A dissertation submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Doctor of Philosophy

MEASURING THE PRODUCTIVITY IMPACTS OF ENERGY EFFICIENCY MEASURES

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ABSTRACT OF DISSERTATION submitted by:

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Sustainable energy policies do not only reduce carbon dioxide (CO_2) emissions but studies have shown that these policies can yield a wider set of multiple impacts (popularly addressed as co-benefits) for the economy and society. However, it is often the case that these impacts are not incorporated during the evaluation of a suitable energy assessment due to lack of mature quantification methodology. Hence, most of the time, the potential of sustainable energy policies are undervalued. Therefore, the aim of this research is to provide better tool and methods to quantify multiple impacts rigorously. In order to achieve this aim, this dissertation proposes a methodological framework and using the framework, this dissertation quantifies productivity impact in a rigorous manner for Hungary and Germany.

Among these wide ranges of multiple impacts, productivity impacts are observed to be one of the biggest impacts, but despite the evidence, productivity impacts are not defined clearly in the context of multiple impacts, and hence it is also not rigorously quantified. Thus, this dissertation defines productivity impacts by defining three key aspects of labour productivity namely active days, workforce performance and earning ability which results from two different improved energy efficiency measures (HVAC system with airtight building envelope and modal shift towards active transportation):

1. **The amount of active time available** for productive work. This can be affected, for instance, by being sick- more precisely absenteeism and presentism, which reduce the amount of active time available.
2. **Workforce performance within a certain time frame**. Indoor air quality and thermal comfort of tertiary buildings can improve the mental wellbeing of the entire workforce and this can result in more productive time for work.
3. **Earning ability/value added per unit of time worked.** Poor indoor air quality and thermal discomfort can affect the future earning ability of a child by disrupting education.

The result shows that Germany and Hungary can gain 7.7 days/person and 3.21 days/person, year by having more deep retrofit-type residential and tertiary buildings such as deeply retrofitted buildings, passive houses, and nearly zero energy buildings. Germany and Hungary can gain 331 million and 5 million Euros/year respectively by gaining more active days due to more deep retrofit-type residential buildings. Similarly, by having more tertiary deep retrofit-type buildings, Germany and Hungary can gain 332 million and 2 million Euro/year respectively. This dissertation further shows that Germany and Hungary can gain 1870 and 3849 healthy life years/million population, year respectively by having more deep retrofit-type residential buildings. In addition to avoided sick days, by working in deep retrofit-type tertiary buildings, Germany and Hungary can gain around 85 million euro/year and 1.8 million euro/year respectively by improving the mental well-being. Lastly, this dissertation results also show that by opting for the modal shift towards active transportation, Germany and Hungary can gain 2.5 hours/driver, year and 0.5 hours/driver, year respectively. By quantifying productivity impacts this dissertation shows the significance of productivity impacts of sustainable energy policies and concluded that multiple impacts could be another incentive for a policymaker to design a sustainable energy policy.

Key words: Multiple impacts, Productivity impacts, Energy efficiency measures, Health, Quantification, Monetization, Well-being.

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List of abbreviations:

AR	Assessment report
COMBI	Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe
CO_2	Carbon dioxide
CO	Carbon Monoxide
COPD	Chronic obstructive pulmonary disease
DALY	Disability adjusted life years
GJ	Gigajoule
Gt	Gigatonnes
GHG	Greenhouse gas
GDP	Gross domestic product
HVAC	Heating ventilation and air conditioning
IPCC	Intergovernmental Panel on Climate Change
IEA	International energy Agency
KM	Kilometer
kWh/m²a	kilowatt hour/ per square meter and year
ug/m3	Micrograms/cubic meter air
MTOE	Million tonnes of oil equivalent
MI	Multiple impacts
NZ$	New Zealand dollar
NOx	Nitrogen oxides
O3	Ozone
PM	Particulate matter
PJ	Petajoule
SO_2	Sulphur dioxide
OECD	The Organisation for Economic Co-operation and Development
VOLY	Value of a life year
VOC	Volatile organic compound
WHO	World Health Organization

CHAPTER 1: BACKGROUND AND TOPIC OUTLINE

“Where words come out from the depth of truth

Where tireless striving stretches its arms towards perfection

Where the clear stream of reason has not lost its way

Into the dreary desert sand of dead habit”

Rabindranath Tagore. Where The Mind Is Without Fear

1.1 Rationale:

The importance of energy conservation and energy efficiency are well-documented but we often forget the rationale behind it. The primary objective of energy conservation is to save energy. But, energy conservation has additional effects as well. For instance, saving energy does not only reduce its impact on the environment but also reduces the cost of living and/or improves the health condition by improved air quality.

As Nobel laureate physicist Steven Chu wrote in his letter on 1 February 2013, to the Energy Department employees “as the saying goes, the Stone Age did not end because we ran out of stones; we transitioned to better solutions. The same opportunity lies before us with energy efficiency and clean energy”. With different conservation techniques, in other words, with different low carbon techniques, we can not only mitigate adverse environmental impacts, but also there is an opportunity to augment social welfare through the co-benefits of various low-carbon techniques.

1.2 Background:

1.2.1 The bigger picture: Energy and climate change

Access to energy services is a key component in the twenty first century in order to meet social and economic development needs and improve human welfare (IPCC 2007). The most common way to produce energy is to use and process fossil fuels such as coal, oil and natural gas. The use of fossil fuels does not only produce energy but it also produces waste gases such as carbon dioxide (CO_2). This contributes to about 78% of the total greenhouse gas (GHG) emission increase (IPCC 2014). The effect of GHG emissions on climate is one of the most significant environmental impacts of the present decade (IPCC 2014). Moreover, the GHG emissions are one of the key factors to accelerate climate change (Emberson et al. 2012). It is concluded in Intergovernmental Panel on Climate Change’s (IPCC) fourth assessment report

(AR 4) that "most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". Thus, the use of fossil fuels should be reduced not only to save the natural fossil fuel stock but also to mitigate climate change impacts.

The significance of climate change is unquestionable today. It is scientifically proven that climate change is exposing individuals, societies, economic sectors and our ecosystems to risk (where risk is defined in the IPCC 2014 report as the potential for consequences when something of value is at stake and the outcome is uncertain). These risks from climate change impacts arise from the interaction between 'hazard' (an event or trend related to climate change), vulnerability (vulnerability to harm), and exposure (people, assets or ecosystems at risk) (IPCC 2014). The risks of climate change can be caused from many reasons, but among these reasons, peak resource especially energy extraction have been identified as a key factor which is exposing human civilization to risk (IPCC 2007). More precisely, energy production and use emit two-thirds of the GHG emission (IEA 2015). In addition to contributing to anthropogenic climate change, fossil fuel-based energy systems emit other atmospheric pollutants such as particulate matter (PM), nitrogen oxides (NOx), sulphur dioxide (SO_2) which degrade the air quality and ecosystem (via the processes such as acidification, eutrophication and formation of ground level ozone) (Emberson et al. 2012). Hence, to mitigate these risk factors, energy production and use need to be reduced. However, energy is an important component of our daily life and also it is a key input to enhance the development of a nation. For instance, energy services such as electricity, fuels, mechanical power helps in meeting the essentials of modern day life and access to electricity is a key indicator for a developed nation. Thus, to mitigate these risk factors without disrupting the services, energy efficiency is the first option in the short to mid-term period because with the help of energy efficiency measure one can have the same amount of service by consuming less energy. The International energy

Agency (IEA) 2015 report shows that energy efficiency improvement measures in IEA countries[1] since 1990 have avoided "a cumulative 10.2 billion tons of CO_2 emissions, helping to make the 2 degree warming goal more achievable". Without energy efficiency improvement measures "the world would have used 12% more energy than it did in 2016" (IEA 2017). Energy efficiency can be defined as "using less energy to produce the same amount of services or useful output" and energy efficiency measures can be defined as "actions to improve the energy efficiency of existing technologies, or to replace conventional technologies with new, more efficient ones, are called measures" (Patterson 1996; Couder 2015). Thus, improved energy efficiency measure is an instrument to achieve an improvement in energy efficiency i.e. less energy use for the same services. Therefore, energy efficiency measures can be considered as a tool to mitigate climate change by reducing energy production and use.

1.2.2 Multiple impacts of energy efficiency measures

Sustainable energy policies do not only reduce carbon dioxide (CO_2) emissions but recent studies (see (GEA 2012; Ryan and Campbell 2012; IPCC 2014; Ürge-Vorsatz et al. 2014; IEA 2015) have shown that these policies can yield a wider set of additional benefits for the economy and society. Some studies (see (Worrell et al. 2003; Ürge-Vorsatz et al. 2009; Ryan and Campbell 2012) even suggest that these non-climate benefits such as job creation, GDP growth, enhanced productivity, increase of energy security, positive impacts on health, may have a higher value than the direct energy saving benefit. Thus, to develop more cost-effective sustainable energy policies keeping long-term economic goals in mind, additional benefits/multiple non-climatic benefits have to be accounted more comprehensively in the future assessment (Ürge-Vorsatz et al. 2016). There are several terms used to address the

[1] The IEA is made up of 30 member countries namely Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, The Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States (https://www.iea.org/countries/membercountries/)

additional effects of energy efficiency measures. Among these terms, the most popular terminology is co-benefit. Apart from the co-benefit, there are other terms used such as additional effect, ancillary benefit, non-climatic benefit, non-energy benefit, multiple benefits, and co-impact.

Initially non-energy benefits due to energy efficiency measures were used to categorize into two benefits i.e. co-benefits and ancillary benefits. The AR4 defines the ancillary benefits as side effects of policies aimed exclusively at CO_2 emission mitigation (IPCC 2007). The IPCC AR4 report has also defined co-benefits as the benefits of policies which are implemented for various reasons, including climate change mitigation as one of them. Apart from mitigation, these policies may also have other objectives, such as economic and social development, sustainability etc. The term co-benefit was first used in 1990 and then the IPCC AR3 report distinguished co-benefit or intended positive side effect from an unintended positive side effect (namely ancillary benefits) of a policy (Miyatsuka and Zusman 2010). Co-benefits have immediate welfare effects and these are mostly enjoyed by present generation unlike climate benefits which are mostly enjoyed by future generations (Markandya and Rubbelke 2003; Ürge-Vorsatz et al. 2014). The IEA 2011 report mentioned a new term 'multiple benefits' to capture all these additional positive effects of energy efficiency measures (Heffner and Campbell 2011). The term 'multiple benefits' captures both the intended and unintended benefits of sustainable energy policies (IEA 2014).

These terms such as co-benefits, multiple benefits, non-energy benefits and ancillary benefits only address the positive effects of a policy whereas there could be some negative effects as well. For example, people may lose their jobs in the energy supplying sector due to increasing demand for energy efficiency or transaction cost also considered as a co-cost does not belong to benefit. These negative effects of a climate change policy have referred as adverse side effects, co-costs, disbenefits, and risks (Ürge-Vorsatz et al. 2014). These adverse side effects of an energy efficiency policy also need to be considered in the policy evaluation in order to provide an unbiased evaluation. Figure 1 below organizes all the terms used to address both positive and negative effects of energy policies.

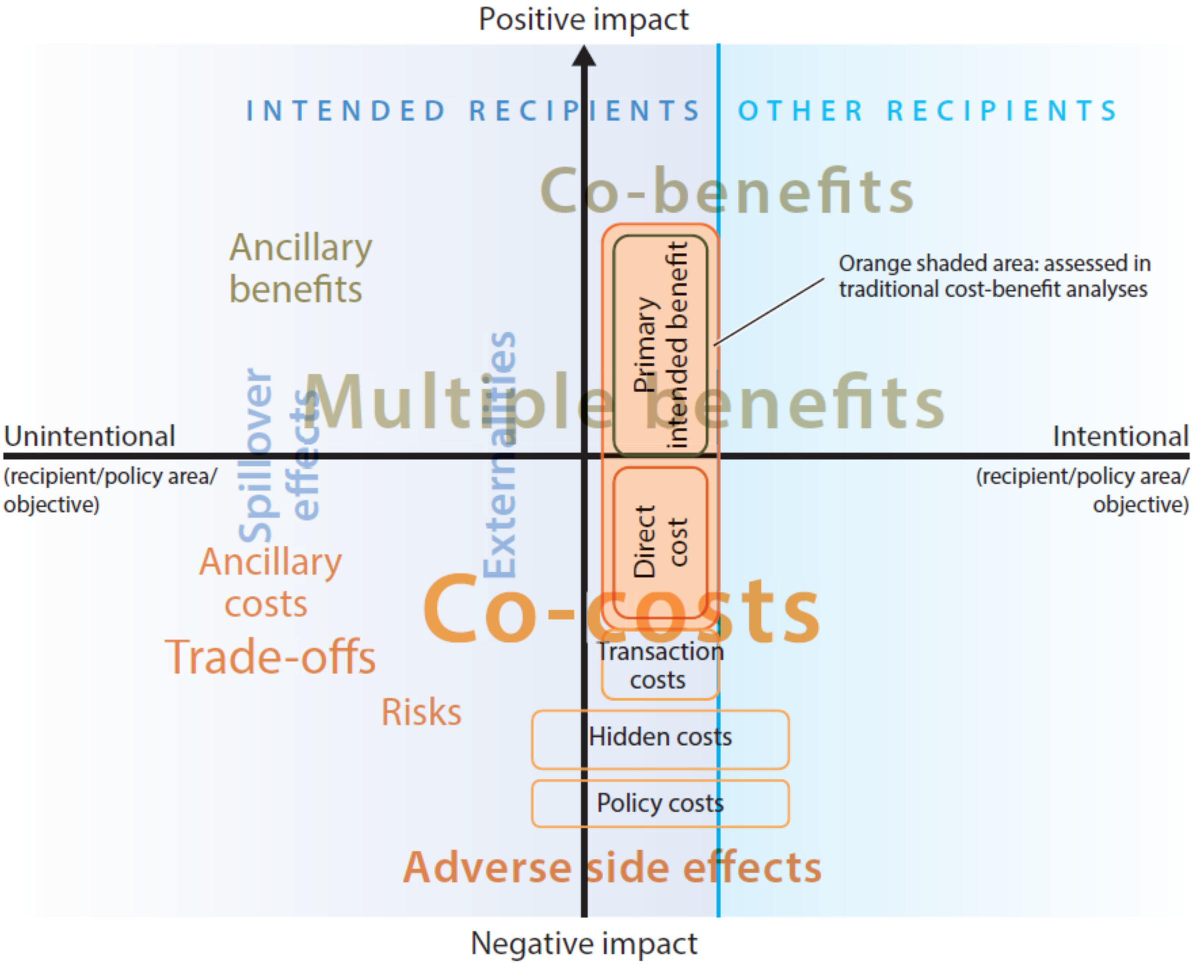


Figure 1: Additional effects of energy efficiency policy

Source: (Ürge-Vorsatz et al. 2014)

Figure 1 shows different effects of an energy policy where these effects are divided into two main categories i.e. co-benefit and co-cost. Ürge-Vorsatz et al 2014 used the term ‘co-impact’ to address these cost and benefit together.

In this dissertation, the term ‘multiple impacts’ is used to avoid further confusion. The term ‘multiple impacts’ was first used in Urge-Vorsatz et al 2016 study. Use of this comprehensive term promises a fair ground for research. More precisely, when we are using the term co-impact, there is an underlying meaning which says that there is a 'main' impact. Suppose all the effects of sustainable energy policies are side effects and energy savings are the main effects then probably we can use the term co-impact without any confusion. But, the literature shows that many times the value of co-benefits/co-impact is much higher than planned benefit (for example, energy savings). For instance, Urge-Vorstaz et al 2015 study shows that the ratio of co-benefits to energy saving is between 0.22-3.21 and the value of health benefits are 1.4 higher in monetary unit than direct energy cost savings which confirms the claim that co-benefits may have higher value than direct energy savings (Ürge-Vorsatz et al. 2015). Thus, mathematically energy savings cannot be considered as 'main' benefit compared to the other benefits of energy efficiency policy. Therefore, the term 'multiple impacts' captures all the additional impacts of sustainable energy policies without any confusion and here the term impact covers both positive and adverse effects of an energy efficiency policy.

1.2.3 Introduction to productivity impact:

Productivity impacts are one of the key multiple impacts of energy efficiency measures. In general, productivity is defined broadly as a relation between input and output. However, the definition of productivity can vary as per the perspectives, such as measurement, labour relations, training and development, management, budget, finance, and sectors (like industry, transport etc.) (Quinn 1978).

There are two key productivity measures that define productivity broadly. These two measures are single factor productivity (ratio between output and a single input) and multi-factor productivity (ratio between output and more than one inputs). Among single factor productivity measure, there are various measures of productivity which includes capital productivity, labour productivity, profitability, and total output productivity (Sauian Sahar 2002). Among all these measures labour productivity and capital productivity are the two most used measures. This dissertation only consider labour productivity which is a well-established indicator for several economic aspects such as economic growth, competitiveness, and living standards in an economy (OECD 2008). Broadly, labour productivity can be defined as the ratio output and labour input. In other words, labour productivity can be measured as the ratio between outputs produced within an economy in a year and total numbers of hours worked by the employees (OECD 2008). This dissertation shows and quantifies how having improved energy efficiency measures can result in productivity gain. A detail analysis of the productivity impact is given in chapter 3 and chapter 4.

