation results in a TBL payback of 9 months. More studies are emerging each year on the productivity and health benefits of daylighting which could be added or averaged to update these calculations.

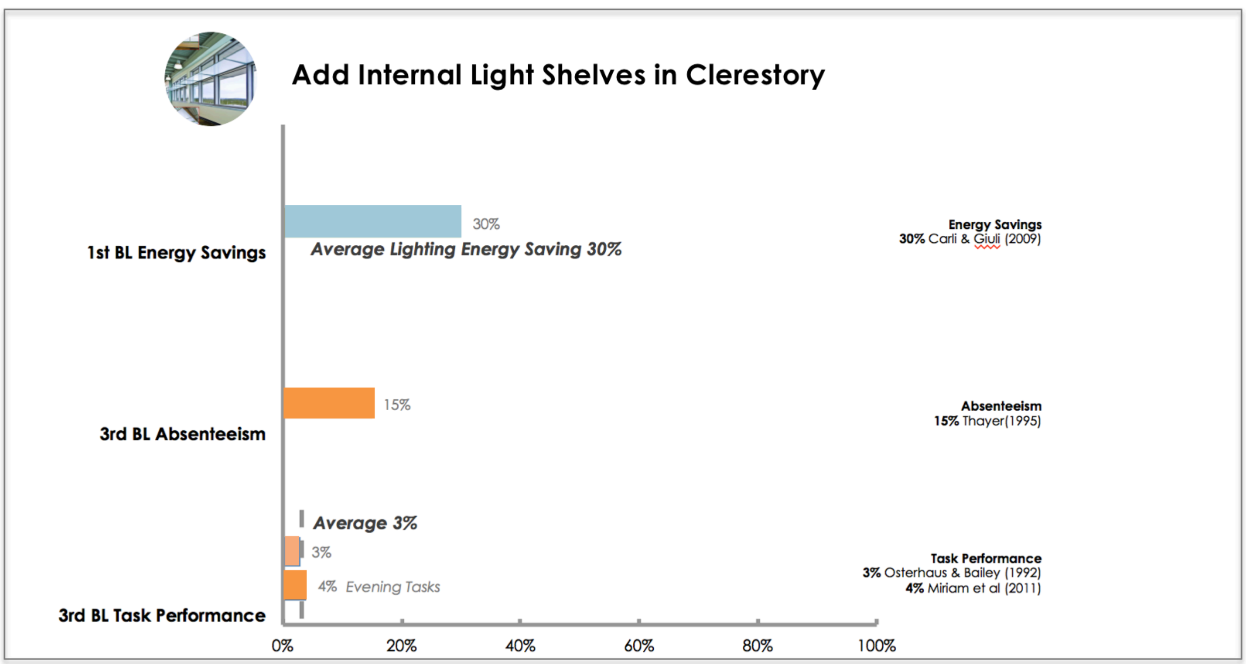


Figure 5.14: Cross sectional chart of the range of research on benefits from adding internal light shelves in the clerestory

Table 5.8: Triple bottom line calculations for investing in light louver/blinds

Costs to install Light Redirection Louvers/Blinds

	Per sq. ft.	Per employee
First cost for the investment (60% window wall ratio, 33% floor area)	$2.20	$220
Initial Investment costs for a 100,000 sq. ft. building	**$73,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
Lighting Energy savings (35%)	$0.24	$48
Annual 1st bottom line savings	**+$0.24**	**+$48**
ROI (Financial)	**22%**	
Payback Period	**4.5 years**	
Cumulative 15-year Net Present Value	**$ 120,680**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.72 kWh	143 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.01	$2.3
CO_2 reductions	$0.01	$1.4
Water savings	$0.003	$0.6
Annual 2nd bottom line savings	**+$0.02**	**+$4.3**
Cumulative ROI (Financial + Environmental)	**24%**	
Payback Period	**4 years 2 months**	
Cumulative 15-year Net Present Value	**$ 156,900**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Absenteeism reduction (15% of 2% year)	$0.68	$135
Productivity increase (3%)	$0.60	$120
Annual 3rd bottom line savings	**+$1.28**	**+$255**
ROI (Financial + Environment+ Human)	**140%**	
Payback Period	**9 months**	
Cumulative 15-year Net Present Value	**$ 773,300**	

Image source - Arab News, 2015. King Fahad National Library, Saudi Arabia

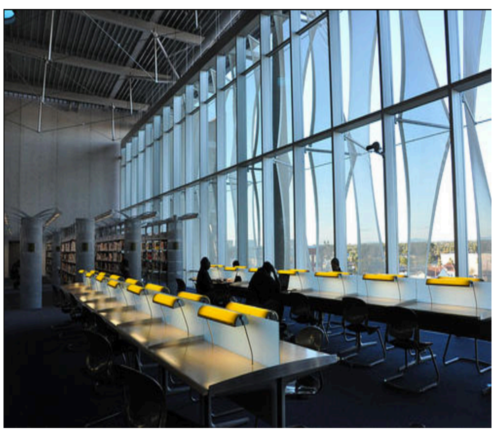
Celebrate external shading

Install external louvers and awnings to: generate up to 30% cooling energy through effective shading with daylight, with a ROI of 5%; additional CO_2 + benefits to increase the ROI to 6%; as well as field and lab identified 2% increase in time dedicated to work tasks to increase the ROI to over 340%!

Dynamic shading devices can be daily or seasonally adjusted to reflect sunlight when required, while allowing daylight penetration & solar gain during the winter

In hot climates, shading the facade is a high priority to avoid overheating in summer. While modern office buildings in the past century were often sleek glass towers, todays design community is rediscovering the power of facades articulated by static fins, louvers, and screens as well as the highest performing dynamic awnings. Fixed overhangs, horizontal louvers and fins, and dynamic awnings are each effective addition to modern facades, providing shade with daylight, without diminishing our views with yesterday's dark glass, eggcrate shades and scrim layers.

Horizontal devices should be the norm for southern orientations, combined horizontal and vertical or dynamic awnings, overhangs for east west, and vertical devices for north facades (Figure below). Today, awnings are made of synthetic fabrics which are fade resistant, water repellant and require less maintenance than they have historically. Openings along the top and sides of the overhang or awning should be provided to prevent heat from being trapped at the window wall.



Vertical awnings on the north face of the Phoenix library *(Phoenix Public Library,2013)*

Horizontal louvers on south face of Stecalite, Noida.

Figure 5.15: Examples of different styles of dynamic shading devices

Awnings offer energy savings with a 20 years payback

The cost of installing external louvers and awnings varies dramatically based on material and assembly, with $5.50/sqft assumed in the TBL calculations. Awnings have a lifetime of 5 years, hence the first cost includes prices for three changes during the analysis period.

The financial ROI is calculated using first costs divided by annual energy savings. The use of adjustable awnings as a shading device can reduce solar heat gain and associated cooling loads in the hot climates by up to 65% on south-facing windows,77% on west-facing windows and 20-25% total cooling energy savings (DOE, 2012; Nagy et al., 2000). Bellia et al.(2013) and Stavrakakis et al (2007) use energy simulations to illustrate 18-20% savings in cooling energy with use of overhangs in building. With energy savings alone, the payback is 20 years.

Awnings offer environmental benefits to shorten the payback to 16 years

Each kWh saved through the use of awning results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 16 years.

Glare control ensures human benefits to shorten the payback to months

The human benefit of shading using awnings include the value of glare control for productivity as well as improved thermal comfort in summer (Zhang & Altan, Osterhaus & Bailey, 2011; Witterseh, 2001). In a 1998 controlled experiment, Witterseh identifies a 54% increase in mathematics accuracy and a 3.5% typing improvement when subjects feel thermally comfortable, rather than too warm, in quiet office conditions (Witterseh, 2001). Incorporating these two benefits in the third bottom line calculation results in a TBL payback of 4 months.

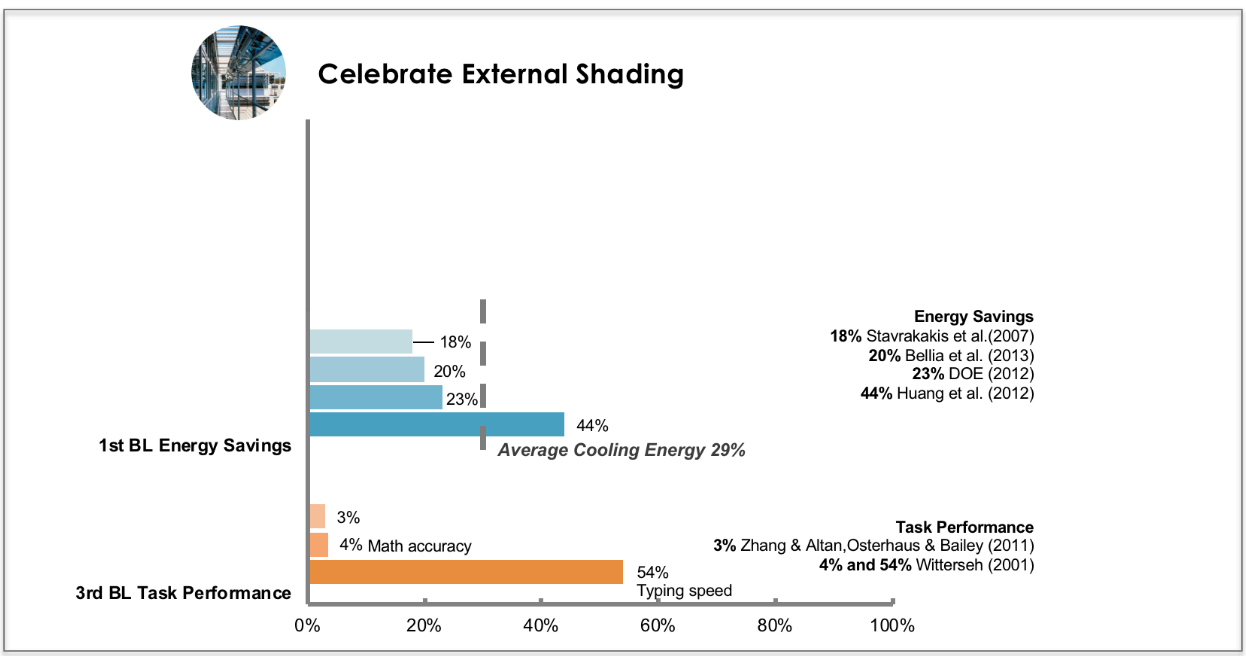


Figure 5.16: Cross sectional chart of the range of research on benefits from adding external shading devices such as overhnags and awnings

Table 5.9: Triple bottom line calculations for investing in canvas awnings for summer shading

Costs of investing in canvas awnings for summer shading

	Per sq. ft.	Per employee
First cost for the investment *(for baseline building with 40% window wall ratio)*	$4.50	$240
Initial Investment costs for a 100,000 sq. ft. building *(for 1/3 baseline building perimeter area)*	**$81,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
HVAC Energy Savings (25%)	$0.06	$12
Annual 1st bottom line savings	**+$0.06**	**+$12**
ROI (Financial)	**5%**	
Payback Period	**20 years**	
Cumulative 15-year Net Present Value	**$30,420**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.6 kWh	120 kWh
Air pollution emissions (SO_X, NO_X, PM, CH4)	$0.01	$2
CO_2 reductions	$0.01	$1
Water savings	$0.002	$0.50
Annual 2nd bottom line savings	**$0.02**	**$4**
Cumulative ROI (Financial + Environmental)	**6%**	
Payback Period	**16 years**	
Cumulative 15-year Net Present Value	**$ 39,550**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Productivity increase (4%)	$4.06	$812
Annual 3rd bottom line savings	**+$4.06**	**+$812**
ROI (Financial + Environment+ Human)	**340%**	
Payback Period	**4 months**	
Cumulative 15-year Net Present Value	**$ 2,098,890**	

Image source - DCI Engineers,2009. Terry Thomas Offices, Washington

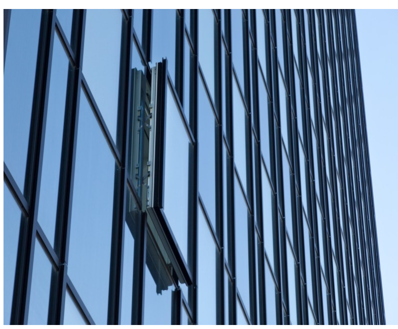
Ensure windows are operable

introduce operable windows for natural ventilation and night cooling to: generate up to 40% HVAC energy savings, with a ROI of 5%; additional CO_2 + benefits to increase the ROI to 7%; as well as lab and field identified 3% increase in productivity, 26% reduction in headache, 30% lower colds and flus and 36% reduction in skin and eye irritation to increase the ROI to 345%!

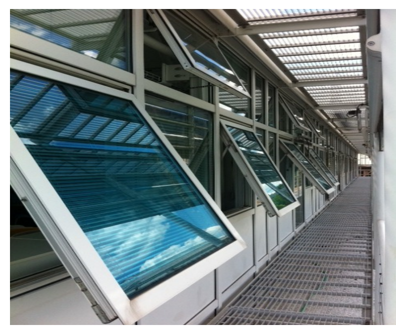
Design for natural ventilation should address the site-specific limits of climate, outdoor air quality, noise, security, and local building codes.

This investment requires introducing operable windows for natural ventilation and night cooling. Operable windows are important on a variety of levels specially since they enable physical connection with the outside and create a sense of personal control. Business-as-usual buildings reveal the rising trend of sealing office facades. This is a disadvantage during brown outs or black outs, as the building runs out of air and starts to overheat. Moreover, sealing building facades eliminates the opportunity to use natural ventilation for cooling and breathing, or night ventilation to pre-cool the building for the next day.

To avoid the possibility of rain coming in, and to ensure controlled air flow, the use of awning, drop-kick, and pop-out windows are emerging in modern offices (Figure below). For hot and dry climates, natural ventilation can be pursued on moderate days if air quality and noise are not a local issue. More critically, night ventilation cooling can be pursued on nights that are predicted to be cooler than 70°F and combined with thermal mass or phase change materials to store 'coolth' for conditioning on the following day.



Example of pop-out window in high rise building



Awning windows opened manually

Figure 5.17: Two examples of operable windows used for facilitating natural ventilation in offices

Operable windows offer energy savings with a 19-year payback

The cost of natural ventilation is related to the additional costs of window hardware and the manual or automated system for control, while night cooling requires the addition or exposure of thermal mass in the airstream.

The financial ROI is calculated using first costs divided by the annual energy savings. 17% to 48% reduction in ventilation loads (Milne et al., 2007; Wang et al., 2015) and up to 35% pre-cooling load (Emmerich, Climate Suitability Tool) has been achieved in naturally ventilation. Even in continental climates, natural ventilation can result in 10-25% fan energy savings (Guzowski, 2003). With the energy savings only, the payback is 19 years.

Operable windows offer environmental benefits to shorten the payback to 14 years

Each kWh saved through introducing operable windows results in reductions in environmental CO_2, CH_4, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 14 years.

Natural ventilation ensures human benefits to shorten the payback to months

Human benefits from natural ventilation in the workplace can be measured. A 3% to 5% improvement in productivity has been measured in two case studies. In a meta-analysis Wargocki et al. (2000) identify an overall productivity improvement of 3.6% due to an increased ventilation rate; while Seppänen et al. (2003) identify a productivity increase of 4.9% due to night-time ventilative cooling. A cross sectional study by Zweers et al. (1989) measured 20% lower asthma symptoms in building with operable windows. 9% to 56% lower skin and eye irritation symptoms have also been achieved in naturally ventilated buildings in multiple studies (Toftum,2010; Teeuw et al., 1994; Burge et al., 1987; Olli & Fisk, 2002; Zhounghua et al.,2012). A 2010 cross sectional study by Toftum identifies up to 9% lower prevalence of eye irritation and higher satisfaction in occupants in naturally ventilated offices compared to sealed offices. In addition, 9% to 45% reduction in headaches and 10% to 45% lower colds and flus symptoms have been measured in multiple field studies (Teeuw et al., 1994; Burge et al., 1987; Olli & Fisk, 2002; Gao et al.,2003; Harrison et al,1992; Kroeling,1998). A cross sectional study by Zhounghua et al. (2012) identifies a reduction in SBS symptoms with the presence of operable windows and indoor plants, resulting in an average 16% reduction in headaches and 42% reduction in sinus conditions. Incorporating these benefits in the third bottom line results in a TBL payback of 2 months.

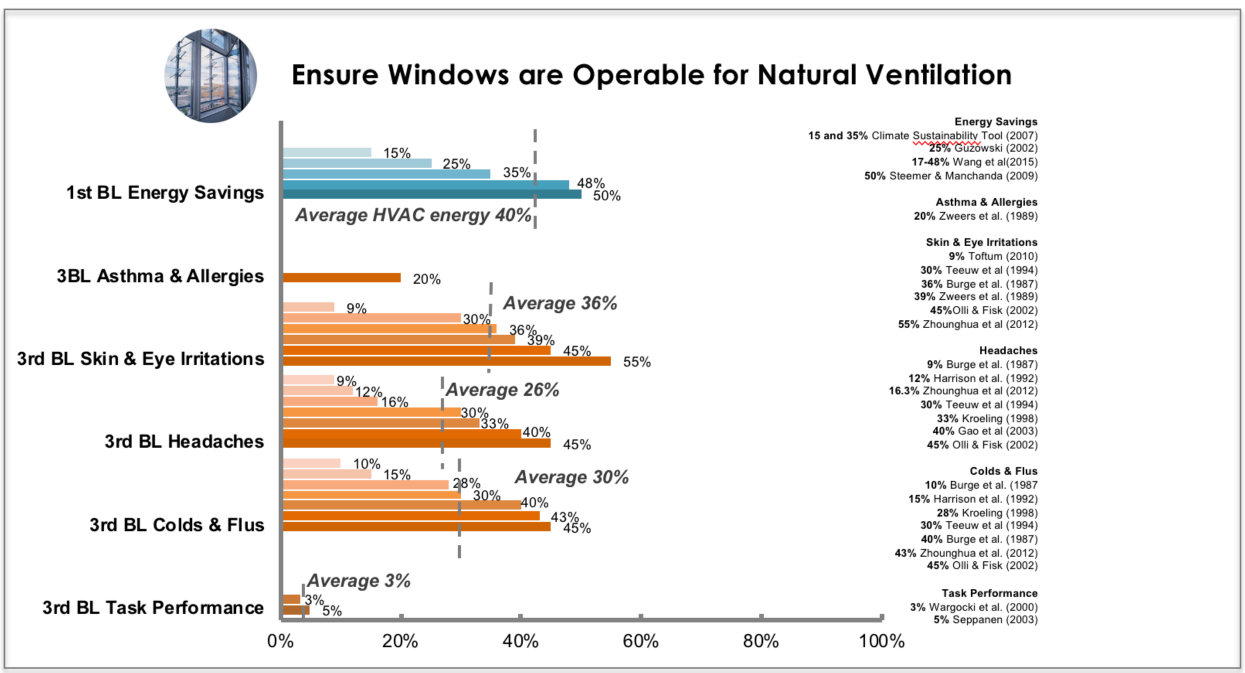


Figure 5.18: Cross sectional chart of the range of research on benefits from operable windows for natural ventilation

Table 5.10: Triple bottom line calculations for introducing operable windows for natural ventilation and night cooling

Costs of buying operable windows for natural ventilation and night cooling

	Per sq. ft.	Per employee
First cost for the investment	$15	$360
Initial Investment costs for a 100,000 sq. ft. building *(for 1/3 baseline building perimeter area)*	**$120,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
HVAC Energy Savings (40%)	$0.09	$19
Annual 1st bottom line savings	**+$0.09**	**+$19**
ROI (Financial)	**5%**	
Payback Period	**19 years**	
Cumulative 15-year Net Present Value	**$ 73,000**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.96 kWh	192 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.02	$3
CO_2 reductions	$0.01	$2
Water savings	$0.004	$0.8
Annual 2nd bottom line savings	**+$0.03**	**+$5.8**
Cumulative ROI (Financial + Environmental)	**7%**	
Payback Period	**14 years**	
Cumulative 15-year Net Present Value	**$94,950**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Headache reduction (26% * $73)	$0.10	$19
Cold & flu reduction (30% * $68)	$0.10	$20
Skin & eye irritation reduction (41% * $86)	$0.15	$31
Asthma & allergies reduction (20% * $105)	$0.10	$20
Productivity increase (3%)	$5.62	$1,125
Annual 3rd bottom line savings	**+$6.21**	**+$1241**
ROI (Financial + Environment+ Human)	**345%**	
Payback Period	**2 months**	
Cumulative 15-year Net Present Value	**$ 805,700**	

Integrate underfloor air and networking

Implement underfloor air HVAC and flexible data and power networking to: generate up to 16% of HVAC energy savings and 78% churn cost savings with a ROI of 44%; additional CO_2 + benefits to increase the ROI to 46%; as well as field identified 14% reduction in cold and flus and 3% higher productivity to increase the ROI to over 360%!

Underfloor air is an innovation in engineering practice to deliver flexible, user-based services for air quality, thermal comfort and network access.

In this investment, the plenum below a raised floor is used to deliver ventilation and space conditioning and network access rather than a ceiling plenum. Underfloor air (UFA) system allows reconfiguration of the density and location of diffusers to provide space conditioning at the level of the building occupants for increased energy efficiency, improved ventilation and air quality as well as greater user comfort and control.

UFA systems deliver air through two ways – a pressurized plenum or distributed fans that have relocatable floor diffusers or desktop air diffusers at the occupant end. The pressurized plenums and central fans work in combination with unducted distribution of cooling and ventilation air from risers, or partially or fully ducted distribution of air, while distributed fan system employs individual fans within the floor plenum to assist in air distribution. Return air from the space is removed at the ceiling to maximize the vertical airflow patterns for pollution removal and stratification benefits.

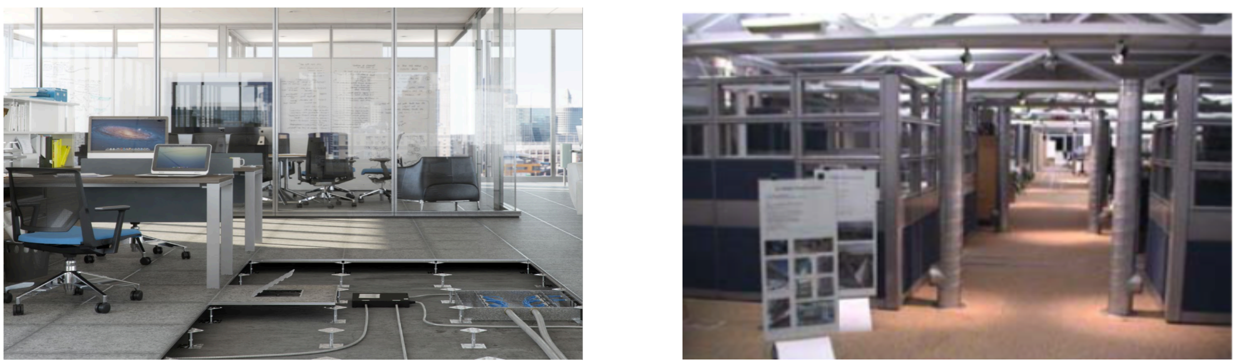


Figure 5.19: Access to air, power, voice, and data under the floor enables quicker reconfigure of the layout with minimal downtime (Image sources - IFMA Boston, 2014 and CBPD,2009).

UFA offers substantial churn cost savings with a payback of little over 2 years

The material and labor cost premiums for implementing UFAD system range from $2.15/ft2 to $3.50/ft2 for a median UFAD building compared to poke through system. (CBE, 2006; York,1992; CBPD). This is largely due to a cost premium for raised access flooring and electrical wiring, although the HVAC system is slightly cheaper for building with UFAD.

The financial ROI is calculated using first costs divided by annual energy and churn cost savings. 5% to 34% reduction in annual HVAC energy consumption has been achieved with the use of UFA systems (Milam,1992, Hu et al 1999 and Akimoto et al, 1999). Studies also demonstrate an average 78% reduction in annual churn costs (CBPD /Owens Corning office,1997; Becket, 1992, York, 1993 and Toothacre,2003) as raised floor enable quicker change of floor layouts, power and cabling. In new construction, raised floors also improve flexibility for building services and decreases floor to floor height, resulting in a $0.43 to 2/sqft integrated first cost savings, compared to a conventional overhead HVAC system and poke-through wiring (Milam,1992 and Flack and Kurtz,1996). With the energy and churn cost savings the payback for UFA systems is little over 2 years.

UFA system offers environmental benefits to shorten the payback to 2 years

Each kWh saved through UFA systems results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 2 years.

Better air quality ensures human benefits to shorten the payback to months

The human benefits from integrating UFA system and networking can be measured. UFA systems increase thermal satisfaction and lower indoor pollutant concentration resulting in an increase in productivity and fewer colds and flus. A 19% self-reported improvement at office tasks is captured in a 2014 field study by Mariusz et al. combined with findings from Huizenga et al. (2006). In another study Fisk et al. (2005) estimate an average 13% reduction in indoor pollutant concentration due to UFA delivery. A 1989 analysis by the U.S. EPA identifies a 3.3% productivity loss due to substandard air quality. Together, these two studies suggest a potential 0.5% productivity increase due to the use of an underfloor air system. Incorporating the health and productivity benefits in the third bottom line calculation results in a TBL payback of 3 months.

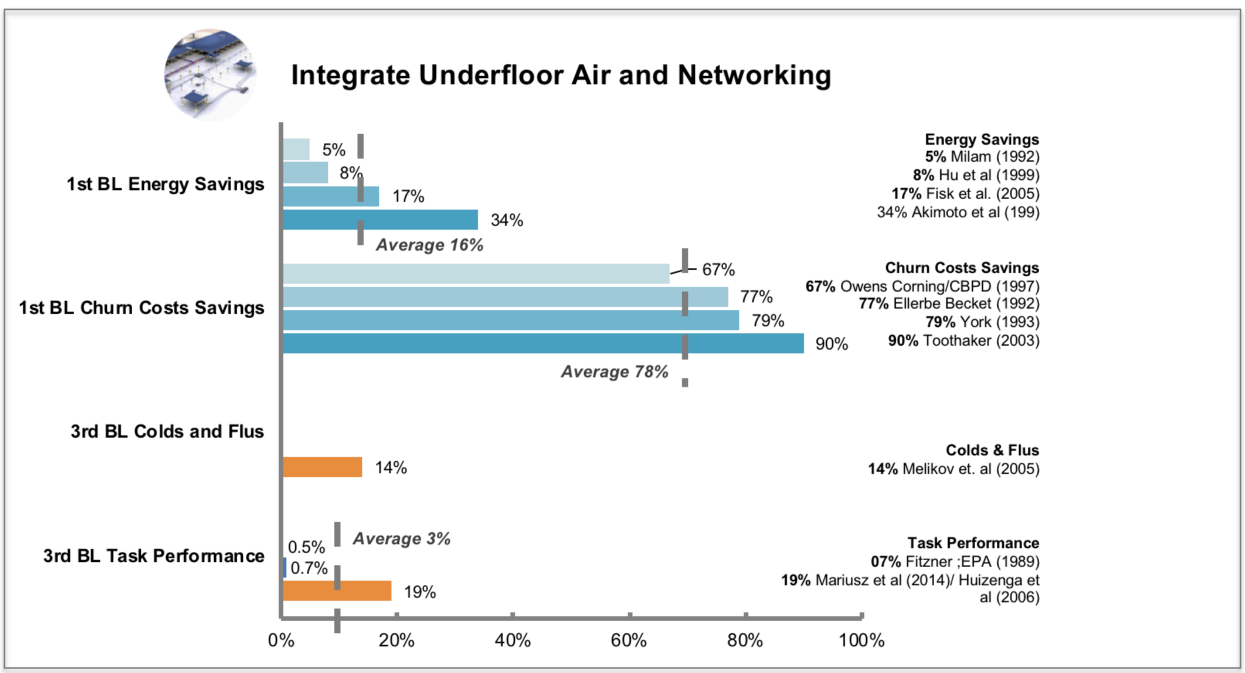


Figure 5.20: Cross sectional chart of the range of research on benefits from integrating under floor air distribution and networking

Table 5.11: Triple bottom line calculations for implementing underfloor air distribution and networking

Costs of integrating underfloor air and networking

	Per sq. ft.	Per employee
First cost for the investment	$2.15	$430
Initial Investment costs for a 100,000 sq. ft. building	**$215,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
HVAC Energy Savings (16%)	$0.04	$8
O & M Savings	$0.19	$38
Churn Cost savings (78%)	$0.72	$144
Annual 1st bottom line savings	**+$0.95**	**+$190**
ROI (Financial)	**44%**	
Payback Period	**2 years**	
Cumulative 15-year Net Present Value	**$ 723,150**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.42 kWh	82 kWh
Air pollution emissions (SO_x, NO_x, PM, CH4)	$0.01	$1.20
CO_2 reductions	$0.01	$1.00
Water savings	$0.001	$0.30
Annual 2nd bottom line savings	**$0.02**	**$2.50**
Cumulative ROI (Financial + Environmental)	**46%**	
Payback Period	**2 years**	
Cumulative 15-year Net Present Value	**$ 732,450**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Cold and flu reduction (14% of $68)	$0.05	$10
Productivity increase (3%)	$6.75	$1350
Annual 3rd bottom line savings	**+$6.80**	**+$1360**
ROI (Financial + Environment+ Human)	**360%**	
Payback Period	**3 months**	
Cumulative 15-year Net Present Value	**$ 5,680,720**	

Image source: Loftness, V. (2017) "Taking Biophilic Research into Practice". Living Future 2017 Conference

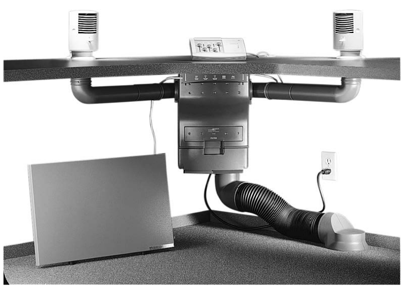
Engineer individual temperature control

Introduce individual temperature control to generate: up to 20% of HVAC energy savings for greater occupant comfort with a ROI of 6%; additional CO2 + benefits that increase the ROI to 7%; as well as research identified 5% higher productivity that increasse the ROI to over 288%!

Thermal control for individuals can be achieved through task conditioning, or individual unit controls for temperature, air speed and air direction

This investment introduces individual control zones for every workstation, by providing task cooling (water based radiant or air based) in occupied spaces. Separating ambient from task cooling conditions can save energy and increase occupant comfort and performance. This is especially important given the 30-40% of today's workspaces are empty at any particular point of the work day, and 50% of the workplace that is dedicated to support spaces and circulation could have a less restrictive comfort band.

Task cooling is most achievable in HVAC systems that have decoupled ventilation from thermal conditioning. Beyond desk fans which do provide a level of convective cooling, task cooling is not a typical technology. The water-based task cooling systems include radiant ceiling panels and individually addressable "paddle coils" or Coolwaves™ a form of chilled beams. The air-based task cooling system include desk based mixing boxes from Johnson Control (see Figure) Personal Environmental Modules™. Similarly, the Canadian Government developed a ceiling based mixing box (Task Air Module) for individual temperature control without compromising ventilation.



PEMs provide mixing boxes at every desk to provide occupant control over air temperature, speed & direction.

LTG coolwave system with two chilled water coils *(Image source – CBPD)*

Figure 5.21: Examples of air and water-based task cooling systems

PEM offers energy and facility management savings with a payback of 16 years

There is still no marketplace for task cooling, thus the cost of PEMS, TAMS and radiant ceilings range from $600-1000 a workstation. There is also an energy penalty when task cooling systems are provided. However, studies demonstrate that individual temperature control combined with responsive central systems can yield energy savings, a gain that can only grow with flex-work schedules.

The financial ROI is calculated using first costs divided by the annual HVAC energy savings. 10% to 30% energy savings have been achieved when occupants had individual temperature control (Newsham & Mancini et al., 2009; Kaczmarczyk et al.,2008 / Schiavon, 2008; Sekhar, 2005; Zhang et al., 2009). Since hot and cold complaints translate into facility management costs, the second benefit of task cooling is the elimination of these costs calculated at 10% of total FM costs/year. With energy and facilities management cost savings the payback for the investment is 16 years.

Temperature control offers environmental benefit to shorten payback to 15 years

Each kWh saved through individual temperature controls results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 15 years.

Temperature control ensures human benefit to shorten payback to months

The ability for individual workers to control the temperature at their workstation has been shown to improve individual productivity at a range of tasks from typing and addition to creative thinking by 3.5-36.6%. For instance, in a lab experiment among 20 male students with personalized ventilation in Poland, Bogdan et al. achieved an average of 13% improvement in perceived productivity ($p<0.05$) by providing face-level personalized thermal control. Given assumptions about the percent of time spent at various tasks, these studies demonstrate from 3 to 7% increase in overall productivity (Witterseh, 2001; Wyon, 1996; Bauman et al.,1992; Boerstra et al.,2015; Tanabe et al.,2007; Kaczmarczyk, 2008; Wyon,1996; Melikov et al.,2012). Incorporating the individual productivity gains in the third bottom line reduces the TBL payback to four months.

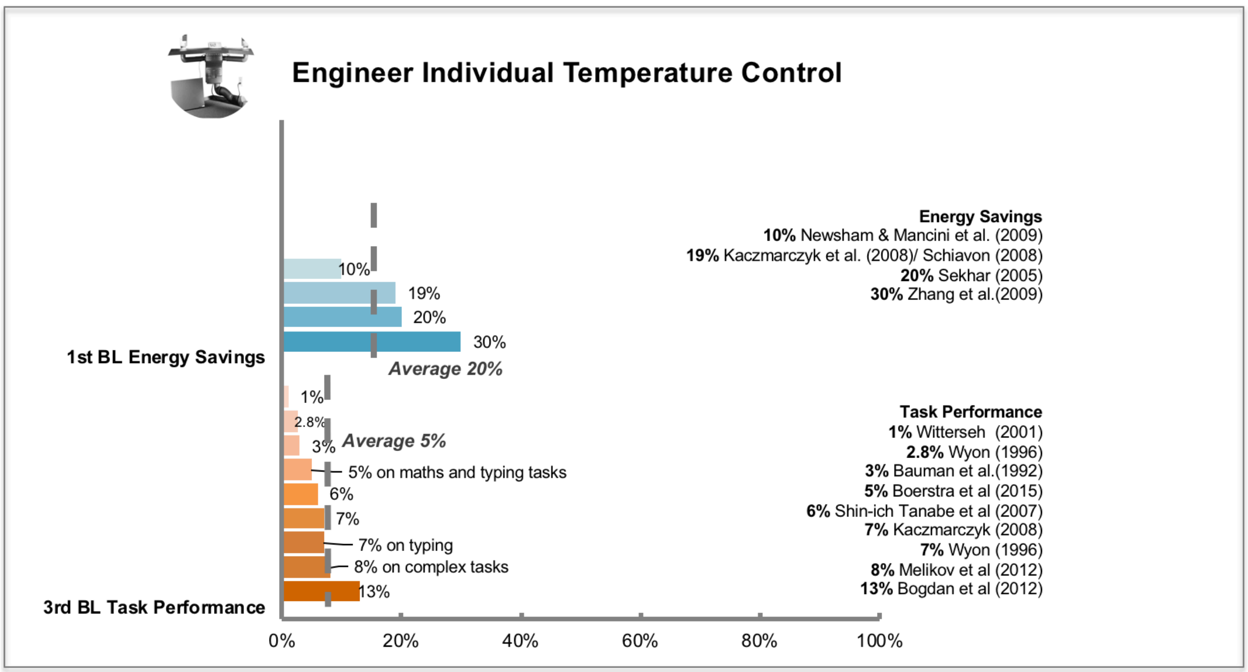


Figure 5.22: Cross sectional chart of the range of research on benefits from providing individual temperature control in workspaces

Table 5.12: Triple bottom line calculations for implementing individual temperature control using task cooling

Costs to engineer individual temperature control using task cooling

	Per sq. ft.	Per employee
First cost for the investment	$4	$800
Initial Investment costs for a 100,000 sq. ft. building	**$400,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
HVAC Energy savings (20%)	$0.05	$10
O & M Savings	$0.20	$40
Annual 1st bottom line savings	**+$0.25**	**+$50**
ROI (Financial)	**6%**	
Payback Period	**16 years**	
Cumulative 15-year Net Present Value	**$ 188,625**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	0.48 kWh	96 kWh
Air pollution emissions (SO_X, NO_X, PM, CH4)	$0.01	$1.5
CO_2 reductions	$0.01	$1
Water savings	$0.002	$0.4
Annual 2nd bottom line savings	**+$0.02**	**+$3**
Cumulative ROI (Financial + Environmental)	**7%**	
Payback Period	**15 years**	
Cumulative 15-year Net Present Value	**$ 199,600**	

3rd Financial + Environmental + Human Capital savings

	Per sq. ft.	Per employee
Productivity increase (5%)	$11.3	$2250
Annual 3rd bottom line savings	**+$11.3**	**+$2250**
ROI (Financial + Environment+ Human)	**288%**	
Payback Period	**4 months**	
Cumulative 15-year Net Present Value	**$ 8,356,350**	

Invest in whole building performance goals

Focus on high performance, whole building goals that promote components and subsystems to improve the quality of the individual workplace to: generate up to 50% energy savings and 5 % rental premiums with a ROI of 60%; additional CO2 + benefits that increase the ROI to 68%; as well as research identified 8% higher time dedicated to work tasks, 24% reduction in absenteeism and 28% lower asthma and allergy instances that increase the ROI to over 220%!