1.2.4 Motivation: challenges-related to quantification of multiple impacts

It is often the case that these additional effects are not incorporated while assessing a sustainable energy policy. One of the reason behind not incorporating the impacts are their complexities in quantification methods compared to the direct impact evaluation such as direct energy cost or emission reduction (Ürge-Vorsatz et al. 2016). However, it is important to note that to develop cost-effective sustainable energy policies and optimized long-term strategies, multiple non-energy benefits have to be accounted more comprehensively in the decision making analysis (Ürge-Vorsatz et al. 2014). In most cases, there are two key reasons behind not incorporating the non-climate related impacts into a decision making analysis:

1) The wide impacts of sustainable energy policies or energy efficiency policies are often not completely identified.
2) Even if many of the impacts are identified, they are often not quantified and thus not attributed to an energy policy.

Furthermore, many of these benefits are non-marketable, indirect, thus difficult to be quantified and monetized. Thus, it is difficult to understand the net effect of a sustainable energy policy.

Productivity being one of the important multiple impacts, also has these challenges in regard to quantification. In addition to these challenges, most of the studies have not clearly defined productivity impact as one of the multiple impacts of energy efficiency despite the fact that sustainable energy measures such as improved energy efficiency measures, have a positive effect on labour productivity (by improving health and well-being) as well as on industrial productivity (by improving input efficiency) (Fisk 2009; Worrell et al. 2003). Also, the outcome of the studies (see (Fisk, & Rosenfeld 1997; Fisk 2000; Worrell et al. 2003; Chapman et al. 2009) conducted on productivity impact varies largely since the outcomes are sector specific and these studies have major gaps in the context of geographical and/or technical coverage. These gaps and disperse findings make the consideration of productivity impact in energy related policy making and policy evaluation difficult today (Ürge-Vorsatz et al. 2015). However, by not quantifying them, we can easily underestimate the potential of a sustainable energy policy. In addition, it needs to be noted that this lack of methodology to quantify productivity impact as well as the other multiple impacts, certainly does not make them any less significant but the failure to estimate the impacts, especially the benefits, results in less investment in sustainable energy measures. The IEA 2012 report expresses the same concern quoting "these foregone benefits represent the opportunity cost of failing to adequately evaluate and prioritize energy efficiency investments and this opportunity cost may be very large, and in particular in the context of increasing global demand, stress on resources, and climate concerns, they may represent a cost that we cannot afford to bear". Thus, there is a need to provide a broader quantitative understanding of multiple impacts especially productivity impacts in relation to improved energy efficiency measures in order to fill in these gaps.

1.3 Research aim:

The key research aim of my dissertation is to provide a better tool and methods to quantify multiple impacts of sustainable climate policies. As discussed in section 1.2.4, in order to provide a better tool and methods of quantification, first the multiple impacts of sustainable climate policies need to be identified then they have to be quantified (if not monetized) to understand the magnitude of multiple impacts as well as the importance of climate policies.

1.4 Research question:

To achieve the research aim mentioned in section 1.3, the following research question need to be answered:

- How to quantify the multiple impacts especially productivity impact of improved energy efficiency measures in a theoretically and methodologically rigorous manner?

1.5 Objective:

To achieve my research aim, this dissertation is taking productivity impact as a representative of multiple impacts to develop a rigorous methodological framework. Thus, keeping in mind the research aim and research question the following objectives have been defined:

- **Objective 1:** Clearly define productivity impacts in the context of multiple impacts of sustainable climate policies.
- **Objective 2:** Provide the methodological framework to quantify productivity impact.
  - **Sub-objective 1**: Identify the pathways from implementing energy efficiency measure to productivity impact.
  - **Sub-objective 2**: Develop context specific equations to quantify productivity impacts. Here, context implies both sector and specific sustainable energy measure.
- **Objective 3:** Quantify productivity impact for a few specific cases.
  - **Sub-objective 1:** Productivity impact would be measured for specific sustainable energy measures in two different scenarios at national level in the year 2030.

Scenario one would estimate the productivity impact of energy efficiency measures if no further sustainable energy actions are taken i.e. reference scenario in the year 2030.

The second scenario would estimate productivity impact of sustainable energy measures in the year 2030 if energy efficiency measures are taken i.e. efficient scenario.

The year 2030 is taken in order to estimate the potential of sustainable energy policies, keeping the EU 2030 framework for climate and energy in mind. Also, 2030 is the target date for delivering on the sustainable development goals.

- **Objective 4**: Assess the significance of productivity impact for two specific cases.

Multiple impact assessment results are better compared across different energy efficient options for implementation or scenarios rather than across assessment methods (Ürge-Vorsatz et al. 2016). Therefore, in this dissertation, two different scenarios are used in order to understand the extent of productivity impact.

1.6 Scope of the research

This dissertation is framed within the following boundaries which define the scope of the research:

Methodological framework: This dissertation provides a theoretically consistent methodological framework to rigorously quantify multiple impacts especially productivity impacts. This study uses scenario analysis to understand the magnitude of productivity impact by using this methodological framework.

Productivity indicators: By using this methodological framework, this study proposes a few indicators to measure productivity impact. However, by using this framework any other impact can also be measured. In this study, productivity impact is taken as an example to show how the methodology works.

Timeframe: The analysis of productivity impact through its indicators is estimated for the year 2030. As discussed in section 1.5, the year 2030 is selected considering the EU 2030 framework for climate and energy.

Energy end-use sectors and improved sustainable energy measures: Two end-use sectors namely building and transport sector have been selected. In building sector both residential and tertiary sector have been considered. For these two end-use sectors, two different energy efficiency measures are considered. More precisely, for building sector, improved Heating ventilation and air- conditioning (HVAC) system with airtight building shell has been considered and for transport sector modal shift towards active transportation has been considered.

Geographical: This study estimates productivity impact of improved energy efficiency measures for two European countries namely Hungary and Germany.

1.7 Coverage

This study takes Hungary and Germany as case studies to understand the significance of productivity impact of improved energy efficiency measures. The objective of taking two countries is not to compare between themselves but rather to show how substantial productivity impact can be in two different countries. In the following section the reasons behind selecting these two countries are discussed in brief.

Hungary: Hungary can be considered as a representative case of Eastern Europe. Post 1989 reforms in Hungary were accompanied by high inflation rate, increase in unemployment rate, and decrease in per capita income (Kremer, Sziklai, and Tausz 2002). Post reforms period affects energy prices as well (due to withdraw in price subsidy) and the consequences of reforms were higher for the lower income households (Kocsis 2004). With the lasting impacts of the reforms along with other factors, Hungary still has a very low per capita income level among European member states (OECD 2016). In addition, in the year 2011, Hungarian constitution recognized the right for healthy living and working environment (annex XVII) also it acknowledges the need for decent housing and public services. These articles of the fundamental constitution of Hungary provide a legal ground to have a healthy work and living environment.

However, despite these articles, Hungary is performing poorly compared to the OECD average by having poor housing conditions, poor health conditions and low self-reported well-being (UN 2015; OECD 2016). Furthermore, it is important to remember that Hungary is an energy import dependent country. Hungary's energy supply heavily depends on natural gas and crude oil import. As per Embassy of Hungary's (London) fact sheet, 80% of the natural gas is imported from the Russian Federation.

Therefore, in order to improve the economic well-being, energy efficiency can play an important role by improving labour productivity through improving health condition which can accelerate income and well-being (OECD 2016). Thus, the role of sustainable energy measures and productivity impact becomes crucial for Hungary, which makes Hungary a suitable study ground to showcase the significance of multiple impacts related to sustainable energy measures.

Germany: Germany can be considered as a representative of the more economically powerful and politically stable Western Europe. The German economic growth has been stable over the past years. In 2014 the real GDP growth was 1.6% and in 2015 it became 1.7% (European Comission 2016). Furthermore**,** Germany's unemployment rate is the lowest in European Union and income inequality is quite low compared to other OECD countries (OECD 2016). That is why Germany is considered to be as one of the most developed economy in the world.

Despite all these positive aspects, Germany's labour productivity growth is not satisfactory compared to other OECD countries. In fact, overall productivity growth of Germany is weakened compared to other OECD countries and maintaining a steady productivity growth is crucial in order to achieve a long-run sustainable growth (OECD 2016). Thus, labour productivity can certainly play a crucial role in accelerating the economic productivity (OECD 2016).

Germany and Hungary make a suitable study ground to research the potential of productivity impact of improved energy efficiency measures in the context of well-being, welfare, and quality of life and as well as their potential to improve the building and transport sector. More precisely, Hungary is still undergoing a socio-economic transition as many other post-communist EU countries, and thus these two case studies enable a diverse opportunity to study the role of energy efficiency in achieving a higher well-being through labour productivity in the EU context.

1.8 Context of this dissertation:

This dissertation is a part of the Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe (COMBI) project (COMBI 2015). The COMBI project is a part of the European Union's Horizon 2020 research and innovation programme under grant agreement No 649724. The COMBI project aims at calculating the energy and non-energy impacts of energy efficiency measures for all European Union member states and then develop an online- visualization tool to show different impacts of energy efficiency. I am working as a researcher in the COMBI project where I am responsible for quantifying productivity impact of energy efficiency measure and also for developing a synthesis methodology to aggregate multiple impacts. The COMBI project mainly focuses on creating a user-friendly tool which can be used by the policy maker to see the significance of mainly five type of multiple impacts namely health, social welfare, resources, macro-economic impacts and energy security. Within the broader context of the COMBI project, my dissertation's main aim is to contribute to the methodological advancement of multiple impact quantification by using two case studies of productivity impact quantification in two different countries.

1.9 Structure of the dissertation:

This dissertation is structured in seven chapters. This first chapter introduces the context, research problem, objectives, scope and justification of the study. Chapter 2 first introduces the concept of energy efficiency, multiple impacts and productivity impact. Then it discusses how multiple impacts and energy efficiency can achieve a higher well-being. Chapter 3 describes the technical details of energy efficiency measures and then it talks about how different energy efficiency measures can influence productivity impacts.

Chapter 4, 5 and 6 describe the contributions of this dissertation where chapter 4 talks about this dissertation's methodology and how this methodology can deal with challenges related multiple impacts evaluation. Moreover, chapter 4 provides a review of existing methodology and identifies the need of a new methodological framework. Chapter 5 lists down all the data used as input and the relevant assumptions of the methodological framework. Chapter 6 presents the results which are estimated by using the methodology described in chapter 4. Also, it provides some reasoning of the results. A sensitivity analysis is conducted in chapter 6 to strengthen the contribution of this dissertation. Lastly, chapter 7 discusses productivity impacts and multiple impacts further in the context of well-being. Finally, this chapter states the limitation of the study and after discussion on the limitations, this dissertation ends with concluding all the concepts, methodology, results, and its possible use.

CHAPTER 2: THEORETICAL FRAMEWORK: ENERGY EFFICIENCY, MULTIPLE IMPACTS, PRODUCTIVITY IMPACT AND WELLBEING

"It is theory that decides what can be observed".

Albert Einstein

2.1 Theoretical framework:

2.1.1 Introduction to energy efficiency measures: Concept and definition

Reduction of energy use without disrupting the development and standard of living is a key challenge of the twenty first century. Moreover, the world population have been constantly increasing over time which result in increase in the total demand for energy which is mostly supplied via fossil fuel based energy system. The fossil fuel based energy system contributes to the anthropogenic climate change by emitting carbon dioxide (CO_2) and other greenhouse gases (Wei et al. 2007). There are mainly two key global threat of increasing energy demand and use:

1. Most of the energy systems globally are carbon intensive and thus emission of greenhouse gases (GHG) also increases along with energy use and production. With the increase of GHG emission, the adverse effects of climate change are also increasing over time globally (Davis et al. 2010; IPCC 2014).
2. The fossil fuel stock is limited as it is a natural resource. Thus, excessive use of fossil fuel would convert them as scare commodity (Shafiee & Topal 2009).

With challenges like the above mentioned ones, the possible solution is to use the alternative energy approach (such as solar, wind etc.). However, the alternative energies are not yet developed enough to meet the global energy demand. Therefore, efficient use of energy becomes necessary to reduce GHG emission without disrupting the standard of living. The efficient use of energy is obtained mainly by two key ways:

1. By technological improvement- Technological improvement basically reduces the input use to produce the same output level. In other words, by having technological improvement, same amount of energy services can be obtained by using less energy.

2. By behavioral/lifestyle change- Behavioral change or lifestyle change is another approach to reduce energy use where individuals who are the energy users change their behavior to reduce energy use.

Both technological improvement and behavioral/lifestyle change can be considered as instruments to save energy (Roy et al. 2012).

Energy efficiency in general can be defined as using less energy input to produce the same or higher amount of energy services (Patterson 1996). More precisely, energy efficiency can be defined as “energy services provided per unit of energy input” (Asif & Muneer 2007). However, both of these definitions indicate an efficient use of energy input. Thus, the most popular indicator of energy efficiency is ‘energy intensity’ which can be defined as “the amount of energy used per unit of gross domestic product (GDP)” (IEA 2016). As per IEA 2017 study, 12% energy use was avoided globally in 2016 due to the fall in energy intensity which means more GDP can be produced for each unit of energy consumed. This improvement (means decline in per energy input used) in energy intensity results from implementation of energy efficiency measures globally (IEA 2017). This decline in energy use would not only result in less GHG emission but also saving energy results in improved energy security (Jansen and Seebregts 2010). However, it is important to note that the energy intensity varies across different sectors, such as industry, transport, building, agriculture etc. For instance, as per IEA 2017 market report, industrial final energy use has declined by 0.9% annually on an average between 2000 and 2014 annually in OECD countries. On the other hand, energy intensity in the transport sector increases by 15% globally due to growing demand for personal vehicles mostly in non-OECD countries (IEA 2017).

Although energy efficiency can play a crucial role in saving energy and thus, in mitigation of climate change, the effects of energy efficiency measures are not restricted only to climate change mitigation. Rather, it goes beyond economic and environmental aim. In the next section, it is discussed how energy efficiency and its measures go beyond economic and environmental goal.

2.1.1.1 Energy efficiency and well-being:

Challenges, such as climate change and air pollution, include further aspects such as equity and morality which are rarely included in the modern energy planning and analysis process (Bolla et al. 2011). These challenges can be expressed as 'energy related externality' (Bolla et al. 2011; Stern 2006) . To tackle these challenges, energy efficiency is often seen as a mitigation option.

There are mainly two key aims behind every energy efficiency measure implementation:

1) Environmental aim: Reduction in energy consumption would result in less natural resource extraction, less waste generation which ultimately reduces CO_2 emission.
2) Economic aim: Reduction in cost of operations and reduced cost of energy services (Bolla, et al. 2011).

By achieving these two key aims, energy efficiency measures can achieve a higher well-being. It is often the case that the term welfare is used as a synonym of well-being because both welfare and well-being refer to overall standard of living in financial and material ways (Liberty Fund 2012). However, there is a difference between welfare and well-being. Well-being is a much broader concept and welfare or as economists refers economic well-beings is a key component of well-being (Lequiller and Blades 2014). Welfare describes how well-off a person is i.e. the material living conditions whereas well-being describes how well a person is (Lequiller and Blades 2014). Welfare or economic well-being indicates only the material well-being and that is why economists and statisticians sometimes refer welfare as economic well-being. However, economic well-being is alone not sufficient to measure overall well-being as there are other aspects of human life such as jobs and earnings, housing, health, work and life balance, education etc. which are equally important to being well-off. Thus, Lequiller and Blades 2014 study disaggregates well-being into two key domain: 1) welfare (or economic well-being, and 2) quality of life.

Energy efficiency by achieving environmental aim, can improve the standard of living by having less outdoor pollution and hence improved health condition (Lean, & Smyth 2010). Improvement of standard of living implies improved welfare. Furthermore, by using energy efficiency measures, one can enjoy same energy related services with less energy use. In other words, it can be said that the affordability of an individual would go up after installing an energy efficiency measure. For instance, energy efficiency measures result in decrease in energy prices 'triggered by the efficiency gain' and expenditure savings through energy savings (Nässén, & Holmberg 2009). Thus, a higher economic well-being can be achieved. Also, the energy cost savings increase other energy-consuming goods and services which are not affordable previously which also implies improve in standard of living hence improvement of well-being (Ürge-Vorsatz and Tirado-Herrero 2012). To conclude, energy efficiency can not only save energy cost savings, but also achieve a higher economic well-being and improved quality of life, it results in higher well-being in general.

2.1.2 Definition of multiple impacts

As discussed in chapter 1, there are many terms which are used to address the non-energy benefits of climate change policies. Most of these terms are synonymous (for example, co-benefits, mutual benefits, collateral benefit, secondary benefits, externalities etc.) but in some cases these terms have a slightly different meaning (Floater et al 2016). For example, the IPCC third and fourth assessment reports define co-benefits and ancillary benefits as benefits intended by policy and unintended benefits by policy respectively. Though co-benefit is the most popular term to address the non-energy effects of climate change policy, but there are some concerns about using this term as co-benefits only imply the benefits of a policy rather than the whole effects including the negative ones (Ürge-Vorsatz et al. 2014). More precisely, using the term co-benefit may bias the research as it includes only the benefits of the policy. This bias may lead to overvaluation of a policy. Thus, in this study, to address all the effects and also considering the significance of the additional effects of energy policies compared to energy savings, the term 'multiple impacts' is used. In order to understand the term 'multiple impacts' more deeply, we need to explore the existing definitions of co-benefits/ancillary benefits. Thus, with the help of table 1 below, the definition and concepts of co-benefits which are used in literature until now, are discussed:

Table 1: Definition of co-benefits

Definition of co-benefits/additional effects of climate change policies	**Study**
Co-benefits can be defined as the benefit for the local environment as a climate mitigation/adaptation policy	(Hamilton, Kirk, Akbar 2010)
"Co-benefits are the win-win strategy aimed at capturing both development and climate benefits in a single policy or measure"	(Miyatsuka and Zusman 2010)
"The potential developmental benefits of climate change mitigation actions in areas other than GHG mitigation"	(Santucci et al 2014)
"For GHG mitigation policies, co-benefits can be defined as effects that are additional to direct reductions of GHG and impacts of climate change and have estimated to be large, relative to the costs of mitigation (e.g. anywhere from 30% to over 100% of abatement costs)"	Defined by OECD 2015 quoted at (Floater et al 2016, p: 14)
Co-benefit is an intended approach to capture both development and climate benefits in a single policy or measure	(ACP 2016)
Co-benefit is a positive outcome of an intervention to mitigate/adopt climate change	(Doll & Oliveira 2017)

Source: Own elaboration

In table 1, the definition provided by IPCC AR3 and AR4 reports are not included as they are already discussed in the beginning of section 2.1.1. From table 1, it can be seen that some studies are using the term 'co-benefits' and 'ancillary benefits' interchangeably. Also, from these definitions two analyses become clear:

1. Co-benefits are seen as a separate benefit-mostly to the local environment in addition to global climate change mitigation/adaptation effort.
2. A climate change policy can result in local non-energy benefits which can be realized within short time period. Thus, to realize the immediate local benefit a local government may push for global climate change policies irrespective of the result of the policy is intended or unintended.