Image source: Loftness, V. (2017) "Taking Biophilic Research into Practice". Living Future 2017 Conference

Integrate and optimize all major high-performance building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity

Invest in whole building components and subsystems that directly affect the quality of the individual workplace. This investment relates to new high performance whole building projects (typically LEED projects) and major building systems renovations that demonstrate significant life cycle value. While the practices or technologies employed in green buildings are constantly evolving, the goals remain the same to include energy and water efficiency, material efficiency, IEQ enhancement by addressing indoor air quality, thermal and lighting quality, operation and maintenance optimization in harmony with natural features and resources surrounding the site (EPA, 2010)(WBDG, 2009).

Figure 5.23: Daylit atrium of Phipps Center for Sustainable Landscapes on left. McDonell & Brauer Hall with solar thermal collectors and PV cells on the right (Image source: USGBC, 2017)

LEED buildings offer substantial energy & churn cost saving and rental premium

Multiple studies have estimated the incremental costs for LEED projects and concluded a 2% to 5% increase in the upfront costs to support high performance technologies and systems. The selection of high performance technologies and systems on average can result in life cycle savings of 20% construction costs (Kats & Capital, 2003).

The financial ROI is calculated using first costs divided by annual energy and churn cost savings and rental premiums. 33 to 73% energy savings has been achieved in LEED projects (Agha-Hossein et al.,2013; Betterbricks, 2006; Pendelberry et al., 2012; Torcellini et al., 2002; Kats, 2003). 66% reduction in churn costs has been estimated in a study by Pilon and Gee (2003) in Herman Miller facility with high performance lighting, daylighting and natural ventilation. LEED buildings command 3% to 7% rent and sales premium relative to comparable buildings (Bond & Devine, 2016; Fuerst and McAllister, 2011; DePratto, 2015; Eichholtz et al., 2010 and 2013; Kok, Miller, & Morris, 2012). With the first bottom line savings, the payback for investing in LEED buildings is close to 2 years.

LEED buildings offer environmental benefits to shorten the payback to 1.5 years

Each kWh saved through LEED buildings results in reductions in environmental CO_2, SO_X, NO_X, particulates, and water. As carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, shifting them to economic benefits. The second bottom line calculation combines the economic gains from the first bottom line with the environmental benefits to achieve paybacks of 1.5 years.

Whole building goals ensures human benefits to shorten the payback to months

The benefits of investing in whole building performance goals can be measured in human health and productivity benefits. An average of 28% lower rate in asthma and allergy symptoms has been achieved in two studies (Grady et al,2010 and Singh et al.,2009). In the 2010 study Grady et al. identify a 50% reduction in self-reported asthma, respiratory allergies, and stress related absenteeism in employees who moved from conventional offices to LEED Platinum and Gold building. There is an average 24% lower absenteeism rate in buildings that include high performance design strategies including daylight, a narrow floor plan to allow seated outside (Browning,1992; Singh et al., 2009; Verrifone/Pape, 1998). 3% to 15% increase in productivity has also been achieved in field and lab studies (Singh et al.,2009; 6.84% Zhang et al,2010; Newsham,2013; Clausen et al., 2004; Rosekind et al,2010; Allen et al.,2012). In a controlled lab study at Syracuse, MacNaughton et al. (2012) identify a 42% to 61% increase in cognitive scores in high performing green certified building conditions with low VOC concentrations and high outdoor air ventilation rates (indicated by CO_2 level) compared to conventional offices ($p<0.0001$). Incorporating the health and productivity benefits in the third bottom line results in a TBL payback of 3 months.

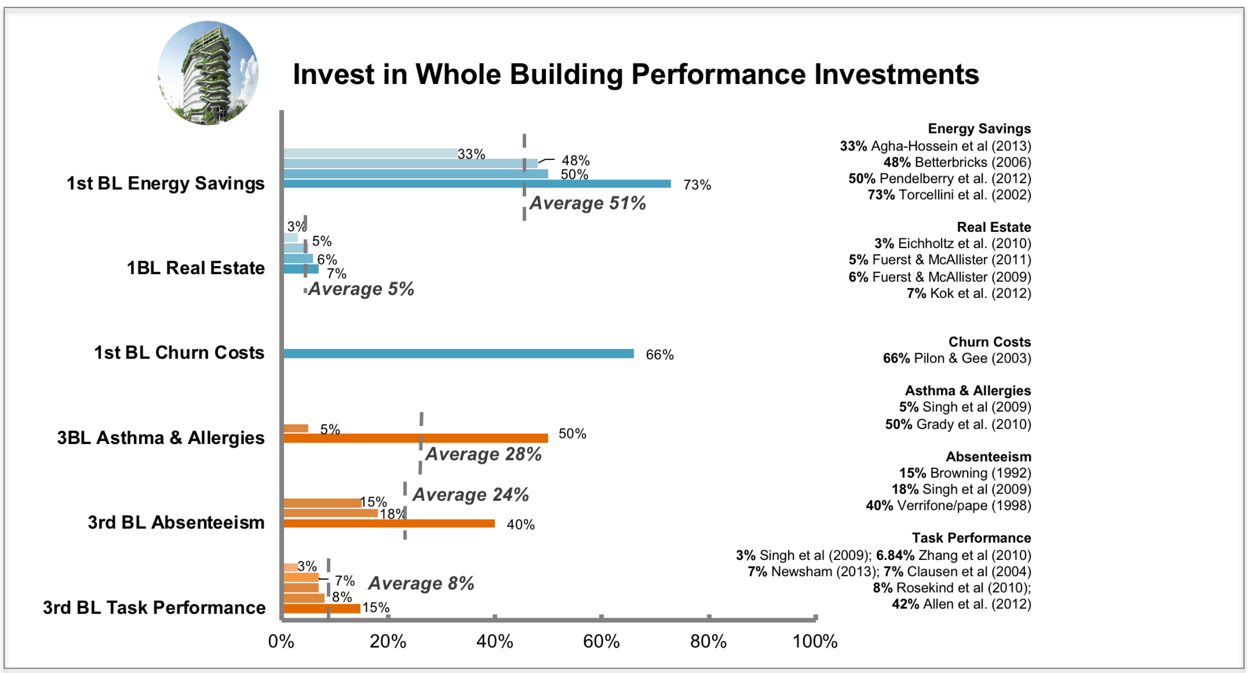


Figure 5.24: Cross sectional chart of the range of research on benefits from investing in whole building performance investments

Table 5.13: Triple bottom line calculations for investing in whole building performance investments

Costs of investing in whole building performance goals

	Per sq. ft.	Per employee
First cost for the investment	$5	$1000
Initial Investment costs for a 100,000 sq. ft. building	**$500,000**	

1st Financial Capital savings

	Per sq. ft.	Per employee
Energy Savings (50%)	$1.25	$250
Churn Cost Savings (66%)	$0.59	$118
Annual Rent Increase (5%)	$1.18	$236
Annual 1st bottom line savings	**+$3.02**	**+$604**
ROI (Financial)	**60%**	
Payback Period	**1.8 years**	
Cumulative 15-year Net Present Value	**$ 2,294,350**	

2nd Financial + Environmental Capital savings

	Per sq. ft.	Per employee
Environmental benefits from energy savings of:	12.45 kWh	2,490 kWh
Air pollution emissions (SO_X, NO_X, PM, CH4)	$0.20	$40
CO_2 reductions	$0.13	$25
Water savings	$0.05	$10
Annual 2nd bottom line savings	**+$0.38**	**+$75**
Cumulative ROI (Financial + Environmental)	**68%**	
Payback Period	**1.5 years**	
Cumulative 15-year Net Present Value	**$2,578,750**	

3rd Financial + Environmental + Human Capital savings

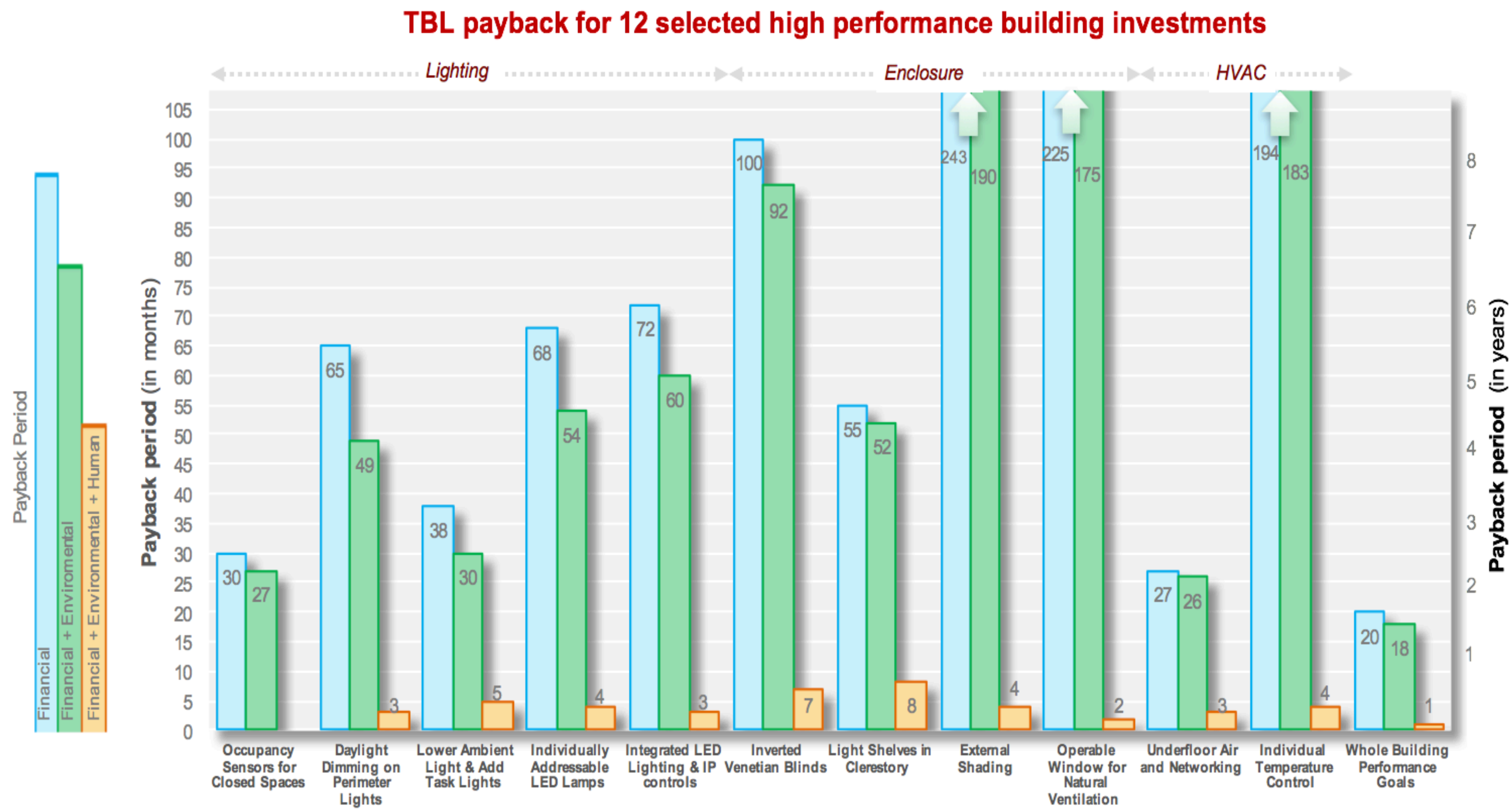
	Per sq. ft.	Per employee
Cold & flu reduction (5% * $68)	$0.02	$3
Asthma & allergies reduction (50% * $105)	$0.27	$53
Absenteeism reduction (15% of 2% year)	$1.08	$216
Productivity increase (8% * 35%)	$6.30	$1,260
Annual 3rd bottom line savings	**+$7.66**	**+$1532**
ROI (Financial + Environment+ Human)	**220%**	
Payback Period	**1 month**	
Cumulative 15-year Net Present Value	**$ 8,404,580**	

5.3 TBL accounting rapidly accelerates payback

Based on cost data collected from vendors, manufacturers and trade literature, first bottom line simple paybacks for 12 energy retrofit measures ranged from 2-20 years, combining both energy and facility management savings. When the environmental benefits of the electricity savings are included, simple paybacks were accelerated to 1.5-18 years. Most strikingly, when the human benefits of reduced health costs, lower absenteeism, and improved task performance or productivity are included, the paybacks for investments in energy efficiency in US offices are often less than one year. Figure 5.25 allows decision-makers to view all 12 energy retrofit measures comparatively. Setting priorities between the 12 could be set by the lowest overall ROI (or the highest NPV) or set by the most affordable capital investment per employee with measurable environmental and human benefits reflected in ROI or NPV values.

Setting Priorities with no capital budget constraints
Based on the twelve TBL calculations outlined, if the decision maker is not capital budget constrained, and is willing to invest greater cash upfront, then investing in whole building projects and major renovations (typically LEED) followed by enclosure investments is the most strategic investment for conserving energy and for improving the conditions for task performance and health (figure 5.3). Whole building projects are often first cost intensive, but offer substantial first bottom line savings that include energy, facility maintenance and churn cost savings, as well as rental premiums that shorten the payback period. Then, the addition of the environmental benefits further reduces the payback for whole building investments. Most significantly, however, when human benefits are calculated, the ROI and payback periods for whole building performance investments and enclosure investments become significant. In this scenario, any action that increases thermal and visual comfort and gives occupants more control over the air, lighting, thermal and spatial quality of the workplace, results in the highest ROI when all three bottom line savings are integrated.

Setting Priorities with capital budget constraints
When the decision maker is capital constrained, the list of energy investments with environmental and human benefits might be sorted differently. Lighting and daylighting upgrades will be the most strategic investments, however the prioritization of different lighting investments will vary based on the condition of the existing lighting and daylighting assemblies. If the one-year carrying costs are the extent of a the company's leadership ability with minimal first cost investment, installing vacancy sensors in closed offices, conference rooms, toilets and shared spaces has the highest ROI, followed by lowering ceiling task-ambient lighting to 200-300 lux by de-lamping and purchasing task lamps for every employee. The environmental benefits of reducing electricity use for lighting mirror the energy benefits, so the priorities remain the same. The human health and productivity benefits of the lighting technologies, however, establish a different set of investment priorities. In this case, any action that increases daylighting, or supports daylight variability with electric lighting, yields the highest ROI when energy, environmental and human triple bottom line calculations are included.



	Occupancy Sensors for Closed Spaces	Daylight Dimming on Perimeter Lights	Lower Ambient Light & Add Task Lights	Individually Addressable LED Lamps	Integrated LED Lighting & IP controls	Inverted Venetian Blinds	Light Shelves in Clerestory	External Shading	Operable Window for Natural Ventilation	Underfloor Air and Networking	Individual Temperature Control	Whole Building Performance Goals
Example initial costs ($ per employee)	$150 per room	$180	$200	$550	$950	$350	$220	$240	$360	$430	$800	$1000
Financial savings ($ per employee)	$62	$40	$64	$96	$158	$37	$48	$12	$20	$190	$50	$604
Environmental Savings (linked to energy savings)	$4	$4	$16	$27	$32	$4	$4	$4	$6	$3	$3	$75
Human Saving (Health & productivity gains)	-	$72	$368	$2,372	$2250	$405	$255	$812	$1240	$1360	$2250	$1532

Figure 5.25: Investment priorities based on financial, environmental and human cost-benefits

Revisiting metrics for decision making – capital plus carrying cost based decision making
Using financial metrics like payback and ROI, to evaluate and prioritize high-performance initiatives helps to reduce a complex investment into a single number. This is particularly useful when there are multiple investment opportunities with varying first and 'carrying' costs and environmental and human benefits. The TBL of 12 building investments reveals that priorities should depend on the ability to invest based on net present value rather than first cost, the 'carrying costs' that reflect environmental and human cost-benefits as well as the "hard" energy cost benefits.

5.3.1 Limitations

Drawing conclusions from the TBL calculation of these 12 investments has limitations. First, there are significant variations in the first costs based on different regional and national manufacturers, vendors, and installers.. Some technologies are quantified per running foot rather than per square foot, and need to be normalised to building floor area costs and even per employee. This is true specially for enclosure investments like blinds and light shelves that are priced per running foot of material. Where multiple costs for the same technology were available an average first cost increase has been calculated.

The first bottom line savings are based on published field and lab studies. The actual energy, facility, maintenance and churn cost savings will depend on existing building assemblies and operations, as well as design considerations like climate and orientation.

The addition of environmental benefits in the second bottom line always accelerates payback of the investment. The environmental benefits may only be valued by decisionmakers, however, if the organization is: required to meet energy reduction goals for city, state or federal mandates; will be disclosing baseline energy use and annual accomplishments for Energy Portfolio or 2030 commitments; or the organization has made sustainability a centerpiece of their market growth.

Finally, there is still a paucity of US field studies that link high performance building systems to health or productivity benefits, critical to the third bottom line. These twelve TBL calculations have relied on a mix of national and international laboratory and field case studies that may have cultural and economic differences.

Nonetheless, a TBL cost optimization framework, including energy and facilities cost savings, as well as environmental, human health and productivity benefits, can influence decision makers to move beyond first-cost decision making. The calculations are completed in three successive ROI groups to offer decisionmakers the choice of where they are willing to draw the line, with 'hard' economic cost benefits in the first bottom line, environmental cost-benefits that may be legislated or incentivized in the second bottom line, or the human cost-benefits that should drive standards and investments in buildings in the third bottom line. To support the reliability of the TBL methodology and validate how information on the TBL cost benefits would impact and shift the decision-making patterns from a least-first-cost approach to an approach that utilizes the TBL calculations, Chapter 6 of the dissertation includes an evaluation of its usefulness with a range of stakeholders.

Chapter 6

Proving the Value of TBL Calculations

A major focus of this research was to develop a Triple Bottom Line (TBL) cost-benefit framework and decision-support methodology and to evaluate how knowledge of TBL impacts investment decisions from a least first cost approach to an approach that utilizes the TBL. To support the validity and reliability of the TBL framework and evaluate how information on the TBL cost benefits would impact decision outcomes, calculations for a high-performance building investment was provided to different stakeholders in the building profession. The stakeholder responses helped understand the acceptable thresholds for investing in high performance building systems given the TBL calculations.

6.1 Approach to testing the validity and reliability of TBL calculations

To evaluate the impact of the TBL calculations on building investment decision outcomes, repeated measures within subject experiment design was selected. In such a design, each subject is measured multiple times in all of the experimental conditions on the same dependent variable, thus controlling for variability between subjects. In the TBL study, the decision to invest in a lighting retrofit was tested under four conditions - when only the first cost information is provided (control group) followed by the information on the financial bottom line, environmental bottom line and human bottom line calculations (treatment groups).

During the design of the experiment, three iterations of TBL communication approaches were tested with a range of stakeholders engaged in decision making in the built environment. A "likelihood to invest" survey was developed in which one set of TBL calculations for a lighting retrofit were provided to participants. Savings Calculations were provided to decision makers in an effort to capture the willingness to invest in lighting upgrades when first cost knowledge is followed up with first, second and third bottom line ROI and payback. The survey was offered in person in the form of both a smart phone application at continuing education events for real estate brokers, architects and LEED accredited professionals and an online user survey for a broader set of stakeholders. The in-person surveys yielded 45 participants and the online survey has been tested with over 100 stakeholders.

The survey was tested in two rounds- round one with in person surveys and round two with online surveys. The findings from the two rounds of survey are described below.

6.2 First Round Survey

The initial 'voting game' survey was a short five question survey was developed to collect user responses on decision to invest when TBL information is provided to decision makers. The first question in the short survey was used to calibrate user responses, followed by four questions that present the cost for lowering the ambient light levels and adding a task light for each workstation and the associated TBL cost benefits. The next question provided information on the total cost of the retrofit, followed by sequential information on the three different bottom line calculations. For each question participants were asked to respond on a seven-point Likert scale, that had responses from 'absolutely not' to 'absolutely yes' in their willingness to invest in the retrofit. Figure 6.1 describes the question on the third bottom line calculation.

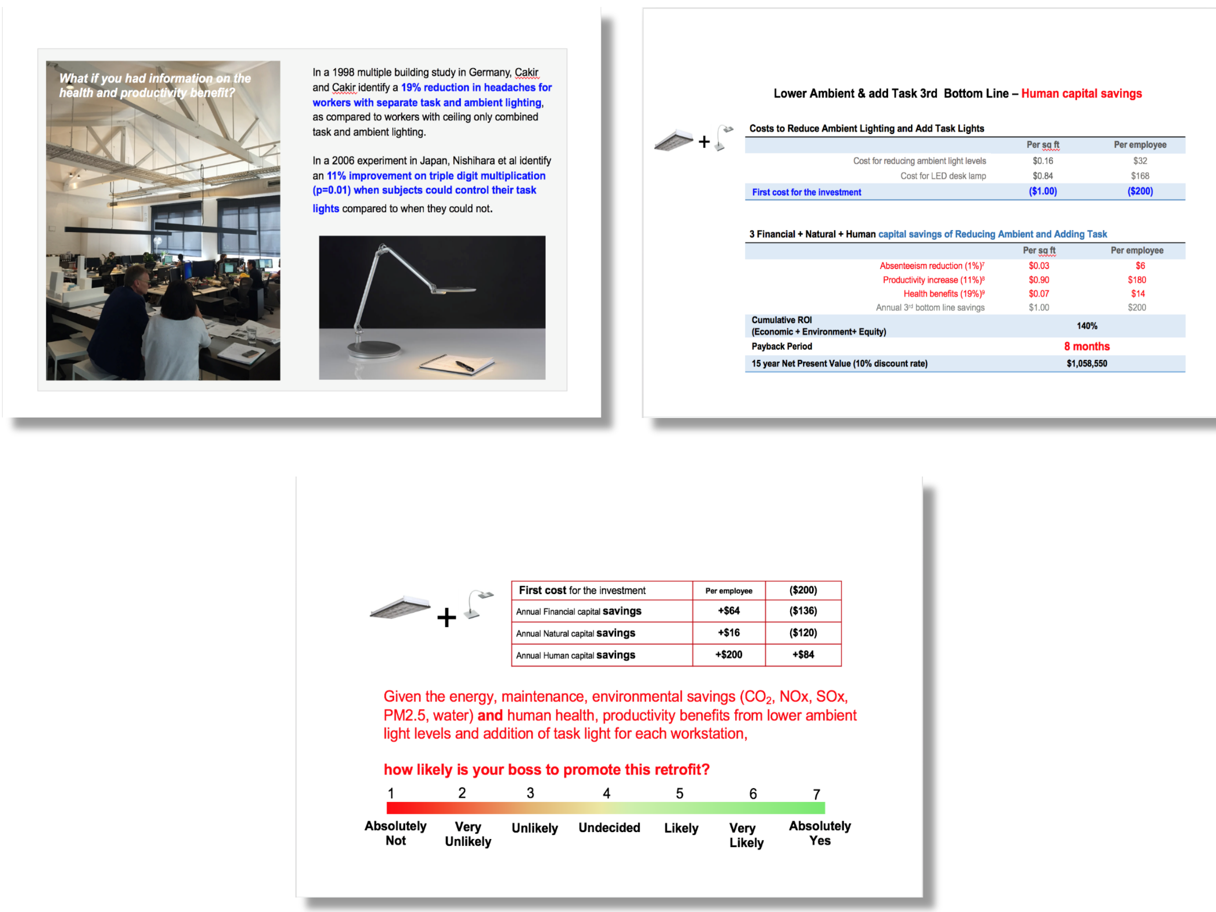


Figure 6.1: Round one survey question presenting the integrated human bottom line calculation. In the first slide participants are provided evidence related to the benefit from investing in the lighting retrofit, followed by the TBL calculation and finally asking for the decision to invest in the last slide.

Participants were asked to take part in a simulated environment where they were to play the role of a decision maker contemplating a lighting upgrade and answer a series of related questions. Subjects willing to be part of the study were asked to provide real time response through a smart phone or an online web interface. The online polling application ‘poll everywhere’ was used to gather real time responses when TBL calculations were sequentially presented to participants.

The survey was administered at multiple conferences and continuing education session for real estate brokers, architects, LEED professional and other building professionals. The conference and continuing education platforms allowed for the testing of the methodology by a larger professional audience, identify key trends and gather feedback on how investors make decisions.

The survey was presented for the first time to twenty-eight participants at the *ACEEE’s 2016 National Symposium on Market Transformation* in Baltimore on March 21st. Figure 6.2 shows survey responses and the shift in the decision-making pattern to the ‘likely’ side’ when the information on the TBL calculations was provided. 90% of the participants were ‘unlikely’ or ‘undecided’ to invest in the lighting upgrade when just the information on the cost for the lighting retrofit was provided. However, when all three bottom line calculations were provided, 92% of the participants changed their decision and were likely to invest in the lighting upgrade. Only 8% remained unlikely to invest even after the integrated TBL information was provided. The increase in likelihood to invest may be explained by the more ‘energy efficiency’ motivated audience that participated in the survey (figure 6.2).

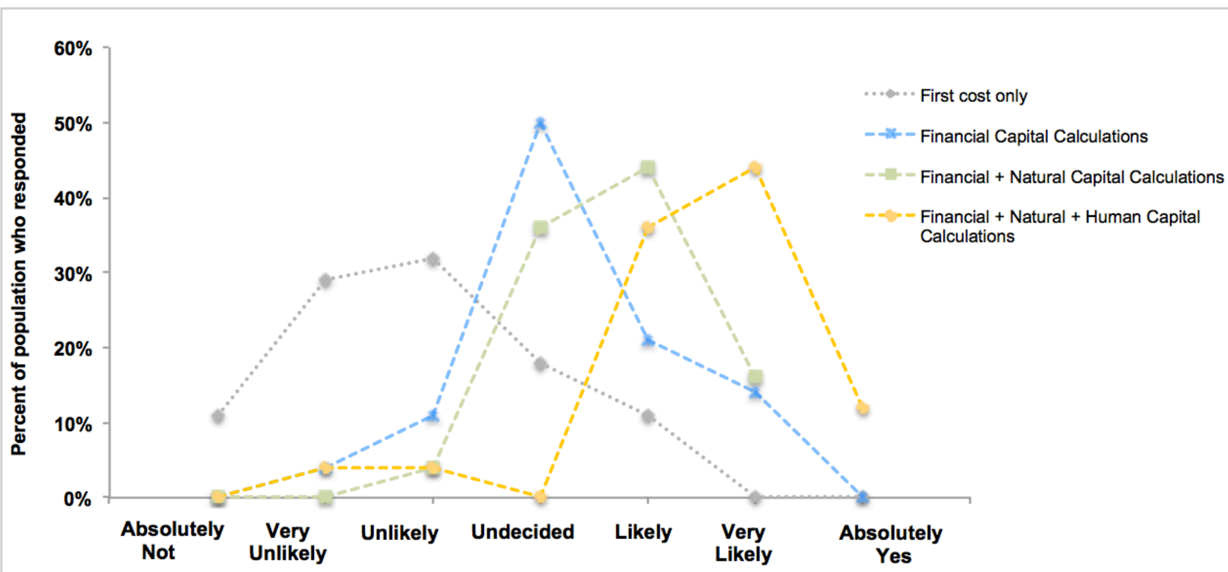


Figure 6.2: Likelihood of investing in lighting upgrade given first cost then 1st, 2nd and 3rd bottom line. Responses from the evaluation of methodology by user groups at ACEEE conference with 28 participants

The survey was also presented at 2016 *Real Estate Broker’s Training* in Pittsburgh on April 7th, 2016 as part of a continuing education event for real estate brokers, developers and building professionals. Figure 6.3 presents the change in decision making after each set of TBL information was introduced. More than 50% of the 15 participants who responded to the survey questions, were willing to invest based on the first cost information itself. Whereas, when the successive triple bottom line calculations were provided 66% of the participants were willing to upgrade lighting. Surprisingly, 25% of the respondents remained undecided with 10% not likely to invest at all. The limited sample size and participation of brokers and developers who were interested in promoting least first cost development and were driven to invest based on the cost information only may explain this trend. In the verbal feedback provided by this group on what would be potential barriers to adopting the TBL methodology - issues such as investment financing once the building has been sold, ownership and lease agreements were identified as likely to play a key role in how decisions to invest are made, in addition to the cost for the lighting retrofit.

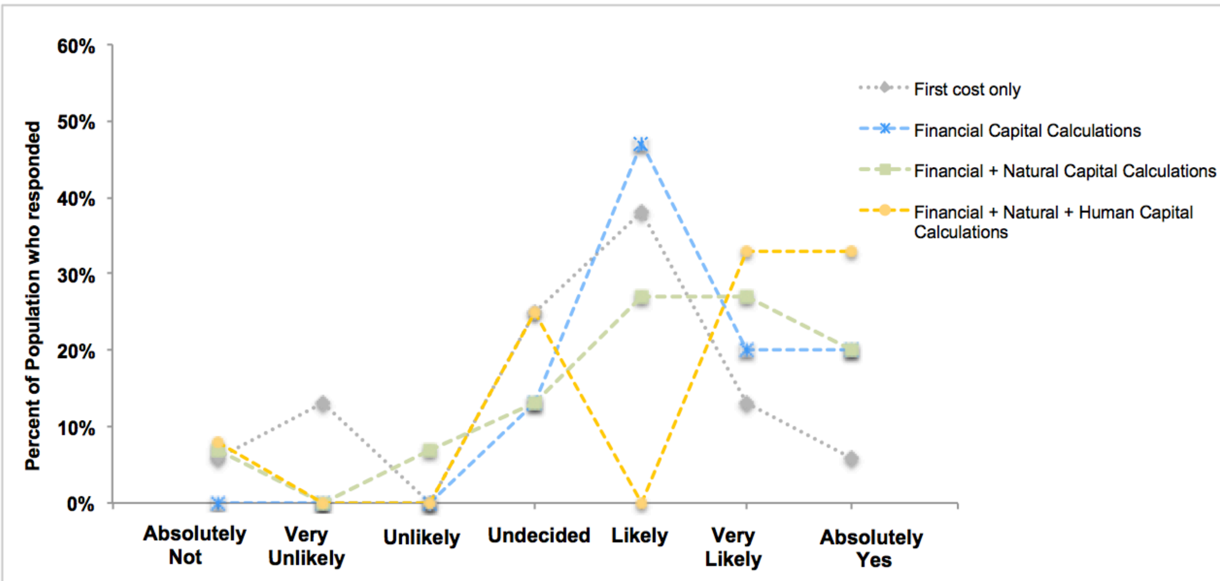
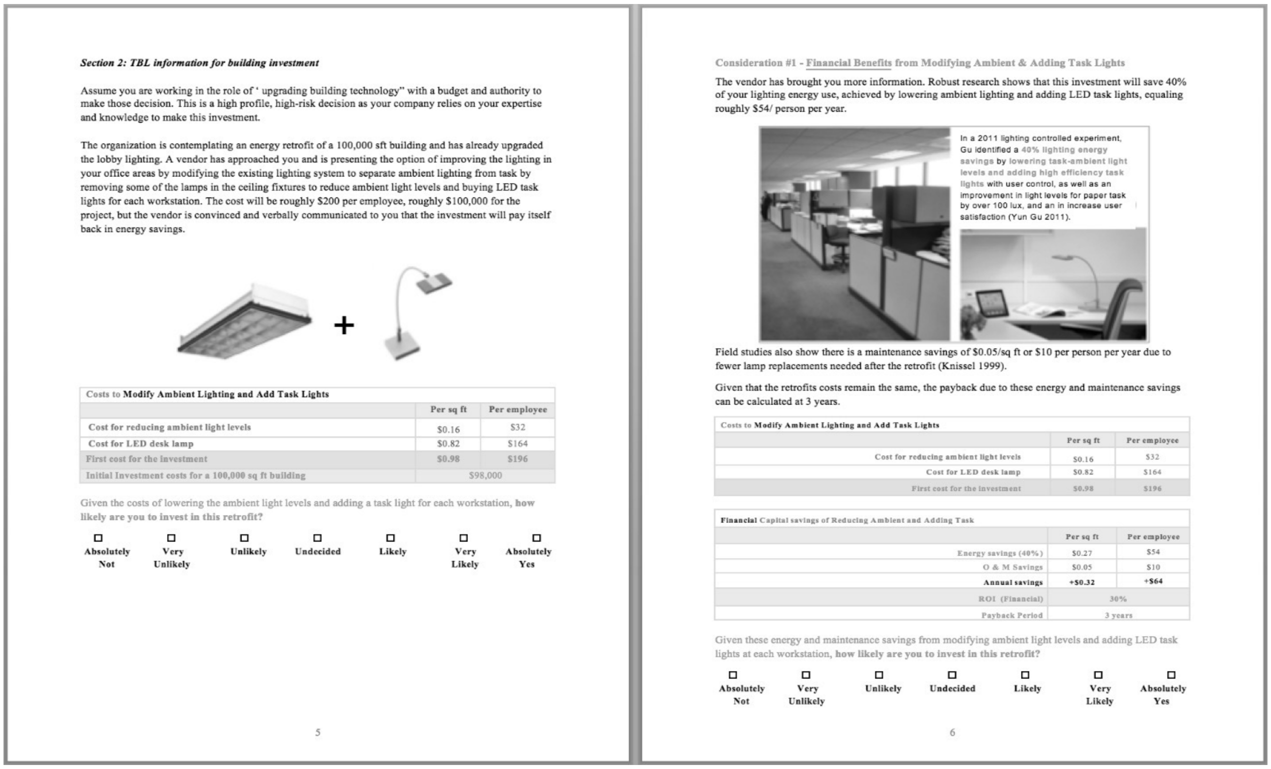


Figure 6.3: Likelihood of investing in lighting upgrade given first cost then 1st, 2nd and 3rd bottom line. Responses from the evaluation of methodology by 15 real estate brokers at Pittsburgh

Analysis of the round 1 survey responses revealed that there might have been a selection bias during population sampling when survey was administered at different conferences. Most of the conferences and events had an audience who were already motivated towards energy efficiency. There may also be the possibility of a consistency bias in the way participants answered the survey. In surveys with sequential questions, there is a desire of participants to appear consistent by answering related questions in a consistent manner (Weisberg et al.1996). To address these concerns, the 'likelihood to invest' survey was further refined to isolate the impact of user biases and expertise.

6.3 Second round online survey

Based on first round survey results, questions on the participant's educational and professional background, role in the organization, their expertise and the ability to make building investment decisions were added to the 'likelihood to invest' survey. The 'likelihood to invest' survey was modified to include two parts – first to gather information on participant's background and the second to record the decision outcomes when TBL information is presented. TBL calculations for the lighting retrofit were provided using four questions, with the first question giving only the first investment cost for the upgrade, followed by three questions that provided first, second and third bottom line ROI and payback. An example of the question included in section two of the survey is illustrated in figure 6.4 and the complete survey is included in the Appendix E.



Section 2: TBL information for building investment

Assume you are working in the role of ' upgrading building technology" with a budget and authority to make those decision. This is a high profile, high-risk decision as your company relies on your expertise and knowledge to make this investment.

The organization is contemplating an energy retrofit of a 100,000 sft building and has already upgraded the lobby lighting. A vendor has approached you and is presenting the option of improving the lighting in your office areas by modifying the existing lighting system to separate ambient lighting from task by removing some of the lamps in the ceiling fixtures to reduce ambient light levels and buying LED task lights for each workstation. The cost will be roughly $200 per employee, roughly $100,000 for the project, but the vendor is convinced and verbally communicated to you that the investment will pay itself back in energy savings.

Costs to **Modify Ambient Lighting and Add Task Lights**		
	Per sq ft	Per employee
Cost for reducing ambient light levels	$0.16	$32
Cost for LED desk lamp	$0.82	$164
First cost for the investment	$0.98	$196
Initial Investment costs for a 100,000 sq ft building	$98,000	

Given the costs of lowering the ambient light levels and adding a task light for each workstation, **how likely are you to invest in this retrofit?**

☐ Absolutely Not ☐ Very Unlikely ☐ Unlikely ☐ Undecided ☐ Likely ☐ Very Likely ☐ Absolutely Yes

5

Consideration #1 - Financial Benefits from Modifying Ambient & Adding Task Lights

The vendor has brought you more information. Robust research shows that this investment will save 40% of your lighting energy use, achieved by lowering ambient lighting and adding LED task lights, equaling roughly $54/ person per year.

In a 2011 lighting controlled experiment, Gu identified a 40% lighting energy savings by lowering task-ambient light levels and adding high efficiency task lights with user control, as well as an improvement in light levels for paper task by over 100 lux, and an in increase user satisfaction (Yun Gu 2011).

Field studies also show there is a maintenance savings of $0.05/sq ft or $10 per person per year due to fewer lamp replacements needed after the retrofit (Knissel 1999).

Given that the retrofits costs remain the same, the payback due to these energy and maintenance savings can be calculated at 3 years.

Costs to **Modify Ambient Lighting and Add Task Lights**		
	Per sq ft	Per employee
Cost for reducing ambient light levels	$0.16	$32
Cost for LED desk lamp	$0.82	$164
First cost for the investment	$0.98	$196

Financial Capital savings of Reducing Ambient and Adding Task		
	Per sq ft	Per employee
Energy savings (40%)	$0.27	$54
O & M Savings	$0.05	$10
Annual savings	**+$0.32**	**+$64**
ROI (Financial)	30%	
Payback Period	3 years	

Given these energy and maintenance savings from modifying ambient light levels and adding LED task lights at each workstation, **how likely are you to invest in this retrofit?**

☐ Absolutely Not ☐ Very Unlikely ☐ Unlikely ☐ Undecided ☐ Likely ☐ Very Likely ☐ Absolutely Yes

6

Figure 6.4: Second round online survey question introducing the cost of the lighting upgrade and the first bottom line calculation.

6.3.1 Sample characteristics

The modified likelihood to invest survey was administered to different stakeholders using the online *Qualtrics* platform. Convenience sampling technique was used to select subjects for the study. A total of 125 stakeholder responses were collected. Out of the 125 responses, only 114 were complete and could be used for the analyses. Five major stakeholder groups were identified based on the professional background of the survey participants. Figure 6.5 presents the 114 responses categorized into five groups.

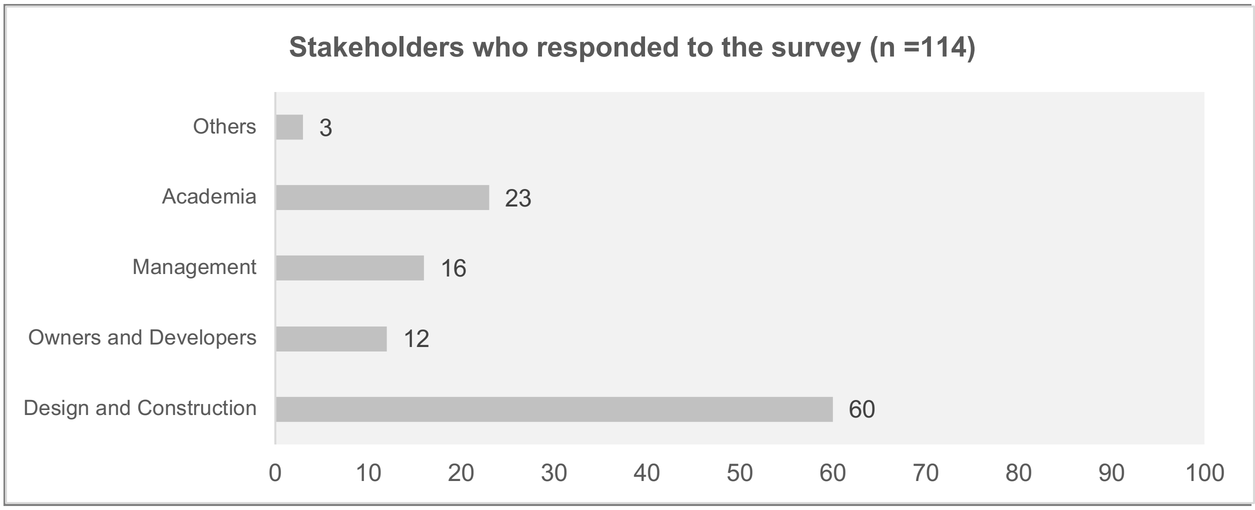


Figure 6.5: Round two survey responses categorized into five major stakeholder groups (n=114)

The first group consisted of *design and construction* professional, who are actively engaged in the building design and construction activities; second group comprised of *owner and developers* who invest capital in real estate; third group is the *management group* and includes facility managers, real estate executives, appraisers, accountants and sustainability expert and consultants. This group includes sustainability consultants and experts as their role per the survey response, relates to providing tools and expertise to manage and improve an organization's sustainability performance. The fourth group comprises of the *academia* with educators, business school and public policy students. This group has participants who are going to be the future decision makers. The fifth group includes all other professions.

Based on the survey responses, there is a wide range of work experience amongst the different stakeholders. Figure 6.6 presents the years stakeholders have worked in the construction industry. 34% of the participants have been in the construction field for up to 5 years; 19% for about 5 to 10 years, while 32% of the sample population has been working in the field for more than 20 years.

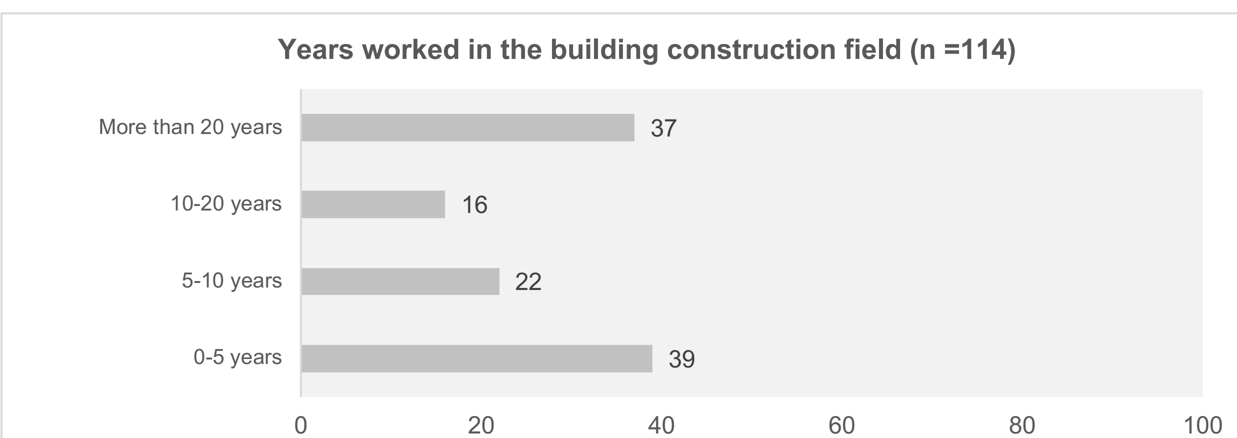


Figure 6.6: Stakeholder work experience in the construction field varies among survey participants

To ensure population sampling was not biased to professionals with prior knowledge of energy efficiency and sustainability, participants were asked to identify how long their experience involved making the use the knowledge of sustainability. Figure 6.7 illustrates that almost all the participants had prior knowledge of sustainability. However, 68% of the participants have been using the information in the last ten years. Since academic disciplines organized around sustainability have increased over the recent few years (that includes the development of the TBL accounting framework) it may be difficult to fully isolate the impact of prior knowledge of sustainability and energy efficiency on the shift in decision making outcomes.

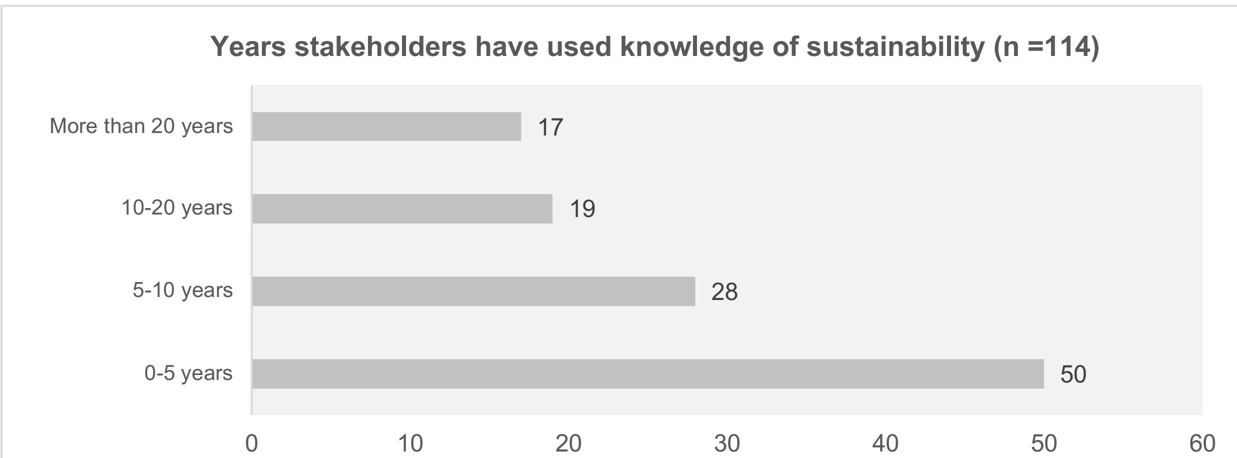


Figure 6.7: Majority of the stakeholders have prior knowledge of sustainability, making it difficult to isolate the impact prior knowledge on the decision-making pattern.

Apart from gathering information on participant's profession and their expertise, stakeholders were also asked if they had the ability to make building investment decisions. This ensured stakeholders who had influence or decided on building investments were included in the study. Figure 6.8 reveals 82% of the stakeholders who participated in the study made or influenced building investment decisions, with only 18% not influencing or making any such decisions.

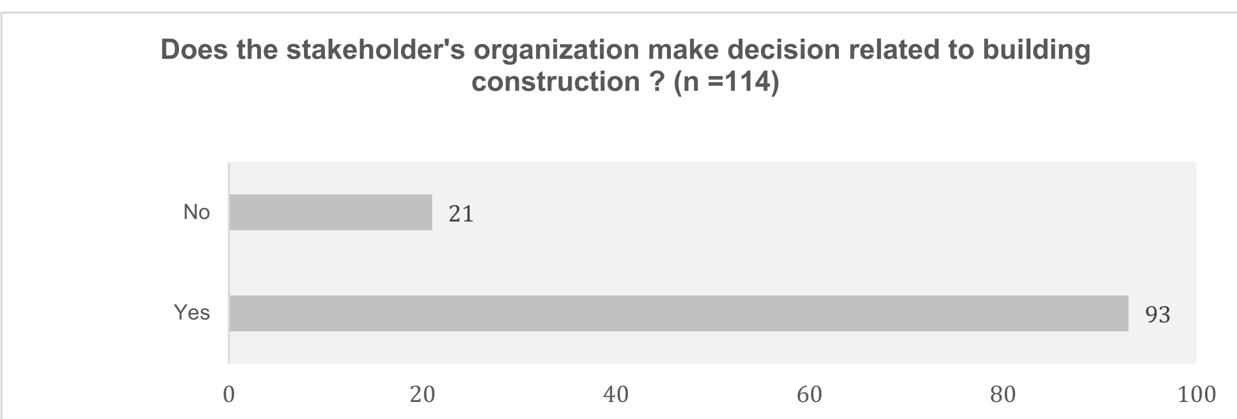


Figure 6.8: Majority of the survey respondents state they influence building investment decisions

As discussed at the beginning of this section, second part of the survey recorded the decision outcomes after the TBL information is provided. The survey responses to the four questions on the likelihood to invest in the lighting upgrade given the first cost followed by first, second and third bottom line ROI and payback are presented in figure 6.9. There is a visible shift in the decision-making pattern when participants are provided information on the financial, environmental and human cost benefits of investing in high performance lighting retrofit.

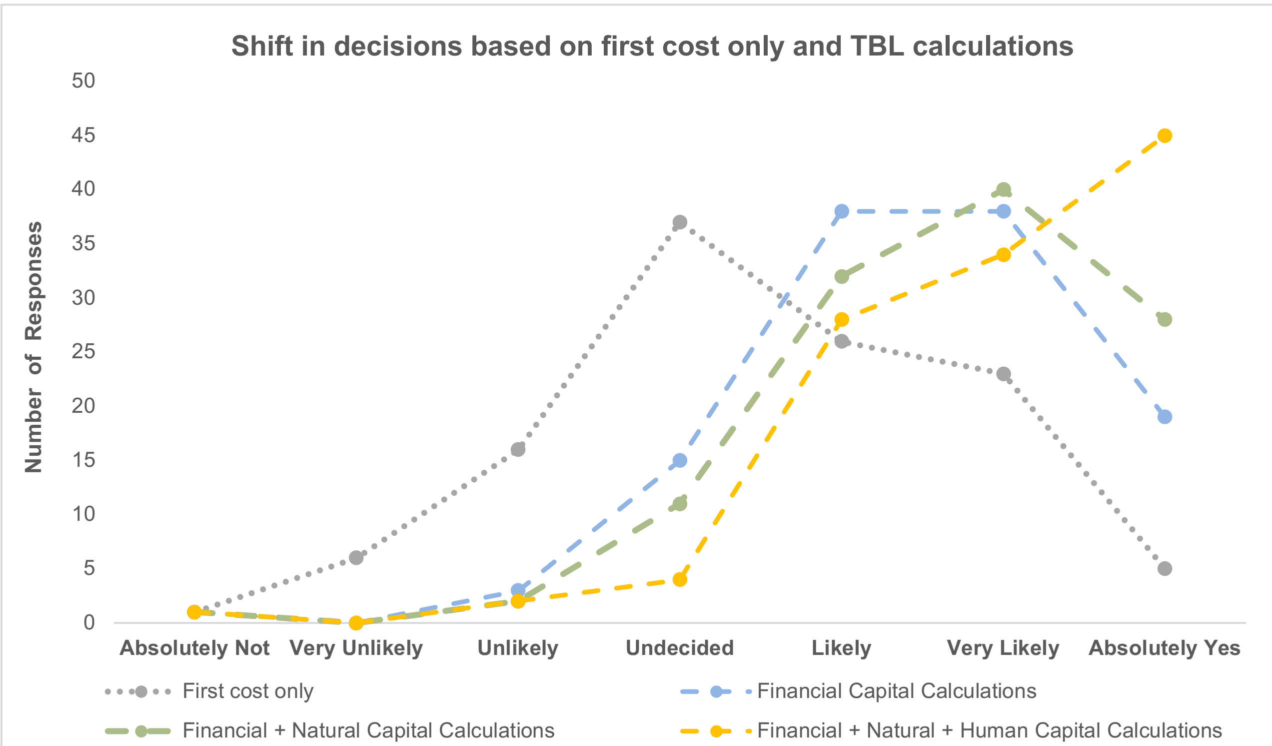


Figure 6.9: Likelihood to invest given the first costs, followed by the first, second and third bottom line calculations

6.3.2 Shifts in decision outcomes

To evaluate the impact of TBL information on the decision outcomes, further analyses was completed. The analysis helped determine whether there were any statistically significant differences between the decision-making pattern under the four conditions of information on the first cost, first bottom line calculation, second bottom line calculations and third bottom line calculations.

All survey responses

The size of each level of the within subject factor was equal (n=114). Figure 6.10 illustrates the distribution of the data and its skewness to the right as the TBL information became available. For the analyses, the Likert scale of *'Absolutely Not'* to *'Absolutely Yes'* was coded from 1 to 7 respectively, with 'undecided' responses coded as 4. 54 participants (47% of the sample population) were willing to invest in the lighting retrofit based just on the first costs, with 37 'undecided' responses (32%) and 23 (20%) 'unlikely' to invest responses when they were provided the information on the first cost for the investment. After cumulative third bottom line calculations were presented, only 3 participants were unlikely to invest, while 4 remained undecided.

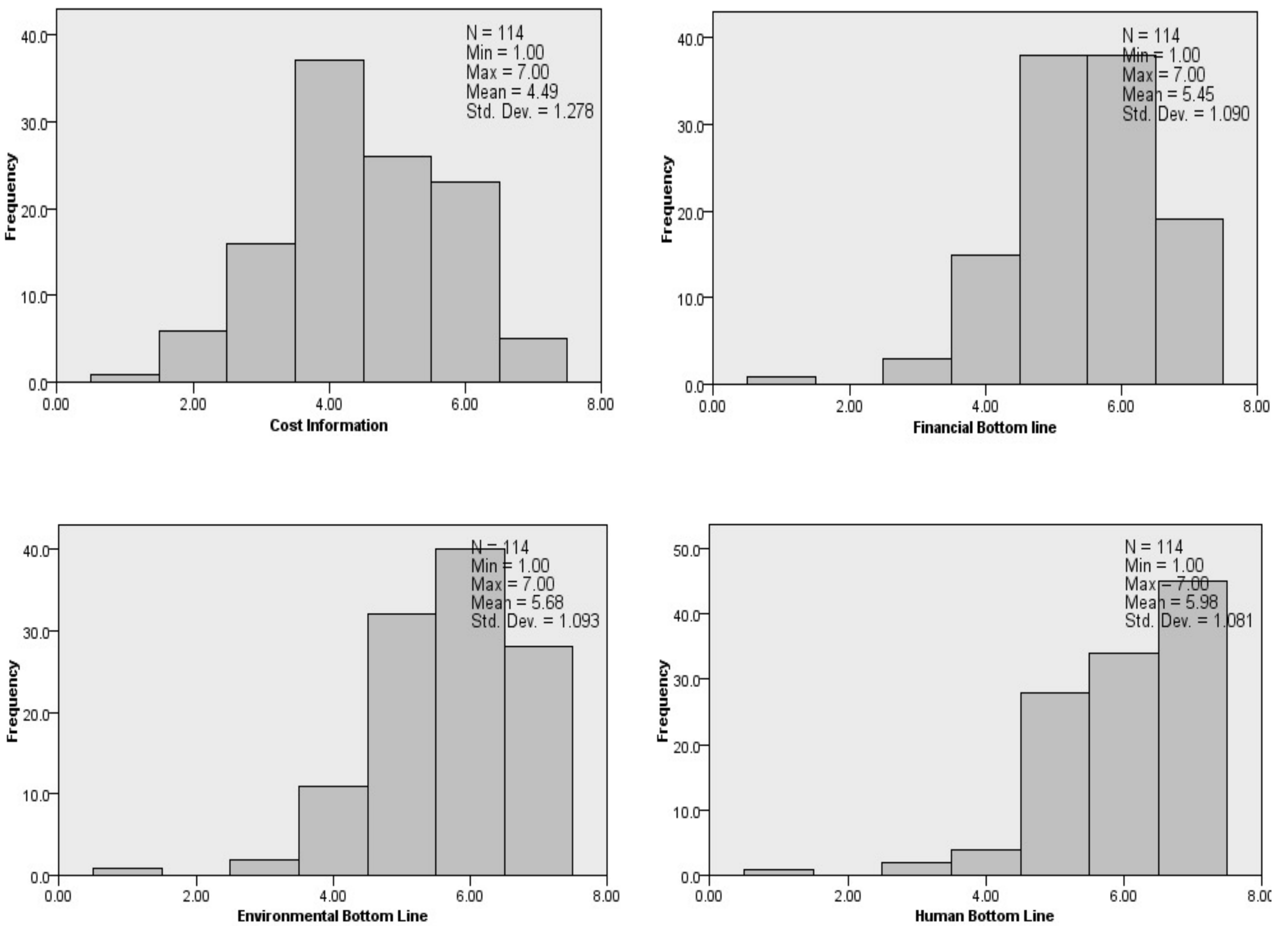
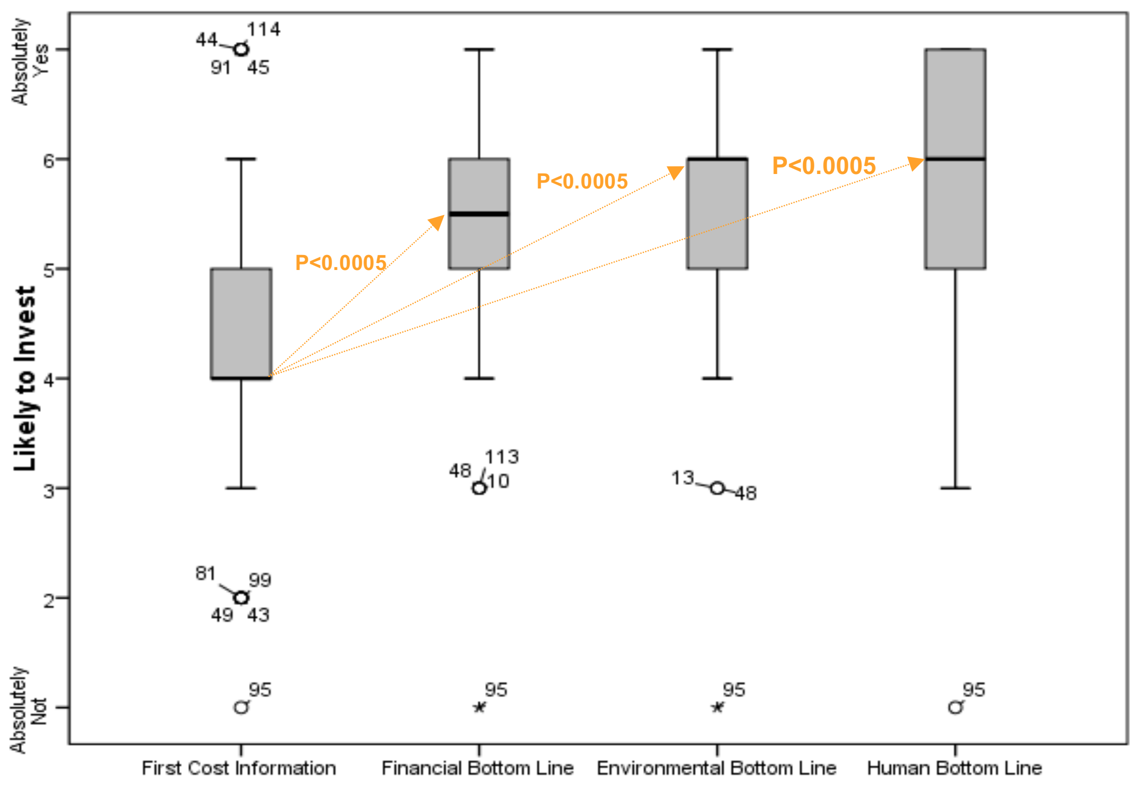


Figure 6.10: Distribution of the TBL survey responses. There is a marked shift to right after each tier of information is provided to the participant (n=114)

The changes in the mean scores were also calculated for dependent variable under the four different conditions. Box plots in figure 6.11 display the distribution of data and observations that are numerically distant (outliers) from the rest of the data. The mean for the first group was 4.49±1.28 when only the first cost information was provided to users, increasing to 5.45±1.09 when 1st bottom line information is provided; to 5.68±1.09 when the second bottom line calculations are revealed and finally to 5.98±1.08 when the cumulative third bottom line calculations are presented. There was a trend of increase in the likelihood to invest in the lighting retrofit after each successive bottom line information was provided. This indicates that the decision to invest changes in favor of the lighting retrofit as the financial, environmental and human cost benefit calculation is made available.



	N	Mean	Std. Deviation
First Cost Information only	114	4.49	1.28
Financial Bottom line	114	5.45	1.09
Environmental Bottom Line	114	5.68	1.09
Human Bottom Line	114	5.98	1.08

Figure 6.11: There is a marked difference in the means under the four conditions

A Friedman test was run to determine if there were differences in decision to invest in the lighting retrofit when given first costs for the investment followed by the information on the financial, environmental and the human bottom line calculations. The analysis revealed that the decision to invest in the lighting retrofit was statistically significant different when the information on the lifecycle financial, environmental and human cost benefit calculation was provided during the intervention, $x^2(3) = 162.73$, $p < .0005$.

Pairwise comparisons were performed (SPSS Statistics, 2012) with a Bonferroni correction for multiple comparisons. Post hoc analysis revealed the decision to invest in the lighting upgrade was statistically significantly different when the responses from the group with only first cost information were compared to the group with the information on the financial bottom line ($p < .0005$). The decision to invest in the lighting upgrade was also statistically significantly different when control group with information on the first cost was compared to the groups with the information on the integrated financial and environmental bottom line ($p < .0005$) and the integrated financial, environmental and human bottom line (p <

.0005). Figure 6.12 below shows the pairwise comparisons, with orange color lines representing the statistically significant comparisons. The change in decision given first, second and third bottom line information may be explained by the order of the TBL calculations that are cumulative and presented in a successive manner. While there are increases in the number of people who changed their decision based on the TBL information, most stakeholders changed their decision based on the first bottom line calculations. The difference between financial and human bottom line is also significant, but it is difficult to separate out the impact and effect of the third bottom line calculations, as some of the decision makers may have been convinced with just the first bottom line information.

Sample 1 – Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig	Adjusted significance
First Cost – Financial BL	-.952	.171	-5.566	.000	**.000**
First Cost – Environmental BL	-1.272	.171	-7.438	.000	**.000**
First Cost – Human BL	-1.689	.171	-9.875	.000	**.000**
Financial – Human BL	-.737	.171	-4.309	.000	**.000**
Environmental – Human BL	-.417	.171	-2.437	.015	.089
Financial – Environmental BL	-.320	.171	-1.872	.061	.367

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.
Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 6.12: Pairwise comparison revealed the decision to invest in the lighting upgrade was statistically significantly different when compared with the base case (p<0.0005). The orange colored lines represent the statistically significant pairwise comparisons

Conditional sampling of the unlikely and undecided responses

To further understand the impact of the TBL information on decision outcomes, next level of statistical analysis was done using conditional sampling technique. The restricted sample included 'unlikely to invest' and 'undecided' responses when given the first cost information. As stated previously, 54 participants were willing to invest in the lighting retrofit given when given the first costs for the investment, these responses were omitted from this analysis since the goal was to evaluate the impact TBL knowledge had on decision making. After removing those responses, there were 37 'undecided' (32%) and 23 (20%) unlikely to invest responses given only first cost information. Figure 6.13 illustrates the distribution of the data and the shift to the right as TBL information became available. Once the financial bottom line calculation was provided, 42 (37% increase) stakeholders from the conditional sample were in favor of investing in the lighting retrofit. Towards the end when both the cumulative and successive second bottom line environmental and third bottom line human calculations were provided, only 2 participants out of the 60 remained unlikely to invest or were still undecided.

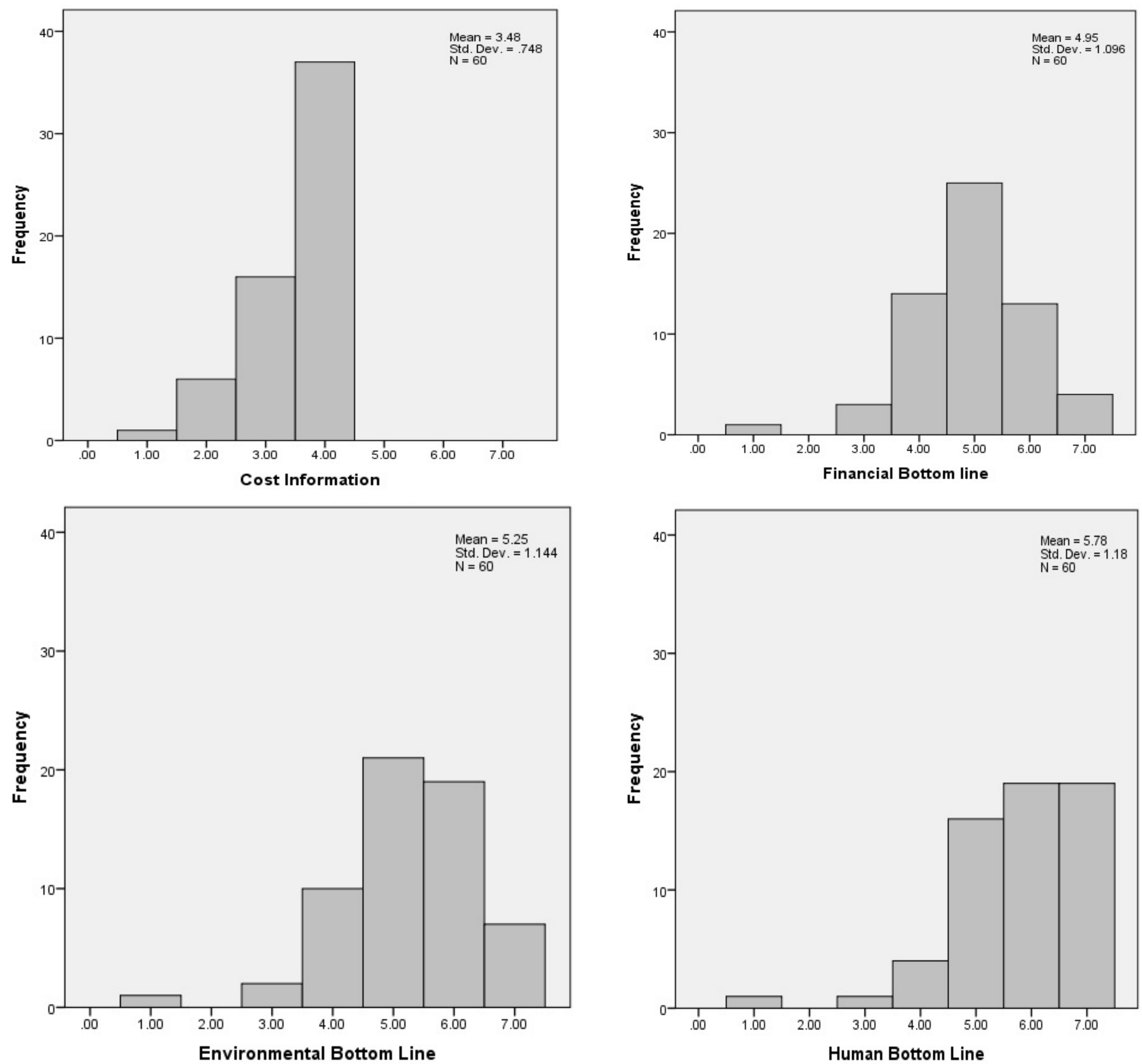
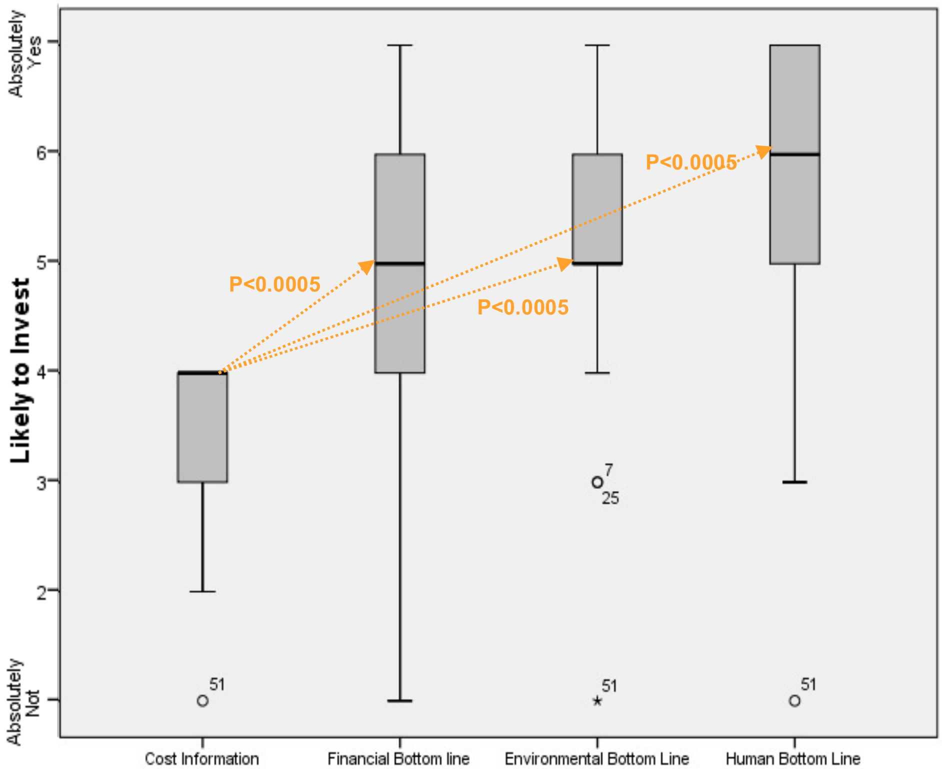


Figure 6.13: Distribution of the 'unlikely 'and 'undecided' responses to invest when given only the first costs reveals that as TBL information is made available, stakeholders are more willing to invest (n=60)

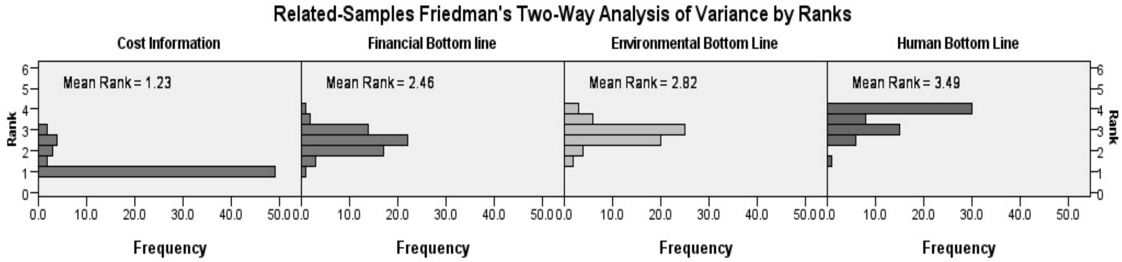
Based on the distribution above, there is a visible trend of increase in the likelihood to invest in the lighting retrofit after each successive bottom line information is provided. Box plots and the accompanying table in figure 6.14 further illustrates the difference in means under the four conditions. The mean for the first group when the first costs for the investment were provided, also the control group was 3.48 ± 0.75, increasing to 4.95 ±1.09 when 1st bottom line information is presented; to 5.25 ±1.14 when the second bottom line calculations are revealed and finally to 5.78 ±1.18 when the cumulative third bottom line calculations are presented.