To avoid these 'intended' and 'unintended' confusion, IEA 2012 and 2014 studies use the word 'multiple benefits' to capture all the effects of a climate change policy considering the multi objective framework of IEA countries.

This analysis also shows that the additional effects of any climate change policy are perceived as positive. However, it may not be the case. For instance, due to energy efficiency measures energy demand may reduce which may cause some job loss at the energy producing sector or a person shifting from motorised to non-motorized mode, such as cycling would expose to more air pollution and hence more related health effects (De Hartog et al. 2010; Ürge-Vorsatz et al. 2016). Thus, considering only the positive effects i.e. the co-benefits would bias an evaluation or in other words over valuate a policy. Urge-Vorstaz et al. 2014 study uses the term 'co-impact' to avoid this bias in the evaluation. However, as discussed in chapter 1- section 1.2.2, the additional effects of policy could be higher than the main effect of the policy. In addition, a local government may prioritize their objective based on the problems they are facing. For instance, if a nation has poor air quality then it may want to implement a global climate change policy to improve the air quality. Thus, addressing an effect of climate change policy as 'co' may not always be right.

Therefore, this dissertation uses the word 'multiple impacts' to denote both the positive and adverse effects of a sustainable energy policy and also to acknowledge the multi objective framework of European Union.

The climate change polies can yield a wider set of benefits for the economy and society such as job creation, GDP growth, productivity, increase of energy security, positive impacts on health, as well as ecosystems improvements (Sauter and Volkery 2013; GEA 2014; IPCC 2014; Ürge-Vorsatz et al. 2014). Although the multiple impacts (MI) are discussed mostly in the context of energy efficiency, it has prominence in the broader energy and climate change context as well (Ürge-Vorsatz et al. 2016). The discourse of multiple impacts in the context of energy efficiency gains attention after the IEA works in 2012 and 2014 (Ürge-Vorsatz et al. 2016). More precisely, IEA works in 2012 and in 2014 are the first to show how the additional effects of energy efficiency improvements contribute to maximize the welfare and well-being of a society (IEA 2014). For instance, improved energy efficiency measures would reduce energy use which also implies energy cost/utility cost savings. These cost savings increase the disposable income. Additionally, energy savings would also reduce energy production related to air pollution which results in outdoor pollution emission. Less outdoor pollution would further result into improvement in health and productivity. There are other dimensions of energy savings such as reduction in energy consumption which would reduce scarcities in energy resources and ultimately would result in reduction of social inequities (Ürge-Vorsatz et al. 2016).

Figure 2 shows some of the possible co-benefits (also termed as multiple benefits) of a successful energy efficiency measure which can help us understand the vast potential of sustainable energy policy to some extent:

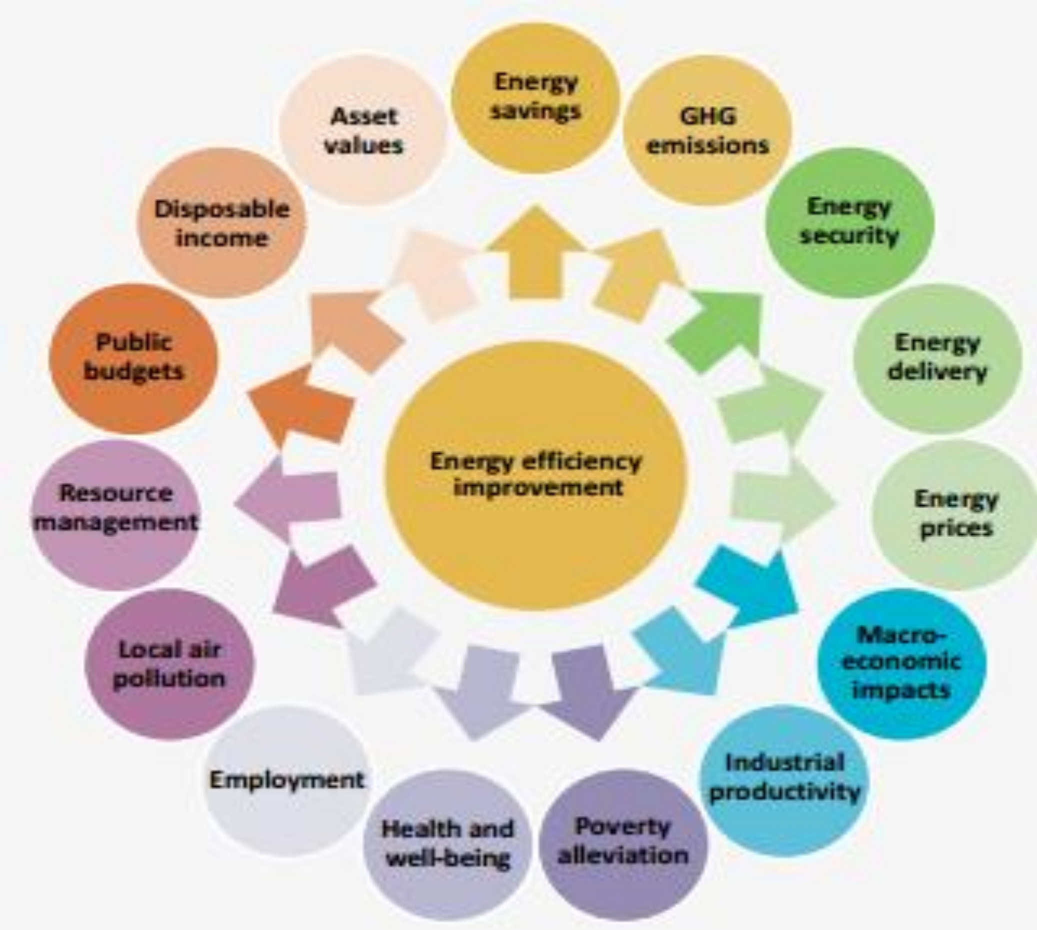


Figure 2: The possible multiple impacts of energy efficiency measures

Source: (IEA 2014)

Figure 2 shows these multiple impacts of sustainable energy policy which go beyond the well-established main aim of any sustainable energy policy i.e. energy savings and greenhouse gas reduction.

2.1.2 Types of multiple impacts

The multiple impacts of energy efficiency are typically experienced at local level whereas the reduction in GHG emission yields a national/global impact (Metz et al. 2007). Thus, the economic policies concerning local development should definitely consider the multiple impacts of improved energy efficiency measures. However, depending on the size and magnitude of the multiple impacts, the overall effect of energy efficient measure could be understood i.e. whether the policy would be beneficial for the society/individual or not it depends on the size and magnitude of the impacts. The scale and magnitude of the impact would vary as per the sector and sector specific energy efficiency measures. For example, building related energy efficiency measures would result in certain impacts for example, energy poverty alleviation which would not be seen from the energy efficiency measures in industry sector. Furthermore, sector specific sustainable energy policies can result in an array of multiple impacts. Few studies try to organize this array of impacts into different categories. For example, the building sector-related energy efficiency policies can be categorized into five key broader categories namely health, ecological effects, social effects, economic effects and service provision benefits (Ürge-Vorsatz et al. 2009). To explain this further, table 2 shows different categories of impacts in building sector with an example:

Table 2: Typology of benefits of energy efficiency in the buildings sector and examples

Category	**Sub-category of the impacts**	**Examples and supporting literature**
Health effects	Reduced mortality and morbidity	Reduced mortality and morbidity due to improved indoor quality and through reduced thermal stress in better buildings (Howden-Chapman et al. 2009).
Social effect	Energy poverty	The intensity of energy poverty can be minimised by saving utility bills; level of reduced fuel / electricity debt; improved state of health (Healy 2003; Schuessler 2014).
Ecological effect	Effects on ecosystem	Less acidification and eutrophication due to improvement in outdoor air quality. For instance, after

Category	Sub-category of the impacts	Examples and supporting literature
		installing energy efficient hot water boilers, less energy would be consumed and due to which pollutant emission would be reduced to some extent which ultimately results in less acidification and eutrophication (Scheuer et al. 2003).
Economic effects	Productivity impact, employment effect, public budget and energy security	Due to improved indoor air quality more work opportunities arise. Furthermore, for retrofit purpose more labour is required which reduces the unemployment rate. Also, due to reduced dependence on imported energy, government expenditure reduces (Fisk 2000;Ürge-Vorsatz et al. 2010).
Service provision benefits	Transmission and distribution loss reduction and utilities insurance savings	Energy savings due to implementation of energy efficiency measures, results in a smaller amount of energy (e.g, electricity, gas) transported to the household; hence the elimination of energy losses. In addition, Insurance cost would reduce as a result of more compact services such as fewer gas leakages (Schweitzer and Tonn 2002).

Source: Adapted from (Ürge-Vorsatz et al. 2009)

A substantial potential of improved energy efficiency measures can be seen by identifying a broad range of categories (health, economic, ecological, social and service provider impacts) which are beyond the traditional focus on energy demand reduction, but many of the categories are interconnected (for example health and social impacts) (Ürge-Vorsatz et al. 2009). This categorization would not help in identifying all the interactions among impacts, because categorizing and then quantifying the impacts according to their category may lead to double counting.

Another crucial aspect of identifying impacts is sector specific energy efficiency measure - which means different energy efficiency measures in different sectors may result in different impacts which may fall in different category. For example, due to implementation of energy efficiency measures in the industrial sector there could be many impacts, such as improved equipment performance, minimization of waste etc. which can belong to a completely new category. Wornell et al 2003 study categorizes multiple impacts of industrial sector into six broader category, namely waste (for example, reduce water waste), emissions (for example reduced Sulphur di oxide), operation and maintenance (eg: increased facility reliability), production (eg: increase output), working environment (eg; reduce the need of personal protective requirement) and other (eg: decrease liability) (Worrell et al. 2003). Similarly, for transport sector or agriculture sector, the related multiple impacts can also be categorized. Studies mostly evaluate sector specific single impact (refer to table 2) and even evaluation of these single impacts can also be proven to be larger than the main benefit of an energy efficiency measure i.e. reduction in energy consumption. For instance, Ürge-Vorsatz et al. 2009 found out that some of the impacts of improved energy efficiency can deliver 2.5 times the value of the energy demand reduction.

Due to these interlinkages between categories, it would not be helpful for quantification of impacts to identify impacts as per their category because due to these interlinkages double counting error may occur. Therefore, it can be safely said that categorization of impacts cannot help in enabling all the interaction and thus quantification, but however it can provide a good understanding of sector specific multiple impacts.

2.1.3 Empirical evidence of multiple impacts

From the discussions so far, it is evident that a different range of multiple impacts results from energy policies. However, if these impacts are not quantified then they cannot be incorporated into a policy evaluation. In other words, not incorporating impacts would lead to undervaluation of a policy. For instance, Urge-Vorsatz et al 2014 study argues the inclusion of additional non-energy benefits into policy assessment can significantly change the final outcome. According to this paper, without the proper integration framework, the assessment of even single impact seems impossible. Stechow et al in their paper 'Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis reviews and analyses the IPCC WGIII AR5 results' reveals that the impacts are difficult to quantify because of the incommensurability and uncertainties of the quantification results. The authors have suggested the following in the quantification methodology: 1) shifts the perspective from local to economy wide and global, 2) multiple objectives of a policy should be taken into account during the analysis, and 3) expresses the quantification results in economic term precisely in monetary term, rather than nonmonetary terms (Stechow et al. 2015).

Quantification and monetization of these impacts are not easy and hence there are a limited number of case studies conducted about the magnitude of multiple impacts. Table 3 below shows some of the case studies conducted on multiple impact quantification for different energy efficiency measures in different sectors. These studies mentioned in table 3, have estimated multiple impacts mostly based on small sample survey. Thus, the coverage only shows the study area and not the sample size.

Table 3: Results of a few empirical studies on energy efficiency impacts summarized

Impacts	**Energy efficiency technique used**	**Magnitude of the impacts**	**Ratio between multiple impacts and direct savings**[2]	**Coverage of the study**	**study**	**Study description**
Health benefit, CO_2 reduction and effect on ecosystem	Metering and regulation; minimum standards for the insulation in new buildings; energy efficiency labelling of household appliances; energy savings awareness raising and education; Energy Saving Credit Programme	Health benefit of 370 mill. US $- 1170 mill. US $ can be gained; 30-35 mill. US $ can be gained by avoiding the building maintenance cost; and 86-222 mill US $ can be gained by reducing the CO_2 emission.	2.43	Hungary	(Aunan, and Seip 2000)	This paper assesses the cost and benefits of the implementation of a few specific energy efficiency program in Hungary.
Productivity impact	Energy efficiency improvements in iron and steel industry	Nearly 170 PJ of potential energy savings per year for the entire sector.	2	US	(Laitner, Ruth, & Worrell 2001)	This study shows that the inclusion of the productivity benefits in the cost calculations improves the potential of energy efficiency for the entire sector.

[2] Ratio is calculated by diving the monetary value or physical value of multiple impacts and direct savings i.e. energy cost savings. In some cases, the physical values and energy savings are in same unit, hence division is possible.

Impacts	Energy efficiency technique used	Magnitude of the impacts	Ratio between multiple impacts and direct savings[2]	Coverage of the study	study	Study description
Health and comfort benefits	Household renovation	The overall value of MI is calculated 4723 million Euro over 31 years at a 5% discount rate.	1.7	Ireland	(Clinch and Healy 2001)	This study provides a template for ex-ante economic evaluation of domestic energy efficiency measures by taking Ireland household as a case study.
Ratepayer benefits, Household benefits, Societal benefits	Weatherization assistance program for low income homes in the US	$3346 (in 2001 $ per household)	*1.05*	USA	(Schweitzer and Tonn 2002)	This project summarizes findings attributable to the weatherizing program. The study finds that the overall, societal benefits are estimated to be substantially larger than the ratepayer and household benefits.
Economic and social benefits	CO_2 emissions abatement policies in residential sector	A reduction of 5953 kt CO_2 could be achieved	0.45	Greece	(Mirasgedis et al. 2003)	This paper proposes a methodological framework to evaluate the economic value of CO_2 emissions abatement policies in residential sector, considering both economic and social cost/benefits.
Health benefits	Retrofitting of household with insulation	The total benefits account for $1.3 billion per year from health improvements and $5.9 billion per year from energy cost savings by	0.22	USA	(Levy, and Spengler 2003)	This paper proposes a risk-based model to estimate the health benefits from marginal energy usage reductions.

Impacts	Energy efficiency technique used	Magnitude of the impacts	Ratio between multiple impacts and direct savings[2]	Coverage of the study	study	Study description
		insulating 46 million homes in the USA				
Ancillary savings and production benefits	Industrial energy efficiency measure such as equipment replacement, technological upgrades and reconfiguration of existing equipment	The total cost sums up to $68.2 million and the payback including ancillary savings is slightly less than one year.	0.44	USA	(Lung et al. 2005)	This study examines the importance of ancillary benefits by evaluating ancillary savings and production benefits of industrial energy efficiency measures.
Health and environmental benefits	Retrofitting of household with insulation	The total benefits would be NZ$ 3374 per household at 5% discount rate	1.87	New Zealand	(Chapman et al. 2009)	This study shows the benefits of housing insulation in New Zealand by quantifying health and environmental benefits.
CO_2 and other pollutant savings	Residential sector (improved insulation, high efficiency boilers and heating controls) and small-business sectors efficiency measures	710 million Euro by 2030 and total energy savings by 2030 is 5340 GWh	1.23	Ireland	(Scheer and Motherway 2011)	This paper presents an economic evaluation of energy efficiency improvements made in the residential and small-business sectors in 2009-2030.
Health benefits	Building retrofitting with higher insulation	1266 million NZ$ over 30 years at 4% discount rate	83	New Zealand	(Grimes et al. 2012)	This study summarises the cost-benefit analysis of the warm up New Zealand program.

Impacts	Energy efficiency technique used	Magnitude of the impacts	Ratio between multiple impacts and direct savings[2]	Coverage of the study	study	Study description
	and installing clean heating					
Environment and health effects	China's national energy conservation policy	3 \$/t CO_2 to 39 \$/t CO_2 at the national level can be achieved	-	China	(Yang et al. 2013)	This study analyses the impact of environmental and health-related impacts of the climate policy and mitigation technology assessment of the cement sector in China.
Health benefit	Energy saving technique in the cement industry	The estimated monetary gain due to health improvement in S1 would be around \$11.9/person, which is equivalent to 0.73% of GDP in 2010, and the value of monetary gain in S2 due to health improvement would be \$23.6, which is 1.45% of GDP in 2010.	-	China	(Hasanbeigi, et al. 2013)	This Study estimated health impact due to reduction in SO_2 and PM2.5 in Shanghai province in China through scenario analysis.