	N	Mean	Std. Deviation
First Cost Information only	60	3.48	.75
Financial Bottom line	60	4.95	1.09
Environmental Bottom Line	60	5.25	1.14
Human Bottom Line	60	5.78	1.18

Figure 6.14: Difference in means indicates that the decision to invest is impacted when financial, environmental and human bottom line calculations are presented (n=60)

A Friedman test was run to determine if there were any statistically significant differences in decision to invest in the lighting retrofit when given first costs for the investment followed by the financial, environmental and the human bottom line calculations. The decision to invest in the lighting retrofit was statistically different when the information on the lifecycle financial, environmental and human cost benefit calculations were provided, $x^2(3) = 124.68$, $p < .0005$. Figure 6.15 provides a summary of the statistical analysis.



Total N	60
Test Statistic	124.680
Degrees of Freedom	3
Asymptotic Sig. (2-sided test)	.000

Figure 6.15: The decision to invest is statistically significantly different from the base case when TBL information is provided to users

Pairwise comparisons were performed (SPSS Statistics, 2012) with a Bonferroni correction for multiple comparisons. Post hoc analysis revealed the decision to invest in the lighting upgrade was statistically significantly different when comparing the decision outcomes for the group with information only on the first cost information (control group) to when financial bottom line calculation, followed by the successive and cumulative environmental bottom line and human bottom line calculation is compared ($p < .0005$). The figure below shows the pairwise comparisons, with orange color lines representing the statistically significant comparisons.

Sample 1 – Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig	Adjusted significance
First Cost – Financial BL	-.1.225	.236	-5.197	.000	**.000**
First Cost – Environmental BL	-1.583	.236	-6.718	.000	**.000**
First Cost – Human BL	-2.258	.236	-9.581	.000	**.000**
Financial – Human BL	-.1.033	.236	-4.384	.000	**.000**
Environmental – Human BL	-.675	..236	-2.864	.004	**.025**
Financial – Environmental BL	-.320	.171	-1.872	.061	.367

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.
Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 6.16: Pairwise comparison reveals the decision to invest in the lighting upgrade was statistically significantly difference (p<0.0005). The orange cells represent the significant comparisons

Even though the pairwise comparison between groups with information on financial bottom line and human bottom line calculations as well as groups with environmental bottom line and human bottom line calculations revealed statistically different decision outcomes when additional information was made available. However, the design of the experiment and the order in which the cumulative and iterative TBL calculations were presented to users did not allow for this level of investigation.

Conditional sampling by stakeholder group

Another objective of user testing of the TBL calculations was to identify if the decision outcomes differed within different stakeholder groups. Using conditional sampling, participant responses were separated by the stakeholder category described at the beginning of this section. Three groups - design and construction professionals; Academia and management group had sufficient sample size to facilitate further statistical analyses.

Design and construction professionals

This group consists of 60 responses from architects, engineers, project managers, contractors and professionals actively engaged in the process of design. There was an upward trend in the number of design and construction professionals likely to invest in the lighting investment as seen in figure 6.17, when given the successive integrated triple bottom line calculations. The analyses of the 60 responses within this group reveals that if professionals are provided with only the first bottom line financial calculations, there will be more investment in the lighting upgrade ($p<0.0005$). when the cumulative second bottom line calculations are provided then there are few more professionals willing to change their decisions ($p<0.0005$). Finally, when the integrated financial, environmental and human bottom line calculation is provided majority of the participants are convinced to invest in the lighting retrofit ($p<0.0005$).

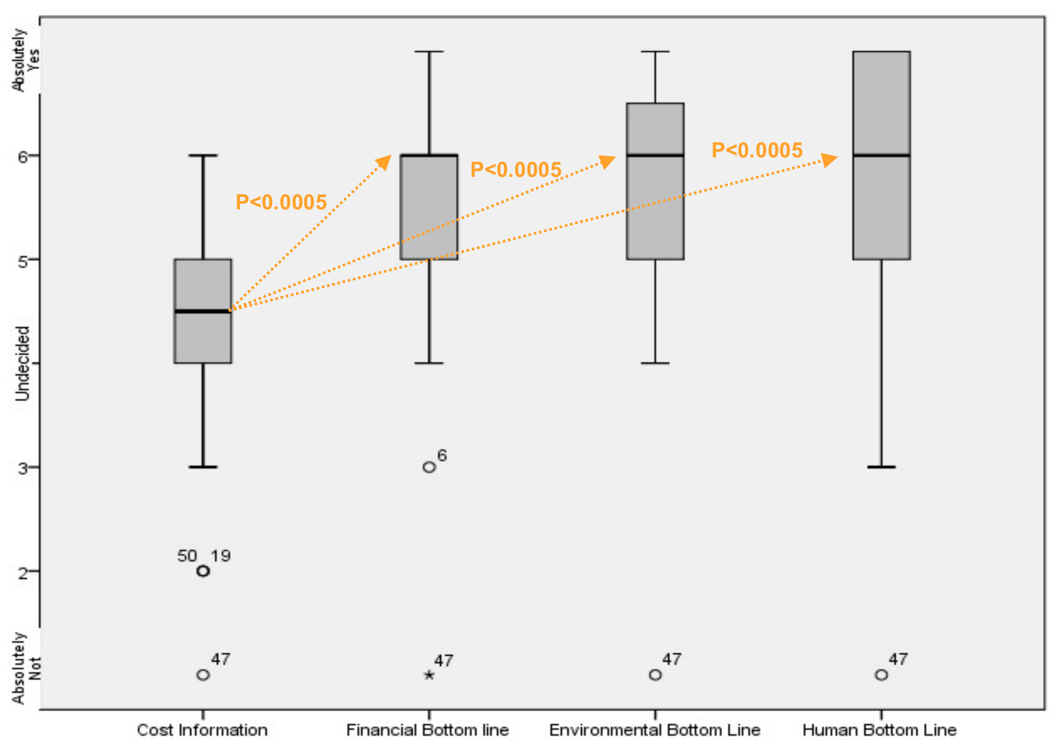


Figure 6.17: Likelihood to invest for the design and construction professional given the first costs, followed by the first, second and third bottom line calculations (n=60)

Academia group

Analysis of the limited sample of academicians (n=23) demonstrated that when information on the combined financial and environmental cost benefits and the integrated third bottom line calculations is provided they were more likely to invest in the lighting retrofit. There is a trend of increase in the likelihood to invest in the lighting upgrade given the second and third bottom line ($p<0.0005$). This trend seen in figure 6.18 may be due to the study sample comprising of educators, researchers, business school and environmental policy students, who may already have prior knowledge on the issues of sustainability and impact of the construction industry on the environment. The composition of this sample group may also explain the low impact of the first bottom line calculations on the decision to invest.

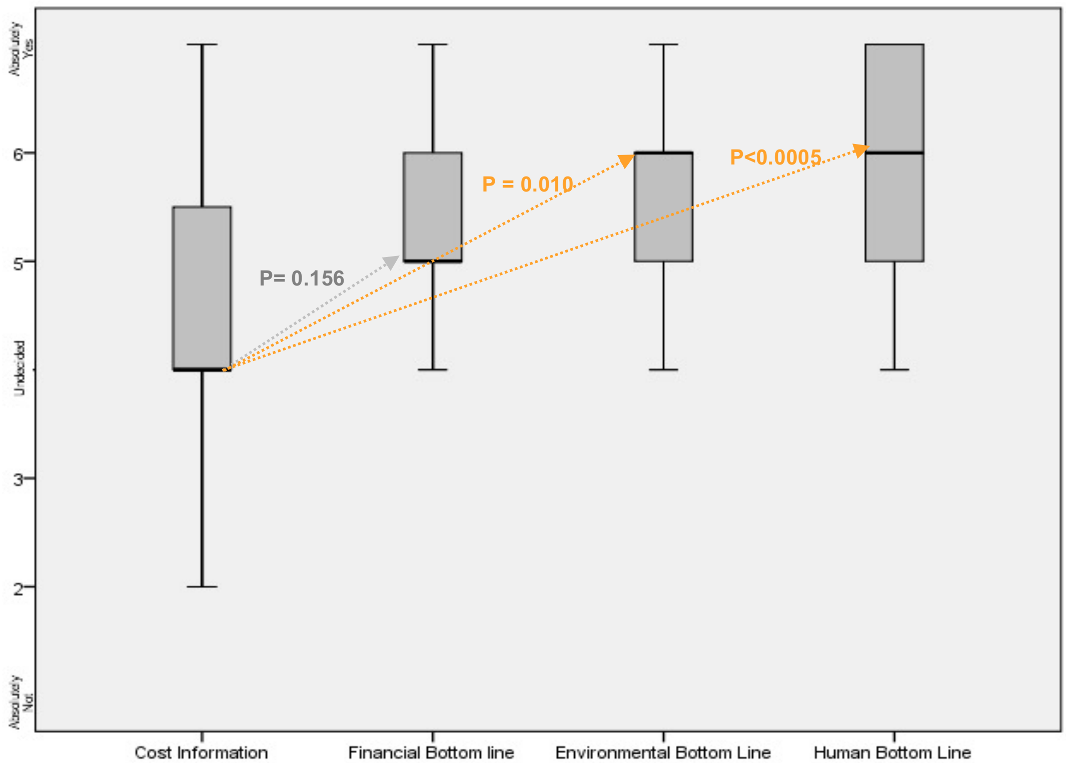


Figure 6.18: Likelihood to invest for the academia group given the first costs, followed by the first bottom line financial calculations, second bottom line and third bottom line calculations (n=23)

Management group

The management group includes real estate executives, facility managers, appraisers, sustainability consultant who engage in capital and operational budget expenditure decisions in the built environment. When the responses (n=16) within this group were analyzed a trend of increase in the likelihood to invest in the lighting retrofit given the second and third bottom line ($p<0.0005$) was observed. This noticeable trend as observed in figure 6.19 may be due to the limited study sample comprising of professionals knowledgeable of the lifecycle benefits from upgrading to high performance lighting.

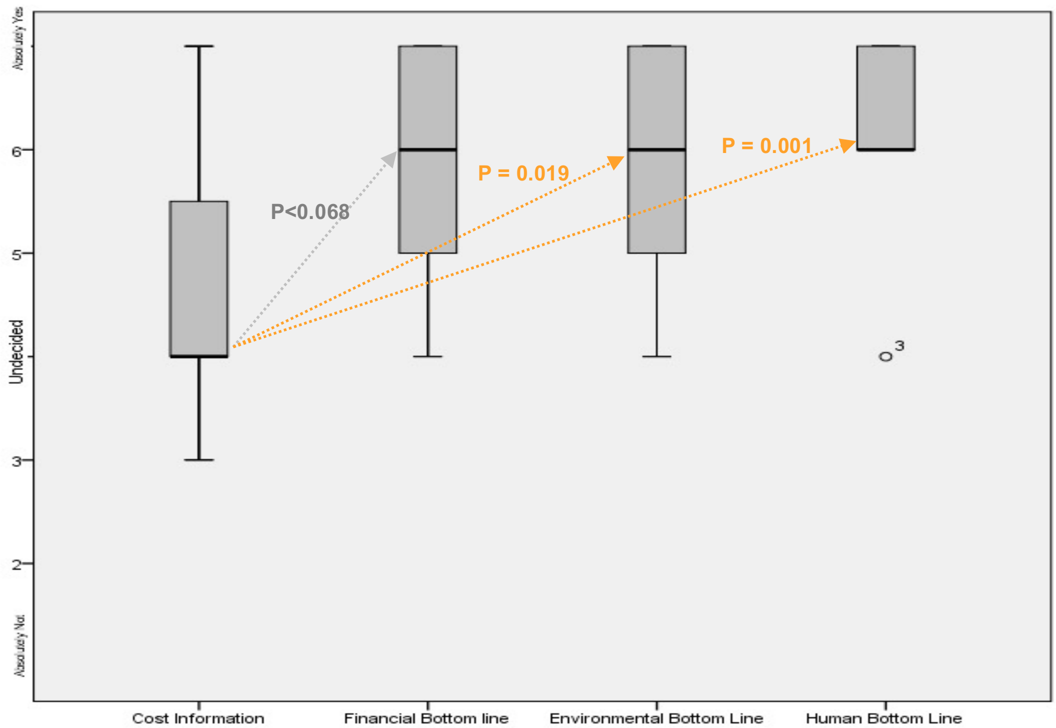


Figure 6.19: Likelihood to invest for the academia group given the first costs, followed by the first bottom line financial calculations, second bottom line and third bottom line calculations (n=16)

The sample size for the other stakeholder groups was not adequate to facilitate further analyses. The statistical analysis for the different stakeholder groups confirms the importance of the first bottom line financial calculations in encouraging additional investment in high performance building investments, and how the shift to an integrated bottom line cost benefit approach provides the opportunity to overcome the least cost decision making prevalent in the construction industry.

6.4 Future research opportunities

There are limitations on the conclusions drawn from this survey which relate to the design of the study and the user responses. The study design did not allow for the testing of the value of the TBL information on the decision maker, instead the study evaluates the impact of TBL information on the decision outcome which was the key goal of this research. Since the financial, environmental and human calculations are integrated and presented in a successive manner, the effect of each bottom line calculation is also difficult to separate out.

The study has been designed using a repeated measure design, where a single participant is exposed to different conditions, which in this study relates to participants being provided different bottom line information. While this type of experiment design controls for the variability amongst subjects, it poses the risk of a consistency bias in the way participants answer the survey. When responding to surveys with sequential questions, there is a desire of participants to appear consistent by answering related questions in a consistent manner (Weisberg et al.1996). There may be a possibility that some participants may have responded in a sequential manner without fully grasping the calculations.

A total of 125 subjects participated in the survey, out of which only 114 were fully complete and analyzed. To further investigate the impact of TBL information on different stakeholder groups, a larger sample size would be required. At the moment, prevalent trends for each group have been discussed.

The other limitation relates to the use of TBL calculations for a single high-performance lighting retrofit in the survey. The value of TBL calculations on decision outcomes is evaluated using the payback, ROI and NPV. The payback of this investment given only the first bottom line costs and benefits is 3 years, which meets the investment payback threshold for corporate investors. Future research could test user response to TBL calculations for a longer payback, low ROI investment.

These limitations provide opportunities for future research where a larger of set of investments can be reviewed to analyze how they affect the decision outcomes.

Chapter 7

Conclusion, Limitation and Future Research

Standard practice for designing, constructing and managing buildings is to control upfront costs often with preset financial limits (Newton et al., 2009; Romm 1998). projects that exceed the preset capital budgets have little or no potential for weighing investments for operational savings. Instead, 'value engineering' often eliminates investments for operational gains to ensure the project does not exceed available capital. Even when an operational budget is included, traditional financial analysis does not provide a full picture of the benefits of capital expenditures for high performance built environments.

7.1 Review of the research

The introduction of Triple Bottom Line (TBL) accounting provides building decision makers operational, environmental and human impact quantification to support informed decisions for maximum Return on Investment. This thesis proposes a Triple Bottom Line cost-benefit framework and decision-support methodology that account for financial, environmental and human capital to support the shift from least first cost investment decision-making to high performance buildings and building retrofit investments.

This TBL framework includes first bottom line calculations that capture the hard financial cost-benefits of energy, facility management savings, replacement savings, churn cost savings and real estate premiums as relevant to varying building investments. The second bottom line calculations capture the environmental cost-benefits to quantify the economic value of reduction in CO_2, CH_4, SO_X, NO_X, particulates, and water demands directly linked to electric energy savings. The third bottom line captures the relevant human cost-benefits of reduced headaches, colds and flus, asthma and allergies, absenteeism savings and improved productivity benefits that are directly linked to different investments in improved IEQ. With the development of TBL framework and decision support methodology, the thesis subsequently tests, sets of TBL calculations with key stakeholders in the built environment to identify impacts on decision-making outcomes.

This chapter concludes this dissertation by highlighting the contributions, limitations and future direction for the research. The primary contribution is the refinement of a decision support methodology. The contribution of the thesis is anticipated to be at both the macro policy level and the building specific decision-making level. At the macro policy level, the TBL decision support methodology can be used as a tool to help identify investments that reduce the energy and carbon footprint of the building sector and contribute to meeting the United Nation's sustainable development agenda (United Nations, 2015). At the building scale, the methodology will assist real estate decision makers select building systems and technologies that improve indoor environmental quality and occupant health, productivity and comfort.

7.2 TBL accounting critical to meet UN's Sustainable Development Agenda

TBL accounting for building investments will support the United Nation's 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDG's). The SDGs were adopted by world leaders in September 2015 and apply to all countries but are not legally binding (United Nations, 2015). They set an agenda and targets for governments and businesses to work together with the UN to end all forms of poverty, fight inequalities, tackle climate change and environmental protection while addressing a range of social needs including education, health, education, social protection and job opportunities.

Contribution 1: supporting environmental and human focused policies

The TBL methodology developed as part of this research can directly assist with fulfilling 5 out of the 17 goals – affordable and clean energy; resilient infrastructure, sustainable cities and communities, responsible consumption and production, and climate action.

Goal 7: To ensure access to affordable, reliable, sustainable and modern energy for all.

This goal ensures universal access to modern energy services, improved energy efficiency and increased use of renewable sources. Energy production and use is the dominant contributor to climate change, accounting for around 60% of total global GHG emissions and reducing the carbon intensity of energy is a key objective in long-term climate goals (United Nations, 2015). The TBL methodology accounts for the environmental impacts of electrical energy in order to support a greater level of accountability in the building sector. By illustrating the full impact of fuel mix choices and plant efficiencies on first and second bottom lines, decision makers have the full information that can accelerate the move towards a clean energy portfolio, with less polluting fuel sources.

Goal 9: To build resilient infrastructure, promote sustainable industrialization and foster innovation

Investments in infrastructure, sustainable industrial development and technological progress is key to economic growth, social development and climate action. In developing countries, basic infrastructure like roads, information and communication technologies, sanitation, electric power and water remains scare (United Nations, 2015). All three bottom lines of TBL accounting can shift the decision-making process to favor infrastructure investments with the greatest life cycle benefits, improving the impact of financial, environmental and human capital.

Goal 11: Make cities inclusive, safe, resilient and sustainable

This goal is focused on ensuring that rapidly growing cities are inclusive, safe, resilient and sustainable. The world's cities occupy just 3% of the Earth's land, but account for 60-80% of energy consumption and 75% of carbon emissions (United Nations, 2015). Rapid urbanization is exerting pressure on fresh water supplies, sewage, the living environment, and public health. The second and third bottom line of TBL accounting can support design decision-making, communication and Corporate Sustainability reporting (CSR) to help businesses and governments move beyond first cost decision making to support investments in resource and energy efficiency that can reduce the per capita environmental impact of cities.

Goal 12: Ensure sustainable consumption and production patterns

This goal promotes sustainable consumption and production patterns by "promoting resource and energy efficiency, sustainable infrastructure, and providing access to basic services, green and decent jobs and a better quality of life for all." One of the targets is to encourage companies to adopt sustainable practices and to integrate sustainability information into their reporting cycle to ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles. The second bottom line of TBL accounting will help decision makers select investments with the lowest environmental impact and maximum corporate sustainability gains.

Goal 13: Take urgent action to combat climate change and its impact

This goal advocates for an urgent action to tackle climate change and its impact. Climate change is caused by GHG emissions from human activities which results in change in weather patterns, rising sea level, and more extreme weather events. A wide array of technological measures and changes in behavior can limit the impact of climate change. The first and second bottom line of TBL accounting can encourage investment in energy efficiency and reduce the associated GHG emissions, to address the 40% of GHG emissions due to the built environment in order to combat climate change.

7.3 TBL accounting model for the built environment

While a Triple Bottom Line standard has been on the books for a decade ((Elkington, 1997), there is no measurable application of TBL accounting in the building industry, or in business school education. The NIST/ FEMP Life Cycle Costing Manual from 1996 includes first bottom line calculations of life cycle energy and facility savings, and outlines approaches to second and third bottom line calculations for the future. This thesis builds on numerous cost accounting developments for sustainable design (Figure 7.1) to advance a framework and an illustrated approach to completing full TBL accounting and tests its value with the decision-making community.

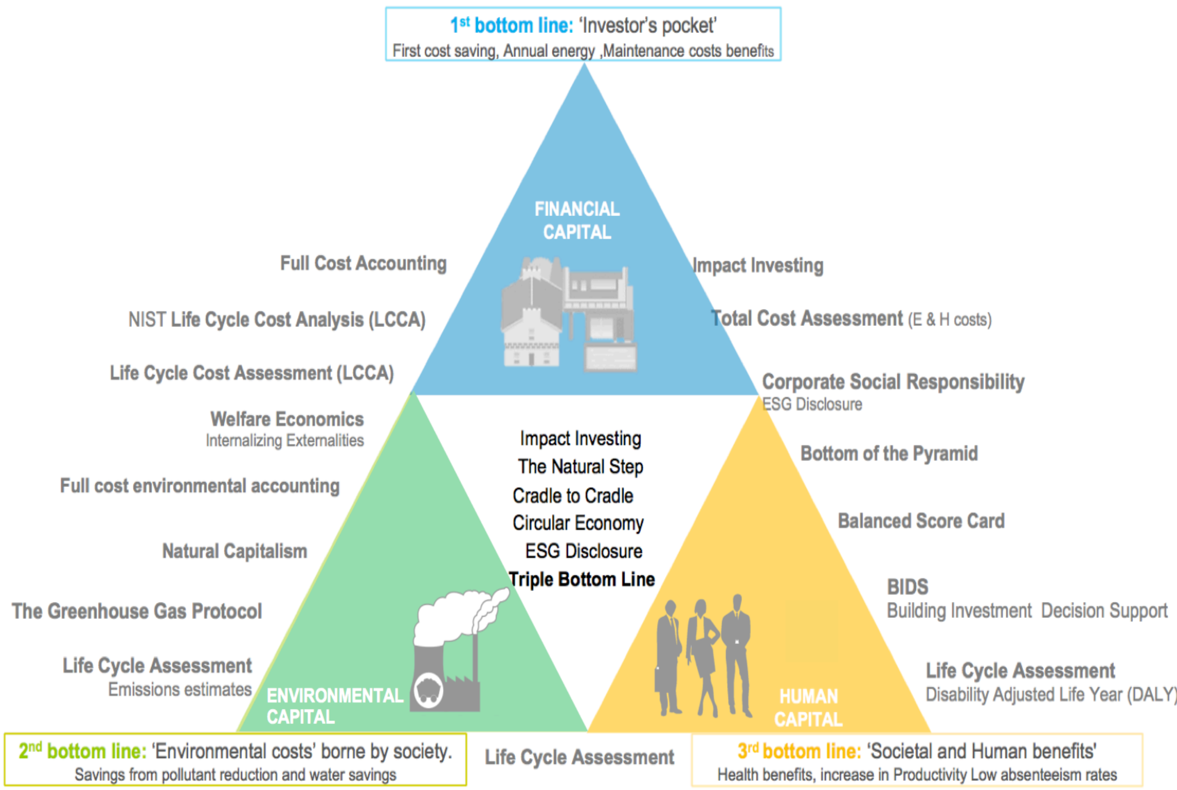


Figure 7.1: Sustainability frameworks, tools and processes reviewed

Contribution 2: Development of TBL methodology for building decision-making

A methodology for Triple Bottom Line accounting of the cost-benefits of energy investments related to operational, environmental and human outcomes was developed to support life cycle calculations to inform and convince decision-makers to make investments in energy efficiency for *multiple* reasons. Twelve energy retrofit strategies and integrated solutions (Table 7.1) were identified to illustrate the energy, maintenance, churn and waste reduction benefits as well as human health and productivity benefits with investment specific data collection for first and third bottom line assessments. For each investment iterative and cumulative net present value (NPV) calculations, return on investment (ROI) and simple paybacks were calculated.

Table 7.1: Detailing energy investments for TBL calculations

Lighting Investments
Occupancy sensors for closed spaces
Daylight dimming for perimeter lights
Lower ambient light & add task lights
Individually addressable LED lamps
Integrated LED fixtures w IP controls
Whole Building Performance Investments
Building performance goals

Enclosure Investments
Blinds for light redirection, shade, glare control
Internal light shelves in clerestory
External shading/awning for shading
HVAC Response Investments
Operable windows for natural ventilation
Underfloor air and networking
Individual temperature control

In the process of developing the methodology and calculations, information on first cost tradeoffs, outcomes beyond first cost such as energy and facility savings, and human benefits linked to each type of investment was critical background work for completing a TBL calculation.

Outcomes beyond first cost

Owners and Developers use total first costs or costs per square foot as the 'currency' for making design decision and this metric often binds the full set of design and delivery stakeholders. There are a range of life cycle costs and benefits that can offset or exceed the first cost considerations. This research provides an increased understanding of the financial, environmental and human outcomes specific to investments in the built environment. Within a longer list of financial, environmental and human outcomes that could be included in each bottom line six factors were selected in each for this research to illustrate the TBL methodology (blue highlights in figure 7.2).

Financial Capital: Economic impact	Natural Capital: Environmental impact of energy use and power generation	Human Capital Savings
First Cost/ Mortgage savings	CO2	Task performance
Energy savings	Methane	Absenteeism
Facilities management savings	SO_X	Headaches
Churn costs	NO_X	Colds and Flus
Replacement waste savings	Particulates PM2.5	Skin and Eye irritations
Real estate value/vacancy	Water	Asthma and Allergies
Peak energy savings	Particulates PM10, PM0.05	Infections
Tax/Code/Insurance	Ozone	Seasonal Affective Disorder
Salvage savings	Mercury	Musculo-Skeletal
Water savings	Fly ash, soot	Fatigue
Promotion/marketing costs	smog	Stress and Depression
	Nuclear waste disposal	Staff attraction/retention
	Waste water from fracking	User Perceived Productivity
	Methylmercury in waste water	Job Satisfaction
	Hazardous air pollutants (HAP)	Environmental Satisfaction

Figure 7.2: Outcome factors for consideration in each of the Triple Bottom Lines set in a framework for building investment decision making

To quantify the first bottom line benefits a literature review was undertaken to identify lab and field research, case studies and cost benefit studies that link the selected 12 investments to tunnelling through the cost barrier (ref), facility management savings, churn savings, waste and replacement savings, and real estate value.

Building 2nd Bottom Line environmental calculations linked to energy use

A second bottom line assessment calculation was developed to capture the environmental cost/benefits related to energy savings, quantifying the economic value of reductions in CO_2, CH_4, SO_X, NO_X, PM and water demands directly linked to electric energy savings. Three types of data were assembled for the 2nd bottom line environmental benefit calculation of energy savings: electricity fuel sources and plant quality, their respective pollution consequences, and economic values for pollution reduction. The data was gathered for three economies with different economic and sustainability goals – India was selected to represent an emerging economy; the US to represent a country with mid-level sustainability goals; and the EU to represent a leading economy with low carbon growth goals. For the purpose of this research, they represent the spread of environmental impacts of energy use based on fuel source and source-to-site multipliers (Figure 7.3).

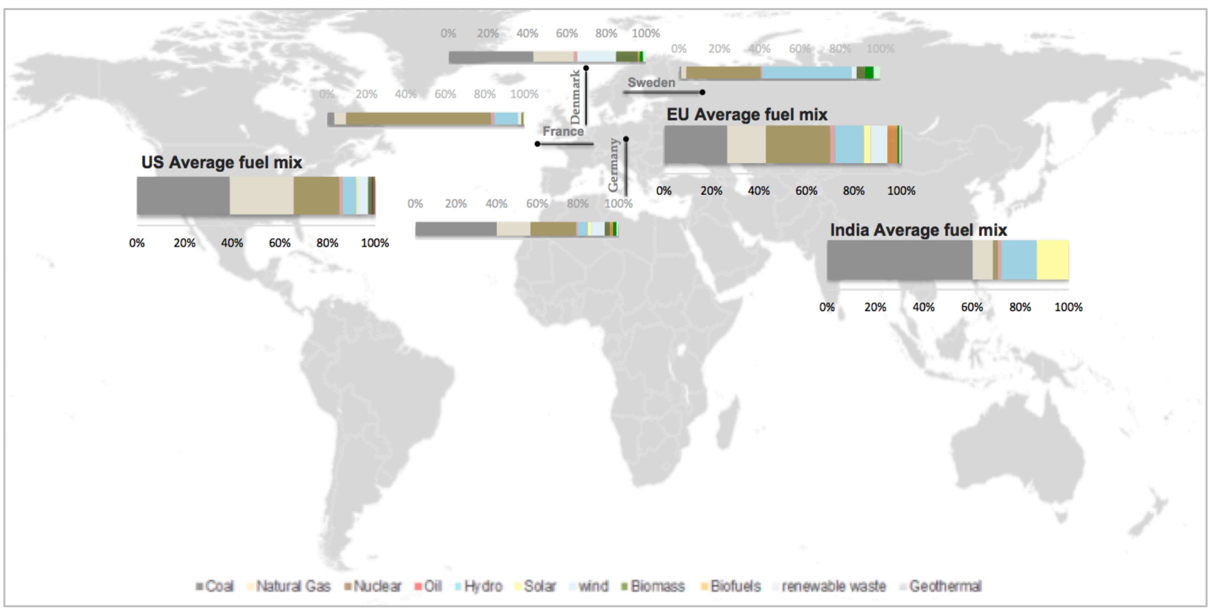


Figure 7.3: Developing a dataset for environmental cost-benefits of electricity use in three economies, given the economy's fuel mix and efficiencies

An up-to-date data base of information on the different fuel sources and mix for power generation in these three economies was developed, capturing the emissions of selected greenhouse gases and pollutants given plant efficiencies. The environmental costs of six environmental challenges – CO_2, CH_4, SOx, NOx, PM2.5 and Water – contributed by the fuel mix in those three economies were assigned 2nd Bottom Line Benefits for each kilowatt-hour of electricity saved, based on US 2016 averaged economic values for pollution avoidance (Figure 7.4).

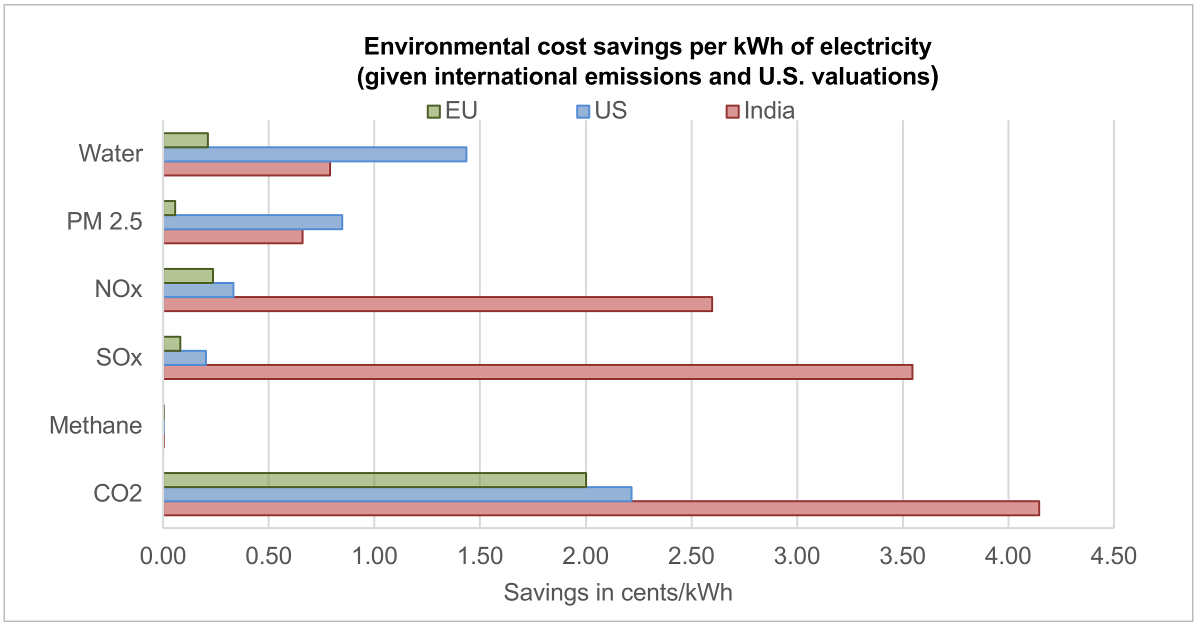


Figure 7.4: Range of values/kWh for avoidance of selected environmental costs for 3 global scenarios

Building 3rd Bottom Line human health and productivity calculations

To quantify the third bottom line benefits, a literature review was undertaken to identify lab and field research, case studies and cost benefit studies that statistically linked the selected investments to human health and performance outcomes in selected retrofit areas: daylighting, shading, natural ventilation, mixed mode conditioning and whole building performance investments. Where multiple studies for the same benefit category are available, an average value was used for completing the TBL calculations. One example of the cumulative literature on benefits from investing in "whole building performance" standards is included in figure 7.5, and the entire set is found in chapter 5.

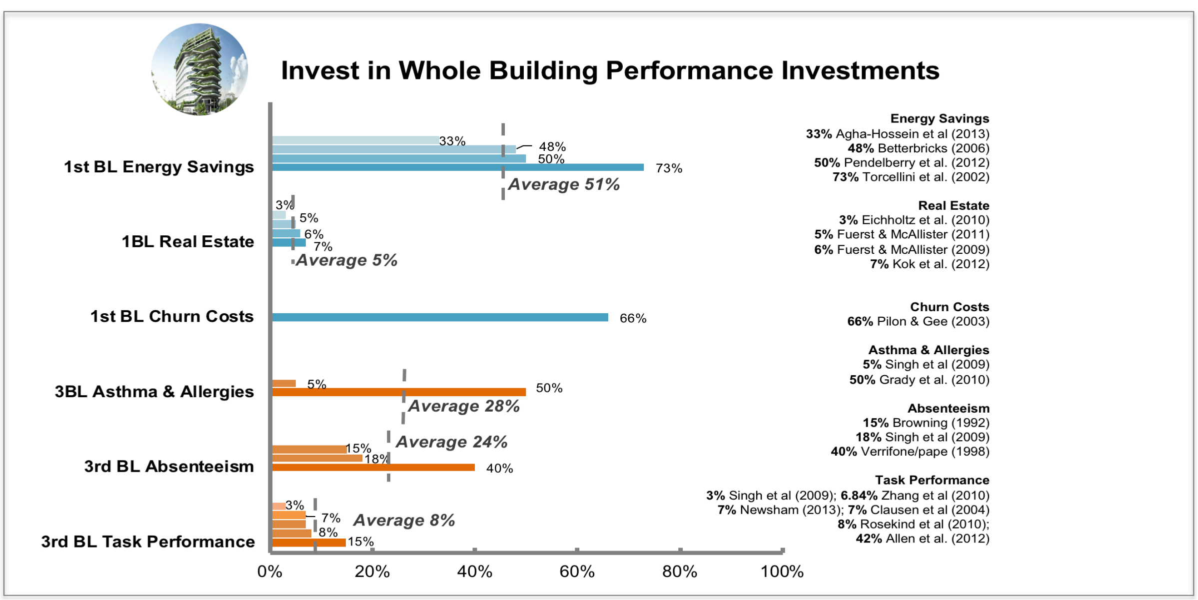


Figure 7.5: Cross sectional chart of the research on benefits from Whole Building Performance investments

The TBL methodology uses the Carnegie Mellon Building Investment Decision Support tool (BIDS™) baselines to establish baseline human health, productivity and other costs of business today to calculate how the positive health and productivity benefit create value and generate the potential cost savings. For third bottom line calculations, annual baseline costs for human benefits were assembled to include salary costs for white collared workers, absenteeism rates in organizations, health care costs, cost for the specific illnesses, amongst other assumptions needed for completing the human cost benefit calculations.

Contribution 3: Supporting Investment Prioritization through TBL

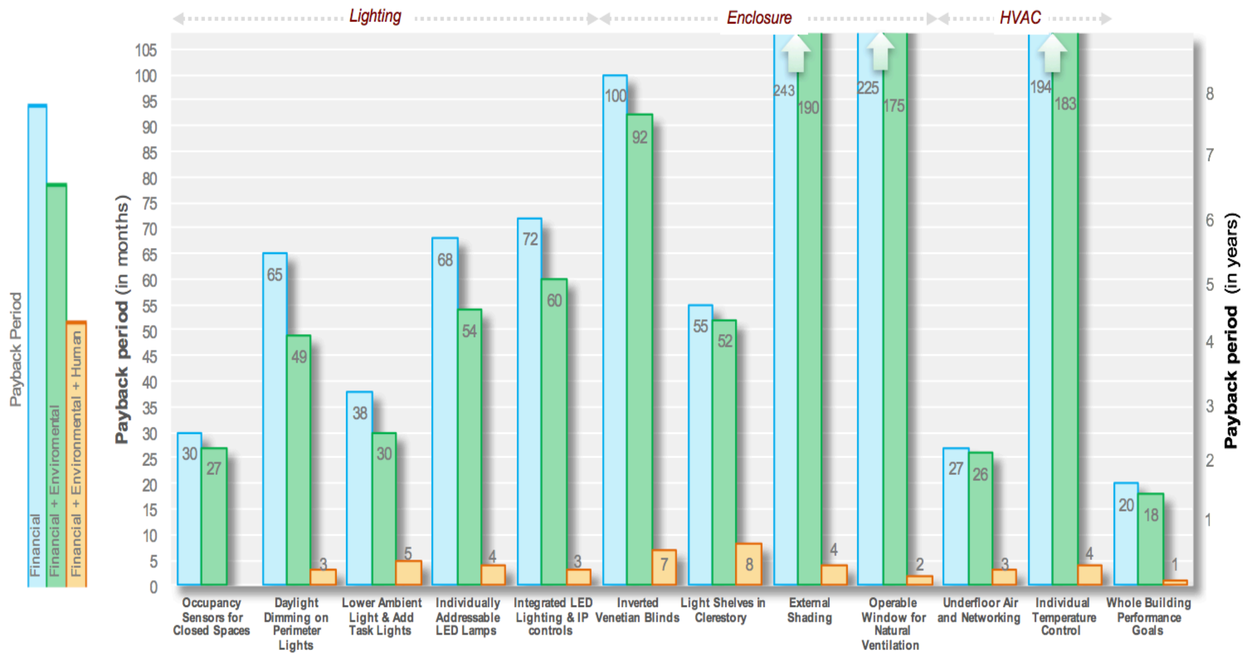
While the completion of five to fifteen-year energy payback calculations (first bottom line) can prompt increased investments, the addition of environmental and human benefits (second and third bottom line) provides the 'tipping point' for the level of design, engineering and investment needed for high performance building systems and technologies that save energy and improve the quality of the indoor environment for workers.

Setting Priorities with no capital budget constraints

Based on the twelve TBL calculations outlined, if the decision maker is not constrained with a capital budget, and is willing to invest greater cash upfront, then investing in whole building projects and major renovations (typically LEED) followed by enclosure investments is the most strategic investment for conserving energy and for improving the conditions for task performance and health (see figure 7.6). Whole building projects are often first cost intensive, but offer substantial first bottom line savings that include energy, facility maintenance and churn cost savings, as well as rental premiums that shorten the payback period. Then, the addition of the environmental benefits further reduces the payback for whole building investments. Most significantly, however, when human benefits are calculated, the ROI and payback periods for whole building performance investments and enclosure investments become significant. In this scenario, any action that increases thermal and visual comfort and gives occupants more control over the air, lighting, thermal and spatial quality of the workplace, results in the highest return on investment when all three bottom line savings are integrated.

Setting Priorities with capital budget constraints

When the decision maker is capital constrained, the list of energy investments with environmental and human benefits might be sorted differently. Lighting and daylighting upgrades will be the most strategic investments. However, the prioritization of different lighting investments will vary based on the condition of the existing lighting and daylighting assemblies. If the one-year carrying costs are the extent of a company's leadership ability with minimal first cost investment, installing vacancy sensors in closed offices, conference rooms, toilets and shared spaces has the highest return on investment, followed by lowering ceiling task-ambient lighting to 200-300 lux by de-lamping and purchasing task lamps for every employee. The environmental benefits of reducing electricity use for lighting correlate with the energy benefits, so the priorities remain the same. The human health and productivity benefits of the lighting technologies, however, establish a different set of investment priorities. In this case, any action that increases daylighting, or supports daylight variability with electric lighting, yields the highest return on investment when energy, environmental, and human triple bottom line calculations are included.



Example initial costs ($ per employee)	$150 per room	$180	$200	$550	$950	$350	$220	$240	$360	$430	$800	$1000
Financial savings ($ per employee)	$62	$40	$64	$96	$158	$37	$48	$12	$20	$190	$50	$604
Environmental Savings (linked to energy savings)	$4	$4	$16	$27	$32	$4	$4	$4	$6	$3	$3	$75
Human Saving (Health & productivity gains)	-	$72	$368	$2,372	$2250	$405	$255	$812	$1240	$1360	$2250	$1532

Figure 7.6: Investment priorities based on financial, environmental and human cost-benefits

Contribution 4: Communication & Testing of TBL methodology

Communication of the usefulness of the TBL methodology to corporate decision makers, business school educators, architecture, engineering and construction firms as a CSR strategy is key to move beyond first cost decision. To evaluate usefulness of the TBL calculations developed as part of this research, several iterations of TBL communication approaches were tested with a range of stakeholders. A “likelihood to invest” survey was developed in which one set of TBL calculations for lighting retrofits were provided in an effort to capture the willingness to invest in lighting upgrades when first cost knowledge is followed up with first, second and third bottom line ROI and payback.

A total of 125 responses were gathered using the online survey, with 114 responses completed. A description of an investment in task lights and lowered ambient lighting with a first cost of $200 per employee left 59 stakeholders ‘unlikely’ or ‘undecided’ for the energy savings investment. After *each* set of financial, environmental and human cost benefit was introduced in a triple bottom line calculation, the responses revealed a measured shift in decision-making towards the energy investment ($p<0.005$). With just the introduction of the first bottom line information of energy and FM savings, a large number of decision makers changed their decision. They were willing to invest in the lighting retrofit and made the decision to invest based on financial life cycle cost savings and not just the information on first costs. Since the environmental costs and benefits offered only small improvements in the payback, the shift in decisions is not as pronounced. However, the human costs and benefits paybacks calculated in the third bottom line led to a significant shift in the decision to invest in the lighting upgrade ($p<0.005$), removing most of the uncertainty around the energy investment.

7.3 TBL future research direction

There are some limitations to the research presented in this dissertation, that relate to variability in the costs and savings used and the method used for collecting data for developing the TBL calculations and the design of the user study and the subsequent analyses. The limitations and the approach to address them in future research are discussed below.

Collaborate to create a larger international and regional data base on first costs and first bottom line cost-savings

In the process of developing and testing the TBL methodology and calculations, information on first cost tradeoffs, outcomes beyond first cost like facility and churn cost savings, linked to each type of investment was critical background work. The first costs vary based on different regional and national manufacturers, vendors and international literature, which affects the ROI, payback periods. Also, the 1st bottom line savings for the 12 investments are based on published field and lab studies and the actual energy, facility, maintenance, churn and real estate cost savings may differ from the assumptions in the studies, as they depend on existing building assemblies, building operation and design conditions.

To address the variability in first costs and 1st bottom line cost savings, a larger international and regional database on the costs and 1st bottom line savings can be created in collaboration with Means and other similar international construction cost sources, and associations for facility management professionals such as IFMA.

Collaborate to create a self populating international and regional data base on environmental cost benefits

The addition of environmental benefits of reducing electricity demand in the 2nd bottom line calculations accelerates payback of the investment. The environmental impacts can be quantified only if the organization is required to meet energy reduction goals for city, state or federal mandates; or the organization will be disclosing baseline energy use and annual accomplishments for Energy Portfolio or 2030 commitments; or the organization has made sustainability a centerpiece of their market growth.

To assist decision makers with the 2nd bottom line calculations, it is critical to create an international and regional database on emissions factors and the respective societal monetary valuations. In the U.S, EPA's Emissions and Generation Resource Integrated Database (eGRID) already tracks the environmental characteristics of almost all electric power generated. A self populating database tied to national (e.g eGRID) and international sources, hosted by an organization like the United Nations, can facilitate 2nd bottom line calculations globally by offering a comprehensive exchange database with credible data sources. In future, using the international database the 2nd bottom line calculations can become more dynamic, allowing for the customization of assumptions by the end user, to represent region specific fuel mix, emissions and respective environmental valuations. The dynamic nature could also allow user to change the inputs with time as more data becomes available and account for the variability in environmental costs.

Promote international investments in lab and field studies linking physical environments to human health and productivity

The third bottom line justifications are dependent on research studies that link high performance systems to health and productivity outcomes. Given the lack of field studies, the research relies for now on available international laboratory and field case studies to support TBL life cycle decision making. To gather additional quantifiable data on the human health and productivity benefits, there is a need to promote international investments in lab and field studies that link physical environments to human health and productivity.

Efforts similar to the BIDS tool that has over 600 studies quantified in seven categories of investments across 100 design decisions, need to be undertaken to assist 3rd bottom line calculations. In future, the 3rd bottom line calculations can be customized as more quantitative studies on the human health and productivity benefits from high performance technologies emerge. Additionally, the repository of research literature linking high performance building systems to health and productivity outcomes could be provided to building decision-makers to promote TBL decision-making.

Launch TBL in Business Schools or test in educational course modules

The current study design for user response to TBL calculations tests a single set of TBL calculations with a short payback in the first bottom line calculations. This approach may not truly reflect the impact of the cumulative and successive TBL calculations, as decision makers may decide to invest based on just the 1st bottom line calculations. The TBL decision making methodology can be launched in business schools as a communication and CSR strategy to understand the thresholds for decision making and encourage future decision makers to move beyond first cost decision to support investments in energy efficient technologies. A larger of set of investments with a much longer payback in the 1st bottom line calculations can be tested as part of an educational course module, to ensure business school students are exposed to the power of TBL accounting.

The building industry needs to address the issue of who pays and who gains?

The overall success of the TBL decision support methodology is dependent on building stakeholders who have or are planning to integrate sustainability into their day to day decision making process. While making building investment decisions, operational budgets that should typically address 1st bottom line issues like energy and water use, churn costs amongst other expenses, tend to be first cost driven and are often combined with capital budget decisions. When making operational budget decisions it is critical at the very least to consider the 1st bottom line lifecycle costs benefits. To ensure 1st bottom line lifecycle cost benefit driven decision making, building codes and standards can be made more stringent, to mandate investments with proven lifecycle benefits. This will encourage investments in high performance technologies and systems that have TBL benefits and assist decision makers to move beyond least first cost decision making pattern.

Also, setting a higher maintenance budget can allow for larger amount of upfront capital to meet the operational needs of the building. The commericial building industry can adopt manufacturing industry's key performance indicator (KPI) for operational excellence and set operational budgets as 2 to 4% of the replacement value of the asset. The KPI of *Maintenance cost per replacement assest value*, is the universal benchmark that allocates maintenance costs as a percent of replacement asset value of plant and equipment (Lifetime Reliability Solutions - Mike Sondalini, 2017). A 2% of replacement asset value as annual operational, maintencace and repair budget is considered to be at the forefront of best maintenance practices (Sondalini, 2018) and will be an improvement on the budget considerations set by different building stakeholders.

The first bottom line benefits include direct cash savings for the owner or investor, but the second and the third bottom line benefits are more tenuous. The second bottom line savings are becoming more tangible as federal and state manadates, CSR inititatives and market mechanisms are setting economic values for the avoidance of greenhouse gases or pollutant emission, specifically a dollar value per ton for monetizing those reductions. There is also the evidence of human health and productivty benfits from high performance building investments, but the issues of who gains when the owner or the investor does not pay for health insurance or does not occupy building. Further research that relies on multimethod approaches to develop first cost and 1st bottom line cost savings, regional and international environmental cost benefits and human health and productivity benefit databases can elevate this TBL decision support methodology for building investments into an online tool with the ability to customize the TBL factors. The focus of this dissertation has been on developing content and algorithms that are utilized for the TBL calculations, the next step would be to convert it into an active user-friendly tool.

7.4 Conclusion

This research proposes an empirical approach to TBL calculations that integrates the economic, environmental and human cost benefits to accelerate investments in high performance building technologies. The development of a new methodology for capital expenditures in investments in the built environment can provide compelling arguments for decision makers and encourage the widespread adoption of high performance building technologies.

In the first bottom line, this research quantifies the 'financial' or capital costs and benefits of high performance building investments, by broadening the category of associated benefits beyond energy savings (Birkenfeld et al., 2011). Traditionally, building investment decisions are made using a value engineering approach, which is driven by the agenda of cost reduction rather than valuing the benefit of different alternatives. Using net present value (NPV) and return on investment (ROI) indices, well-known in financial practices, the first bottom line calculation in this thesis moves away from a 'first least cost' to a life cycle approach to account for multiple non-energy financial benefits that can directly be quantified for the building decision maker.

To advance a second bottom line that can be translated into Corporate Sustainability Reporting, the thesis provides a methodology for capturing the environmental benefits of reducing electricity demand related to carbon, air quality and water resources. These calculations are based on three sets of information - electricity fuel sources and power plant quality, the respective air pollution and water consumption consequences, and emerging valuation incentives for pollution reduction. The methodology focuses on critical greenhouse gases CO_2, CH_4; SO_x; NO_x, as well as particulates and water use, for three global scenarios – an emerging economy such as India, a country with mid-level sustainability goals such as the US, and a leading economy with low carbon growth goals such as the EU - in order to represent the range of environmental impacts of electric energy use. The capital saved by avoiding the environmental impacts of electricity use based on fuel source and mix can thus be added to each kilowatt-hour of electricity saved in a second bottom line calculation.

To advance the third bottom line, this thesis engages a methodology for measuring and quantifying human benefits from building investments based on ongoing development of CMU CBPD's BIDS toolkit. The methodology is built on the field and laboratory research findings that link high performance building design decisions to human health and individual and organizational productivity. This thesis advances an approach to handling the third bottom line calculations, including an approach to establishing baselines, applying a broad base of laboratory and field findings.

Given first cost data from vendors, first bottom line simple paybacks for 12 energy retrofit measures ranges from 2-20 years - with energy and facility management savings. When the environmental benefits are included, simple paybacks were accelerated to 1.5-18 years. Most strikingly, when human benefits are included - from reduced headaches and absenteeism to improved task performance or productivity - paybacks for investments in energy efficiency in US offices are often less than 1 year.

To support the validity and reliability of results, both quantitative and qualitative methods were used to validate how Triple Bottom Line (TBL) cost benefits might impact and shift decision-making patterns from a least-first-cost approach to an approach that includes TBL information. Field testing of the potential influence on decision makers to move beyond first-cost decision-making to support investments in high performance, energy efficient technologies revealed the positive impact of TBL accounting for decision makers ($p<0.05$). The introduction of TBL accounting for decision-makers in the built environment may be the most critical catalyst for investments in building energy improvements.

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Chapter 5: Generating Triple Bottom Line Proof Sets

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Appendices

Appendix A1: Testing Existing Single BL, Double BL & T BL approaches

To illustrate the feasibility of using an approach that integrates the economic, environmental and human benefits of quality built environments in the building investment decision-making process, seven select models that were discussed in section 1.2, were applied to an example investment decision to illustrate differences, strengths and weaknesses. Out of the sustainability frameworks considered, most tend to favor either the environmental or the social considerations (Kats & Capital, 2003)(Birkenfeld et al, 2011), as illustrated in table 1.

One real life scenario being faced by decision-makers is the question of whether to upgrade all of their buildings task-ambient lighting from fluorescent to LED lamps, or even full fixture replacement. T upgrade to LED lamps would require capital investment both to replace lamps and to replace the ballasts with “kits” that might require specialized workers. Compared to a ‘do nothing’ scenario that involves keeping the old T8 or T12 lamps in place, with ongoing replacements as needed.

Using each of the seven SBL/DBL and TBL accounting practices, the two investment scenarios can be evaluated related to financial, environmental and human benefit criteria. It is assumed the investor will make decisions based on a rational model and invest in either of the two scenarios motivated by conscious calculation of advantages over the cost incurred (Allison, 1969).

In the case of selecting between retrofitting with LED lamps and not doing anything at all, the traditional Life Cycle Cost Analysis (LCCA) approach would account only for all the relevant economic or first bottom line factors (USDA, 2013) such as the energy savings that could be accrued by retrofitting, manpower and disposal savings .

Given the more DBL approaches like Natural Capitalism and Full Cost Accounting method, keeping the T-12 would be the advisable alternative (Gluch & Baumann, 2004) due to material or waste concerns. These frameworks put a high value on preserving the ecosystems and call for a more productive use of natural resources to solve problems, which would mean keeping the T-8 not the T-12 that have PCB in the magnetic ballasts are now illegal to keep , to reduce the wasteful and destructive flow of resources (Lovinset al., 1999).

With LCA as DBL environmental decision support tool, with considerations for the societal impact from a system (Björklund, 2012), the decision to invest shifts from doing nothing to investing in LED when the natural and human cost savings are included. Based on the Natural Step and C2C guidelines, the investment of LED makes sense when the first bottom line, manpower and human cost savings are taken into consideration or if the materials are up-cycled (Braungart et al., 2007).

A TBL accounting framework, on the other hand, allows for including all the benefits and thus changes the decision to upgrading with LED lamps when the natural and human cost savings are included. Incorporating the LCCA (FBL) and TBL frameworks, it is easier to justify the upgrade to a better lighting system. This can be explained by the ability to integrate the two often ignored categories of environmental and human benefits into the decision-making process.

Table 1: **Comparison of sustainability frameworks for the two lighting investment choices**

	1st bottom line: Financial capital		2nd bottom line: Natural capital		3rd bottom line: Human capital	
						
Life Cycle Cost Analysis (LCCA)		$	Does not account for environmental outcomes		Does not account for human outcomes	
Natural Capitalism	$		$		Does not account for human outcomes	
Full cost accounting	$		$		Does not account for human outcomes	
Life Cycle Assessment	$		$			$
The Natural Step	$		$			$
Cradle to Cradle	$			$ When materials are up- cycled		$
Triple Bottom Line (TBL)	$			$		$
LCCA+TBL		$		$		$

Building rating system like LEED and WELL have been instrumental in bringing in sustainability frameworks like Life cycle cost analysis (LCCA), Life cycle assessment (LCA), Cradle to Cradle (C2C), and TBL, into mainstream architectural design decision making through its Materials and Resource credits. As planning, designing and constructing buildings comprises a myriad of decisions the addition of triple bottom line (TBL) calculations that capture the economic, environmental and human cost benefits (i.e. profit, planet and people), offers life cycle arguments for investments that save energy and improve the quality of the indoor environment for the workers.

Appendix A2: Steps to develop the TBL Decision Support Methodology

Five tasks describe the approach taken for this thesis, illustrated in figure 1.7. The first three tasks utilized quantitative research methods while task four represents a qualitative research phase. Under Task 1 'identifying the scale of the challenge', emerging accounting approaches, theories and tools for evaluating sustainable initiatives were identified and categorized into three categories – financial, environmental and human capital. A comparative analysis of the different frameworks, their quantitative approaches and metrics, was subsequently performed. Task 2 involved selecting the approaches that could be best adapted to decision making in the built environment, identifying the 1st, 2nd and the 3rd bottom line metrics, and developing the 2nd and 3rd bottom line databases and calculations. Task 3 was focused on testing the developed methodology with twelve high performance building technologies and systems to demonstrate the viability of the methodology to quantify cost benefits across financial, environmental and human capital values. Task 4 was focused on validating the impact of TBL calculation with key users. User surveys and unstructured interviews were used to assess how TBL calculations impact building investment decision process and identify barriers to its widespread use. Finally, Task 5 was focused on generating a step-by-step guide that can be used by decision makers to evaluate future building investments using the developed TBL Total Cost of Ownership methodology.

Identifying the scale of the challenge

Under task 1 identifying the scale of the challenge, emerging theoretic and quantitative approaches and tools used by corporations were identified and categorized into three groups. The categorization was done on the ability of the approaches to evaluate either the economic, environmental or the social costs benefits or the combination of these factors. To identify the frameworks, tools and theories an extensive review of the business theories, models and architectural guidelines and reports was completed.

Following the identification of the different valuation approaches, to illustrate the feasibility of using them in the building investment decision-making process, seven models were selected and were applied to an investment decision. This is illustrated in chapter 1, table 1, using a set of two investments that are mutually exclusive. In this scenario, the upgrade to LED lamps would require capital investment, compared to a 'do nothing' scenario that involves keeping the old T12 lamps. Using sustainability frameworks, the two investment scenarios are compared along the financial, environmental and human benefit criteria to understand which framework allowed for 'full cost accounting' of the costs and benefits associated with the investing in high performance building systems. As a conclusion, the TBL framework was selected to map the benefits from high performance building systems and technologies in three categories: (1) Financial capital (Economic) (2) Natural capital (Environmental) and (3) Human capital (Equity). (Elkington, 1997).

Selecting framework for new methodology

Selecting the Total Cost of Ownership – LCCA/TBL with defined scope

As discussed in chapter 1, the first bottom line calculations capture the financial cost-benefits and most often include the energy savings resulting from the retrofit actions. For the purpose of this research, the cost savings will be calculated using the LCC approach and will be completed only for the operational or the 'use' phase of the building. These costs and benefits directly hit the pocket of the owner. The natural capital cost savings in the second bottom line relate to the environmental consequences of energy generation and depend in part upon what type of fuel source or mix (clean or dirty) is displaced. The cost savings for the second bottom line have only been calculated at the power plant scale and are built for four greenhouse gases, CO_2, CH_4, SOx, NOx, as well as particulates and water use, given three global scenarios – an emerging economy like India, economies with mid-level sustainability goals such as U.S., and economies in the forefront of defining climate change policies as demonstrated by few high performing countries in the EU. The third bottom line captures the human benefits that are linked to improved thermal, lighting, and air quality. The figure below defines the boundary for completing the three bottom line calculations.

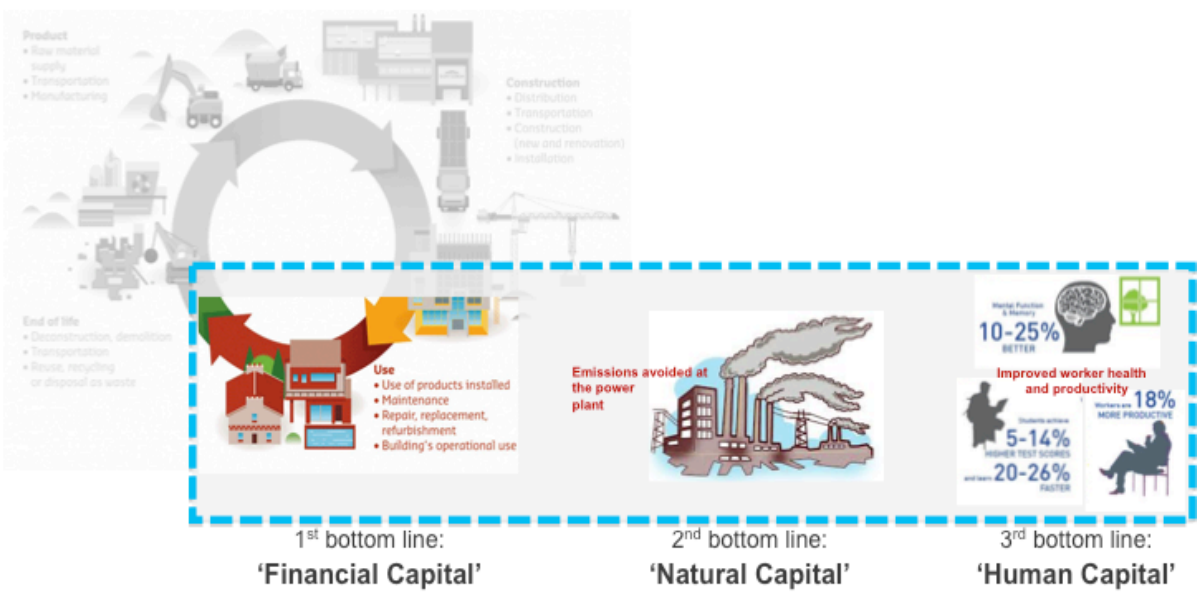

Figure A.1: TBL calculation boundary

Selecting performance indices

Next activity in task 2 was to identify the financial, natural and human impacts of building investments that can be measured and quantified. To fully understand the performance benefits beyond energy, an extensive literature review was conducted to identify published laboratory, simulation and field research that statistically linked investments in high performance building systems with performance indices such as energy and FM savings, resource and environmental benefits, and human health and productivity. Out of the several existing metrics that are tracked as part of architectural guides and a company's CSR efforts, eighteen frequently tracked metrics were combined to create the new methodology. While a review of all the related literature is beyond the scope of this thesis, peer- reviewed literature that has been influential in quantifying the impact of selected outcomes was examined. Only the outcomes in the 'use' phase of the building operation were considered as this phase entails most of the operational costs and GHG emissions.

To summarize, out of the more than 40 performance outcomes identified a set of 6 financial, 6 natural and 6 human outcomes were selected that were included in new TBL methodology. Figure 8 provides a summary of outcomes under each category. The indicators are selected based on the available quantitative data and the frequency by which they were tracked by businesses under the different sustainability assessment approaches to meet CSR goals and report on the ESG issues.

Financial Capital : Economic impact of investments	Natural Capital :Environmental impact of energy use and power generation	Human Capital Savings:
First Cost/ Mortgage savings	CO2	Task performance
Energy savings	Methane	Absenteeism
Facilities management savings	SO_X	Headaches
Churn costs	NO_X	Colds and Flus
Waste savings	Particulates PM2.5	Skin and Eye irritations
Real estate value/vacancy	Water	Asthma and Allergies
Peak energy savings	*Particulates PM10, PM0.05*	*Backache*
Tax/Code/Insurance	*Ozone*	*Infections*
Salvage savings	*Mercury*	*Seasonal Affective Disorder*
Water savings	*Fly ash, soot*	*Musculo-Skeletal*
Promotion/marketing costs	*smog*	*Fatigue*
	Nuclear waste disposal	*Stress and Depression*
	Waste water from fracking	*Staff attraction/retention*
	Methylmercury in waste water	*Job Satisfaction*
	Hazardous air pollutants (HAP)	*Environmental Satisfaction*

Figure A.2: List of outcomes to include in TBL calculations

Testing with selected design options

Following the selection of the framework and review of multiple sources to identify performance indicators that can be quantified under the financial, natural and the human capital categories, TBL calculations were developed for select building investments. Off all the possible investments, key investments that would demonstrate viability of TBL methodology, both the ones easy to validate such as lighting and daylighting investments and difficult like HVAC investments were identified.

The age and poor performance of many existing lighting systems, the poor utilization of daylight and the 40% lighting energy use in US offices, offers an excellent opportunity for this research to have tangible impacts across the U.S. and abroad. When an emphasis on carbon impacts shifts the discussion to source energy use (inclusive of energy losses at the power plant and in transmission), lighting becomes the most significant energy load at over 33%. In addition to lighting being the largest site electric load, lighting investments not only have short-term economic returns represented through the energy and facility management savings, but also environmental impacts through the reductions in energy use and waste stream. In addition, lighting systems also impact human health and performance. For example, exposure to full spectrum daylight can have an influence on human health and absenteeism, as the natural changes in light levels regulate melatonin production that synchronizes the circadian rhythms that stabilize our sleep cycles (Figueiro, M. and Rea, 2010). The empirical data on the performance along financial and human bottom lines makes lighting and day-lighting investments a prime candidate to test the TBL calculation methodology.

Lastly, through field interviews with electric utilities in the state of Pennsylvania, it has been ascertained that to meet the goals set by the Pennsylvania Act 129, the largest number of rebates are offered for lighting and HVAC upgrades. This act requires the state's seven electric distribution companies to develop energy efficiency and conservation programs for reducing the amount of electricity consumed by customers and utilities have identified lighting and HVAC upgrades to have a significant impact in achieving this goal. Following the focus on lighting and day-lighting investments in the first phase of TBL calculation development, the next phase focused on enclosure and building HVAC response to demonstrate how TBL calculations can be completed.

Creating financial, natural and human data sets

Based on the performance data for eight building investments three databases will be created and populated with quantitative data on the financial, natural and human outcomes. The natural capital database differs somewhat as it is independent of the building investment choices and contains the emissions data for three different scenarios – India, US and the EU to enable customized line calculations

The financial benefits from the selected set of high performance technologies were identified from published international field studies and literature. To identify the building investments that have measurable financial outcomes for the indicators outlines in the previous section, Google Scholar was used to identify journals, databases and other university research databases and reports. If the publications had quantitative outcome for the identified set of building investments, they were reviewed and coded into an excel database.

To develop a methodology for capturing the environmental benefits of reducing electricity demand for sustaining air and water resources, the calculations are built for select greenhouse gases CO2, CH4, SOx, Nox, as well as particulates and water use, for three global scenarios – an emerging economy (India), economies with mid-level sustainability goals (US), and economies in the forefront of defining climate change policies (EU). To build the natural capital database federal, state and international literature that provides quantitative data on the pollutants and greenhouse gas emissions linked to electricity generation were reviewed. In addition, literature from the last ten years that provides data on the fuel sources for electricity generation, power plant quality, respective air pollution and water consumption consequences, and emerging valuation incentives for pollution reduction were sought. An exception to the temporal filter was made when the data for the environmental valuation incentives was being collected.

The third bottom line calculation relies on the identification of quantitative data from laboratory and field studies that directly link improved lighting quality for today's predominantly computer work tasks, to health and productivity benefits. The human capital benefits are based on the review of journals, databases and other university research databases and reports (see appendix for the list of sources). The quantitative outcome for the set of building investments was coded into a database using a two-fold approach – a numeric value for the quantitative benefit from the investment and a score for the qualitative parameters of the publication.

Developing TBL calculation equations

The meet the objective of developing a new approach to investments that integrates financial, natural, and human benefit in the built environment, common economic metrics will be used. The future benefit values will be discounted to their present values and included in an iterative and cumulative net present value (NPV) calculations, return on investment (ROI) and simple paybacks. NPV reflects a stream of current and future benefits and costs and results in a value in today's dollars that represents the present value of an investment's future financial benefits minus any initial investment.

In this research, the first bottom line financial calculations will use the already established LCC equation and modify it to account for the savings from investing in a high-performance building systems. Some additional savings such as churn savings, waste savings and real estate value benefits will be added to modify the existing equation.

The natural capital calculations are customizable and based on data collected for three scenarios discussed in detail in chapter 3. For the second bottom line calculation, the capital saved by avoiding the environmental impacts of electricity use, based on fuel source and mix, plant efficiencies and scrubbers, for selected emissions and pollutants at the power plant will be added to each kilowatt-hour of electricity saved. The following equations were used to calculate the savings.

The third bottom line calculations were based on the baseline data and life cycle arguments developed as part of Carnegie Mellon's BIDS tool. New building cases were added to the existing proof sets and the baseline information was refined. The equations for calculating the human capital cost savings are investment specific, as the range of health and productivity benefits that are included vary on a case-by-case basis and need to be customized for each investment.

Demonstrating and assessing the usability of TBL

To evaluate the impact of the developed TBL methodology on how building investment decisions are influenced, the calculations for a building investment was provided to key users and their responses were recorded and analyzed. The group of key users include facility managers, building owners, developers, brokers and financiers who play a key role in building capital expenditure decision making process.

Prototype of survey instrument and questions

The first activity under this task of validating TBL methodology and its impact on decision-makers was to develop an instrument that allowed collection of user responses on how decisions change when TBL information is provided. To achieve this goal, an online polling application 'poll everywhere' was used to gather real time user responses when TBL calculations are sequentially presented to them. User responses are sent through smart phones or through the online web interface and then visualized using the application's analytical tools.

To test the ability of this application in collecting field data, a prototype survey was administered to Carnegie Mellon's School of Architecture graduate students. Students were part of a simulated environment and were asked to play the role of an owner and answer a set of five questions to test the polling application. The first question was used to calibrate user response, followed by four questions whose responses were used. The first of the four questions provide information on the total cost of a retrofit, followed by three questions that provide sequential information on the different bottom line calculations. For a given retrofit, for each question users are asked to select where on a seven-point Likert scale with responses from 'absolutely not' to 'absolutely yes' they are willing to invest in the retrofit. Based on user responses survey questions were modified.

Test surveys and feedback:

Once the polling instrument was tested, the survey questions were administered in conferences and public gathering for building professionals. This allowed for the testing of the methodology by a larger professional audience and helped identify key trends and gather feedback on how investors make decisions based on available TBL information. The surveys were completed under a simulated scenario, where participants were asked to play the role of an owner, to control for the background of the participants. It is acknowledged that there may be selection bias in the population that is surveyed in conferences. There may also be a consistency bias, where there is a desire of participants to appear consistent by answering related questions in a consistent manner (Weisberg et al.1996)

Round one survey: Preliminary testing of the survey has been completed in two conferences. The survey was administered in ACEEE conference in Baltimore on March 21st, 2016, followed by a Real Estate Broker's Training program organized by the local chapter of USGB in Pittsburgh on April 7th, 2016.

Round two surveys: To further examine the preliminary findings from surveys administered at conferences, that suggest a causal relationship between the shift in decision-making pattern to information on TBL calculations, a more detailed survey that gathered detailed background information of the participant was designed. Questions on the educational background, professional information, role in the organization of the respondent, their expertise and the ability to make building investment decisions were added to identify if these factors had any impact on the decision outcomes when TBL calculations are provided to users. The TBL decision maker survey was refined so as to isolate the impact of user biases and expertise. The revised survey was pilot tested and is included as part of the Appendix.

Appendix B: First Bottom Line Savings Proforma

Building Description:	
Number of stories	
Square footage	100,000 sft
Year built	
Type pf property	Office
Energy Efficiency Improvement:	
Description of the investment	
First cost for the investment	$
Initial Investment cost for investment	$
Assumptions	
Average energy savings from investment (%)	x %
Life of the investment	15 years
Discount rate	6%

Potential 1st bottom Line savings
Energy savings: Energy and water use are a substantial cost of building operations that can be reduced by investing in energy efficient high- performance building technologies that are part of green building design. This investment saves x% of the total energy/lighting/HVAC energy used.
Facility management savings: Building maintenance includes the routine ground and janitorial maintenance, processing of work orders and deferred maintenance for non-capital projects. Investing in this retrofit reduces the maintenance costs through fewer material and man hours required.
Waste and replacement savings: Sustainable products or systems specified for a building provide financial benefit due to fewer frequent replacement cycles and decreased cleaning and maintenance requirements.
Churn savings: There are significant cost-benefits to investing in high performance quality building systems to reduce the cost of "churn". Within buildings, churn is the cost of moving employee, either internally or externally. The cost of installing a UFAD system is $xx and the savings accrued through reduced churn costs is $yy
Integrated first cost savings: Counting only the energy costs as the only benefit from high performance building investments overlooks the avoided capital expenses. These capital expense savings are achieved through the capital equipment that can be reduced or completely eliminated when investments are made in high performance technologies.
Real estate savings: Multiple studies show rents and occupancy rates are higher in green high performing buildings compared to conventional buildings. LEED certified buildings with higher levels of certifications indicate an average 3% higher rent and have a higher occupancy rate (Eichholtz et al., 2010b).