Source: Adapted from (Ürge-Vorsatz et al. 2015; Ürge-Vorsatz et al. 2016)

In table 3, 12 case studies are presented and all of them show multiple impacts have a significant importance compare to energy cost savings. The ratio between multiple impacts and direct savings lies between 0.45-2.43. Grimes et al. 2012 study's result is an outlier hence not considered in this range. Apart from these 12 case studies, there are other studies as well some of which are mentioned in later chapters and some of the studies have not quantified the direct savings hence are not incorporated in this list. However, the purpose of this table is not to list-down all the case studies on impact quantification but, rather show the magnitude of impacts compares to energy cost savings benefit. By seeing the magnitude of impacts compare to energy cost savings, it gets clear how much a policy can be undervalued, if multiple impacts are not incorporated. Another important point from table 3 is the type of impacts covered in studies. More precisely, most of the studies presented in table 3, quantified health benefits. The magnitude of health impacts also varies across different studies. Lastly, it can be concluded from table 3 that the multiple impacts have a significant effect and considering the monetized value of the impacts, if the impacts are incorporated into decision making analysis then they can have a significant effect on policy design.

2.1.4 Defining productivity impact

Productivity impact is one of the crucial multiple impacts of improved energy efficiency measure (Fisk 2002;Chatterjee and Urge-Vorsatz 2017). In fact, many studies (see (Porter & Van der Linde 1995; Boyd & Joseph 2000) argue that productivity impact is equal or greater than energy cost savings.

Productivity can be broadly defined as the “ratio of a volume measure of output to a volume measure of input use”(OECD 2001). However, the definition of productivity varies as per the perspectives (such as measurement, labour relations, training and development, management, budget, and finance) and sectors (such as building, industry, transport etc.)(Quinn 1978). Table 4 shows the key existing definitions of productivity measurement. These definitions clarify the concept of productivity or being productive.

Table 4: Definitions of productivity

Reference	**Definition**
(Quinn 1978)	Defined productivity from two different perspective; economic and industrial engineer defines productivity as input-output ratio with quality of the output and administrator defines productivity as “better performance”.
(Koss and Lewis 1993)	“Quality or state of bringing forth, of generating, of causing to exist, of yielding large result or yielding abundantly”
(Rogers 1998)	“Ratio of output to input for a specific production situation”.
(Leaman and Bordass 1999)	"The ability of people to enhance their work output through increases in the quantity and/or quality of the product or service they deliver"
(Al-Darrab 2000)	Productivity =(Output/ Input) x Quality factor
(Boyd & Joseph 2000)	"Output per unit of non-energy input(s) increase because of a project identified to increase output per unit of energy"
(Tangen 2002)	Relation between input and output which can be applied at different levels of aggregation in the economy.

Reference	Definition
(SPRING 2011)	Measures effectiveness and efficiency of an organization in generating output with the resources available
(Atkinson 2013)	Economic output per unit of input.

Source: Own elaboration

All these definitions mentioned in table 4, reflects the broader definition of productivity i.e. the relation between input used and output. In addition to output and input use, these definitions also indicates another aspect of production namely quality. However, measuring quality of an input is difficult and often it does not get quantified.

Though productivity is a well-used term in academic and industry circles but despite its frequent use, productivity is often get confused with the term ‘performance’. Performance can be defined as “a metric used to quantify the efficiency and/or effectiveness of an action” (Tangen 2004). Another close concept to ‘productivity’ and ‘performance’ is efficiency which can be defined as using less input to produce same or more volume of output (Tangen 2004). Conceptually, performance and efficiency are measuring the same thing i.e. input efficiency which improves the ratio between volume of output and volume of input use. In other words, input efficiency improves productivity. More precisely, increase in input efficiency means less input use per output, and then productivity improves (i.e. growth of productivity). Hence, input efficiency can be considered as an indicator of measuring productivity. Therefore, since both performance and efficiency measure input efficiency, they are considered as indicators of measuring productivity.

Until now there is a limited number of studies (such as, (Fisk 2000; Fisk 2002; Howden-Chapman et al. 2009) which measure productivity impact of sustainable energy policies by measuring only a few handful aspects of productivity, such as absence from work or work performance. Both work performance and absence from work measure productivity through input efficiency/inefficiency-more precisely, labour input efficiency/inefficiency. Literature have defined labour productivity mostly in three ways:

1. Productivity improvement due to improved indoor air quality: Studies (Fisk and Rosenfeld 1997; Wargocki, et al. 1999; Wargocki, et al. 2000; Wyon 2004) have shown that improved indoor air quality enhances the performance of an employee. Poor air quality affects productivity due to 'sick building syndrome' which results in loss of work opportunity (Burge 2004). The quality of indoor air can be improved significantly by climate change polices and the effect of improvement on productivity and health could be quite vast. For instance, Chapman et al 2009 study find that as a result of building retrofitting, benefit from health and productivity would be around 2488 New Zealand dollar (NZ$) per household.
2. Productivity improvement due to thermal comfort: The link between thermal comfort and productivity is well-established in academic literature. Studies show that if temperature of a workplace is controlled to provide comfort then employee's performance can improve significantly (McCartney, and Humphreys 2002; Witterseh, Wyon, and Clausen 2004; Akimoto,Tanabe, Yanai, and Sasaki 2010). If the optimum thermal comfort level could not be maintained then productivity decreases significantly. For instance, Seppanen et al 2004 study finds that an average of 2% decrease in work performance per degree Celsius has been established when the temperature is above 25°C.
3. Decline in absenteeism due to improvement in indoor air quality: Poor indoor air quality does not only affect work performance but it affects quantity of labour input directly through the absenteeism of employees (Joshi 2008). Several diseases such as respiratory diseases, allergies etc. caused due to poor indoor air quality, can result in

absenteeism (Milton, Glencross, & Walters 2000; Fisk 2002; Seppänen,& Fisk 2005). Mendall et al. 2002 study estimated that by reducing indoor air quality induced absenteeism, US economy can gain more than $6 billion.

These aspects of labour productivity are defined in the context of building sector, more precisely tertiary building sector. However, there could be other aspects of labour productivity resulting from energy policies which have not been discussed in the literature. Similar to building sector, transport sector specific sustainable energy policies can result in productivity gain by avoiding activity-restriction days (Trubka et al. 2010; Mueller et al. 2015). However, the effect on labour productivity in transport sector related sustainable energy policies, are not widely researched. Again similar to building sector, there could be other aspects of labour productivity which are further discussed in chapter 3 further.

Apart from labour productivity, climate change policies can result in other type of productivity as well such as crop productivity in agricultural sector, input efficiency for industrial sector (Olesen, & Bindi, 2002; Worrell, et al. 2003). These productivity improvement are also equally significant and relevant to explore the full potential of climate change policies. For instance, Worrell et al 2003 study shows that without including productivity benefits, the potential for energy savings drops by half from 3.8 GJ of steel to 1.9 GJ. However, since the scope of this dissertation is only limited to labour productivity, industrial and agricultural productivity have not been discussed here.

2.1.5 Importance of productivity impact:

Productivity is one of the most important drivers of economic growth and sustainability and also depends on the availability of the inputs. Despite its importance, many studies have argued that "productivity has been relegated to the second rank and it is ignored" (Singh, Motwani and Kumar 2000). However, due to increasing global economic competence, it would be difficult to ignore labour productivity in the long-run. Thus, to regain the importance of productivity, a precise identification of different aspects of labour productivity is required to quantify it rigorously. As already discussed in chapter 1, section 1.2.3, this dissertation only measures labour productivity-more precisely, labour input efficiency. Improvement in labour productivity results in a steep rise in output which results in overall productivity growth and productivity growth is considered as an index for economic growth (Steindel, and Stiroh 2001; OECD 2011). This dissertation measures labour productivity mostly due to improvement in health and from table 3, it can be seen that health and productivity benefits are the largest multiple impacts. The review in table 3 also confirms that health benefits are the most studied impact. Furthermore, Urge-Vorsatz et al. 2015 study shows that magnitude wise, health and productivity impacts are the most important impacts of all other impacts of sustainable energy policies.

Apart from the magnitude of productivity impacts, this dissertation selects productivity impact among many other impacts due to the following reasons:

1. **Relevance**: The relevance of productivity is of equal importance for both individuals, society and investors. Productivity improvement for individuals implies higher standard of living which is beneficial at the societal level as well (Brynjolfsson 1998). On the other hand, for an investor productivity improvement implies input efficiency which leads to profit maximization (Sauian Sahar 2002).
2. **Entry point for a policy maker**: Considering the magnitude of productivity (refer to table 3) of improved energy efficiency measure, a policy maker can design a sustainable energy policy by seeing the effects of energy efficiency measures on productivity. In long-run the importance of productivity is more crucial compared to short-run. That is why to explain the significance of productivity Nobel laureate economists Paul Krugman said “Productivity isn’t everything, but in the long run it is almost everything.

A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker”.

3. **Goes beyond economics**: Productivity improvement in the context of this study context also refers to improvement in living standards and state of health which have an ethical ground as well. More precisely, in this dissertation improvement in productivity is obtained by utilizing the labour inputs at optimum level which is ‘the right thing to do’ (Bowman and Williams 2004). Hence, in this dissertation productivity and ethics are reciprocally integral because ethics is about ‘doing the right thing’ and productivity is about ‘doing things right’ and installing energy efficiency measures results in productivity improvement which means ‘doing right things right’ (Fisk 2000; Bowman and Williams 2004).

Moreover, productivity impacts of improved energy efficiency measures are not measured rigorously so far. Also, there are gaps in methodology to quantify productivity in the context of energy efficiency, hence research on productivity impact has a great potential to contribute to the knowledge pool. Thus, considering all these reasons, I chose productivity impact among all the multiple impacts.

2.1.6 Productivity impacts and well-being:

This dissertation postulates two layer framework where national well-being is explained by individual well-being with respect to more work time opportunity and improved quality of life through improvement in the state of health and less time spent in road congestion. On one hand, travel time saving from congestion may not only be spent in work but, it can be spent in leisure as well. However, time spent in leisure also improves quality of life and hence it improves overall well-being (Lequiller and Blades 2014). On the other hand, healthy life implies more productive years and hence, healthy life also indicates enhanced earning opportunity (Van

Praag et al. 2003). By following similar logic, productivity impact through health improvement has a positive effect on economic well-being because health reflects the constituent of well-being which means improvement in health would result in more earning opportunities because health is a key component of well-being (Dasgupta, and Weale 1992). Thus, by improving the state of health and by saving travel time, productivity improvement can achieve a higher well-being by achieving a higher economic well-being and improved quality of life. The details of each indictor of productivity studied in this dissertation are mentioned in chapter 4.

2.4 Summary of the chapter:

To summarise, this chapter discusses the need for efficient use of energy and furthermore, it discusses how sustainable energy policies can achieve a higher wellbeing. This chapter starts with defining the different concepts used for energy efficiency and their multiple impacts. Based on these concepts and definitions, this chapter proposes to use the term multiple impacts to address all the additional effects of energy efficiency measures. The empirical evidence of the different type of multiple impacts is presented by reviewing existing studies to show the importance of multiple impacts. Lastly, this chapter highlights the importance of productivity impact and also discusses how productivity can lead towards social welfare/economic wellbeing.

CHAPTER 3: FROM IMPROVED ENERGY EFFICIENCY TO PRODUCTIVITY

"On climate change, we often don't fully appreciate that

it is a problem. We think it is a problem waiting to happen."

Kofi Annan

3.1 Energy efficiency measures

3.1.1 Defining energy efficiency measures:

As discussed in chapter 1, section 1.2.1, energy efficiency measure is an instrument to achieve an efficient use of energy i.e. using less energy for the same services. This study takes two such key energy efficiency improvement measures across two different sectors namely:

1. Improved heating, ventilation, and air-conditioning (HVAC) system with an airtight building envelope in residential and tertiary buildings, and
2. The modal shift towards active transportation in transport sector.

The modal shift towards active transportation is a non-technical measure and as per the technical definition of energy efficiency, it should not be considered as energy efficiency measure. However, a behavioural change such as modal shift can reduce energy use and hence these behavioural changes can be considered as 'energy efficient'(Roy et al. 2012). Behavioural change such as modal shift can have a significant implication on energy consumption and thus, along with technical measures, behavioural measures should also be seen as an instrument of reducing energy use (Wilhite et al. 2000; Roy et al. 2012). The modal shift towards active transportation can improve the efficiency of the transport sector. The European transport policies to foster sustainability and reduced environmental impacts have been emphasizing modal shift towards active transportation as an energy efficient transport (Ntovantzi et al. 2015). The energy efficiency potential of modal shift is quite high, but still, it needs to be researched in order to understand its full potential as an energy efficiency measure (Faberi et al. 2015). The shift from car to slow mode of transports such as walking, cycling and also to public transports such as rail, metro, buses, are considered as energy efficiency improvements (Faberi et al. 2015). Therefore, in this study, the modal shift towards active transportation is treated as an energy efficiency context.

In building sector, this dissertation accounts for residential building sector and tertiary building sector where residential building means where people reside and on the other hand, tertiary building sector covers hotels and restaurants (food), healthcare (hospitals etc.), education (schools, universities etc.), private and public offices, “trade” (wholesale and retail), and other (mainly sports facilities, entertainment). Tertiary buildings or buildings in the service sector do not include buildings in industry or agriculture.

These two energy efficiency improvement measures are selected from the COMBI project action list (http://combi-project.eu/- WP 2). COMBI project is a part of the European Union’s Horizon 2020 research and innovation programme under grant agreement No 649724. From COMBI’s list of 21 improved energy efficiency actions of COMBI, this dissertation selected two improved energy efficiency measures in two different sectors on the basis of the three following criteria:

- The biggest energy savings potential action in the building sector is selected. To be precise, improvement in HVAC system with an airtight building envelope has around 68% energy savings potentiality (Couder 2015).
- The relevance of energy efficiency measure to health and productivity is also another key criterion for the inclusion of these measures.
- To see the significance of behavioral change in terms of its multiple impacts especially productivity impacts.

In the following sections, each of the two energy efficiency improvement measures is discussed.

3.1.2 Energy efficiency measure in building sector- improved HVAC with airtight building shell:

As per IPCC AR5 report, the building sector contributes "32% of total global final energy use and 19% of energy-related GHG emissions, in 2010" (IPCC 2014). According to major studies such as (IPCC 2007; Ürge-Vorsatz and Tirado-Herrero 2012), building end-use sector has the major potential to offer cost-effective mitigation potential. Thus, installing energy efficiency measures in the building sector would not only reduce energy consumption but it would also mitigate GHG emissions. Additionally, building-related energy efficiency measures have multiple impacts which make them crucial in the context of policy evaluation.

As per Urge-Vorstaz et al. 2012 report, a significant share of building sector related GHG emission can be avoided by improving the following elements:

- Building envelopes
- Heating and cooling system
- Hot water heating
- Lighting
- Appliances

Among the above-mentioned list of Urge-Vorstaz et al. 2012 study, building envelope and space heating have the largest share of energy use in both residential and tertiary building sector. Installing HVAC system in an airtight building can save up to 60% energy consumption in the residential building sector and 55% in the tertiary building sector by the year 2030 (Couder 2015). In addition to energy savings, the HVAC system dilutes more than 80% of the indoor air exposure mainly aerosols which results in the improvement of indoor air quality (Bonetta et al. 2010). Indoor air condition is dependent on some time-dependent factors such as humidity, indoor air temperature, indoor air velocity etc. and most of these factors can be controlled by an energy efficient HVAC system (Atthajariyakul and Leephakpreeda 2004). Hence, it is safe to say that an energy efficient HVAC system can obtain acceptable indoor air quality with efficient energy consumption.

Buildings without airtightness consume more heat because outdoor air comes indoor through building leakages across building shells (Liu, and Nazaroff 2001; Urge-Vorsatz et al. 2012). Even buildings with HVAC system can have the same issue if they have a leaked building envelope (Urge-Vorsatz et al. 2012). In addition, faulty design and installation can also cause discomfort and fewer energy savings. In fact, microbiological growth may take place inside an HVAC system equipped with "low-efficiency filters, humidifiers that use water recycling or in areas in which water condensation remains stagnant and large recirculation of the air is present" (Bonetta et al. 2010). These microorganisms inside HVAC can spread in the indoor air which may cause several respiratory diseases. Thus, while installing an HVAC system, it is important to make sure that the system especially the ducts have been designed and installed properly.

Most of the HVAC system is designed for extreme conditions and since most of the time key operations such as occupancy, ambient temperature etc. keep on changing, the system can become unstable without having a control system. Thus, the control system is another key component in the HVAC system. Control system mainly controls temperature (thermostat control) and time (programmable timer). These control systems ensure heating and cooling operation only when it is required which saves energy along with maintaining thermal comfort (Eskom 2015).

3.1.3 Type of energy renovation in building sector:

People spent 90% of their time in indoor and if the indoor air quality is not healthy then health risk would increase rapidly. The two key issues with indoor quality in Europe as per WHO 2010 report are 1) Biological indoor air pollutants such as dampness and mould, 2) Chemical indoor pollutants such as radon, carbon monoxide etc. To improve the indoor air, adequate air circulation is mandatory and as discussed air circulation through ventilation should be maintained in an airtight building. Thus, renovation of the old building is a requirement not only to reduce energy use, but also in order to improve the indoor environment.