Annual 1st bottom Line savings		
	Per employee	Per square foot
Energy Savings		
Facility management savings		
Waste and replacement savings		
Churn savings		
Integrated first cost savings		
Real estate		

Financial Returns	
Return on Investment **(ROI)**	
Simple **Payback**	
Net Present Value **(NPV)**	

Appendix C: Second Bottom Line - Environmental Capital database

To advance a 2nd bottom line that can be translated into Corporate Sustainability Reporting, the TBL framework focuses on capturing the environmental benefits of reducing electricity demand towards sustaining air and water resources. The six environmental outcomes – CO2, CH4, SOx, NOx, PM and water demands relative to 2nd bottom line performance dramatically vary with the different electricity fuel sources and power plant quality. To address the uncertainties the 2nd bottom line, the calculations are built for three scenarios based on the use of the worst to best fuel sources. The 2nd bottom line calculations for three global scenarios – an emerging economy (India), economies with mid-level sustainability goals (US), and economies aggressively addressing climate change (EU) illustrate the possible range of environmental cost-benefits offered by electric energy savings. The Calculations reflect three types of information –

1. Electricity fuel source & power plant quality to determine air pollution & water demand
2. Measurable environmental outcomes (air pollutants and water use) and
3. Emerging valuation incentives for pollution reduction and water conservation.

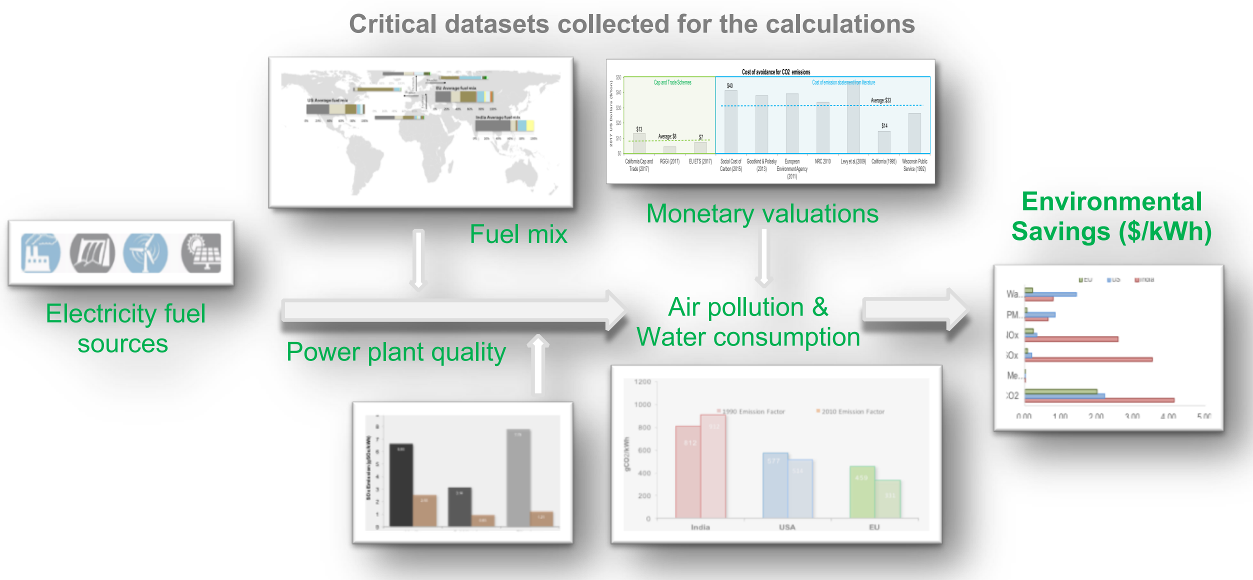

Figure C1: Overview of the diversified Economy Database and Calculations for 2nd Bottom Line

1. Electricity fuel sources and power plant quality

Based on the most commonly used fuels for electricity generation, the 2nd bottom line approach is built using a data base on the 6 environmental impacts of electricity generation from eleven different fuel sources. As each building projects specific fuel mix and power plant efficiencies will impact the GHG, pollutant emissions and water demand, the environmental impacts will also vary based on the fuel mix.

The fuel sources have been identified from International Energy Agency's energy statistics and include coal, natural gas, oil, nuclear, hydro, biofuels, bio waste, geothermal, solar and wind. Global trends in the fuels used for electricity generation reveal the ongoing dominance of coal worldwide, even though it is diminishing in the US and Europe (figure C2) (IEA, 2011). Coal is considered to be a dirty source of energy as it is by far the largest contributor to energy related CO_2 emissions (Foster & Bedrosyan, 2014). With the availability of cleaner sources of energy such as natural gas and renewables, a decline in the quantity of coal for power generation is projected.

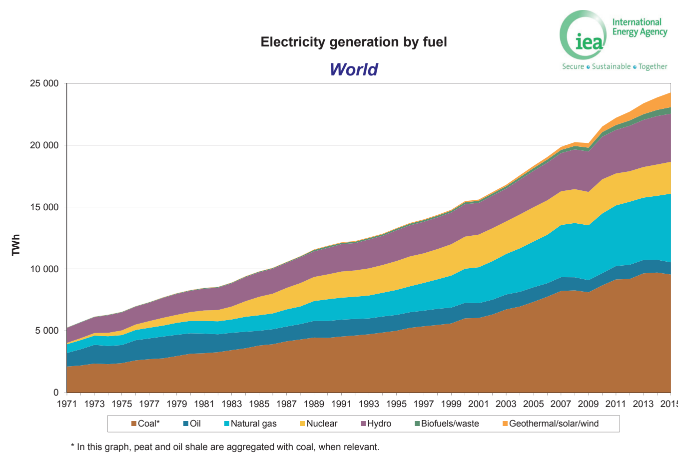

Figure C2: Dominance of coal in energy production

As state earlier, each country's specific fuel mix impacts their greenhouse gas (GHG) and pollutant emissions. The fuel mix in different countries reveals variability in the percentage of coal used for electricity generation (table C1 and figure C3), ordered from the cleanest to the dirtiest source mix. In the case of emerging economies represented by India, 61% of the mix is dominated by coal (Kate & Ian, 2015; Vasudha Foundation, 2014), followed by a 40% for the US and 27% for the EU.

Table C1: Each country's specific fuel mix impacts their GHG and pollutant emissions

	India	US	EU	Germany	Denmark	France	Sweden
Coal	60.6%	39.0%	26.7%	40.9%	43.8%	3.5%	1.0%
Anthracite			0.3%				
Sub- Bituminous		19.3%	0.1%				
Bituminous		17.2%	15.7%	18.2%	43.8%	3.5%	0.6%
Lignite		2.5%	10.1%	22.7%	0.0%		0.4%
Natural Gas	8.5%	27.0%	16.6%	16.6%	20.4%	5.9%	2.4%
Nuclear	2.1%	19.0%	26.9%	22.5%	0.0%	74.2%	38.4%
Oil		1.0%	1.9%	1.3%	2.1%	1.5%	1.2%
Diesel	1.0%						
Kerosene							
Hydro	15.2%	6.0%	12.3%	4.6%		12.3%	46.1%
Solar	13.0%	0.4%	2.6%	2.0%		0.1%	0.0%
wind		4.4%	7.2%	6.4%	20.1%	1.8%	2.4%
Biomass		1.7%		2.2%	10.8%	0.1%	4.8%
Biofuels			4.1%	2.3%	1.0%	0.2%	0.0%
renewable waste			0.6%				
Geothermal		0.4%	0.2%	0.0%			
Non renewable waste			0.8%	1.3%	1.8%	0.5%	3.9%
Other gasses		1.0%					
Total	100%	100%	100%	100%	100%	100%	100%

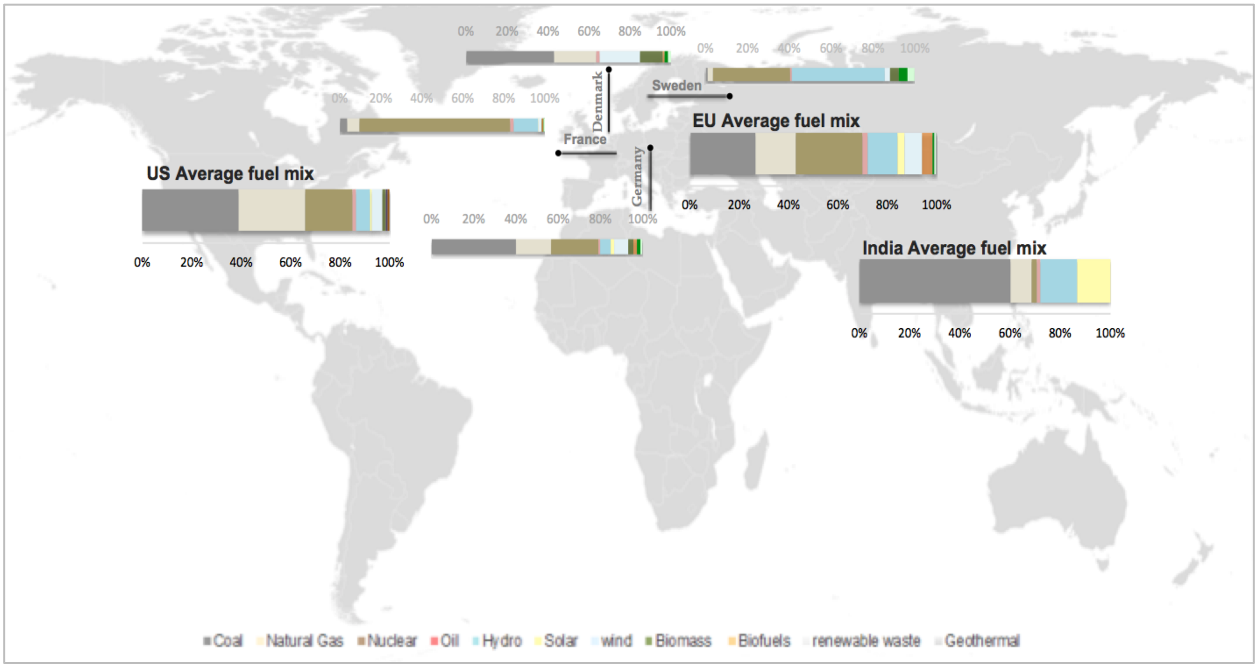

Figure C3: Each country's specific fuel mix impacts their GHG and pollutant emissions

Data compiled from:

Central Electricity Authority. (2015). Growth of Electricity Sector in India from 1947-2015.

EIA. (2015). Table 7. 2b Electricity Net Generation: Electric Power Sector. Retrieved from http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_6.pdf

Eurelectric (2014) Electricity for Europe Facts and Database "Electricity Generation by Primary Energy". Retrieved http://www.eurelectric.org/factsdb/

IEA (International Energy Agency). 2012a. "CO2 emissions by product and flow," IEA CO2 Emissions from Fuel Combustion Statistics (database)

IEA. 2012c. "World Energy Balances," IEA World Energy Statistics and Balances (database)

October, R. (2010). Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Coal-Fired Electric Generating Units. Energy, (October).

Planete energies. (2015). About the Energy Mix.

Even where a downward trend in the use of coal is projected, the type of coal used for electricity generation can have a significant impact on the amount of emissions from the power plant. The type of coal accounts for a significant variation in carbon content that governs power plant GHG emissions (Garg et al., 2006). CO2 emissions output is lower when higher qualities of coal are used compared to the coal fired power plants that burn lower quality coal like lignite (Figure C4, Cai et al, 2012). In combination with power plant combustion efficiencies, this variation in the CO2 emission outputs from the different types of coal used for electricity generation is also evident at the country level (figure C4). For example India has the highest CO2 emission output per kilowatt-hour of electricity due to the use of low quality coal (Cropper et al., 2012).

The combination of coal quality, combustion technology, and operating conditions of a power plant determine other emissions from power plants beyond carbon. In the US, coal fired power plants are the largest sources of sulfur dioxide (SOx) emissions. The use of emission control equipment - flue gas desulfurization (FGD) scrubbers - has significantly reduced the SOx emission levels (EIA, 2011). Regardless of coal type, power plants that have scrubbers have substantially lower SOx emissions than unscrubbed coal-fired plants (figure C4), providing another tier of pollution savings for emerging economies and economies with mid-level sustainability goals as they shift away from dirty sources of electricity generation.

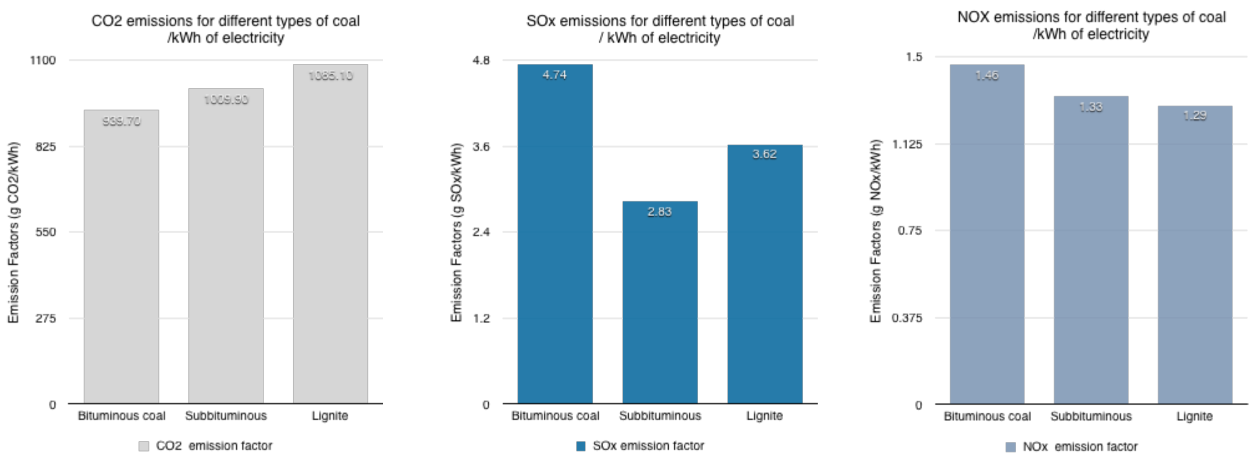

Figure C4: CO2, SOx and NOx emission differs by the type of coal used

2. Measurable environmental outcomes of electricity generation

This TBL methodology captures the impact of fuel sources and mix for electricity generation and the power plant quality for selected greenhouse gases and pollutants - CO2, CH4, SOx, NOx, PM2.5 and water use - for which quantifiable data is available. These are pollutants that cause a majority of the environmental damages that arise from burning fossil fuels to generate electricity (Kats & Capital, 2003) and are known contributors to global warming. These pollutants are also known to cause respiratory illness, cancers, and developmental impairment, increasingly quantified by the international community (Venema and Barg, 2003).

The emission values for EU are based on the lowest value of emissions and water demand for electricity generation from four countries – Germany, Denmark, France and Sweden (table C2). The assumption is that each of these countries that rely on different fuel mix for electricity and follow more efficient practices for power generation, will provide the lowest range of emissions for each of the selected environmental outcomes. For instance, Germany predominantly uses coal with higher plant efficiencies and its CO_2 emissions will be used for the average EU value. Denmark majorly relies on coal, natural gas and as well as a high percentage of wind power and could provide the emission values for using wind power. France uses a high percentage of nuclear energy, and could provide the emission value for nuclear energy, while Sweden fuel mix has a high percentage of hydro power and could provide the lowest value of emission. The table below summarizes the emission values.

Table C2: Average emission factors for EU are based on the lowest emission values from four EU countries

EU - lowest values from four countries (kg/kWh)						
	CO2	Methane	SOx	NOx	PM 2.5	Water
						gallons/kWh
Average	0.4538	0.00001	0.0004	0.0009	0.0000	0.2341

GHG and air pollutant emissions and water demand for electricity generation for the EU compiled from following sources:

Ambiente, A. E. de. (2012). Why did greenhouse gas emissions increase in the EU in 2010? 1–19. http://doi.org/10.1007/s13398-014-0173-7.2

Brander, A. M., Sood, A., Wylie, C., Haughton, A., Lovell, J., Reviewers, I., & Davis, G. (2011). Technical Paper | Electricity-specific emission factors for grid electricity. Ecometrica, (August), 1–22.

Covenant of Mayors. (2015). Technical annex to the SEAP template instructions document: The Emission Factors.

Defra/DECC (2011b). Consultation on GHG Emissions. http://www.defra.gov.uk/consult/2011/05/11/ghg-emissions/

Eurostat. (2015). Electricity and heat statistics. Eurostat Statistics Explained. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat

European Environment Agency. (2012). Structure of CO2 emissions from thermal power plants in.

IEA (2010). CO2 Emissions from Fuel Combustion – Highlights (2010 edition).

IEA (2011a). Statistics by country/region for coal and peat, oil, and natural gas (data

IEA (2011b). Statistics by country/region for electricity/heat (data

RWE Corporate Website. (2016). RWE Key Data Tool. Retrieved from http://www.rwe-datatool.com/

The emission values for US (table C3) and India (table C4) are included in the table below along with the sources used to derive the values.

Table C3: National average breakdown by different fuel source and rank of coal available for US

US (kg/kWh)						
	CO2	Methane	SOx	NOx	PM 2.5	Water
						gallons/kWh
National Average	0.5027630	0.0000990	0.0036900	0.0006918	0.0004756	
Coal						0.4700000
Anthracite						
Sub- Bituminous(scrubbed)	1.0099000	0.0000115	0.0009300	0.0013302	0.0000260	
Sub- Bituminous (unscrubbed)			0.0031400			
Bituminous(scrubbed)	0.9397000	0.0000108	0.0012100	0.0014642	0.0001786	
Bituminous(unscrubbed)			0.0077900			
Lignite(scrubbed)	1.0851000	0.0000116	0.0025500	0.0012887	0.0002365	
Lignite(unscrubbed)			0.0066600			
Natural Gas	0.4087000	0.0000079	0.0000000	0.0000630	0.0000008	0.2900000
Nuclear	0	0	0	0	0	1.3227513
Oil						
Diesel	0.8693000	0.0000368	0.0006710	0.0000027	0.0000681	
Kerosene						
Hydro	0	0	0	0	0	18.0000000
Solar	0	0	0	0	0	
wind	0	0	0	0	0	
Biomass	0	0.0005155	0.0001892	0.0000017	0.0023435	

GHG and air pollutant emissions and water demand for electricity generation for the US compiled from following sources:

Brander, A. M., Sood, A., Wylie, C., Haughton, A., Lovell, J., Reviewers, I., & Davis, G. (2011). Technical Paper | Electricity-specific emission factors for grid electricity. Ecometrica, (August), 1–22.

Cai, H., Wang, M., Elgowainy, a, & Han, J. (2012). Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors and Their Probability Distribution Functions for Electric Generating Units. Argonne National Laboratory

EIA (2011) Coal Plants without scrubbers account for a majority of U.S SO2 emissions. Retrieved from http://www.eia.gov/todayinenergy/detail.cfm?id=4410

EPA. (2015). eGRID2012 Summary Tables. Clean Air Markets Division, Office of Atmospheric Programs U.S. Environmental Protection Agency.

EPA, 2011a. The Emissions & Generation Resource Integrated Database (eGRID 2010 Version 1.1),

EPA, 2007a. 2007 Annual, All Programs, Unit-Level Emission Database.

IEA. (2012). Water for Energy: Is energy becoming a thirstier resource? World Energy Outlook, 1–33.

Torcellini, P., Long, N., & Judkoff, R. (2003). Consumptive Water Use for U.S. Power Production.

Table C4: National average emission factors are available for Indian fuel sources

India (kg/kWh)						
	CO2	Methane	SOx	NOx	PM 2.5	Water
						gallons/kWh
National Average	0.9400	0.00002	0.0080	0.0043	0.0023	0.8771

GHG and air pollutant emissions and water demand for electricity generation for the India compiled from following sources:

Brander, A. M., Sood, A., Wylie, C., Haughton, A., Lovell, J., Reviewers, I., & Davis, G. (2011). Technical Paper | Electricity-specific emission factors for grid electricity. Ecometrica, (August), 1–22.

Coal Directory of India, Coal Controller's Office, Ministry of Coal, Kolkata, various editions up to 2013-2014.

Cropper, M., Gamkhar, S., Malik, K., Limonov, A., & Partridge, I. (2012). The Health Effects of Coal Electricity Generation in India, (June), RFF Discussion Paper 12–25. http://doi.org/10.2139/ssrn.2093610

Feng, K, Hubacek, K, Siu, YL et al. (2014) The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis. Renewable and Sustainable Energy Reviews, 39. 342 - 355. ISSN 1364-0321 https://doi.org/10.1016/j.rser.2014.07.080

Indian Petroleum and Natural Gas Statistics, Ministry of Petroleum and Natural Gas, New Delhi, various editions from 2000-01 to 2013-14.

Mittal, M. L. (2010). Estimates of Emissions from Coal Fired Thermal Power Plants in India, 39, 1–22.

Monthly Generation Review, March 2014, Central Electricity Authority, Ministry of Power, New Delhi, 2014.

Renewable Energy in India: Progress, Vision and Strategy, Ministry of New and Renewable Energy, 2010.

The UN Energy Statistics Database

3. Societal monetized values of selected emissions, pollutants and water demand

The last dataset used to calculate the 2nd bottom line savings is monetary valuation for the selected air pollutants, greenhouse gases and water use for electric power generation set by different countries and international treaties. For each environmental outcome considered in the calculations, the societal monetary valuations were collected from both literature and trading schemes in the US and EU (table C6). At the time of data collection, India did not assign a value to the environmental outcomes of electricity generation.

Table C6: Societal monetary valuations for pollutant emission and water demands

	Trading Schemes			Cost of Emission Abatement						
	California Cap and Trade (2017)	RGGI (2017)	EU ETS (2017)	Social Cost of Carbon (2015)	Goodkind & Polasky (2013)	European Environment Agency (2011)	NRC 2010	Levy et al.(2009)	California (1995)	Wisconsin Public Service (1992)
CO2	13	4.35	7.19	$41	$38	39.18	$34	$47	$14	$26

	Cost of abatement		
	ExternE (1998)	California (1995)	Wisconsin Public Service (1992)
Methane	976	$241	$384

	Trading Schemes		Cost of Emission Abatement						
	CA Emission Credit (2016)	Title IV - CAIR SO2 Cap and Trade (2008)	EPA BenMAP (2013)	Goodkind & Polasky (2013)	NRC (2010)	Levy et al.(2009)	Clean Air for Europe Programme (2005)	Wisconsin Public Service (1992)	Mass. Dpt of utilities(1990)
SOx	20,000	130.75	35,000	11,978.86	6510.98	16,327.66	12,909.86	24,967.13	2809.33

	Trading Schemes		Cost of Emission Abatement							
	CA Emission Credit (2016)	NOx BTP (2008)	EPA BenMAP (2013)	Goodkind & Polasky (2013)	European Environment Agency (2011)	NRC (2010)	Levy et al.(2009)	Clean Air Europe Programme (2005)	Wisconsin Public Service (1992)	Mass. Dpt of utilities(1990)
NOx	31,400	673	5200	3467.57	12,492.91	1,796.13	5,476.78	9,839.07	4,710.78	12,173.75

	Trading Schemes			Cost of Emission Abatement						
	EPA BenMAP (2013)	Goodkind & Polasky (2013)	Roald, Dickens and Butterick (2013)	Victoria Transport Policy Insitute (2012)	MIRA (2011)	NRC (2010)	Muller and Mendelsohn (2010)	Levy et al.(2009)	Clean Air for Europe Programme (2005)	European Commission (2002)
PM	130,000	19,439.39	43,350.88	198,874.63	133,387.96	10,664.54	1313.42	82,151.76	59,911.78	22,723.33

	Cost of water		
	EPA BenMAP (2013)	Goodkind & Polasky (2013)	Roald, Dickens and Butterick (2013)
Water	130,000	19,439.39	43,350.88

For the complete set of references see references for chapter 3

Environmental costs and savings calculation:

Finally, summarizing the downstream externality reduction benefits of each kilowatt hour of electricity saved at the site, table C7 illustrates CO2, SOx, NOx, PM2.5 and water demand reductions for three global scenarios – an emerging economy (India), economies with mid-level sustainability goals (US), and economies in the forefront of defining climate change policies (EU), given US valuations for pollution reductions but international power sources and generation effectiveness.

Table C6: The Environmental Cost Savings per KWh of Electric Energy Savings (given Country Emissions and U.S. Valuation)

Cost Savings (cents/kWh)

	India	US	EU
CO2	4.14469	2.41228	2.00074
Methane	0.00091	0.00038	0.00033
SOx	14.00288	0.74742	0.70537
NOx	2.59773	0.51237	0.50877
PM 2.5	6.59182	1.36307	0.05732
Water	1.75410	0.94000	0.46811

Appendix D: Cross section of research studies by investment

1. Install occupancy sensors for closed spaces

Lighting control – NCAR / Maniccia et al 1999 (Office)
Lighting control = Energy savings
In a 1997 field experiment at the National Center for Atmospheric Research in Boulder, Colorado, Maniccia et al. identified a 43% reduction in lighting energy use in private offices due to occupancy sensors, & an additional 15% savings due to manual switching & dimming controls for each user.

D. Maniccia, B. Rutlege, M.S. Rea and W. Morrow. (1998) Occupant use of manual lighting controls in private offices. Illuminating Engineering Society of North America 1998 Annual Conference: Proceedings. IESNA: New York, NY. 490-512

Three Austrian Office Buildings – Mahdavi et al. 2008
Lighting control = Energy savings
In a 2008 field study of 48 offices in three office buildings in Austria, Mahdavi et al. identify a 66 to 71% potential for reducing lighting energy use by utilizing occupancy sensors and daylight responsive dimming devices. This corresponds to a cumulative annual energy saving potential of 17kWh/m² when compared to offices without occupancy sensors and dimming controls.

Mahdavi, A.; Abdolazim, M.; Elham, K.; and Lyudmila, L. (2008): Occupants' Operation of Lighting and Shading Systems in Office Buildings: Journal of Building Performance Simulation;

U.S. Commercial Building Meta-Analysis / Williams et al 2012
Lighting Controls = Energy Savings
In a 2012 meta-analysis of 88 installation and simulation studies presenting 240 savings estimates for commercial buildings in the United States, Williams et al identify a 24% - 36% energy savings when methods of lighting controls, including daylighting, institutional tuning, personal tuning, or occupancy sensing are used for building lighting controls. Additionally, a statistically significant ($p<0.05$) energy savings of 38% was identified when multiple control strategies were used for building lighting control.

Williams, A., Atkinson PE, B., Garbesi PhD, K., Page PE, E., Rubinstein FIES,F. (2012) "Lighting Controls in Commercial Buildings." Leukos, Volume 8 No. 3, 161-180.

NCAR Office / Maniccia et al. 1999
Lighting control = Energy savings
In a 1997 field experiment at the National Center for Atmospheric Research in Colorado, Maniccia et al identify a 43% reduction in lighting energy use in private offices due to occupancy sensors, and an additional 15% savings due to manual switching & dimming controls for each user.

D. Maniccia, B. Rutlege, M.S. Rea and W. Morrow. (1998) Occupant use of manual lighting controls in private offices. Illuminating Engineering Society of North America 1998 Annual Conference: Proceedings. IESNA: New York, NY. 490-512

2. Add daylight dimming on perimeter lights

Lighting – Jennings et al 2000
Lighting control = Energy Savings
In a 2000 controlled field experiment at the Phillip Burton Federal Building in San Francisco, Jennings et al. identified an average 46% reduction in lighting energy use from occupancy sensors and daylight dimming controls in perimeter offices, or a 43% reduction in lighting energy use from occupancy sensors and task tuning (dimming light level to a task-appropriate level) in perimeter offices.

Jennings, J.D., Rubinstein, F.M., DiBartolomeo, D., Blanc, S.L. (2000). Comparison of Control Options in Private Offices in an Advanced Lighting Controls Testbed. Journal of the Illuminating Engineering Society, Summer 2000.

Li et al. 2014
Daylight Control = Energy Savings
In a 2004 field experiment of an open space office at the City University of Hong Kong, Li et al identify a 33% reduction in electric use for artificial lighting when luminaries were under the automatic daylight dimming control as compared to conventional electric lighting.

Li, Danny H.W.; Lam, Tony N.T. and S.L. Wong. 2004. "Lighting and energy performance for an office using high frequency dimming controls" Energy Conversion and Management; 47, 2006, pp:1133-1145.

Lighting - Verderber and Rubinstein 1984
Lighting Control = Energy Savings
In a 1984 simulation study supported by meta-analysis, Verderber and Rubinstein identify 64% lighting energy savings in a 30% daylit building with daylight dimming controls, automatic scheduling, tuning, and lumen depreciation, compared to a conventional lighting system with no controls.

Verderber, R., and Rubinstein, R. (1984) Mutual Impacts of Lighting Controls and Daylighting Applications. Energy and Buildings 6:2, pp. 133-140.

Day Lighting Control - Lee and Selkowitz 2006
Daylight Control Systems = Energy Savings
In a 2004 study involving the mock-up of the New York Times office building, Lee and Selkowitz identify a 59% savings in lighting energy consumption due to the use of daylight control systems with automated roller shades and DALI ballasts, as compared to a base case building with a conventional lighting system. Post occupancy, in 2008, the New York Times building achieved 70% lighting energy savings. Lighting power density reduced from 1.28/sf. to 0.39/sf. without affecting the design luminance level of 500 lux at workstations.

Lee, E. S. and Selkowitz, S. E. (2006): The New York Times Headquarters Day lighting Mockup; Monitored performance of the day lighting control system: Energy and Buildings; 38, pp. 914–

929. LBNL-56979.

Office/ Boyce, (2000)
Individual Lighting Control = Energy Saving
In 2000, field experiment on three individual windowless offices evaluated the impact of dimmable individual lighting control system on office's energy consumption and occupant's task performance, Mood and illuminance. It was found the offices with dimmable lighting control system consumed 35-42% less energy than the office without dimmable lighting control system.

Boyce, P.R, Eklund N. H, and Simpson S.N. (2000) Individual Lighting Control: Task Performance, Mood, and Illuminance

Office Building in Albany, NY/ P R Boyce et al 2006
Dimming control= Energy Saving+ Workers' Productivity
In a 2006 field study of an office building in Albany, New York, Boyce et al identify a 20% decrease in energy consumption due to the use of dimming control system instead of fixed lighting system with the illuminance of 500lx, a illuminance which is widely chosen by workers for paper-based work in office buildings and used as upper limit of working plane illuminances recommended for offices in the UK and North America, as design criterion of lighting system. In another field study, Boyce et al identify an increase in worker's productivity due to the use of dimming control system.

P R Boyce, J A Veitch, G R Newsman, C C Jones, J Heerwagen, M Myer, C M Hunter. Occupant use of switching and dimming controls in offices, 2006

Lighting Control– Bodart, M. et al 2000
Day lighting + Lighting Control = Lighting Energy Savings
In 2000 a simulated office lab experiment conducted by Bodart et al. in Belgium, found a 50-80% reduction (64% on average) in lighting energy consumption resulting from the introduction of an artificial light management system which continuously dims artificial light according to daylight availability from various window configurations having a 61% visual transmittance glazing within 2.7 meter perimeter only single office environments for all cardinal building orientations. Lighting sensors were assumed to be in the center of the room 80 cm (31.5 inches) from the floor during the simulations.

Bodart, M. et al. (2000). Global energy savings in offices buildings by the use of day lighting. Energy and Buildings v. 34 Published 2001. 421-429.

Access to Natural Environment – Software Co. / Figueiro et al 2002
Daylighting = Individual Productivity + Energy Savings
In a 2001 field study at a software development company, Figueiro et al identify a 15% increase in time dedicated to work tasks and a 35% decrease in electric lighting use for occupants of windowed offices, as compared to occupants in interior offices with no access to daylight, in winter months.

Figueiro, M., Rea, M., Stevens, R., and Rea, A. (2002). Daylight and Productivity: A Field Study. In Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.

Lockheed 157 / Thayer 1995, Romm and Browning 1994
Daylighting = Reduced Absenteeism + Energy Savings
In a 1995 building case study of Lockheed Building 157 in Sunnyvale, California, Thayer identifies 50% savings in lighting, cooling and ventilation energy and 15% reduced absenteeism due to the daylighting design, which integrates layout, orientation, window placement, type of glazing, light shelves, and ceilings.

Thayer, Burke Miller (1995) Daylighting & Productivity at Lockheed. Solar Today, Vol.9, 1995. Romm, Joseph I. and Browning, William D. Greening the Building and the Bottom Line.

3. Lower ambient light & add task lights

Lighting control- Linhart 2011 (Office)
Low-Light power density lighting and visual comfort = productivity
In a 2008 one-month controlled lab study with 20 students in the LESO building in Switzerland, Linhart et al. identified that by switching the lighting scenarios from 4.5 W/m2, 232 lux to 3.9 W/m2 353 lux, comparable visual comfort and productivity of computer-based tasks. It was also identified that a 25% improvement of productivity in simple paper-based tasks could be achieved ($p<0.05$).

Linhart, F., & Scartezzini, J. L. (2011). Evening office lighting - visual comfort vs. energy efficiency vs. performance? Building and Environment, 46(5), 981–989. http://doi.org/10.1016/j.buildenv.2010.10.002

Lighting – Knissel / IWU 1999
Lighting Control = First Cost Savings + Energy Savings + Maintenance Savings
In a 1999 simulation study of an office building in Frankfurt, the Institut Wohnen und Umwelt Darmstadt (IWU) identify an 88% reduction in primary energy consumption, from 82 kWh/m2 to 10 kWh/m2, as a result of effective daylighting, split task and ambient lighting, high performance parabolic louver fixtures and daylight dimming controls. Through cost calculations, the IWU also determined that these energy savings can be achieved with first cost savings of $11/m2 ($1/sq.ft) and maintenance savings of 4.70/m2 ($0.05/sq.ft).

Knissel, Jens; Institut Wohnen und Umwelt, Darmstadt, Germany (j.knissel@iwu.de)

Lighting – Cakir and Cakir 1998
Lighting control = Individual productivity + Health
In a 1998 multiple building study in Germany, Çakir and Çakir identify a 19% reduction in headaches for workers with separate task and ambient lighting, as compared to workers with ceiling-only combined task and ambient lighting.

Cakir, A.E. and Cakir, G. (1998) Light and Health: Influences of Lighting on Health and Well-being of Office and Computer Workers, Ergonomic, Berlin.

Lighting Control – Juslen et al 2007 (Industrial)

Controllable task lighting + increased light levels = Individual productivity

In a 2003 building case study of a factory in Finland, Juslen et al identify a 4.43% improvement in the factory worker productivity (measured in product output) by providing individually-controlled, dimmable task lighting capable of increasing maximum desktop illuminance to 3000 lux, as compared to non- dimmable task lights that limited total desktop illuminance to 700 lux.

H. Juslen, M. Wouters, A. Tenner (2007) The influence of controllable task-lighting on productivity: a field study in a factory. Applied Ergonomics

Lighting Control - Juslen et al 2007 (Industrial)
Additional localized lighting = Individual Productivity

In 2007 study, Juslen et al identified average of 3% improvement on productivity by measuring machine repairing time localized task lighting in shift work in a Finland chocolate factory package room with 16 subjects. Although some important factors varied during the test period, short-term and long-term absenteeism were each reduced by 4% and 17% compared with the situation before the addition of lighting installation.

Juslen,H.T., Verbossen, J & Wouters, M.C.(2007). Appreciation of localised task lighting in shift work – A filed study in the food industry/ International Journal of Industrial Ergonomics (37), 433-443.

A Lab study in Taiwan/ Kuang-Sheng Liu et al. 2010
Lighting control = Individual productivity + Energy saving

In a study about the influence of visual fatigue on working performance when using visual display terminals(VDTs) in 2010, Kuang-Sheng Liu identifies that with LED lighting, the productivity is better. And in terms of productivity, the 200lux lighting environment was better than the 500lux lighting. Replacing the T5-500lux with LED-200lux can achieve 3.18% increment of productivity.

Liu, Kuang-Sheng Liu, Che-Ming Chiang, Yu-Sen Lin. 2010, Influences of visual fatigue on the productivity of subjects using visual display terminals in a light-emitting diode lighting environment', Architectural Science Review, 53: 4,384- 395.