There are many types of renovation or retrofits option available for buildings such as stabilization strategy (STA) (where only incremental intervention happens without changing the appearance or substance of the buildings), the substitution strategy (SUB) (where certain elements of the buildings are changed completely) and the double-skin façade strategy (DSF) (where partially stabilizing the existing façade takes place with adding an new glass skin) (Rey 2004). However, it is important to note that these building elements have a limited span which varies considerably. Generally, the duration of a retrofit cycle would be around 25-30 years (Rey 2004).

The main objective of energy retrofit measures is to reduce the energy consumption while these measures need to be cost-effective as well. However, studies show that the most efficient retrofit measures are not always the most cost-effective energy saving options (Doyoon 2010; Chidiac, Catania, and Morofsky 2011). For instance, improvement in the thermal efficiency of the window can result in the largest energy savings, but also the investment in the window efficiency is quite high. On the contrary, improvement in walls brings not only energy savings but the investment for this is lower than that for the window (Chidiac, Catania, and Morofsky 2011). Hence it is not always the case that measures with the largest energy savings potential are the most cost-effective option as well.

Furthermore, the standard retrofit measures such as building shell upgrades can be combined with more radical measures to utilize the natural light and also to use solar energy for heating and cooling (Ürge-Vorsatz et al. 2007). Therefore, depending on the renovation, there are different types such as light retrofitting, medium retrofitting and deep retrofitting. The standard types of retrofitting also varies as per the climatic condition. For example, light type of retrofitting means 5 cm external insulation added to the wall in a building in Rome. However, the same light type of retrofit scheme, in Helsinki is 10 cm external insulation added to the wall (Boneta 2014; COMBI 2018).

In order to retrofit a building the following conditions need to be installed/maintained as per Couder 2015 study:

1) A high level of insulation needs to be installed on the building envelope particularly in the roof and wall.
2) Energy efficient windows should be installed which includes insulating windows with double low-e glazing and low conductive frames.
3) Optimal fenestration for (passive) solar gains and daylighting, for new construction.
4) Minimum thermal bridging. No (new construction) or reduced (retrofits) thermal bridges.
5) High level of air tightness or air sealing. Restrict the (uncontrolled) passage of air through the building envelope, with air changes per hour (ACH) ≤ 3.0 for retrofits; and ≤ 0.5 with mechanical ventilation including efficient heat recovery for new construction (Couder 2015).
6) The right size of the heating system in order to provide the adequate heating.
7) Opting for the right heating systems that can operate efficiently at part load. For example, install a variable capacity boiler systems (Couder 2015).

In general, different buildings are categorized based on many other factors such as location (urban, rural, slum), building type (single-family, multifamily, commercial and public buildings), and building vintage (existing non-retrofitted, new, light retrofitted, medium retrofitted and deep retrofitted) (Urge-Vorsatz et al. 2012). Furthermore, the urban residential buildings can be classified further into single family and multi-family based on the population living in each type of building. Table 5 shows the share of the population living in different classified buildings across 4 regions.

Table 5: share of population living in single and multi-family buildings.

Location	Single family type buildings	Multifamily type buildings
US	72%	28%
EU-27	41%	59%
China	3%	97%
India	25%	75%

Source: (Urge-Vorsatz et al. 2012)

Table 5 shows that majority of the population in Europe lives in multi-family buildings (more levels, terraced, etc.) , while in the US the scenario is opposite i.e. more people are living in single-family type buildings (detached or attached). However, in China and India, majority of the people are living in multi-family type buildings and one of the reasons behind this scenario could be the huge population of these two countries. Now, these different types of retrofit require maintaining specific criteria to renovate building envelope and as discussed, these criteria vary across different building types and different countries (mainly because of the difference in temperature).

3.1.3.1 Passive houses and NZEB buildings

Apart from different types of retrofitting, there are few energy efficient building types which ensure optimal energy savings with the healthy indoor environment. There are few relatively new concepts of these kinds of buildings namely passive houses and nearly zero buildings

(NZEBs) which can be both residential and tertiary types. Both passive house and NZEBs type of buildings are discussed below in detail:

Passive houses: The concept of the passive house refers to certain construction standard which helps in meeting the criteria of low energy house standard. These construction standards can be met by using different energy-saving technologies, sustainable design and materials (Schnieders and Hermelink 2006). There are three basic components of passive houses namely superinsulation, heat recovery and passive solar gain (Schnieders and Hermelink 2006). In addition, passive houses have a continuous supply of fresh air through a mechanical HVAC system. The airflow is regulated to deliver optimum health and comfort benefit (Audenaert, De Cleyn, and Vankerckhove 2008).

Studies show that in winter time the mean temperature of passive houses remains between 21-22 degree and in summertime the mean temperature lies within 27 degrees (Schnieders and Hermelink 2006). The ventilation system in passive houses is generally driven by highly energy efficient motors which consume an average 0.4 W/(m3/h) or less energy (Schnieders and Hermelink 2006). Figure 3 below shows the ventilation system in passive houses.

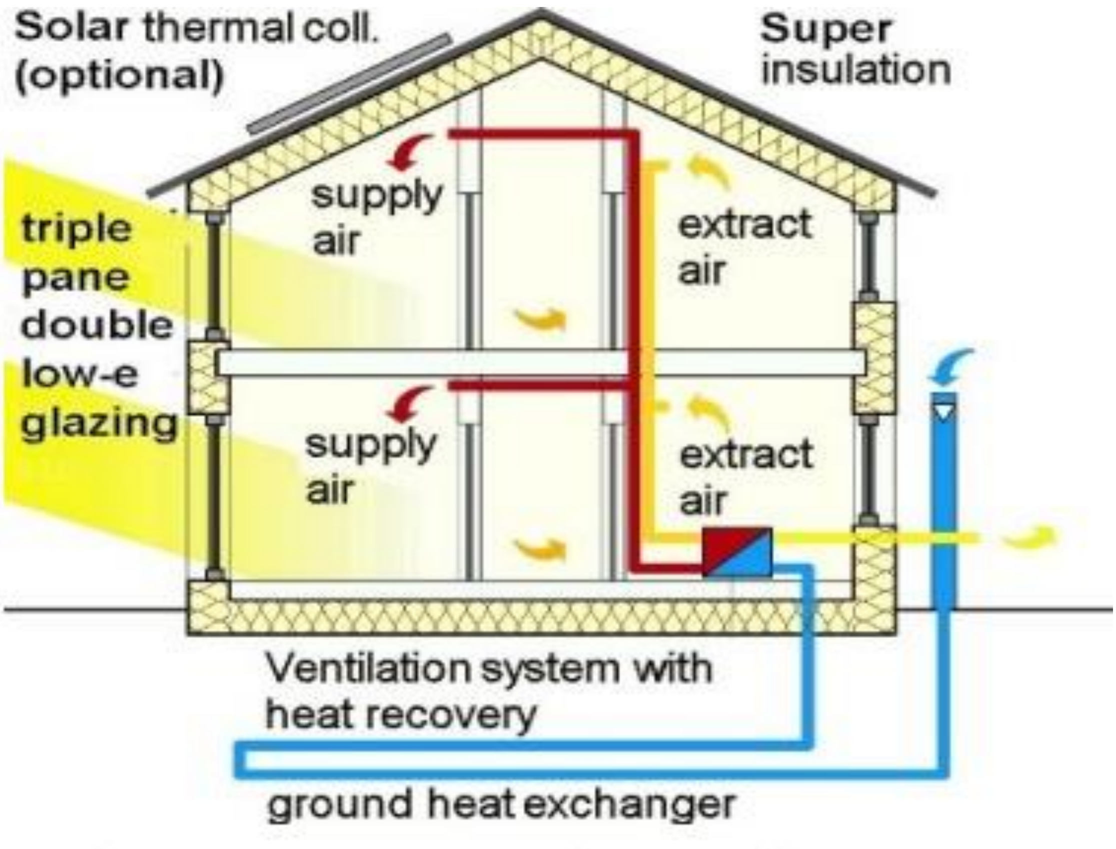


Figure 3: Ventilation system in passive houses

Source: (Passipedia 2017)

Similar to the normal mechanical ventilation system, the ventilation system in passive houses follows the same principle i.e. it removes the used air from the bedroom, kitchen, bathroom, toilet and in return fresh air from outside replaces the indoor air. As per Passipedia website "ventilation can also take place if a simple exhaust air system and external air inlets are used. The external air inlets let fresh (cold) air in the required amounts into the rooms. However, for the Passive House, the ventilation heat losses that would be caused by the disposal of the unused extract air would be much too high. It would only be possible to adjust the energy balance with a high heating output". Thus, the heat recovery system is a crucial component in the passive house design. Heat recovery system recovers the heat from the exhaust air and by using a heat exchanger, it transfers the heat back into the supply air without mixing the air flows. The modern ventilation technology allows a heat recovery rate up to 95 % (Passipedia 2017). Moreover, heat recovery systems help in recovering the heat in the following way:

The used polluted heated air flows through a duct and transfers its heat to the plates above and below. Then, it cools down and exits from the other side of the duct. Outdoor fresh air comes through the other side of the ducts and on the other side of the plates. Then, the used fresh air takes up the heat and becomes warm (but still fresh). Then it is ready for supply air.

Nearly zero energy buildings: Nearly zero-energy building (NZEB) refers to a building which requires a low amount of energy and this requirement should be covered from renewable sources, including energy from renewable sources produced on-site or nearby (Kurnitski et al. 2011). The building sector is responsible for 36% CO_2 emission in Europe, and hence the importance of the new concepts such as nearly zero buildings is growing as a mitigation tool for greenhouse gas reduction (BPIE 2011).

Furthermore, the recast Directive on the energy performance of buildings (EPBD) stipulates that "by 31 December 2020, all new buildings are nearly zero energy buildings and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings" (EU DIRECTIVE 2010). This means that in less than one decade, all new buildings would have a high energy performance and their energy needs would cover by renewable energy sources. In order to have a low energy demand, buildings would need to have a high level of insulation, energy efficient windows, mechanical heating, and ventilation system with heat recovery along with other equipment similar to the passive house and deep retrofitted buildings (BPIE 2011). However, the technical requirement of NZEB would vary as per the country's national, regional or local conditions (EU DIRECTIVE 2010). The difference between a passive house and NZEB mostly concerns with total primary energy input and annual heating demand. More precisely, in passive houses, the annual heating energy requirement must not exceed 15 kWh/m²a and the total primary energy input must not exceed 120 kWh/m²a (Schulze Darup, et al. 2015). Whereas, in NEBs, there exists no such stringent mandates regarding heating demand and primary energy input. However, the energy source for NZEB should be covered from the renewable energy source and for the passive house, there is no such requirement.

3.1.4 Energy saving potential of transport sector

The transport sector is gaining importance in modern urbanization. As per IPCC AR 4 report, the biggest concern in the transport sector is associated with road accidents, air pollution, traffic congestion, and petroleum dependence (IPCC 2007). In addition, oil is the most used natural resource for road transport which accounts for 81% of total energy use (Chapman 2007). Over 53% of global oil consumption is used to meet 94% of total transport energy demand and rest of the energy demand were met by electricity, natural gas and other fuels (IEA 2012; Sims et al. 2014). As per IPCC AR5 report, the transport sector is responsible for 23% of total energy-related CO2 emissions (6.7 Gt CO2) (Sims et al. 2014). The transport sector is crucial since it is not only used for communication but for delivery of goods and services too. Furthermore, transport has become a major industry in itself. Passive mode of transport such as car usage is responsible for several GHG emissions. Fuglestvedt, et al. 2008 study summarizes the four main ways by which emissions from this mode of transport can affect climate:

1) Emission of direct GHG mostly CO_2,
2) Emission of indirect GHG such as ozone (O3), nitrogen oxides (NOx), carbon monoxide (CO), and Volatile organic compound (VOC),
3) The direct effect of emission of aerosols such as black carbon, organic carbon, and sulfur compounds, and
4) The indirect effect of aerosol emission which changes the distribution and properties of clouds.

Furthermore, it was believed that increasing travel demand can be satisfied by having more motorways. However, this assumption is proven wrong by the rise in congestion time. It is realized that increase in cars and motorways can have other side-effects such as air pollution, traffic congestion, noise and road accidents along with excessive use of fossil fuel which is a non-renewable energy source (Greene and Wegener 1997). Therefore, the modal shift towards active transportation such as walking, cycling etc. could be an optimum solution to these problems (Cuenot, Fulton, and Staub 2012). The modal shift in passenger transport do not only reduce traffic congestion but it also has a potential for EU 27 countries to save 9% of energy use which is equivalent to 14 MTOE by 2030 (Couder 2015).

3.1.4.1 Modal shift towards active transportation:

The modal shift towards active transportation could potentially contribute towards the transition to a more energy-efficient transport sector because modal shift can help in achieving the 60% GHG emission reduction target by 2050 set in the 2011 White Paper (Faberi et al. 2015). The active form of transportations includes walking, cycling and use of public transport. These are called active because to use these modes of transport some kind of physical activity is required. Even public transport falls into this category since it requires some walking or cycling at either end of the journey (Shannon et al. 2006). The choice of mode of transport depends on several factors such as the type of journey, service performance, flexibility and comfort etc. (Kuppam, and Pendyala 1999; Cools et al. 2009).

The rate of active transportation per country is taken from COMBI input data which calculates the rate of modal shift by considering the use of active transportation in 2015. For example, the share of slow modes such as cycling and walking during peak hours in Hungary was 19.2% in 2015 and in Germany, the share of slow mode during peak hours was 34.4% in 2015 (COMBI 2018). It is worth noting that as per the COMBI assumption, the mode of transport reported here is during peak hours (6:00-10:00 and 16:00-20:00) only when most of the people commute. Further details of modal shift effects are discussed in section 3.2.2.

3.2 Energy efficiency and its impact

Different energy efficiency measures yield different impacts. Thus, this dissertation considers two specific energy efficiency measures namely heating-ventilation and air-conditioning system (HVAC system) with proper building shell and modal shift towards active transportation. By installing these energy efficiency measures indoor exposure can be reduced. As a result of modal shift measure, more time can be gained by avoiding road congestion and outdoor exposure. The impact on productivity by adopting these two energy efficiency measures is discussed in the sections below.

3.2.1 Productivity implication of HVAC with building shell:

As discussed in section 3.1.2, installing an energy efficient HVAC system in an airtight building can save up to 60% energy consumption in residential building sector and 55% in tertiary building sector. In addition to energy savings, the HVAC system dilutes more than 80% of the indoor air exposure mainly aerosols via constant adequate air exchange rate (Bonetta, et al. 2010; Couder 2015). Simultaneously, an airtight building shell would reduce the infiltration of outdoor air pollutants which also result in improvement of indoor air quality. This improvement in indoor air quality ultimately improves productivity by reducing indoor exposure-related disease.

In most cases, building sector related energy efficiency measures have an effect on productivity via the lens of indoor air quality. For example, due to the implementation of energy efficiency measure such as installing the HVAC system with proper building shell stimulates the indoor air exchange rate which reduces the pollutant concentration. Source of these pollutants could be both from indoor and outdoor. Outdoor pollutants infiltrate indoor through building cracks and ventilation (Asikainen et al. 2016). These pollutants can be a cause for not only many diseases but it also can affect the performance of a worker. For instance, Hepm 2004 study shows that when pollen concentration increases labour productivity decreases and vice-versa.

Indoor air quality plays an important role in the general state of health as people spend most of their time indoors i.e. either at work or at home or school (WHO 2006). WHO 2006 guidelines for indoor air quality identify three specific issues which are affecting indoor air quality and human health. These three key issues are:

1) Biological indoor air pollutants such as dampness and mould,
2) Chemical indoor pollutants such as radon, CO etc., and
3) Pollutants from indoor combustion of fuels.

Studies show that sufficient air exchange rate is one of the key tools in order to remove humidity, carbon dioxide, bioeffluents and other pollutants of indoor air (WHO 2006; Asikainen et al. 2016). Despite this fact, presently, ventilation standards in nonindustrial buildings are seen to meet the comfort requirements of occupants or to control the intensity of odour presence (Hänninen, and Asikainen 2013). Thus, ventilation related health benefits are ignored so far. Although studies have shown that thermal comfort improves the performance of an individual, it has little to do with eradicating diseases related to indoor air quality (Wargocki et al. 2002; Asikainen, et al. 2016). Ventilation exchanges indoor air (polluted) with outdoor air (presumably fresh and clean air, but contains some outdoor pollutants) in order to provide an optimum condition to live healthy in the indoor environment (Wargocki et al. 2002).

Ventilation does not only provide fresh air for breathing but it also reduces moisture and dilute indoor pollutant exposure which ultimately improves human health (Wargocki et al. 2002). There exists an inverse relationship between the indoor air pollutant concentration and the rate of ventilation. This means the higher rate of ventilation, the lower the corresponding indoor concentration, the later however never reaches zero (Atkinson 2013). Figure 4 shows this relationship between the rate of ventilation and indoor pollutant concentration.

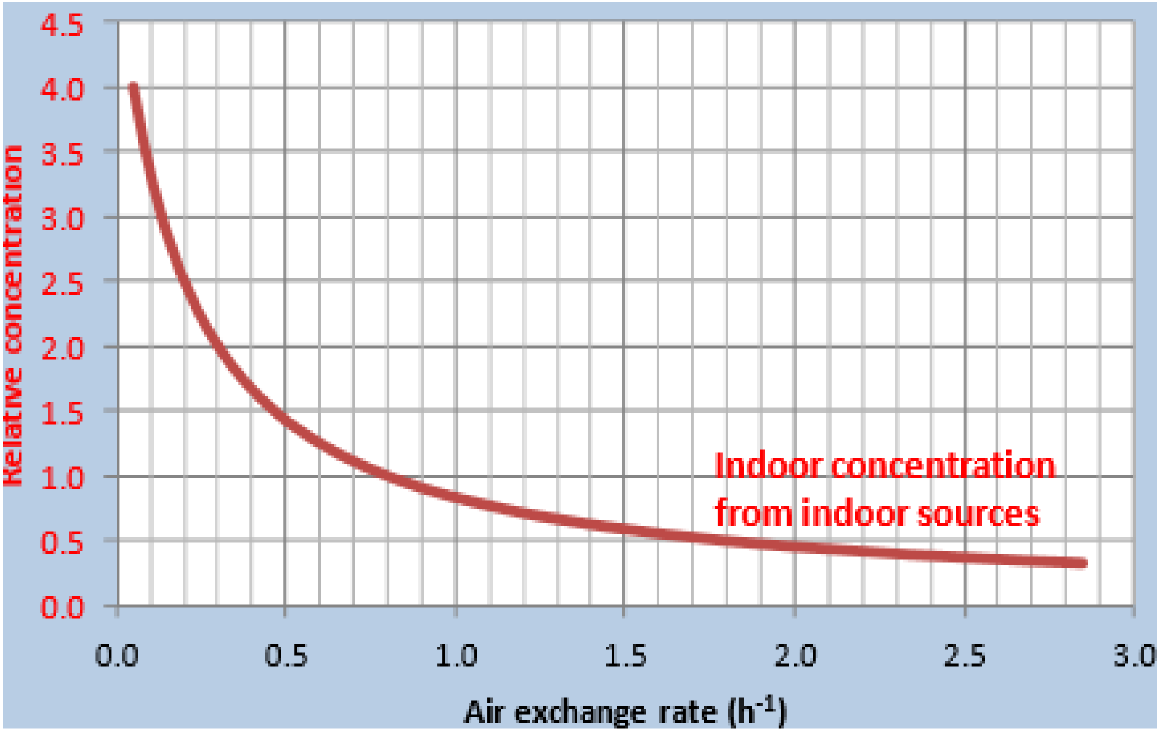


Figure 4: Relation between air exchange rate and indoor air pollutant concentration. X axis shows the air exchange rate, per hour (ach, h-1) which is the rate of ventilation and Y axis shows the relative concentration of indoor pollutants

Source: Hänninen and Asikainen 2013

Several studies argue on the appropriate amount of ventilation rate "but the common conclusion was increasing the ventilation rate from 10 l/s per person up to 20 l/s per person may further reduce sick building symptoms" (Wargocki et al. 2002). In tertiary buildings, higher ventilation rate up to about 25 l/s per person is associated with reduced prevalence of indoor air quality related diseases (Hänninen and Asikainen 2013; Asikainen, et al. 2016). Any rate below 10 l/s per person ventilation rate, would lead to high indoor humidity, and moisture on building structure (Wargocki et al. 2002; Fernandes et al. 2009). High indoor humidity and moisture result in high dust mites presence and higher microbial growth which could be a source of building-related disease (Fisk, and Rosenfeld 1997; Jones 1999; Fernandes et al. 2009). Ventilation process involves airflow between the rooms by either natural forces such as thermal buoyancy and wind or by mechanical processes such as air-conditioning. This air circulation inside the buildings does not only reduce moisture but it also improves thermal comfort level which ultimately has an impact on work performance (Wargocki et al. 2002; Li 2007). Ventilation plays a dual role by reducing indoor air pollutant concentration and on the other hand by infiltrating outdoor pollutants such as particulate matter, particulates of biological origin (microorganisms, pollen, etc.), NOx, Ozone (O3) etc. (Asikainen et al. 2016). In buildings with the HVAC system installed, it is possible to reduce the concentrations of certain outdoor pollutants indoor by installing an efficient filter (Fernandes et al. 2009). However, if HVAC system is not properly maintained then it can be a source of pollutants (such as VOC) itself (Wargocki et al. 2002). Thus, it is crucial to maintain the HVAC system. More precisely, it is necessary to clean the component and surface of the HVAC system which includes changing the cooler coil, humidifier and cleaning the duct frequently (Fernandes, et al. 2009). Furthermore, if HVAC system is installed in a non-airtight building then the effect of installing HVAC system will be minimized since outdoor air pollutants would enter the building through the envelope (wall, roof) cracks (Asikainen et al. 2016). The building envelope is the physical border which separates the building interior and exterior. By improving the conditions of a building envelope, a building would not only consume less energy for heating, cooling, lighting but also the outdoor pollutants infiltration would be less (Chwieduk 2003; Sadineni, Madala, and Boehm 2011). Thus, it can be said that a good quality building envelope does not only save energy but it also improves the building's indoor air quality. Therefore, it is important to make the building airtight before installing an HVAC system otherwise the effects of HVAC system would be minimized due to the presence of outdoor air pollutants.

3.2.1.1 Building related diseases which are affecting productivity

The burden of disease includes many diseases such as asthma, cardiovascular disease, cold and flu, cancer and many unknown symptoms which may be caused by poor indoor building conditions (Jones 1999; Hänninen and Asikainen 2013; Asikainen et al. 2016). Mainly two key terms are used to define these diseases and symptoms related to poor building conditions. Among these two terms, the most popular term to define this situation is called 'sick building syndrome' (SBM). Redlich et al 1997 study describes 'sick building syndrome' as "non-specific complaints, including upper-respiratory irritative symptoms, headaches, fatigue, and rash, which are usually associated with a particular building by their temporal pattern of occurrence and clustering among inhabitants or colleagues". The other term used to define the situation is building related-illness (BRI). BRI is caused by specific pollutant exposures in indoor environments (Redlich 1997). Cross 2001 study describes BRI as diseases occurring at schools or commercial buildings. However, studies have confirmed that building related illness depends on building environment and not on building types (Redlich 1997; Kreiss 2005; Crook, and Burton 2010). Though, it is true that for some contagious diseases such as cold and flu, eye infection etc. the intensity of BRI could be much higher at office buildings, but still these type of illnesses have nothing to do with the type of buildings, but rather they depend on occupancy rate (Kreiss 2005; Crook, and Burton 2010).

The burden of diseases due to indoor exposure to pollutants could be as high as 10,000 disability adjusted life years loss (DALY) per million (Hänninen and Asikainen 2013). Figure 5 below shows the intensity of indoor air pollution exposure.

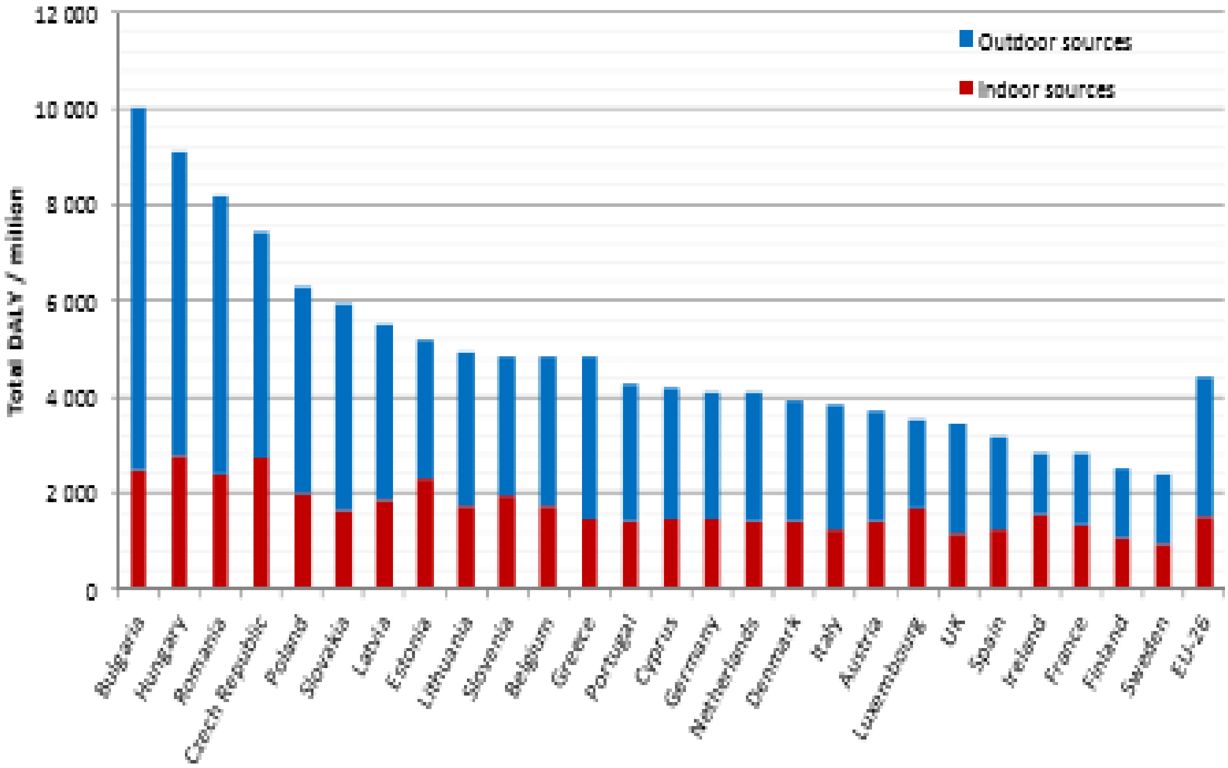


Figure 5: Total burden of disease as DALY/million population from indoor exposures in European countries

Source: (Hänninen and Asikainen 2013)

Figure 5 shows not only the effects of indoor air pollutants but also the effects of outdoor air pollutants infiltrating indoor.

The section below discusses these indoor and outdoor air pollutant concentration-caused or building related-diseases and mental well-being related effects one by one.

Asthma: Poor ventilation and absence of filtration in buildings can cause lower respiratory i.e. asthma and acute COPD diseases (Jones 1999; Fisk 2000; Guarnieri, and Balmes 2014). As per global asthma network (GAN) 2014 report, asthma can be defined as "disease of the bronchial tubes in the lungs (the airways) and people with asthma typically experience wheezing, a high-pitched whistling sound heard during breathing, especially when breathing out" (GAN 2014).

Exposure-related to building dampness, house dust mites, moulds and bacteria lead towards lower-respiratory diseases (Norbäck et al. 1999). Among the indoor air pollutants, exposure to mould is a major concern for human health. Mould augmentation largely depends on several in-house characteristics such as house surface, humidity, and temperature (Rylander and Lin 2000). As per Fisk's study, exposure to mould in a building is associated with 100% increases in asthma (Rylander, and Lin 2000; Fisk 2002). On the other hand, exposure to particulate matter (PM), ozone, nitrogen dioxide and other air pollutants which are generated mainly from traffic and power generation, can cause asthma and other respiratory diseases (Guarnieri and Balmes. 2014). These outdoor air pollutants infiltrate indoor through the cracks in building envelopes.

The effect of asthma and allergy would vary as per the age and their effect on productivity would also be different. For example, if a child misses too many school days due to asthma then it would have an impact on the parent's income and it would have an impact on the future earning ability of the child (Chatterjee and Ürge-Vorsatz 2017). In fact, too many school days loss may disrupt a child's learning and could be one of the causes for dropping out of school and it has been observed that children who have asthma, are more absent from school compared to their healthy classmates (Moonie et al. 2006). More details are explained in chapter 4, section 4.3.2.

In addition, there are several outdoor air pollutants such as nitrogen dioxide, particles, and sulphur dioxide which cause asthma. The key source of these air pollutants is fuel combustion from industry and transport (Schwartz, and Morris 1995; Ürge-Vorsatz et al. 2014; Guarnieri, and Balmes. 2014).

Cardiovascular disease: Airborne particle and sulphur dioxide concentrations can cause cardiovascular disease especially ischemic heart disease (Schwartz and Morris 1995). Brook et al 2010 study shows that "a 10-ug/m3 increase in mean 24-hour PM2.5 concentration increases the relative risk (RR) for daily cardiovascular mortality by approximately 0.4% to 1.0%" (Brook et al. 2010). Cardiovascular disease causes the majority of the burden of diseases from air pollution. Among the total burden of diseases in Europe, 57% is contributed by cardiovascular diseases (Asikainen et al. 2016). Asikainen et al 2016 study shows how much various air pollutant cause diseases in the total burden of diseases and "cardiovascular diseases are followed by asthma (total of 12%) and lung cancer (23%)". The rest of the burden (8%) comes from different upper and lower respiratory symptoms and conditions (Asikainen et al. 2016).

Apart from air pollution, another key reason behind the risk of having cardiovascular diseases is physical inactivity. Physical inactivity is responsible for 30% of cardiovascular disease especially ischemic heart disease (WHO 2010). In this study, the modal shift towards active transportation is one of the most important energy efficiency measures and through the modal shift, there can be a positive impact on health as well by being physically active. Similar to asthma, cardiovascular diseases also affect different aspects of productivity (Brunekreef, and Holgate. 2002).

Cold and flu: Diseases such as cold and flu occur mainly due to inhalation of airborne infectious aerosols and aerosols exposure increases by lack of filtration, low air exchange rate, high occupancy rate, air temperature and humidity (Fisk 2000). These infectious aerosols contribute substantially to the common colds and influenza-related respiratory disease (Husman 1996). The key cause of the infection is usually common respiratory pathogens, viruses causing common cold and flu (Miller 1992; Husman 1996). Indoor environmental conditions such as exposure to mould and humidity contribute to higher aerosol exposure (Fisk 2000). Thus, buildings with low ventilation rate would have substantially higher respiratory diseases.

Apart from common cold and flu and asthma, there are several other respiratory diseases such as bronchiolitis, pneumonia which are partially caused by damp and mould (Asikainen et al. 2016). These circulatory diseases cause 40% of excess winter deaths (Marmot Review 2011). Thus, cold, and flu-related productivity loss could be huge.

Cancer: Cancer is a disease which causes "a proliferation of mesothelial cells" (Jones 1999). It is one of the most serious health hazards from indoor exposure. Exposure to both indoor and outdoor air pollutants such as radon, asbestos, formaldehyde, micro-organisms, sulphate, and particulate matter cause cancer especially lung cancer (Jones 1999; Brunekreef, and Holgate. 2002; Boffetta 2006; Hamra et al. 2014). Among these pollutants, particulate air pollutants (equal to or less than 2.5 μm) are the largest threat since they can be breathed deeply into the lung which may cause lung cancer (Pope et al. 1995). These fine particulate matters are mostly derived from combustion of fossil fuels in processes such as transportation, manufacturing, and power generation (Pope et al. 1995; Pope et al. 2002). Pollutants which are derived outside, infiltrate indoor and since people spend most of their time indoors, the exposure period becomes higher inside (Atkinson 2013).

Ability to concentrate and mental well-being: Ability to concentrate depends on work and home atmosphere. One may get disrupted by certain symptoms such as eye irritation (eye tears and eye blinking), skin irritation (Mølhave, Bach, and Pedersen 1986). These irritations may occur due to the presence of fungi and moulds at the workplace or at home. Exposure to moulds and the fungi (especially black fungi) and their spores have certain effects on skin and eye. Mould and fungi growth can be reduced by improving the building shell and by implementing stringent air filtration (Singh 2005). Apart from mould and fungi, indoor CO_2 concentration can hamper a person's concentration by causing several health obstacles such as a headache, fatigue, eye symptoms, nasal symptoms etc. (Apte, Fisk, and Daisey 2000).

On the other hand, studies (see (Shortt, and Rugkåsa 2007; Howden-Chapman et al. 2007; Bond et al. 2012; Liddell and Guiney 2015) have shown that there exists a positive correlation between mental well-being and indoor environment. Mental well-being refers to two dimensions namely mental health and mental disorder. WHO 2013 report defines mental health as “a state of well-being in which the individual realizes his or her own abilities, can cope with the normal stresses of life, can work productively and fruitfully, and is able to make a contribution to his or her community” (WHO 2013). Whereas mental disorder is defined as “a syndrome characterized by a clinically significant disturbance in an individual’s cognition, emotion regulation, or behaviour that reflects a dysfunction in the psychological, biological, or developmental processes underlying mental functioning”(American Psychiatric Association 2013; Liddell, and Guiney 2015). Mental health includes positive outcomes such as greater productivity, an increased resilience to adversity, better physical health and longer lifespan whereas mental disorder includes stress, anxiety, discomfort and depression (Liddell and Guiney 2015). Both mental health and mental disorder are associated with poor housing condition (Howden-Chapman, et al. 2007; Bond, et al. 2012). For example, households with poor thermal comfort are associated with psychosocial stress which deteriorates the mental well-being (Gilbertson, Grimsley, and Green 2012). Another aspect of having mental stress comes from affordability. To be precise, for instance, when people experiencing accumulative sources of stress such as thermal discomfort from a cold and damp house combined with financial worries caused because of high energy price, their mental vulnerability increases exponentially (Liddell and Guiney 2015).

As it is discussed in the above paragraphs, different pollutants can cause different diseases. The pollutant-specific diseases and their sources are shown with the help of table 6 and 7 which summarize the sources of all indoor and outdoor air pollutants. Furthermore, these two tables show not only the sources of these pollutants but also what diseases they can cause.