Lighting Control = Joines et al., 2014 (Office)
Adjustable LED task lighting = Health + Energy Savings

A 2014 intervention study involving 95 Duke Clinical Research Institute office employees provided adjustable 7-watt LED task lights to 48 subjects to replace fluorescent underbin and CFL desk lamps, all with 200-500 lux overhead light. Joines et al. identify a 9.2% reduction in headaches ($p = 0.0118$) while reading or doing close work as the result of 6 months of LED task-light use.

Joines, S., James, T., Liu, S., Wang, W., Dunn, R., & Cohen, S. (2014). Adjustable task lighting: Field study assesses the benefits in an office environment. Work: A Journal of Prevention, Assessment and Rehabilitation, 14(1).

Lighting Control – Nishihara et al. 2006 (Office)
Split Task and Ambient Lighting = Individual productivity

In a 2006 experiment at Waseda University in Japan, Nishihara et al. identified an 11% improvement on a triple digit multiplication task (p=0.01) when subjects could control their task lights (400 lux fixed + 300 lux variable) as compared to when they could not (700 lux fixed). The performance on text typing also tended to be higher (p = 0.09) when task lights were controlled.

Nishihara, N., Nishikawa, M., Haneda, M., and Tanabe, S. (2006) Productivity with Task and ambient lighting system evaluated by fatigue and task performance, Proceedings of Healthy Buildings 2006, Lisbon, Portugal, pp. 249-252

4. Upgrade lighting with Individually addressable LED lamps

Day Lighting Control - Lee and Selkowitz 2006
Daylight Control Systems = Energy Savings

In a 2004 study involving the mock-up of the New York Times office building, Lee and Selkowitz identify a 59% savings in lighting energy consumption due to the use of daylight control systems with automated roller shades and DALI ballasts, as compared to a base case building with a conventional lighting system. Post occupancy, in 2008, the New York Times building achieved 70% lighting energy savings. Lighting power density reduced from 1.28/sf. to 0.39/sf. without affecting the design luminance level of 500 lux at workstations.

Lee, E. S. and Selkowitz, S. E. (2006): The New York Times Headquarters Day lighting Mockup; Monitored performance of the day lighting control system: Energy and Buildings; 38, pp. 914–929. LBNL-56979.

Vattenfall Office / Hedenstrőm et al 2001
Lighting Control = Energy Savings + FM Savings

In a 1991 building case study of a lighting system retrofit at a commercial office in Sweden, Hedenstrőm et al. identified 74% annual lighting energy savings, 66% peak demand reduction, and 77% savings in lighting system maintenance costs due to a new high-performance lighting design with energy-efficient fixtures, high-frequency ballasts and occupancy sensors.

Claes Hedenstrőm, Lars Hedstrőm, Allan Ottosson, "Measure energy savings and cost-effectiveness of the lighting retrofit at Vattenfall's office in Racksta, Stockholm" Uppdrag 2001

Lighting – PP&L / Romm and Browning 1994
Lighting Control = Individual Productivity + Energy Savings

In a 1994 before and after building case study of the Pennsylvania Power and Light (PP&L) drafting office in Allentown, PA, Romm and Browning identify a 13.2% increase in productivity, a 25% reduction in absenteeism and 69% lighting energy savings following a lighting retrofit introducing high-efficiency ballasts, T-8 fluorescent lamps and parabolic louver fixtures.

Romm, J.J., and W.D. Browning (1994). Greening the Building and the Bottom Line - Increasing Productivity Through Energy-Efficient Design. Rocky Mountain Institute.

Lighting - Reynolds Metals / Energy User News 2001

Lighting Control = Energy Savings

In a 2001 case study of the Reynolds Metals Company office in Richmond, VA, Energy User News identifies an 87% reduction in lighting energy consumption following a retrofit with Ledalite's Ergolight intelligent lighting system, in which each luminaire provides personal dimming, occupancy sensing, daylight-responsive dimming and centralized network control.

Reynolds Saves Over 85% in Energy Costs, Improves Lighting Quality. (2001) Energy User News 26:2, pp. 26- 27. Audin, Lindsay (2001) A brainy luminaire for the 21st century. Architectural Record 189:11, pp. 208.

Lighting - B.C. Hydro / Wood et al 2003

Lighting Control = Energy savings

In a 2003 building case study of B.C. Hydro in British Columbia, Canada, Wood et al. identified 80% lighting energy savings following an upgrade with Ledalite's Ergolight intelligent lighting system, in which each direct/indirect luminaire integrates personal dimming, occupancy sensing and centralized network control, as compared to the original lighting system that consisted of 2x4 recessed troffers with two T8 lamps and deep-cell parabolic louvers.

Wood, D.L., Hughes R., and Cristian Suvagau, 2003, Addressable office lighting and control system: Technical considerations & utility evaluations, Energy Engineering, Vol. 100, # 2, p.22

Lighting Controls – Hawes et al 2012 (Office)

High Color Temperature LED Lighting = Improved Individual Productivity

In a 2012 lighting study of workplaces in Massachusetts, with 24 participants, for 5 days of lab experiments, Hawes et al. identified a 8.34% improvement of work performance in visual tasks and cognitive tasks due to the use of LED lighting with high color temperature and adequate illuminance level, as compared to traditional fluorescent lighting.

Hawes, B. K., Brunye, T. T., Mahoney, C. R., Sullivan, J. M., & Aall, C. D. (2012). Effects of four workplace lighting technologies on perception, cognition and affective state. International Journal of Industrial Ergonomics, 42, 122-128.

Lighting - Aaras et al 1998

Lighting Control = Health

In a 1998 controlled experiment, Aaras et al identify a 27% reduction in the frequency of headaches in computer workers when conventional downlighting is replaced by user-controlled suspended indirect- direct lighting (75/25) and venetian blinds are added to windows.

Aaras, A., Horgen, G., Bjorset, H., Ro, O., and Thorsen, M. (1998) Musculoskeletal, Visual and Psychosocial Stress in VDU Operators Before and After Multidisciplinary Ergonomic Interventions. Applied Ergonomics, pp. 335- 354.

Lighting – Wilkins et al 1989
Lighting control = Individual productivity + Health
In a 1989 controlled field experiment at a government legal office in the UK, Wilkins et al identify a 74% reduction in the incidence of headaches among office workers when magnetic ballasts are replaced by high frequency electronic ballasts.

Wilkins, AJ, Nimmo-Smith, I, Slater, AI, Bedocs, L. (1989) Fluorescent lighting, headaches and eyestrain. Lighting Research and Technology 21(1), pp. 300-307.

Lighting - National Lighting Bureau 1988
Lighting Control = Individual Productivity + Energy Savings
In a 1988 before and after building case study of Control Data Corporation in Sunnyvale, California, the National Lighting Bureau identifies a 6% increase in worker productivity and a 65% decrease in lighting energy consumption following a lighting retrofit with high-efficiency fixtures and full-spectrum fluorescent lamps.

National Lighting Bureau (1988) The NLB Guide to Office Lighting and Productivity.
Zmirak, John P., (1993) Workplace Utopia. Success, 40:2, pp. 35-41.

Lighting - Newsham et al 2004 (Office)
Individual dimming control = Individual productivity
In a 2004 controlled experiment of 118 subjects in Canada conducted by Institute of research in construction, Newsham et al identify a 2.09% and 10.19% improvement in typing and computer based complex cognitive tasks respectively among subjects in lab experiment when provided with dimming control for ambient lighting as compared to when there was no dimming control system.

Newsham,G; Veitch, J.; Arsenault, C; Duval,C.(2004). Effect of dimming control on office worker satisfaction and performance, IESNA Annual conference proceedings, Tampa, Florida, July 25-28,2004 (p.p. 19-41), National research council Canada.

Lighting Controls – Hoffmann et al 2008 (Office)
Simulated Daylighting = Individual Productivity
In a 2008 lighting study of office workplaces in Austria, with 11 male participants, for 6 days of simulated full time office work experiments, Hoffmann et al. identified a 33% improvement of mood ratings due to the use of day lighting simulated lighting with 500-1800 lx, 6500 K, as compared to regular fluorescent lighting with 500 lx, 4000 K.
In a 2007 study, Braun-LaTour et al identify a 5.76% work efficiency increase due to positive mood (compared to neutral mood).

Hoffmann, G., Gufler, V., Griesmacher, A., Bartenbach, C.,Canazei, M., Staggl, S., & Schobersberger, W. (2012). Effects of variable lighting intensities and color temperatures on sulphatoxymelatonin and subjective mood in an experimental office workplace. Applied Ergonomics, 39, 719-728.
Braun-LaTour, K. A., Puccinelli, N. M., & Mast, F. W. (2007). Mood, information congruency, and overload. Journal of Business Research, 60(11), 1109-1116.

LED Lighting – Meyers 2009

Lighting Control = Facilities Management Savings + Energy Savings

In a 2009 lighting simulation study of three layouts of healthcare facilities, Meyers identified a 100% savings in maintenance costs and mercury disposal costs and a 76% energy savings by using LED fixtures instead of typical T8 fluorescent fixtures to deliver the same light levels in corridors, 24-hour a day waiting rooms and exam rooms.

Meyers, A. (2009, July 15). Use of LED fixtures in Healthcare Facilities. M+NLB: Mazzetti, Nash, Lipsey, Burch. Retrieved from http://www.mazzetti.com/images/uploads/LED.pdf

5. Replace fixtures with integrated LED lighting and dimming & IP addressable controls

Newsham et al 2007 - Office

Individual lighting control= Energy Saving

In a 2007 glare-free, daylit office laboratory in Ottawa, Canada, G.R. Newsham et al identified individual satisfaction increase and 25% energy saving due to manual control of electric lighting in a daylit space, as compared to a fixed system on the desktop which deliveries 500 lx electric lighting, and 150% increase of energy saving compared to manual control without daylit.

Newsham, G. R., Aries, M., Mancini, S., & Faye, G. (2008). Individual control of electric lighting in a daylit space. Lighting Research and Technology, 40(1), 25-41.

LED Lighting – Meyers 2009

Lighting Control = Facilities Management Savings + Energy Savings

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Meyers, A. (2009, July 15). Use of LED fixtures in Healthcare Facilities. M+NLB: Mazzetti, Nash, Lipsey, Burch.

Lighting - Raytheon / Chamberlain and Fialli 2001

Lighting Control = Energy savings

In a 2001 case study of Raytheon Company's Building 200 in Tewksbury, Massachusetts, Chamberlain and Fialli identified 83% lighting energy savings following an upgrade with Ledalite's Ergolight intelligent lighting system, in which each luminaire integrates personal dimming, occupancy sensing and centralized network control, as compared to the original 2x4 T-12 lighting.

Chamberlain, David R. and Fialli, Tracy L. (2001) The Right Light
Audin, Lindsay (2001) A brainy luminaire for 21st century. Architectural Record 189:11, pp 208.

Lighting Control in Commercial Buildings – Williams et al 2012 (Office)

Lighting Control = Energy Savings

In a 2012 meta-analysis of 88 installation and simulation studies presenting 240 savings estimates for commercial buildings in the United States, Williams et al. identified 24%-36% energy savings when methods of lighting controls, including daylighting, institutional tuning, personal tuning, or occupancy sensing are used for building lighting controls. Additionally, a statistically significant energy savings of 38 % ($p<0.05$) was identified when multiple control strategies were combined for building lighting control.

Williams, A., Atkinson PE, B., Garbesi PhD, K., Page PE, E., Rubinstein FIES,F. (2012) "Lighting Controls in Commercial Buildings." Leukos, Volume 8 No. 3, 161-180.
CBECS (2008) "2003 Commercial Buildings Energy Consumption Survey: Consumption and Expenditures Tables" Energy End-Use Consumption Tables, Table E5.

Lighting Controls – Hawes et al 2012 (Office)
High Color Temperature LED Lighting = Improved Individual Productivity
In a 2012 lighting study of workplaces in Massachusetts, with 24 participants, for 5 days of lab experiments, Hawes et al. identified an 8.34% improvement of work performance in visual tasks and cognitive tasks due to the use of LED lighting with high color temperature and adequate illuminance level, as compared to traditional fluorescent lighting.

Hawes, B. K., Brunye, T. T., Mahoney, C. R., Sullivan, J. M., & Aall, C. D. (2012). Effects of four workplace lighting technologies on perception, cognition and affective state. International Journal of Industrial Ergonomics, 42, 122-128.

Lighting Controls – Hoffmann et al 2008 (Office)
Simulated Daylighting = Individual Productivity
In a 2008 lighting study of office workplaces in Austria, with 11 male participants, for 6 days of simulated full-time office work experiments, Hoffmann et al. identified a 33% improvement of mood ratings due to the use of day lighting simulated lighting with 500-1800 lx, 6500 K, as compared to regular fluorescent lighting with 500 lx, 4000 K.

In a 2007 study, Braun-LaTour et al identify a 5.76% work efficiency increase due to positive mood (compared to neutral mood).

Hoffmann, G., Gufler, V., Griesmacher, A., Bartenbach, C,Canazei, M., Staggl, S., & Schobersberger, W. (2012). Effects of variable lighting intensities and colour temperatures on sulphatoxymelatonin and subjective mood in an experimental office workplace. Applied Ergonomics , 39, 719-728.

Blue-enriched White Light – Airline Office in Poland / Iskra-Golec et.al 2012
Blue-enriched Light = Individual Productivity
In a 2010 field study of an office in Poland Iskra-Golec et al, reported a 9.3%（$p=0.008$）more energetic work status in 1/3 of the work time in Blue-enriched White Light (more short wave light

of 420-480nm) than in White Light. A sleepiness increase of 5.8%(p=0.000) was also reported in 1/3 of the work time.
Assuming the improvement of energy status influence the work productivity to an equal extent, productivity increase was 3.1%. Sleepiness causes effective time loss, so the productivity loss was 1.93%. In all, the productivity increase was 1.17%.

Iskra-Golec et al, Effect of Blue-enriched White Light on the Daily Course of Mood, Sleepiness and Light Perception: A Field Study, Lighting Research and Technology, 22 June 2012.

Lighting – Liu et al (office)
Lighting = Individual Productivity
In a 2010 lab lighting study in Taiwan with 30 participants, Kuang-Sheng Liu et al. identified a 2% increase in individual productivity due to the change of lighting environment from T5 fluorescent lamps to white LED lights under a 200lux condition, when participants are using Visual Display Terminals.

Kuang-Sheng Liu, Che-Ming Chiang & Yu-Sen Lin (2010). Influences of visual fatigue on the productivity of subjects using visual display terminals in a light-emitting diode lighting environment. Architectural Science Review, 53:4, 384-395.

6. Select blinds for light redirection, shade and glare control

Daylight Optimization – De Carli and De Giuli 2009
Active User Behavior + Automated Controls = Energy Savings
In a 2009 building simulation study, De Carli and De Giuli investigated the effects of different types of shading and lighting controls in combination with three types of user behavior for five different latitudes. De Carli and De Giuli determined that a 32% reduction in electricity use could be achieved in an office with automated blinds and lighting controls where users' behavior was categorized as "mixed" as compared to "passive". Additionally, a potential 77% reduction in electricity use was identified in the case of a fully automated system and mixed user behavior as compared to manual controls and passive user behavior.

De Carli, M. and De Giuli, V (2009): Optimization of Daylight in Buildings to Save Energy and To Improve Visual Comfort; Analysis in Different Latitudes: Eleventh International IBPSA Conference; Glasgow, Scotland: July 27-30.

Access to Natural Environment – Choi et al. 2012 (Hospital)
Daylighting = Health
In a 2012 field study of 1,167 hospital patients in Incheon, Korea, Choi et al. identified a 29% reduction in the average length of stay (ALOS) of hospital patients with various illnesses due to higher illuminance levels from daylighting, and a greater ability to vary illuminance levels with vertical blinds in rooms facing the southeast as compared to rooms facing the northwest.

Choi, J.; Beltran, L.; and Kim, H. (2012): Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility: Building and Environment; 50, pp. 65-75.
Healthcare Cost and Utilization Project [HCUP] (2009): Agency for Healthcare Research and

Blinds Control – Lee et al. 1998
Lighting Control = Energy Savings + Individual Productivity
In a 1998 14-month side by side field study in a Federal Office Building in Oakland, California, Lee et al. measured a 7-15% savings in lighting energy and a 19-52% savings in cooling energy as well as identified an increased indoor lighting quality due to the integration of dynamic Venetian blinds shifting from 0° to 45° with a dimmable lighting system responding to daylight.

Lee, E.S., DiBartolomeo,D.L., & Selkowitz, S.E. (1998). Integrated Performance of an Automated Venetian Blind/ Electric Lighting System in a Full Scale Private Office, from http://gaia.lbl.gov/btech/papers/41443.pdf
Lee, E.S., DiBartolomeo,D.L., & Selkowitz, S.E. (1998). Thermal and Daylighting Performance of an Automated Venetian Blind and Lighting System in a Full Scale Private Office, Energy and Buildings, 29(1),47-63

Blinds - Zhang and Altan 2010 & Osterhaus and Bailey 1992 (office)
Glare control = Individual Productivity
In a 1992 lab experiment conducted using 6 female and 20 male subjects, Osterhaus and Bailey found a 3% productivity increase in visual task efficiency at the computer by reducing glare discomfort.

Zhang, Y.; and Altan, H. (2011): A comparison of the occupant comfort in a conventional high-rise office block and a contemporary environmental building: Building & Environment; 46 (2).
Osterhaus, W. and Bailey, I. (1992): Large Area Glare Sources and Their Effect on Discomfort and Visual Performance at Computer Workstations: 1992 IEEE Industry Applications Society Annual Meeting; Houston, TX: LBL-35037.

Access to Natural Environment - SMUD Call Center / Heschong Mahone Group. 2003a
Seated Access to the Natural Environment = Individual Productivity
In a 2003 building case study of the Sacramento Municipal Utility District (SMUD) Call Center, Heschong et al identify an average 6.7% faster Average Handling Time (AHT) for employees with seated access to larger windows and a view with vegetation content from their cubicles, as compared to employees with no view of the outdoors.

Heschong, Mahone Group, Inc. (2003) Windows and Offices : A study of office worker performance and the indoor environments, California Energy Commission Technical Report

7. Add light shelves in clerestory

Daylight Optimization – De Carli and De Giuli 2009
Active User Behavior + Automated Controls = Energy Savings
In a 2009 building simulation study, De Carli and De Giuli investigated the effects of different types of shading and lighting controls in combination with three types of user behavior for five different latitudes. De Carli and De Giuli determined that a 32% reduction in electricity use could be achieved in an office with automated blinds and lighting controls where users' behavior was

categorized as “mixed” as compared to “passive”. Additionally, a potential 77% reduction in electricity use was identified in the case of a fully automated system and mixed user behavior as compared to manual controls and passive user behavior.

De Carli, M. and De Giuli, V (2009): Optimization of Daylight in Buildings to Save Energy and To Improve Visual Comfort; Analysis in Different Latitudes: Eleventh International IBPSA Conference; Glasgow, Scotland: July 27-30.

Daylighting – EPFL / Mirjam, M. et al. (2011)
Daylighting = Individual Productivity + Energy Saving
In a 2011 lab experiment in the Swiss Federal Institute of Technology, Lausanne(EPFL), Mirjam et al identify an average 4.1% accuracy enhancement in the early evening performance for young healthy subjects with prior daylight exposed during the afternoon provided by anidolic daylight system, as compared to those with artificial light exposed provided by conventional fluorescent lighting system.

Mirjam, M. Friedrich, L. Apiarn, B. (2012) Effects of Prior Light Exposure on Early Evening Performance, Subjective Sleepiness, and Hormonal Secretion

Blinds - Zhang and Altan 2010 & Osterhaus and Bailey 1992 (office)
Glare control = Individual Productivity
In a 1992 lab experiment conducted using 6 female and 20 male subjects, Osterhaus and Bailey found a 3% productivity increase in visual task efficiency at the computer by reducing glare discomfort.

Zhang, Y.; and Altan, H. (2011): A comparison of the occupant comfort in a conventional high-rise office block and a contemporary environmental building: Building & Environment; 46 (2).
Osterhaus, W. and Bailey, I. (1992): Large Area Glare Sources and Their Effect on Discomfort and Visual Performance at Computer Workstations: 1992 IEEE Industry Applications Society Annual Meeting; Houston, TX: LBL-35037.

8. Celebrate external shading - check table and figure

Blinds - Zhang and Altan 2010 & Osterhaus and Bailey 1992 (office)
Glare control = Individual Productivity
In a 1992 lab experiment conducted using 6 female and 20 male subjects, Osterhaus and Bailey found a 3% productivity increase in visual task efficiency at the computer by reducing glare discomfort.

Zhang, Y.; and Altan, H. (2011): A comparison of the occupant comfort in a conventional high-rise office block and a contemporary environmental building: Building & Environment; 46 (2).
Osterhaus, W. and Bailey, I. (1992): Large Area Glare Sources and Their Effect on Discomfort and Visual Performance at Computer Workstations: 1992 IEEE Industry Applications Society Annual Meeting; Houston, TX: LBL-35037.

Temperature Control - Witterseh 2001b
Individual temperature control = Individual productivity
In a 1998 controlled experiment, Witterseh identifies a 54% increase in addition accuracy and a 3.5% typing improvement when subjects feel thermally comfortable, rather than too warm, in quiet office conditions (35dBA).

Witterseh, T. (2001) Environmental Perception, SBS Symptoms and the Performance of Office Work under Combined Exposures to Temperature, Noise and Air Pollution. Ph.D. Thesis, Technical University of Denmark, Denmark.

9. Ensure windows are operable for natural ventilation

Access to Natural Environment - Steemers and Manchanda, 2009
Natural Ventilation = Energy use + Occupant satisfaction
In a 2009 cross sectional study of 12 office buildings in the UK and India, Koen Steemers and Shweta Manchanda identify a 50% decrease in the total energy consumption and 20.8% increase in overall occupant satisfaction for the naturally ventilated buildings in UK and a 63% decrease in the total energy consumption and 11.6% increase in overall occupant satisfaction for the naturally ventilated buildings in India, as compared to the air-conditioned buildings in both locations.

Koen Steemers, Shweta Manchanda (2009). Energy efficient design and occupant well-being: Case studies in the UK and India. Elsevier Ltd., 9.

Access to Natural Environment - Zweers T. et al, Office 1989
Access to Operable Windows = Reduction in Sick Building Syndromes
In winter 1988 - 1989 cross sectional study of 61 buildings with 7,043 workers in Netherlands, Zweers T. et al identified percentage reduction in Sick Building Syndromes for fever (45%), skin irritations (49%), nasal (39%), eye irritations (45%) and headaches (51%) in a population of 2,806 workers due to presence of operable windows compared to buildings with air cooling systems only.

T. Zweers, L. Preller, B. Brunekreef, J.S.M Boleji (1992), Health & Indoor Climate Complaints of 7,043 Office Workers in 61 buildings in the Netherlands.

Access to Natural Environment - Toftum 2010 (Office)
Natural Ventilation + Occupant Control = Health
In a 2004-2008 cross sectional study of 24 Danish office buildings and 1,272 occupants, Toftum identified a lower prevalence of building related symptoms and higher occupant satisfaction in the naturally ventilated offices as compared to in sealed offices. Additionally, out of 6 building related symptoms, Toftum identified a 9% lower prevalence of eye irritation in the naturally ventilated buildings as compared to the sealed buildings, thus reinforcing the findings of Hummelgaard et al (2007).

Toftum, J. (2010): Central automatic control or distributed occupant control for better indoor environment quality in the future: Building and Environment; 45(1), pp. 23-28.

Access to Natural Environment - Teeuw et al. (1994) / Governmental Office Study
Natural Ventilation = Health + Individual Productivity

In a 1994 study of 19 governmental office buildings in Netherland, Teeuw et al. identified 30.6% overall reduction in Sick Building Syndrome (SBS) symptoms when the negative-gram rods reduced from 22 to 5 CPU/m3 and endotoxin level reduced from 254 to 35 ng/m3 which happens in naturally ventilated buildings as compare to mechanically ventilated buildings

In a 2000 study, Wargocki et al identify a 1.1% productivity improvement for every 10% reduction in SBS symptoms, implying a 3.3% improvement in productivity in this case.

Teeuw, K. B., Vandenbroucke-Grauls, C. M., & Verhoef, J. (1994). Airborne Gram-negative Bacteria and Endotoxin in Sick Building Syndrome - A Study in Dutch Governmental Office Buildings. Archives of Internal Medicine, 154(20), 2339–2345.

Access to Natural Environment - Burge et. al. 1987(Office)
Natural Ventilation = Improved Health + Productivity

In a 1987 cross sectional study of 42 buildings (4373 office workers) in the United Kingdom, Sherwood Burge et. Al. identify a percentage reduction in self-perceived work-related symptoms-dry eyes (41.9%), Itchy Eyes (29%), runny nose (9.5%), blocked nose (11.1%), dry throat (21.7%), Lethargy (10.7%), Headaches (9.3%), flu (40%), difficulty in breathing (33.3%) and chest tightness (25%) in naturally ventilated buildings as compared to buildings that support other modes of ventilation giving an average reduction of 23.11%.

Wargocki et al in a 2000 study, identify a 1.1% productivity increase for every 10% reduction in SBS complaints, suggesting a 2.54% gain in productivity gain due to natural ventilation.

Burge, S. (1987). Sick Building Syndrome: A study of 4373 office workers. Pergamon Journals Ltd., 31, 493-504. doi:1987.

Access to Natural Environment - Olli and Fisk. (2002)
Natural Ventilation = Reduced SBS symptoms

In a 2002 meta-analysis of 12 studies (467 office buildings and n = 24,000 subjects) across 6 European countries and the USA, Olli et al. (2002) identify a 23-67% decrease in SBS symptoms in naturally ventilated offices as compared to air-conditioned offices in 16 assessments within the 12 studies that spanned four locations. In these studies, the common SBS symptoms that were evaluated across all studies can be grouped as eye symptoms, upper respiratory, lower respiratory and central nervous system.

In a 2000 study, Wargocki et al. (2000) identified a 1.1% productivity increase for every 10% reduction in SBS complaints suggesting a 3.3% - 22% productivity gain due to natural ventilation.

Olli, S., & Fisk, W. J. (2002). Association of ventilation system type with SBS symptoms in office workers. Indoor Air, 12(2), 98-112.

Access to Natural Environment - Zhounghua & Siu-Yu 2012
Indoor Plants + Operable Windows = Individual Productivity & Health

In a 2012 cross sectional study of 30 office buildings in Hong Kong (n = 469), Zhonghua and Siu-Yu identify a reduction in Sick Building Syndrome Symptoms (SBS) with the presence of indoor plants and operable windows, resulting in an average reduction of 42.50% of sinus conditions (p = 0.025), a 47.33% reduction in skin irritation (p = 0.025), a 16.3% reduction of headaches (only significant with the presence of operable windows, p = 0.027), and a 63.60% reduction in eye irritation (only significant with the presence of indoor plants, p = 0.040).

Zhonghua Gou, Stephen Siu-Yu Lau, (2012), "Sick building syndrome in open-plan offices: Workplace design elements and perceived indoor environmental quality", Journal of Facilities Management, Vol. 10 Iss: 4 pp. 256-265.

Access to Natural Environment - Harrison et al (1992) /Office
Natural Ventilation=A Reduction of Symptoms + Increased Productivity

In a 1992 cross sectional building study in Great Britain, Harrison et al found a causal link between symptom prevalence rates and airborne bacteria levels. The study analyzed 15 buildings and 4,610 clerical workers. Symptom prevalence decreased by 20% when buildings utilized natural ventilation versus mechanical ventilation with recirculation. Natural ventilation increases airflow which, according to Wargocki et al, can increase overall productivity up to 1.7% per twofold increase in ventilation rate.

Harrison, J. et al. (01 May 1992). "An investigation of the relationship between microbial and particulate indoor air pollution and the sick building syndrome". Respiratory medicine, 86.3: 225-235. Elsevier. 29 Sep. 2015.

Access to Natural Environment - Gao, Wargocki & Wang, 2014
Demand Controlled Ventilation = Health

In a 2013 controlled field study of 4 classrooms, each with a different ventilation system, with 80-100 students aged 10-15 in Denmark over two 1 month periods in May and December, Gao et al. found significant reductions in self-reported symptoms of sick building syndrome (SBS), including a 39% reduction in headaches in classrooms with automatically opening windows and an exhaust fan controlled by CO_2 sensors ($p<.05$) as compared with classrooms with mechanical ventilation with air filtration. According to Collin et al., headaches account for 1% of school absences.

Gao, J., Wargocki, P., & Wang, W. (2014). Ventilation System Type, Classroom Environmental Quality and Pupils' Perceptions and Symptoms. Building and Environment. 75, p. 46-57.

Access to Natural Environment – Hummelgaard et al. 2007 (Office)
Natural Ventilation = Health + Productivity

In a 2007 study of 9 office buildings in Copenhagen, Denmark, Hummelgaard et al. identified 31% less prevalence of SBS symptoms and 49-86% less self-reported eye itching as an SBS symptom among workers in naturally ventilated buildings compared to workers in mechanically ventilated buildings.

Hummelgaard, J.; Juhl, P.; Saebjornsson, K.; Clausen, G.; Toftum, J.; and Langkilde, G. (2007): Indoor Air Quality and Occupant Satisfaction in Five Mechanically and Four Naturally Ventilated Open-plan Office Buildings: Building and Environment; 42, pp. 4051-4058.

Air - Rios et al. 2009 (Office)
Natural Ventilation = Health

In a 2003 cross sectional study of 3,686 office workers in 2 office buildings in downtown Rio De Janeiro, Brazil, Rios et al. identified a lower prevalence of self-reported work-related symptoms including eye dryness (by 18.6%), runny nose (by 16.1%), dry throat (by 14.3%), and lethargy (by 13.7%) of workers in the naturally ventilated building compared to workers in the sealed office building, despite high levels of RH, PM and VOCs in the naturally ventilated building.

Rios, J.; Boechat, J.; Gioda, A.; Santos, C.; Aquino Neto, F.; and Silva, J. (2009): Symptoms prevalence among office workers of a sealed versus a non-sealed building; Associations to indoor air quality: Environment International; 35 (8), pp. 1136-1141.

Ventilation = Health + Individual Productivity

In a 1988 multiple building study in Berlin and Heidelberg, Kroeling identifies a 33% reduction in reported headaches, a 28% reduction in reported frequency of colds and a 31% reduction in reported circulation problems in naturally ventilated office buildings, as compared to air conditioned office buildings.

Kroeling, P. (1988). Health and well-being disorders in air conditioned buildings; comparative investigations of the "building illness" syndrome. Energy and Buildings, 11(1-3): 277-282.

10. Integrate Underfloor Air and networking

Air - Fisk et al 2005 | EPA 1989 (Office, S, H)

Floor-based ventilation = Energy savings + Improved pollutant removal

In a 2005 building case study, Fisk et al identified an estimated average 16.5% reduction in sensible energy demand and a 13% reduction in indoor pollutant concentration due to underfloor air delivery, as compared with conventional overhead air delivery.

A 1989 analysis by the U.S. EPA indicates that the self-reported productivity loss due to substandard indoor air quality is 3.3%, suggesting a potential 0.43% productivity gain due to underfloor air.

Fisk, W., D. Faulkner, D. Sullivan, C. Chao, M.P.Wan, L. Zagreus and T. Webster. (2005) Results of a field study of underfloor air distribution. LBNL report 57098.
U.S. Environmental Protection Agency (1989) Report to Congress on Indoor Air Quality, Volume II: Assessment and Control of Indoor Air Pollution. (EPA/400/1-89/001C) U.S. Environmental Protection Agency, Office of Air and Radiation, pp. 5-11 – 5-15.

Air – Akimoto et al 1999

Floor-based Ventilation = Energy Savings

In a 1999 controlled experiment and simulation study, Akimoto et al identify 34% cooling and ventilation energy savings from replacing a conventional ceiling-based air distribution system with floor-based displacement ventilation and thermal conditioning.

Akimoto, T., Nobe, T., Tanabe, S. and Kimura,K. (1999) Floor Displacement Air Conditioning: Laboratory Experiments. ASHRAE Transactions, SE-99-7-1, pp. 739-749.

Air – Milam 1992
Floor-based Ventilation = First Cost Savings + Energy Savings
In a 1992 simulation study of an Atlanta office building, Milam identifies $0.43 per square foot savings in first cost and 1.55kWh per square foot energy savings with underfloor air distribution systems, as compared to conventional ceiling-based air delivery systems.

Milam, J.A. (1992) Underfloor Air Distribution HVAC Analysis – Prepared for USG Interiors Inc. Environmental Design International.
Fitzner, K. (1985) Buroklimatisierung. Die Kalte und Klimatechnik, October 1985, pp. 468-478.
Toothacre, Jim (2003). Churn: The High Performance Green Building Trump Card.

Air – Hu et al 1999
Floor-based Ventilation = Energy Savings
In a 1999 simulation study, Hu et al identify 8% energy savings from replacing a conventional ceiling-based ventilation system with floor-based displacement ventilation & thermal conditioning.

Hu, S., Chen, Q., Glicksman, L.R. (1999) Comparison of Energy Consumption Between Displacement and Mixing Ventilation Systems for Different U.S. Buildings and Climates ASHRAE Transactions, Vol.2, pp. 453-464.

Network Access – York 1993
Network Access = Churn Savings + FM Savings
In a 1993 (multiple building/economic analysis) study, York identifies a 79% reduction in churn cost and a 40% reduction in facility management staffing costs annually in a building with a raised access floor and modular wiring, as compared to a conventional building with poke-through wiring distribution and wired systems furniture.

York, T.R. (1993). Can you Afford an Intelligent Building? FM Journal, Sept/October, pp. 22-27

Network Access – Owens Corning / CBPD 1997
Network Access = Churn Savings
In a 1997 building case study of the Owens Corning headquarters in Toledo, OH, the Center for Building Performance (CBPD) at Carnegie Mellon University identifies 67% organizational and technological churn savings, amounting to $300 per move, due to the use of a raised floor with re-locatable data/power boxes and air diffusers.

Center for Building Performance and Diagnostics (1997) Building Study of Owens Corning World Headquarters. Center for Building Performance and Diagnostics (CBPD), Carnegie Mellon University, Pittsburgh, PA.

Network Access – Ellerbe Becket 1992
Network Access = Churn Savings
In a 1992 comparison study commissioned by the United States General Services Administration, Ellerbe Becket identifies a 77% decrease in annual churn cost in a building model with raised access flooring and modular wiring over an identical building model with a cellular floor system.

Ellerbe Becket (1992). GSA Access Floor Study. U.S. General Services Administration, September 10, 1992.

Network Access – South Central Regional Office Building / Toothacre 2003
Network Access = Churn Savings

In a 2003 building case study of two Pennsylvania Department of Environmental Protection office buildings, James Toothaker identifies a 90.1% decrease in churn cost in the new South Central Regional Office Building with underfloor HVAC, power and tel/data systems over an existing DEP building with ceiling-based HVAC and a cellular floor.

Toothacre, Jim (2003). Churn: The High Performance Green Building Trump Card.
Hu, Shiping, Chen, Qingyan and Glicksman, Leon R. (1999). Comparison of Energy Consumption between Displacement and Mixing Ventilation Systems for Different U.S. Buildings and Climates. ASHRAE Transactions, Vol. 2, 4315 (RP-949), pp. 453-464.

Air – Fitzner 1985 | EPA 1989
Floor-based Ventilation = Individual Productivity

In a 1985 controlled experiment, Fitzner identifies a 20% reduction in indoor pollutant concentration in spaces with underfloor air systems, as compared to conventional overhead air delivery. A 1989 analysis by the U.S. EPA identifies a 3.3% productivity loss due to substandard air quality. Together, these two studies suggest a potential 0.7% productivity increase due to the use of an underfloor air system.