Table 6: Sources of indoor air pollutants and disease associated with it

Pollutants	**Source**	**Affected health aspect**
Allergens	Indoor dust, domestic animals, and insects	Respiratory disease, skin and eye irritation
Asbestos	Fire retardant material and insulation	Lung and kidney cancer
Formaldehyde	Particleboard, insulation, furnishings	Cancer, skin and eye irritation
Micro-organisms	People, animals, plants, air conditioning systems	Cancer and heart disease
Pollens	Outdoor air, trees, grass, weeds, plants	Respiratory disease
Dampness and mould	Structural moisture, humidity	Respiratory disease
Radon	Soil, building construction materials (concrete, stone)	Lung cancer
Fungal spores	Soil, plants, foodstuffs, internal surfaces	Respiratory disease

Source: Own elaboration (data extracted from (Jones 1999; Fisk 2000; Katsouyanni 2003; Sundell 2004; Fisk 2009; Hänninen, and Asikainen 2013)

Table 6 shows the indoor air pollutant sources and their consequences on the human health. Here, for radon especially one point needs to be noted that radon infiltrates mainly from the soil below the buildings (Stoulos, Manolopoulou, and Papastefanou 2003). Furthermore, the infiltration of radon may increase at a higher rate of ventilation (Atkinson 2013).

Table 7: Sources of outdoor air pollutants and disease associated with it

Pollutants	**Source**	**Affected health aspect**
Nitrogen dioxide	Outdoor air, fuel burning, motor vehicles in garages	Respiratory and cardiovascular disease
Particulate matter	Tobacco smoke, combustion products	Respiratory ,cardiovascular disease, cancer
Polycyclic aromatic hydrocarbons	Fuel combustion, tobacco smoke	Cancer

Pollutants	Source	Affected health aspect
Sulphur dioxide	Fuel combustion	Respiratory disease
Ozone	Fuel combustion	Respiratory disease
Carbon monoxide	Fuel combustion	Headache, dizzy feeling which affects productivity

Source: Own elaboration (data extracted from (Schwartz, and Morris 1995; Jones 1999; Brook 2004; EPA 2015)

Similar to radon exposure, carbon monoxide exposure may increase at a higher rate of ventilation. Thus, it is important to assume a "mass-balance for a constant source term" for any quantitative burden of disease calculation (Atkinson 2013).

To summarise, this section describes the extent of the burden of diseases from indoor exposure in Europe by discussing indoor exposure-related diseases. Each of these diseases and conditions is explained in detail to provide an overview of the extent of indoor exposure. Also, there could be few symptoms such as a headache, eye and skin irritation, as well as mental health-related issues which cannot be considered as diseases. Hence, these are discussed from concentration ability and mental well-being perspective. By enabling these details, this section also shows how indoor exposure affects productivity through different diseases and mental well-being.

Installing energy efficiency measures such as improved heating, ventilation and air conditioning system in an airtight building, improves indoor air quality which in turn improves health and improvement in health implies an improvement in productivity (Koopman et al. 2002).

3.2.2 Productivity impacts of modal shift towards active transport:

Energy efficiency measures in the transport sector can be crucial as final energy consumption in the transport sector depends on two factors namely 1) specific energy consumption and 2) mobility (Usón et al. 2011). Thus, energy efficiency measure such as modal shift helps saving energy without disrupting mobility. European Commission's 2011 white paper sets the target of reducing 20% of GHG emission from the transport sector by 2030 compared to emissions in 2008 (European Comission 2016). Along with GHG emission, another major issue with the transport sector is its increasing traffic. The increased traffic/road congestion level reduces mobility which is an economic loss to the society (Quddus, Wang, and Ison 2009; Usón et al. 2011). Thus, energy efficiency measure like modal shift towards active transportation can play a crucial role by not only reducing the energy consumption but also by reducing the road congestion.

The use of car has been increasing due to a variety of reasons such as urban sprawl, intrinsic appeal of automobiles, a certain change in the labour market in terms of flexibility and mobility (Greene and Wegener 1997; Cools, et al. 2009). Within the European Union, passenger cars accounted for 83.2% of inland passenger transport in 2013 (Eurostat 2016). Studies show that this dominant car dependence may lead to several adverse socio-economic and environmental impacts (Cools et al. 2009; Cuenot, Fulton, and Staub 2012). The range of adverse impacts is the following:

1. **Environmental damages**- GHG gasses such as CO_2, methane, NOx emit from car fuel which causes serious trouble for the environment.
2. **Economic loss**: Due to use of excessive non-renewable energy sources for cars, the stock of renewable source decreases which also diminishes the value of an economy (Cools, et al. 2009). In Europe, most of the countries use petrol powered engines (Eurostat 2016). For example, in Hungary, around 2.3 million cars run on petrol whereas, in Germany, there are 29.8 million petrol powered cars on the road (Eurostat 2016). These figures show the intensity of dependence on petrol powered engine cars. Moreover, due to excessive car use, the road congestion increases which causes work

time opportunity loss and hence productivity loss. This has further implications on the economy (Cools, et al. 2009).

3. **Societal loss**: Due to excessive passive commute, there could be several health impacts such as traffic casualties, respiratory and cardiovascular diseases and loss of community space (Cools, et al. 2009).

Despite the technological advancements in transport to make cars more eco-friendly still, most of the countries use petrol powered engines in Europe (Cools, et al. 2009; Eurostat 2016). Therefore, policymakers have to put more focus on reducing the car usage.

Lately, many of the European countries are promoting active transportation through their policies such as low-cost rental service of by-cycles, making new and broader cycle and walking ways etc. (De Hartog et al. 2010). However, this attempt for the modal shift is not easy since car is also considered as a social status symbol and this is one of the reasons why people being aware of the adverse impact of cars, are still using them (Cools et al. 2009).

The choice of mode of transport depends on several factors such as the type of journey, service performance, flexibility and comfort etc. (Kuppam, and Pendyala 1999; Cools et al. 2009). For instance, the car users often claim to choose a car as their mode of transport because of its speed, flexibility, convenience and perceived joy of driving (Bamberg 2003; Anable 2005). However, Steg (2005) conducted a case study in the Netherlands and found out that the 'symbolic and affective functions' such as superiority, power, feeling of sensation are also playing a crucial role in determining the choice of transport. Thus, it is safe to conclude that the choice of mode of transport involves many other factors beyond speed, flexibility, and comfort. In this dissertation, however, the choice of transport is beyond the scope of research. More precisely this study quantifies the effects of modal shift towards active transportation, which implies that the choice of transportation is given. The rate of active transportation per country is taken from COMBI input data that calculates the rate of modal shift by considering the use of active transportation in 2015.

Usage of cars mainly have two key effects (apart from energy savings) namely health effects and effects on road congestion. Each of these effects are described below:

3.2.2.1 Health Effects:

The modal shift towards active transportation has two types of health impact: 1) negative health impacts and 2) positive health impacts. Positive health impact includes improvement in health by avoiding outdoor air pollution and noise position, improvement in health by being physically active. On the flip side, negative health impact includes road accidents, more exposure to outdoor pollutants for the individual who has opted for active transportation.

Both of these health effects are discussed in the section below:

1) Positive health effects:

Reduction in air pollution: Usage of motor vehicles can affect the state of health by emitting health hazard pollutants and the emission from the transport sector happens mainly in two ways:

1. Direct CO2 emission from motor vehicle usage: Burning of fuels emits more than 99% of the carbon in a fuel (EPA 2014). Along with CO_2 burning of fossil fuel also emits nitrogen dioxide (NO_2), hydrocarbons and PM. Exposure to these pollutants can cause several diseases such as lung cancer, respiratory disease (Xia et al. 2015). Among these pollutants, the suspended particulate matter of different sizes and composition can shorten the lifespan significantly (Pearce 1996; Krzyżanowski, and Kuna-Dibbert 2005).
2. Indirect emission from congestion: Due to road congestion GHG emission increases. More precisely, if the speed of a vehicle reduces than the moderate speed (40-60 mph)

then GHG emission increases exponentially (Woensel, and Creten 2001; Barth 2009). In other words, if the vehicles spend more time on the road then CO2 from transport sector increases. Thus, again exposure to these pollutants result in diseases such as cardiorespiratory disease, respiratory disease and lung cancer (Woodcock et al. 2009).

Both these direct and indirect air pollutions can cause many health impacts such as chronic obstructive pulmonary disease (COPD), respiratory disease, cardiovascular diseases and lung cancer (Lelieveld et al. 2015). These diseases affect human lifespan as well. Thus, by reducing car usage, air pollution can be mitigated to a significant level. For instance, Dhondt et al. 2013 study shows that active transportation can gain 530 life years by avoiding air pollution. Similarly, Woodcock et al. 2009 study shows that active transportation can reduce 10-19% chances of ischemic heart disease in London and 11-25% chances of ischemic heart disease in Delhi, in a year.

Noise pollution: Exposure to excessive traffic noise (more than 60 decibels) may induce hearing loss and hence, can negatively impact mental and cardiovascular health (James et al. 2014). People who are staying near the highway lane are more exposed to traffic noise compared to the other population. Thus, by reducing cars travels, noise exposure can also get reduced. For instance, Rabl, and de Nazelle, 2012 study estimated active transportation can gain 69.6 million Euros/year in Paris by avoiding noise pollution.

Physical activity: Apart from outdoor pollutant exposure related health impacts, physical inactivity is another major public health challenge. Physical inactivity is a well-established risk factor for the chronic diseases such as coronary heart disease, stroke, and depression (Sallis et al. 2004). Studies show (for example see (Frank et al. 2006; Bassett et al. 2008; De Hartog et al. 2010) that by using active mode of transportation a person can be physically active which reduces the likelihood of these diseases. Usually, a 5 kilometers (KMs) of cycling or 2.5 KMs of walking 5days/week are considered to meet the physical activity standard (Rabl, and De Nazelle 2012). Few of the modes of active transport such as walking and cycling are associated with some psychological and social factors such as bike lens, aesthetic qualities of neighbourhoods etc. (Sallis et al. 2004; Rabl and De Nazelle 2012). The biggest impact of modal shift would be on individual health for being physically active. The estimated life expectancy gain per person can be 3 to 14 months by being physically active which outweighs the risks of modal shift from outdoor exposure (life expectancy loss ranges from 0.8–40 days) (Hu et al. 2004; de Hartog et al. 2010). Another study (see (Rojas- Rueda et al 2012) estimates that by shifting 40% trips from car to the active mode of transportation mainly cycling, the travellers in Barcelona city can avoid 67.46 deaths annually by being physically active.

2) Negative health effects:

The modal shift towards active transport may involve some risks at the individual level. For instance, the air pollution exposure would be greater when a person is walking or cycling instead of driving a car (Bergh 2004; Rojas-Rueda et al. 2012). However, the individual exposure level of traffic-related air pollutants would be higher, although at the societal level the exposure would be less as total air pollutant emission would be less due to the modal shift (De Hartog et al. 2010). Furthermore, for an individual, the risk of being involved in a traffic related accident is higher when a person uses an active mode of transportation especially cycling (Marshall, Brauer, and Frank 2009). However, De Hartog et al. 2010 study argued that traffic accidents related to active transportation are dependent on which age-group is opting for active transportation. To discuss this in detail, table 8 below shows the number of deaths per age-category per billion passenger KMs by cycling and by car usage in the Netherlands.

Table 8: Number of deaths per age category per billion passenger kilometers by cycling and by car usage in Netherlands in 2008.

Age category	Bicycle related traffic deaths	Car related traffic deaths	Ratio
<15	4.9	0.6	8.6
15-20	5.4	7.4	0.7
20-30	4.2	4.6	0.9
30-40	3.9	2.0	2.0
40-50	6.6	1.0	6.9
50-60	9.6	1.2	7.9
60-70	18.6	1.6	11.9
70-80	117.6	7.6	15.4
>80	139.6	8.1	17.1
Total average	12.2	2.2	5.5

Source: (De Hartog et al. 2010)

Data shows that people within the age-group of 18-49 are prone to more traffic-related accidents while driving a car and the opposite is true for people within the age-group of 50 plus. The study by De Hartog et al. 2010 estimates that within the age of 18 to 64 year-old individuals, "the risk of a fatal traffic accident while cycling is about 4.3 times higher compared with the same distance by car driving". However, it is crucial to note that the number of road accidents also depends on the age-group of people who are opting for the modal shift. Table 10 shows that if the average people within average age-group opt for modal shift then the impact would be practically zero and if young drivers shift to cycling then the impact would be negative i.e. there would be less traffic-related accidents (De Hartog et al. 2010).

Studies have used different techniques to estimate these health aspects of active transportation. Table 9 shows below the magnitude of productivity by presenting some studies which have quantified different effects of active transportation which leads to productivity impact:

Table 9: Magnitude of productivity impact of active transportation

Health gain from active transportation	Value of productivity impact	Description of methodology	Coverage	Study
Reduce the risk of obesity by being physically active	4.8% reduction in the likelihood of obesity due to walking	Obesity was measured by using body-mass index and a sample of 10,878 participants to test the relation between physical activity and odds of being obese.	Atlanta, USA	(Frank, Andresen and Schmid 2004)
Physical activity and avoided air pollution from vehicles	7332 DALYs and 530 premature deaths per million population can be saved in London and 12,516 DALYs and 511 premature deaths per million population can be saved in Delhi.	Comparative risk assessment method is used to estimate the health effects.	London and New Delhi	(Woodcock et al. 2009)
Physical activity and air pollution	The estimated annual net health savings in New-Zealand would be $200 million, and in Australia it would be $1.7 billion.	This paper reviewed existing literature on co-benefits of active transportation and the monetize the health benefits for Australia and New Zealand	Australia and New-Zealand	(Giles-Corti, et al. 2010)
Physical activity and air pollution	3–14 months can be gained by being physically active and 0.8-40 days can be lost due exposure to outdoor pollution while cycling	Scenario analysis has been done to estimate the health effects. The scenarios are hypothetical based on the statistics of Netherlands.	Netherlands	(De Hartog et al. 2010)
Physical activity and avoided air pollution from vehicles	5% modal shift towards cycling results in 116 deaths avoided by being physically active and 6 deaths	Different models are used along with existing data to estimate the mortality and morbidity effects.	New Zealand	(Lindsay, Macmillan, and Woodward 2011)

Health gain from active transportation	Value of productivity impact	Description of methodology	Coverage	Study
	avoided by avoiding air pollution			
Physical activity and avoided air pollution from vehicles	Health benefit by switching cars to cycling and walking is worth around 1300 Euro/year and reduction of air pollution is worth around 30 Euro/year in large European cities.	For air pollution ExterE project methodology is used and for physical activity related health benefits WHO methodology is used (i.e. relative risk reduction potential)	Seven large European cities	(Rabl and De Nazelle 2012)

Source: Own elaboration

There are not many studies who have tried to quantify the net health impact of active transportation. From table 9, it can be observed that studies quantifying different health aspect of modal shift use different quantification methods. Studies have used mostly a dose-response based risk reduction models. However, the magnitude of the health impact varies across all these studies due to the use of different methodologies and different geographical coverage. The noteworthy point is that the magnitude of the net health impact is positive in every study described in table 9.

3.2.2.2 Road congestion:

Road congestion is broadly defined as a condition of delay in the road due to excessive number of vehicles using the road, than the design capacity of the road traffic network (Weisbrod 2010; Olawale, Adebambo, and Boye 2015). However, the definition of traffic congestion may vary from perspective to perspective. Broadly, there are three groups of definition for traffic/road congestion i.e. 1) demand capacity related, 2) delay-travel time related, and 3) cost related (Aftabuzzaman 2007). Table 10 provides below a list of definitions of road congestion for these three categories:

Table 10: Definitions of traffic congestion

Categories	Definition	Reference
Demand capacity related definitions	Number of vehicles on road i.e. travel demand exceeds the road capacity.	(Rosenbloom 1978)
	Congestion can be referred as a condition which is caused due to more people travel at a given time than the capacity of the transportation system. More precisely, when number of passengers exceeds the limit of accommodate capacity of transportation system, congestion takes place.	The Institute of Civil Engineers, 1989 cited in (Miller, and Li 1994)
	Congestion can be defined as a state which is characterized by high vehicle densities and low speeds, compare to the reference state which is characterized with low densities and high speeds.	(Bovy, and Salomon 2002)
	When input volume exceeds the output capacity of the road.	(Stopher 2004)
Delay- travel time related definitions	Traffic congestion defined as travel time delay compared to free-flow travel conditions.	(Lomax et al. 1997)
	Traffic congestion refers to as a condition of traffic delay because of the excess number of vehicles which exceeds the traffic network capacity.	(Weisbrod, Vary, and Treyz 2001)
	Congestion occurs in the situation when traffic is moving at speeds below the designed capacity of a roadway.	(Downs 2004)
Cost related definition	"Traffic congestion refers to the incremental costs resulting from interference among road users".	(VTPI 2005)

Source: Adapted from (Aftabuzzaman 2007)

Congestion also represents the tendency of overutilization of a facility. Also, as number of vehicle on road increases, the density of traffic increases and here density is defined as the number of vehicles per lane per kilometre (Stopher 2004). With the increase in density, vehicle speed decreases. However, there is a limit to how much the density can increase. If the vehicles are very close to each other i.e. "bumper-to-bumper" then speed drops to zero. This phenomenon is called traffic jam (Stopher 2004). In this dissertation, road congestion includes both traffic jam i.e. when the vehicles are stopped moving or moving very slowly and there is a delay in travel time compared to a free flow travel condition.