Fitzner, K. (1985) Buroklimatisierung. Die Kalte und Klimatechnik, October 1985, pp. 468-478.
Sodec, F. and Craig, R. (1992) The Underfloor Air Supply System – the European Experience. ASHRAE Transactions, Vol. 90, Part I, pp. 690-695.
U.S. Environmental Protection Agency (1989) Report to Congress on Indoor Air Quality, Volume II: Assessment and Control of Indoor Air Pollution. (EPA/400/1-89/001C) U.S. Environmental Protection Agency, Office of Air and Radiation, pp. 5-11 – 5-15.

Temperature Control - Flack and Kurtz 1996
Underfloor HVAC = First cost savings

In a 1996 building case study cited by Wright, Flack + Kurtz Consulting Engineers identified a $2 per square foot savings in first cost due to integrating HVAC systems and networking beneath a raised floor, as compared to conventional overhead HVAC systems and poke-through wiring.

Wright, Gordon (1996) The underfloor air alternative. Building Design & Construction 37(11)
Fitzner, K. (1985) Buroklimatisierung. Die Kalte und Klimatechnik, October 1985, pp. 468-478.

11. Engineer Individual temperature control

Climate Control – Wargocki and Frontczak 2010 (Office)
Temperature Control = Productivity

In a 2010 meta-analysis of studies concerning human comfort and indoor environmental quality (IEQ), performed between 1977 and 2009 in locations across the world, Wargocki and Frontczak identified that thermal comfort ranks as the highest contributing factor to overall satisfaction with IEQ, and that providing occupants with the ability to control environmental conditions improves satisfaction with IEQ, supporting the decision to provide individual occupant control of the thermal environment.

Frontczak, M. and Wargocki, P (2010): Literature Survey on How Different Factors Influence Human Comfort in Indoor Environments: Building and Environment; 46, pp. 922-937.

Climate Control – Akiyama et al. 2011 (Office)
Radiant Cooling System = Increased Productivity + Reduction in CO_2 emissions
In a 2005 field study of office buildings across Japan, Akiyama et all identified a 9% increase in productivity, and a 1.5 kg-CO_2/m² reduction in CO_2 emissions in offices using task/ambient radiant cooling systems with membrane fabric, compared to those using conventional HVAC systems with individual cooling items such as desk fans and mesh office chairs.

Akiyama, Y.; Tanabe, S.; Nishihara, N.; Kasuya, A.; Wada, K.; Kawaguchi, G.; and Sako, K. (2011): Evaluation of Air Conditioning System and Cooling Items by Productivity and Eco-Efficiency: Proceedings of Indoor Air.

Climate control – Zhang et al. 2009 (Office)
Task Ambient Conditioning = Individual Productivity + Energy Savings
A 2009 field experiment conducted at the University of California at Berkley, Zhang et al. identify a 7.4% improvement in logical thinking and a 13.6% improvement in mental performance due to the use of task ambient conditioning systems. Additionally, TAC assisted HVAC systems were found to save 40% energy for wider (18C-30C) dead band and 30% energy for narrower (20C-28C) dead band than the conventional dead band (21.5C-24C).

Zhang, H.; Kim, D.; Arens, E.; Buchberger, E.; Bauman, F.; and Huizenga, C. (2009): Comfort, Perceived Air Quality, and Work Performance in a Low-Power Task-Ambient Conditioning System: Building and Environment: DOI; 10.1016/j.buildenv.2009.02.016.

Climate control – Bauman et al. 1992 (Office)
Individual temperature control = Individual productivity
In a 1992 multiple building field study of 42 workstations in three Bank of America office buildings in San Francisco, Bauman et al estimate an average 2.8% increase in employee productivity following the installation of Johnson Controls Personal Environmental Modules with individual temperature, air speed, and air direction control, in place of conventional overhead distribution systems.

Bauman, F., Baughman, A., Carter, G., and Arens, E. (1992) A Field Study of Personal Environmental Module Performance in Bank of America's San Francisco Buildings. #CEDR-01-97, Center for Environmental Design Research, University of California, Berkeley, CA.

Climate control – Witterseh et al. 2004 (Office)
Thermal Comfort = Health + Individual Productivity

In a 2000 field experiment of 30 subjects clothed for thermal neutrality at 22°C in an office laboratory at the Technical University of Denmark, Witterseh et al identify an average 32.7% decrease in eye irritation, 37.0% decrease in nose irritation, 30.6% decrease in throat irritation, 44.9% decrease in headache intensity, and a 7.5% increase in self-estimated productivity among subjects in work environments with thermal acceptability (22°C), as compared to those in warm thermal work environments (26°C).

Witterseh, T.; Wyon, D.; and Clausen, G. (2004): The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work: Indoor Air; 14 (Supplement 8), pp. 30-40.

Climate control – Wyon 1996 (Office)
Individual temperature control = Individual productivity
In a 1996 controlled experiment / meta-analysis study, Wyon identifies that providing individual temperature control over a range of 6°K (10.8°F) results in performance improvements of 2.7% on thinking and decision-making tasks, 7% on typing tasks, and 3.4% on skilled manual tasks.

Wyon, D.P. (1996) Individual microclimate control: required range, probable benefits, and current feasibility. In Proceedings of Indoor Air '96: 7th International Conference of Indoor Air Quality and Climate, Nagoya, Vol. 1, pp.1067- 1072.

Temperature control – Tanabe 2006 (Office)
Temperature Control = Individual Productivity
In a 2004-2005 field study at a call center in Japan, Tanabe identified a 2.1% improvement in operator performance (average call response rate) per 1°C decline in indoor temperature for temperatures over 25°C, supporting the need for individual temperature control.

Tanabe, S. Indoor Temperature, Productivity and Fatigue in Office Tasks. Proceedings of Healthy Buildings 2006, Lisbon, Portugal, pp. 49-56.

Temperature control - Boerstra et al (2015)
Presence of desk fans = productivity
In a 2012 laboratory experiment in Denmark, Boerstra et al identify a 4.8% improvement in mathematical and typing tasks among 23 participants by providing the participants with individual desk fans during summer. These desk fans would be controlled collectively via a central system in order to achieve productivity gain.

Boerstra, A., Kulve, M., Toftum, J., Loomans, M., Olesen, B., & Hensen, J. (2015). Comfort and performance impact of personal control over thermal environment in summer: Results from a laboratory study. Building and Environment, 87, 315-326.

Controlled experiment – Melikov et al 2012
Personalized Ventilation= Increased Performance + Energy Savings
In a controlled experiment with 30 students in a climate chamber at the Technical University of Denmark, with 4 workstations and in 5 sets of 4 hours each, Melikov et al identified an 8% increased performance (p=0.048) at Sudoku tasks between a temperature of 28ºC and 70% RH without personalized ventilation and 28ºC and 70% RH with personalized ventilation.

Personalized ventilation makes it possible to raise room temperatures without adversely affecting health, comfort and performance. Sekhar (2005) cites Sekhar (1995) and Tham (1993) for an energy saving of 20% in space cooling when temperature is raised from 23.5ºC to 26ºC.

Melikov, A.K., Skwarczynski, M.A., Kaczmarczyk.J., Zabecky, J. (2013) Use of personalized ventilation for improving health, comfort, and performance at high room temperature and humidity. Indoor Air., 23, 250-263
S. C. Sekhar, N. Gong, K. W. Tham, K. W. Cheong, A. K. Melikov, D. P. Wyon & P. O. Fanger (2005) Findings of Personalized Ventilation Studies in a Hot and Humid Climate, HVAC&R Research, 11:4, 603-620

Temperature control - Bogdan et al. 2012
Personalized Ventilation = Individual Productivity
In a 2012 lab experiment among 20 male students with personalized ventilation in Poland, Bogdan et al. achieved an average of 13% improvement in perceived productivity ($p<0.05$) by providing face-level personalized thermal control (heating/cooling) ±2℃ while maintaining room temperatures at 26℃ in summer and 20℃ in winter.

Anna Bogdan, Anna Łuczak, Marta Chludzińska, and Magdalena Zwolińska. (2012). The Effect of Personalized Ventilation on Work Productivity. International Journal of Ventilation: June 2012, Vol. 11, No. 1, pp. 91-102.

Temperature control - Kaczmarczyk (Office,2004)
Personalized Ventilation System = Individual Productivity
In a 2004 experiment study of office space in Denmark, Kaczmarczyk et al. identified an average 6.7% of self-perceived performance increase due to the use of personalized ventilation system(PVS) compared to mixing ventilation system.

In a 2008 study, Schiavon found that 10~28% cooling energy saving can be achieved by PVS with proper control strategies.

Kaczmarczyk, J., Melikov, A., & Fanger, P. O. (2004). Human response to personalized ventilation and mixing ventilation. Indoor Air, 14(s8), 17-29.

12. Invest in building performance goals

Green Building Economic Study- Eichholtz et al (2010)
Green Building Rating = Increased Rent + Sale Price
In a 2010 economic analysis using CoStar data of approximately 10,000 U.S. commercial buildings, Eichholtz et al identified LEED or Energy Star green building ratings led to a 2.8% to 3.5% increase in rental rates, a 7% increase in effective rent (rent per square foot multiplied by occupancy rate) and a 15.8%-16.8% increase sale prices ($p=0.01$). The authors further identify an additional 1.1% market value increase with each 10% reduction in site or source energy use ($p=0.01$ to 0.05).

Eichholtz, P., Kok, N., & Quigley, J. M. (2010). Doing Well by Doing Good? Green Office Buildings. The American Economic Review, 2494-2511.

CoStar Green Building Economic Study - Kok et al (2012)
LEED EBOM Green Building Rating = Increased Rent
In a 2012 controlled economic analysis using CoStar data for 374 LEED EBOM (Existing Building: Operation and Maintenance) rated and 578 control renovated U.S. commercial buildings in the same 14 markets, Kok et al identified LEED EBOM green rated buildings led to a 7% increase in rent ($p<0.01$) and a 9% increase in effective rent, i.e. the rental rate multiplied by occupancy rate ($p<0.01$).

Kok, N., Miller, N. G., & Morris, P. (2012). The Economics of Green Retrofits. The Journal of Sustainable Real Estate Volume 4, Number 1, 4-22.

CoStar Green Building Economic Study - Fuerst & McAllister (2011)
LEED & Energy Star Green Building Rating = Increased Rent
In a 2011 controlled economic analysis using CoStar data of 626 LEED, 1,282 Energy Star and 24,479 control U.S. commercial office buildings, Fuerst & McAllister identified a 4% to 5% rent premium (p=0.01 - 0.05) for green rated buildings in 81 metropolitan areas and 852 submarkets when controlling for hedonic variables, such as building age, size, height, and location.

Fuerst, F., & McAllister, P. (2011). Green Noise or Green Value? Measuring the Effects of Environmental Certification on Office Values. Real Estate Economics, 45-69.

Whole Building - Fuerst and McAllister, 2009
Green Building eco-labeling (LEED & Energy Star) = Organizational Productivity
In a 2009 multi-building case study of US office buildings, Fuerst and McAllister, identified an increase in organizational productivity by virtue of owning an eco-labeled building. By using advanced regression models, they measured rental and sales price differences between 1,908 eco certified buildings (626 LEED and 1,282 Energy Star) and comparatively similar non-certified buildings chosen from a CoStar database of 24,479 buildings. They found eco-certified buildings to have a rental premium of 6% ($p<0.01$), and a sale price premium of 36% ($p<0.01$), as compared to non-certified buildings.

Fuerst, F., & McAllister, P. (2009). New Evidence on the Green Building Rent and Price Premium. American Real Estate Society Monterery

Whole Building – Singh et al. 2011 (Office)
LEED Office Buildings = Health + Absenteeism Savings + Productivity
In a 2011 multi-building case study, Singh et al. investigated the effects of improved indoor environmental quality (IEQ) on perceived health and productivity of occupants who moved from conventional to green buildings. The study determined that the improved IEQ contributes to 1.75 additional work hours per year for each employee due to perceived improvements in asthma and respiratory allergies, and 2.02 additional work hours per year for each employee due to perceived improvements in depression or stress, along with an additional 38.98 work hours per year due to perceived productivity improvement.

Singh, A.; Syal, M.; Grady, S.; and Korkmaz, S. (2011): Effects of Green Buildings on Employee Health and Productivity: American Journal of Public Health; 100 (9), pp. 1665-1668.

Vamosi, S. (2011): The True Cost of LEED-Certified Green Buildings: HPAC Engineering - News and Articles: Retrieved in November 2011 from <http://hpac.com/columns/engineering-green/true-cost-leed-buildings-0111/>.

Whole Building - Allen et al 2012

Better IEQ conditions + high outdoor air ventilation rate = Improved Cognitive scores

In a (double blind) controlled experiment for office buildings done in TIEQ lab at the Syracuse CoE in 2014, Allen et al identify a 42% increase in average cognitive scores on 'green building day' and 51% increase on 'green+ building day' than the conventional building day ($p<0.0001$) The suggested action is to go for a green office building with a 40 cfm per person outdoor air ventilation rate (550 ppm CO_2 level and 50 micrograms/ m^3 of TVOC).

Allen JG, MacNoughton P, Satish U, Santanam S, Vallarino J, Spengler J.D.; "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments." Environ Health Perspective, 2015

Indoor environmental quality – Newsham et al 2013

Green buildings = Better indoor environmental quality

In post occupancy evaluation of 12 green and 12 conventional buildings across Canada and the United States, Newsham et al identified a 13.5% self-reported mean rated better environmental quality ($p=0.021$) for green LEED certified buildings over conventional buildings. The 12 green buildings were paired with 12 similar conventional buildings nearby.

Newsham.G.R., Birt.B.J., Arsenault.C., Thompson.A.J.L., Veitch.J.A., Mancini.S., Galasiu.A.D., Gover.B.N., Macdonald.I.A., Burns.G.J. (2013) Do 'green' buildings have better indoor environments? New evidence, Building Research & Information, 41:4, 415-434

Halcrow Headquarters/ Agha-Hossein et al 2013

BREEAM Certified Building = Individual Productivity + Energy Savings

In a 2010 pre-occupancy evaluation of Vineyard House Building (VH) and a 2011 post-occupancy evaluation of Elms House Building (EH) on 162 office employees of Halcrow Company in London, Agha-Hossein et al investigate a 17% increase in productivity among employees moved from VH (a typical class office building) to EH building (a "Very Good" BREEAM offices 2008 certified). Also, a 33% reduction in annual energy consumption was observed in EH as compared to VH.

Agha-Hossein, M.M. El-Jouzi, S. Elmualim, A.A. Ellis, J. Williams, M. (2013), Post-occupancy studies of an office environment: Energy performance and occupants' satisfaction, Building and Environment, 69(2013) pp. 121-130

LEED Certification – Office / BETTERBRICKS 2006

LEED Platinum = Energy Savings + CO_2 Reduction + Churn Rate Reduction + Water Savings + Triple Net Savings

A case study of the LEED Platinum Banner Bank Office in Boise, ID that incorporated plug in play design was conducted in 2006 and showed an energy savings of 48%, water savings of

80%, a $14.5/sqft decrease in churn cost, 721 tons/year CO2 reduction, and a $2.10/sqft reduction in triple net costs.

BETTERBRICKS. (2006). Banner Bank Building. Retrieved October 15, 2012, from BETTERBRICKS: http://www.betterbricks.com/commercial-real-estate/case-studies/10053/1

Whole Building - Technical University of Denmark/ Clausen and Wyon 2004
Whole Building = Individual Productivity

In a 2004 chamber study (23 m2) on 99 healthy volunteers, Clausen and Wyon identify 7% increase in individuals productivity who are exposed to an optimized indoor environment (with 45dB traffic noise, appropriate lighting, access to daylight, outside view, clean outdoor air, private workplace and 71.6 F temperature) as compared to individuals exposed to poor environmental conditions.

Clausen, G. and Wyon, D. (2008), The Combined Effects of Many Different Indoor Environmental Factors on Acceptability and Office Work Performance, HVAC&R RESEARCH; 14(1), pp. 103-114

Whole Building – Turner 2006 (Office and Library)
Green Design (LEED Certified Building) = Energy Saving

In a 2006 study of five LEED certified office buildings and two library buildings in the Cascadia region, Turner identifies a median 23% energy savings in the LEED certified buildings compared to the average energy use intensity of typical buildings in that region, constructed to ASHRAE Standard 90.1, 1999.

Turner, C. (2006): LEED Building Performance in the Cascadia Region; A Post Occupancy Evaluation Report: For the Cascadia Region Green Building Council; January 30, 2006.
Steven Winter Associates, Inc. (2004): LEED Cost Study; Submitted to the U.S. General Services Administration: October 2004.

Whole Building – Roulet et al. 2006 (Office)
Low Energy Use and Thermal Comfort = Health and Productivity

In a 2006 meta-analysis of 64 office buildings across nine European countries, Roulet et al. identified 7.6% fewer average building-related symptoms per occupant (Building Symptom Index, BSI) and 7.5% higher overall summer comfort in ‘low’ versus ‘high’ energy office buildings as well as 10% higher productivity in offices that are perceived as ‘neutral’ versus ‘warm’ to ‘hot’ in the summer.

Roulet, C.; Johner, N.; Foradini, F.; Bluyssen, P.; Cox, C.; de Oliveira Fernandes, E.; Muller, B.; and Aizlewood, C. (2006): Perceived Health and Comfort in Relation to Energy Use and Building Characteristics: Building Research and Information; 34(5), pp. 467-474.

Whole Building – Kats et al 2003
LEED Building = Energy Savings

In 2003 multiple building study of 33 LEED-rated buildings in the US, Kats et al identified that an average 1.84% first cost premium for green construction yields average annual energy savings of 28%.

Kats, G. et al. "Costs and Financial Benefits of Green Buildings." October 2003. Available at http://www.cap-e.com/publications/default.cfm

Whole Building – Pilon and Gee 2003/ Herman Miller Marketplace
Whole Building = First cost savings + Churn cost savings + Individual productivity
In two building case study of the Herman Miller Marketplace in Michigan, Pilon and Gee identify 66% churn cost savings and a 7.5% improvement in marketing productivity as well as a 33% reduction in first cost compared to a typical Herman Miller facility. The MarketPlace is an intellisysTM building that incorporates effective daylighting, high-performance lighting, operable windows, occupant thermal controls, computerized building controls, and space planning based on work process needs.

Pilon, Len and Gee, Lori (2003) Herman Miller's MarketPlace Building: Gold LEED Rating, Below Norm Costs, and Successful Partnership. Corporate Real Estate Leader, September 2003

Whole Building – Zion National Park Visitor Center / Torcellini Et Al 2002
Whole Building = Energy savings + First cost savings
In a 2002 building case study of the Zion National Park Visitor Center in Springdale, Utah, Torcellini et al identify a 73% reduction in annual energy use and a 30% first cost savings due to daylighting, efficient lighting, natural ventilation, passive heating and cooling, energy-efficient landscaping, an energy management system, and on-site renewable energy generation, as compared to a base-case, code-compliant visitor center.

Torcellini, P., Judkoff, R., Hayter, S., (2002) Zion National Park Visitor center: Significant Energy Savings Achieved through a whole-Building Design Process from ACEEE summer study on Energy Efficiency in Buildings

Green Buildings – Grady et al. 2010
Indoor Environmental Quality = Employee Health + Productivity
In a 2009 before and after study of 2 companies with a total of 263 employees that moved from conventional offices to LEED Platinum and Gold buildings in Michigan, Grady et al. identify an approximately 50% reduction in self-reported asthma, respiratory allergies, and depression or stress related absenteeism. The study also identifies reductions in affected work hours that ranged between 6 and 10 hours per month for occupants with reported symptoms, as well as a 2.8% perceived productivity increase for general occupants. These outcomes were determined to be due to higher indoor environmental quality.

Grady, S. C.; Syal, M.; Singh, A.; and Korkmaz, S. (2010): Effects of Green Buildings on Employee Health and Productivity: American Journal of Public Health; 100 (9), pp. 1665-1668.
Kats, G. (2003): Green Building Cost and Financial Benefits: Retrieved Nov 3, 2010, from U.S. Green Building Council: http://www.usgbc.org/ShowFile.aspx?DocumentID=1992.

Whole Building – Verifone / Pape 1998
Whole Building = Individual Productivity + Energy Savings
In a 1998 field case study of expanded facilities for VeriFone Inc. in Costa Mesa, CA, Pape identifies a 40% reduction in absenteeism, 5% improved productivity, and 50% energy savings in

a new office building with skylights, high performance glazing, 60% more insulation than code, increased outside air with energy efficient air handlers, a natural gas fired cooling system, and smart lighting with occupancy sensors, as compared to an older Verifone office building.

William R. Pape, (June 1998), Healthy, Wealthy, and Wise,Inc. Magazine, <http://www.inc.com/magazine/19980615/1075-2.html > (retrieved 23 April 2003)
J. J. Romm, Cool Companies -- How the Best Businesses Boost Profits and Productivity by Cutting Greenhouse Gas Emissions, 1999, Island Press, Washington, D.C.

Whole Building – ING Bank / Browning 1992 (Office)
High performance building = Energy savings + individual productivity
In a 1992 building case study of ING Bank in Amsterdam, Bill Browning of Rocky Mountain Institute identifies a 92% reduction in primary energy consumption and a 15% reduction in employee absenteeism compared to the bank's former headquarters, due to high performance design strategies including daylight, a narrow floor plan that allows landscaped views for every occupant, passive solar conditioning, co-generation, and the use of heat exchangers.
Browning, William (1992) NMB Bank Headquarters: The impressive performance of a green building. Urban Land, June 1992, pp 23-25.

Rocky Mountain Institute. International Netherlands Group (ING) Bank, Amsterdam, Netherlands.

Whole Building – Singh et al. 2009
Green Building = Health + Productivity
In a 2009 building case study of an office environment in Lansing, Michigan, Singh et al. identify a 2.6% increase in employee productivity, an 18.3% decrease in employee absenteeism, and a 4.82% decrease in perceived asthma and respiratory allergies, due to green buildings.

Singh, A.; Syal, M.; Grady, S. C.; and Korkmaz, S (2009): Effects of Green Buildings on Employee Health and Productivity: American Journal of Public Health; 100 (9), pp. 1665-1668.

Appendix E: TBL Decision Making Questionnaire

Introduction

Dear Study Participant,

The purpose of this survey is to understand how knowledge of longer term financial, environmental, and human benefits of building retrofit actions might influence your investment decisions.

The survey should not take more than 10 minutes. Your responses are confidential and all personal information will be removed. Please do not to include anything that is both identifiable and private while answering the survey. You can view the IRB consent form.
.

If you are willing to be interviewed over the phone in the second portion of the study, please share your email. Please volunteer only if you do not mind the researchers taking notes on the comments and feedback you provide. Your name will not be attached to any information you provide during this interview.

Thank you for your time and responses. If you would like to receive a summary to see the results from a representation of decision-makers, please share your email at the end of this survey. With any questions please contact Rohini Srivastava at (276)-614-6175, rohinisr@andrew.cmu.edu.

I am age 18 or older.
☐ Yes ☐ No

I have read and understand the information above.
☐ Yes ☐ No

I want to participate in this research and continue with the survey
☐ Yes ☐ No

Section 1: Background Information

1. Your Name (optional)

2. Your Organization (optional)

3. Professional Position or Title

4. How many years have you worked in the building construction field?
   - ☐ 0 – 5years
   - ☐ 5 – 10 years
   - ☐ 10-20 years
   - ☐ More than 20 years

5. What profession do you represent in your current organization?
   - ☐ Owner
   - ☐ Developers
   - ☐ Facility Manager
   - ☐ Architect
   - ☐ Engineer
   - ☐ Project/Construction Manager
   - ☐ Policy makers
   - ☐ Appraisers/accountants/financier
   - ☐ Student
   - ☐ Other: _____

6. How long have you been with your current organization?
   - ☐ 0 – 5 years
   - ☐ 5 - 10years
   - ☐ 10 – 15 years
   - ☐ More than 20 years

7. How many years has your experience involved making use of the knowledge of sustainability?
   - ☐ 0 – 5 years
   - ☐ 5 - 10years
   - ☐ 10 – 15 years
   - ☐ More than 20 years

8. Does your organization make decisions related to building construction?
   - ☐ Yes
   - ☐ No

9. What dollar value of building investments do you influence or make decisions about?
   - ☐ Yes, influence up to $100,000
   - ☐ Yes, decide on up to $100,000
   - ☐ Yes, influence more than $100,000
   - ☐ Yes, decide on more than $100,000
   - ☐ No, I do not influence or make building investment decisions

10. What is the highest level of education you have completed?
   - ☐ High School Diploma
   - ☐ Bachelor's Degree
   - ☐ Master's Degree
   - ☐ Doctoral Degree
   - ☐ Other: _____

11. List the field your degrees are in, and the date received
(For example, B. Arch; MBA etc)

    _____
    _____
    _____
    _____
    _____

Section 2: TBL information for building investment – 4 questions

You are role playing. Assume you are working to 'upgrade building technology' with a budget and authority to make those decision. This is a high profile, high-risk decision as your company relies on your expertise and knowledge to make this investment.

The organization is contemplating an energy retrofit of a 100,000 sqft building and has already upgraded the lobby lighting. A vendor has approached you and is presenting the option of improving the lighting in your office areas by modifying the existing lighting system to separate ambient lighting from task. They recommend removing some of the lamps in the ceiling fixtures to reduce ambient light levels and buying LED task lights for each workstation.

The cost will be roughly $200 per employee, or $100,000 for the project, but the vendor is convinced and verbally communicated to you that the investment will pay for itself in energy savings.

Costs to **Modify Ambient Lighting and Add Task Lights**		
	Per sq. ft	**Per employee**
Cost for reducing ambient light levels	$0.18	$36
Cost for LED desk lamp	$0.82	$164
First cost for the investment	**$1.00**	**$200**
Initial Investment costs for a 100,000 sq. ft building	$100,000	

Question 1: Given the costs of lowering the ambient light levels and adding a task light for each workstation, **how likely are you to invest in this retrofit?**

☐	☐	☐	☐	☐	☐	☐
Absolutely Not	**Very Unlikely**	**Unlikely**	**Undecided**	**Likely**	**Very Likely**	**Absolutely Yes**

Consideration - Financial Benefits from Modifying Ambient & Adding Task Lights

The vendor has brought you more information. Robust research shows that this investment will save 40% of your lighting energy use, achieved by lowering ambient lighting and adding LED task lights, equaling roughly $54/ person per year.

Field studies also show there is a maintenance savings of $0.05/sq. ft or $10 per person per year due to fewer lamp replacements needed after the retrofit (Knissel 1999). Given that the retrofits costs remain the same, the payback due to these energy and maintenance savings can now be calculated at 3 years.

Costs to **Modify Ambient Lighting and Add Task Lights**		
	Per sq. ft	Per employee
Cost for reducing ambient light levels	$0.18	$36
Cost for LED desk lamp	$0.82	$164
First cost for the investment	**$1.00**	**$200**

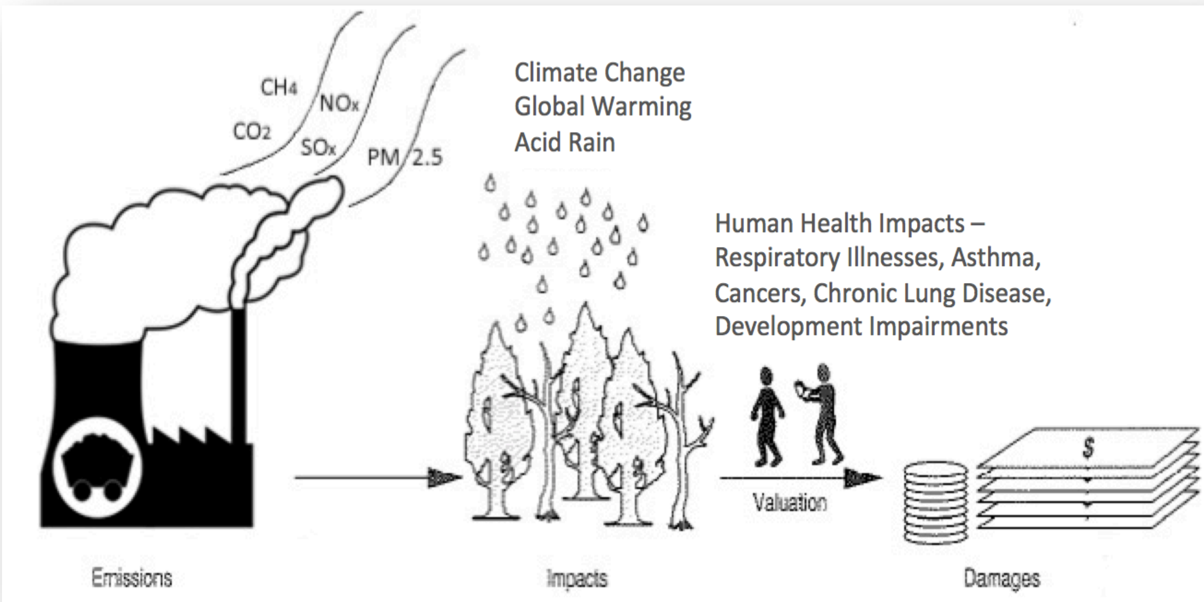
Financial Capital savings of Reducing Ambient and Adding Task		
	Per sq. ft	Per employee
Energy savings (40%)	$0.27	$54
O & M Savings	$0.05	$10
Annual savings	**+$0.32**	**+$64**
ROI (Financial)	**30%**	
Payback Period	**3 years**	

Question 2: Given these energy and maintenance savings, **how likely are you to invest in this retrofit?**

☐	☐	☐	☐	☐	☐	☐
Absolutely Not	**Very Unlikely**	**Unlikely**	**Undecided**	**Likely**	**Very Likely**	**Absolutely Yes**

Consideration: Financial and Environmental Benefits from Modifying Ambient & Adding Task Lights

Since separating ambient and task lighting saves 40% of the lighting energy, the electricity savings has real environmental gains. Every kWh saved also reduces environmental pollution at the power plant, with CO_2, SO_X, NO_X, particulates, and water use benefits. When carbon trading and climate exchanges emerge, along with peak demand control pricing, building owners may directly pocket these savings, making them true economic benefits. In the interim, these actions can be valued as part of the corporate sustainability (CSR) initiatives.



Given that the retrofits costs remain the same, the additive payback due to energy and maintenance savings as well as environmental pollution reduction (CSR benefits) can now be calculated at 2 years

Costs to Modify Ambient Lighting and Add Task Lights		
	Per sq. ft	Per employee
Cost for reducing ambient light levels	$0.18	$36
Cost for LED desk lamp	$0.82	$164
First cost for the investment	**$1.00**	**$200**

1. Financial Capital savings of Reducing Ambient and Adding Task		
	Per sq. ft	Per employee
Energy savings (40%)	$0.27	$54
O & M Savings	$0.05	$10
Annual financial savings	**+$0.32**	**+$64**
ROI (Financial)	**30%**	
Payback Period	**3 years**	

2. Financial + Environmental Capital savings of Reducing Ambient and Adding Task		
	Per sq. ft	Per employee
Environmental benefits from energy savings of:	2.7 kWh	542 kWh
Air pollution emissions (SO_X, NO_X, PM)	$0.04	$8.5
CO_2 reductions	$0.03	$5
Water savings	$0.01	$2
Annual financial + environment savings	**+$0.08**	**+$16**
ROI (Financial + Environmental)	**40%**	
Payback Period	**2 years**	

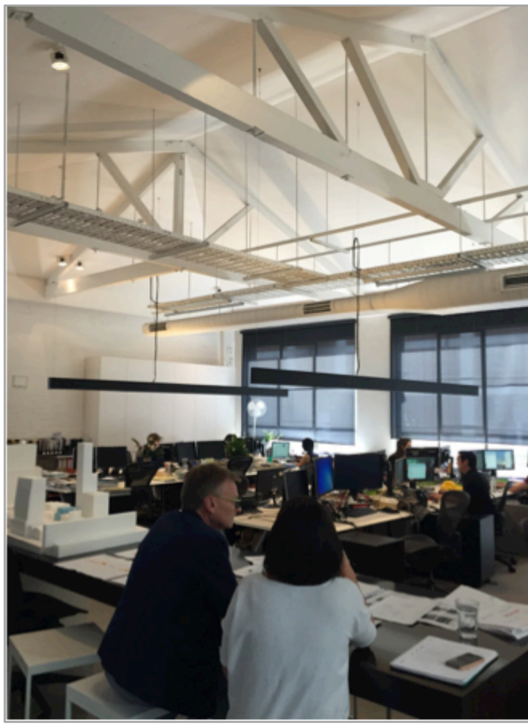
Question 3: Given the energy, maintenance and the environmental savings (CO_2, NO_x, SO_x, PM 2.5 etc), **how likely are you to invest in this retrofit?**

☐ **Absolutely Not** ☐ **Very Unlikely** ☐ **Unlikely** ☐ **Undecided** ☐ **Likely** ☐ **Very Likely** ☐ **Absolutely Yes**

Consideration: Financial, Environmental and Human Benefits from Modifying Ambient & Adding Task Lights

A colleague has brought you additional research of significance. Çakir and Çakir, as well as other researchers, have identified an average 19% reduction in headaches for workers with separate task and ambient lighting, as compared to workers with ceiling-only combined task and ambient lighting in offices. In addition, Nishihara et al. has identified an 11% improvement on complex tasks, such as triple digit multiplication tasks, when subjects can control their light levels through task lights.

These studies reveal benefits for both human health and productivity that can be monetized by capturing the health costs of headaches and associated absenteeism, as well as the productivity loss per employee at complex tasks.



In a 1998 multiple building study in Germany, Cakir and Cakir identify a **19% reduction in headaches for workers with separate task and ambient lighting**, as compared to workers with ceiling only combined task and ambient lighting.

In a 2006 experiment in Japan, Nishihara et al identify an **10% improvement on triple digit multiplication (p=0.01) when subjects could control their task lights** compared to when they could not.

Given that the retrofits costs remain the same, the additive payback due to all three benefit categories - energy and maintenance savings, environmental pollution reduction (CSR benefits), as well as productivity and health benefits - is immediate.

Costs to Modify Ambient Lighting and Add Task Lights		
	Per sq. ft	Per employee
Cost for reducing ambient light levels	$0.18	$36
Cost for LED desk lamp	$0.82	$164
First cost for the investment	**$1.00**	**$200**

1. Financial Capital savings of Reducing Ambient and Adding Task		
	Per sq. ft	Per employee
Energy savings (40%)	$0.27	$54
O & M Savings	$0.05	$10
Annual financial savings	**+$0.32**	**+$64**
ROI (Financial)	**30%**	
Payback Period	**3 years**	

2. Financial + Environmental Capital savings of Reducing Ambient and Adding Task		
	Per sq. ft	Per employee
Environmental benefits from energy savings of:	2.7 kWh	542 kWh
Air pollution emissions (SO_X, NO_X, PM)	$0.04	$8.5
CO_2 reductions	$0.03	$5
Water savings	$0.01	$2
Annual financial + environment savings	**+$0.08**	**+$16**
ROI (Financial + Environmental)	**40%**	
Payback Period	**2 years**	

3. Financial + Environmental + Human Capital savings of Reducing Ambient and Adding Task		
	Per sq. ft	Per employee
Health benefits (19% of $73)	$0.07	$14
Absenteeism reduction (1% of 1.3% year)	$0.03	$6
Productivity increase (10% of 4%)	$0.90	$180
Annual Financial + Environment+ human savings	**$1.00**	**$200**
ROI (Financial + Environment+ human)	**150%**	
Payback Period	**7 months**	

Question 4: Given the energy, maintenance, environmental savings (CO2, NOx, SOx, PM2.5 etc) as well as the human health and productivity benefits, **how likely are you to invest in this retrofit?**

☐	☐	☐	☐	☐	☐	☐
Absolutely Not	**Very Unlikely**	**Unlikely**	**Undecided**	**Likely**	**Very Likely**	**Absolutely Yes**

If you are willing to be interviewed, please share your email:

If you would like to receive a summary to see the results from a representation of decision-makers, please share your email:

Please let us know if you would like to circulate the link for this survey

Thank you for your time!

Survey references

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