In cities with a lot of congestion, the active mode especially bicycle can be faster than travelling by car particularly on short distances (Buis, and Wittink 2000). Thus, opting for the active mode would not only save time spent in congestion but also it would be faster and thus result in having more time in work/leisure. Of course, it is subject to the local circumstances. The effect of road congestion goes beyond time consumption. Studies (see (UNCHS 1995; Johansson 1997; Treiber, Kesting, and Thiemann 2008) show that fuel consumption increases due to congestion and this extra consumption can be costly. For example, in Bangkok city, the cost of extra fuel consumption due to congestion was 1.5 billion US$ per year (Buis, and Wittink 2000). Additionally, this extra fuel usage due to congestion increases pollutants such as carbon monoxide (CO) and hydrocarbons emission are around 50% higher compared to normal traffic flow (Buis, and Wittink 2000). These pollutants have further health related implications such as headaches, cardiovascular diseases, coughing, irritation of eyes etc.(Schwartz, and Morris 1995; Jones 1999; Brook 2004).

Apart from the above mentioned three aspects of labour productivity, the modal shift towards active transportation also results in 1) cost savings by avoiding fuel cost, 2) lower implementation and operational cost, 3) higher use of public transit which increases public revenue, and 4) greater environmental awareness (Cavill et al. 2008; Shaheen,Guzman, and Zhang 2010).

Therefore, considering both the health effects and road congestion effects, the modal shift towards active transportation can have an effect on productivity mainly in four ways:

1) By reducing energy use in the transport sector, there would be less outdoor pollution and henceforth less exposure-related disease. This would result in productivity improvement.
2) By saving time spent in traffic, more productive time is available. Here, the saved time from traffic can be spent both in work and in leisure.
3) Being physically active and having less outdoor pollution, healthy life years can be gained.
4) Negative health impacts hence, decrease in productivity due to higher accident rate and more exposure to the pollutants.

3.2.3 Relationship between health and productivity

It is crucial to define the relationship between health and productivity. In this study, as it is discussed earlier, only labour productivity is measured in the context of multiple impacts and labour productivity is positively correlated with indoor and outdoor air quality. Energy efficiency measures such as improved HVAC system with airtight building envelope and modal shift towards active transportation can improve indoor air quality and outdoor air quality by minimizing exposure to the pollutants (De Hartog et al. 2010; Bonetta et al. 2010).This improvement in indoor and outdoor air quality would improve the state of health and hence labour productivity by increasing work days and better work output per unit of time (Fisk 2000; Brook 2004). This relationship between health and productivity implies that health is an input factor of labour productivity thus improvement in health means an improvement in productivity. Studies have discussed how health effects such as absenteeism (being absent from work), presenteeism (present at work despite being sick) and mental stress can affect labour productivity by reducing labour input (O'Donnell 2000; Boles et al. 2004; Kirsten 2010). Thus, to summarise, this study quantifies the productivity effects resulting from avoiding pollution exposure-related health impacts and these pollution exposures can be avoided or at least can be minimised by installing (or adopting in case of modal shift) improved energy efficiency measures.

It is important to note that the term labour productivity usually refers to the input efficiency of working-aged people who are in the labour market. However, exposure to pollutants affects non-working aged/retired or children in a similar way, if not more. Children still can be considered as a future resource of a nation and thus any diseases affecting children health can be considered as future resource loss, but in case of aged people and housewives, both mortality and morbidity effects due to pollutant-related exposure are often not accounted in the literature. Most of the studies (for example see (Fisk & Rosenfeld, 1997; Goetzel et al. 2003; Miller et al. 2009) related to productivity ignore the fact that the aged population and housewives play an important role in the society by taking care of the family/friends, household work, doing informal work/non-paid. These kinds of work efficiency are referred to as 'social productivity' (Siegrist et al. 2004). Social productivity can be defined as "any activity that generates goods or services which are socially or economically valued by the recipient, whether, or not based upon a formal contract" (Siegrist et al. 2004; Wahrendorf et al. 2008) . In other words, participation to the "care economy" (household work, taking care of the family friends, doing his daily duties etc.) can also be considered as being socially productive (Wahrendorf et al. 2006).

Thus, from the above discussions, two concepts become clearer:

1) Improvement in health improves productivity by avoiding sick days and sick time loss.
2) People who are not in the labour market, get affected by the pollution exposure in the same way as the working population. However, since they are not in any 'economic

contract', the economic concept of labour productivity does not hold true for them, rather the concept of social productivity is more relevant and important for them as well as the society.

From these above two concepts, one dilemma arises here: people who are in the labour market, not necessarily would work all the days saved by avoiding health damages. In other words, avoiding a sick day or sick time does not necessarily mean that the day would be a workday entirely. In that case, this dissertation argues that even if a person who is in the labour market is not working on the saved day, but the person may be socially productive by spending time his/her family or taking part in a caring economy. Thus, in other words, the person may be socially productive while she/he is not working. Moreover, studies have argued that leisure time is as important as time spent in work for the economy since an employee allocates his time in both leisure and work in order to maximise utility (Abbott, and Ashenfelter 1976; Lloyd, and Auld 2002). Considering the significance of social productivity, this dissertation makes an attempt to quantify social productivity as well as details of which are discussed in chapter 4.

3.4 Significance of productivity impact resulting from energy efficiency measures:

Productivity impact of energy efficiency measures is mainly studied at the individual level focusing mostly on single buildings (for example, see (Howden-Chapman et al. 2009; Chidiac et al. 2011) etc.). However, from those single building case studies, productivity impact is clearly visible. Productivity improvement due to energy efficiency measures does not only imply less sick days i.e. more work days but it also includes other key aspects such as performance improvement or improvement in future earning ability.

Table 11 shows few of the similar estimates of productivity impact of energy efficiency measure from existing studies:

Table 11: Productivity impact estimates from existing study-related building sector

Study	Energy efficiency action	Value of productivity impact	Ratio *productivity impact[3]/direct benefit	Coverage
(Fisk 2000)	Improvement in indoor air quality	$17-$48 billion	0.26	USA
(Aunan et al. 2000)	Minimum standards for the insulation of new buildings; energy efficiency labelling of household appliances	$370-$1170 million annually	1.73	Hungary
(Clinch and Healy 2001)	Retrofitting of buildings	€4723 million over 31 years at a 5% discount rate	1.7	Ireland
(Levy et al. 2003)	Retrofitting of buildings	$5.9 billion per year	.22	US
(Howden-Chapman et al. 2009)	Retrofitting of buildings	NZ$2652 per household at 5% discount rate over 30 years	3.37	New Zealand
(Joyce et al. 2013)	Retrofitting of buildings	€42–88 bn per year	1.02	EU

Source: Own elaboration

Table 11 provides evidence on the relative importance of productivity impact of energy efficiency measures compared to the direct benefit i.e. energy cost savings from energy

[3] Most of the productivity impact is occurring from improvement in health. Hence for some of the studies improvement in health value is taken while calculating the ratio. Here, direct benefit refer to the energy cost saving benefit.

efficiency measure. In the studies reviewed, the ratio of productivity impact to energy savings is between 0.22-3.37. This confirms the fact that productivity impact is a key impact of energy efficiency measure. The range of all multiple impacts to direct benefit lies between 0.45-2.43 as discussed in chapter 2, section 2.1.3. If the average ratio is calculated from these two ranges then it can be seen that productivity impact to direct energy savings is higher compared to multiple impacts to direct benefits. Empirically the midrange[4] of productivity impacts to direct energy benefits is higher (1.8) compared to the midrange (1.4) of all multiple impacts to direct benefits. Therefore, empirically also, it can be concluded that productivity impacts are one of the key impacts in terms of their magnitude.

Unlike building sector-related energy efficiency measure, active transportation mainly walking and cycling saves almost full energy use compared to vehicle mode of transport. Thus, calculating the ratio between productivity and the direct benefit is not an option here.

3.5 Summary of the chapter

In this chapter, the energy efficiency measures studied in this dissertation are discussed. As it is described in chapter 1, the main goal of this dissertation is to provide a systematic methodology to quantify multiple impacts of energy efficiency. Hence this dissertation does not focus too much on the technicalities of energy efficiency measures rather it focuses more on the effects of improved energy efficiency measure. Energy efficiency measures are the starting point in this dissertation's methodology which is discussed in detail in the next chapter.

In this chapter, first two specific energy efficiency measures (HVAC system with airtight building envelope and modal shift towards active transportation) are discussed and then how these two measures results in productivity improvements, are discussed. By discussing the

[4] The midrange is defined as the mean of the highest and lowest values i.e. (Maximum + Minimum) / 2. Midrange is a type of average which provides an understanding about a magnitude of a particular dataset.

interaction between energy efficiency measure and its productivity impact, the different indicators of productivity would be defined in the next chapter.

CHAPTER 4- METHODOLOGICAL FRAMEWORK

"The true price of anything you do is the amount of time you exchange for it"

Henry David Thoreau

4.1 Review of existing methodology:

The process of assessing multiple impacts is quite complex since, for different impacts, different quantification methods are used (Ürge-Vorsatz et al. 2015). For instance, for non-marketable impacts, different valuation techniques such as contingent valuation or hedonic pricing can be used and for macroeconomic effects mostly methods such as computable general equilibrium method (CGE) or input-output models are used (Söderholm and Sundqvist 2003; Ürge-Vorsatz et al. 2016). However, these methods have their own limitations due to which impacts cannot be rigorously quantified. There are mainly two types of methods: 1) methods for decision and 2) methods for quantification. In the following section each of these different types of methods are discussed:

1) **Methods for decision:** Decision methods are used to decide whether a policy is profitable or loss-making. In other words, decision methods help to decide policy by comparing the cost with benefits. In order to conduct a decision method, first, the impacts need to get quantified. Thus, decision methods are considered to be the last step of deciding a policy based on the negative and positive effects of the policy. There are mostly three decision methods: cost-benefit analysis, marginal abatement cost curve, and multi-criteria analysis**.**

Cost-benefit analysis: Cost-benefit analysis or CBA method generally uses to see the net value of a particular action (Bergh 2004). There are two main purposes of using CBA:

1. To determine the feasibility of investment, for instance, if benefits outweigh cost then the investment is economically feasible.
2. To provide a basis for comparing different options.

In CBA all costs and benefits are expressed in a monetary unit and it is adjusted as per 'the time value for money'. A value of an investment option in CBA is usually expressed in the net present form i.e. total cost and total benefit of an investment are adjusted for time value and presented in net form. Thus, CBA is a good measure for integration of all the costs and benefits of an energy efficiency policy but in order to conduct a CBA, one needs to have the monetary values for each of the costs and benefits. Cost-benefit analysis is a decision making analysis and it can be conducted only after the quantification and monetization of an impact are ready.

There are other similar approaches, such as cost-effectiveness analysis (CEA), benefit-cost analysis (BCA), cost-benefit ratio (CBR), and benefit-cost ratio (BCR) which are conducted in a similar fashion like CBA. Since the comparison between cost and benefit are beyond the scope of this dissertation, details of these similar cost-benefit approaches are not discussed.

Multi-criteria analysis: Multi-criteria analysis (MCA) helps in establishing a preference between options by referring to an explicit set of objectives (Dodgson et al. 2009). Each option has its measurable criteria to assess and these criteria are set by the decision making body in accordance with the policy objectives (Dodgson et al. 2009). MCA is usually performed by assigning scores to each option and then numerical weights are assigned to define each criterion. The preferred options score higher on the scale, and less preferred options score lower. In practice, scales extending from 0 to 100 are often used, where 0 represents a real or hypothetical least preferred option, and 100 is associated with a real or hypothetical most preferred option (Dodgson et al. 2009). One of the biggest controversies around the valuation technique of MCA is that the scoring technique method is subjective hence uncertain (Davis, Krupnick, and McGlynn 2000).

Marginal abatement cost curve: “A [marginal abatement cost] MAC curve is defined as a graph that indicates the marginal cost (the cost of the last unit) of emission abatement for varying amounts of emission reduction.” (Ekins, Kesicki, and Smith 2011). The purpose of using a MAC curve is to understand the significance of each possible option of reducing emissions. Moreover, the MAC curves can help in deciding for the most preferred option by showing the relative importance of different options in different regions and sectors (Kesicki 2011). MAC curve can be of two types, i.e. expert-based and model-derived curves. Expert-based ECS/MAC curves which are also referred as technology cost curves, can assess the cost and reduction potential of technological mitigation options based on information about technological costs. On the contrary, the model-derived curves are based on the calculation of energy models. The expert-based curves often treat different technological options entirely independently due to difficulties in analysing their interactions – this implies that the different technologies can be applied in any combination, and their impacts are independent of each other. This is often not the case in reality (Urge-Vorsatz et al. 2015). Model derived curves are basically oriented towards economy based top-down model, engineering-orientated bottom-up models or hybrid energy-economy models. In all cases, conservation supply or abatement curves are generated by determining the marginal energy or CO_2 prices resulting from with different energy supplies or emission limits or by determining the energy savings, energy supplies or emission levels resulting from different energy or CO_2 prices.

To summarize, each evaluation technique has its own limitations and uncertainties and some of them are too serious to deal with. Also, not all the methodologies such as CBA or MCA, can quantify individual impact. They can be used for aggregation of quantified individual impacts.

2) **Methods for quantification:** Methods for quantification are the first steps to evaluate a policy. The sole purpose of these types of methods is to quantify the cost or benefit of a policy and then these costs or benefits can be incorporated into a decision type method. Some of the most used methods are described in the following section:

Willingness to Pay (WTP) and Willingness to Accept (WTA): Many of the impacts (such as health, ecosystem, clean air etc.) of energy efficiency measures are non-marketable and hence market prices do not exist for such impacts. However, this does not mean that these impacts are devoid of values. There are some alternative approaches to assign a value for such impacts to enable their potential.

There are mainly two approaches to determine the value for non-marketed impacts:

1. Market based approach, and
2. Stated preference approach

For market-based approaches, such as contingent valuation and hedonic pricing technique are used to evaluate the impact. On the contrary, in the stated preference approach, the consumers are directly asked questions to reveal their preferable amount for a particular good or service. For example, to save a species how much a person is willing to pay. Both WTA and WTP directly represent a person's wiliness to pay or willingness to accept for the environmental damage and hence they can be treated as a value for that environmental damage in the absence of market-price. In both of these methods, the consumer reveals their preferences in terms of WTP or WTA (Söderholm and Sundqvist 2003).

Market based approach is based on "direct observable market interactions" (Gundimeda 2005). For example, how much people are willing to pay in order to avoid any health hazards from air pollution. Health has no direct market value and hence here the valuation is done based on people's WTP or WTA. WTP is generally used when the benefit is measured and WTA is used when certain valuation is done based on compensation. For example, building an industry may pollute the local air hence the local people may claim how much compensation they expect for the air pollution. This compensation amount can be treated as a proxy value for local air pollution. In cases where it is not possible to use any market based information then people are asked questions

One of the biggest criticism of WTP and WTA approach is that they often contain respondent biasness and hence the value of WTP or WTA may not has a proper representation (Phillips et al. 1997). More precisely, individual biasness such as less information about an event (for example, how much air pollution can harm health) may lead to undervalue a particular impact.

Cost of illness method (COI): Cost of illness method measure the disease specific healthcare expenditure of people. COI is used as a proxy for getting the monetize value for any disease. There are two types of cost: 1) total disease cost and 2) incremental disease cost. Total disease cost provides estimate for the disease specific total health care cost and incremental disease cost provide the estimate of the increase in cost that is attributable solely to the presence of the disease (Akobundu, et al. 2006). The most concise critic of this method is that the COI estimates provide higher value for the diseases which are already costly (Koopmanschap 1998). For example, cancer has a higher treatment cost compared to asthma but this does not mean that life loss due to asthma is less painful than life loss due to cancer. The estimation method of COI is criticized on another ground that COI method tends to underestimate health cost (Rice 2000). For instance, in this method pre-mature life loss is estimated using market earnings thus, is using low values for children and retired elderly (Rice 2000).

Dose response model: One of the well-used model in epidemiological studies to estimate health related damages is dose-response model. Dose-response model basically estimates the effect in an organism at different exposure levels (Calabrese and Baldwin 2003). Dose response model is also known as exposure-response model. However, dose and exposure have different implication in the model. For instance, dose implies amount of dose or dosage of a particular biological or chemical object which is being exposed to a person or population whereas exposure implies time dependent concentration of a particular biological or chemical object. The primary criteria to conduct a dose-response model is the determination of the cause-effect relationship (WHO 2008). If the cause-effect relationship exists then only a dose-response model can be used. The dose – response relationship usually depends on the exposure time and exposure route (for instance, inhalation, dietary intake etc.) (Yadav 2013). The results from the dose-response type of models can be used in estimating the risk. More precisely, results of dose-response model estimate the risk of going above the safety level (i.e. magnitude and type of health impacts) (Yadav 2013). Thus, while using a dose-response model, it is always advisable to know about the 'safety level' in order to correctly interpret the data. However, sometimes the 'response' to the amount of same 'dose' may vary across different persons. In other words, the dose-response model may not be always linear (Aune et al. 2011).

Modelling techniques of MI: There is no specific modelling technique for multiple impacts. Most of the modelling techniques estimate energy consumptions and energy system-related GHG emission. However, some of these modelling techniques can be used to measure some of the impacts as well. Modelling techniques for energy consumption are mainly divided into two types: top-down models and bottom-up models. This division of model classes is mainly based on the data inputs of energy systems and the comprehensiveness of endogenous market adjustment (Böhringer, and Rutherford 2008). Top-down models take an economy-wide perspective which assumes imperfect market, spill over effect and income effects among different agents such as household and government (Böhringer, and Rutherford 2008). Thus, top-down economic models such as Input-Output analysis, partial or Computable General Equilibrium (CGE) models are generally used to assess macro-economic impacts such as GDP, public budget etc. (Ürge-Vorsatz et al. 2015). For instance, input-output modelling mainly depicts the inter-industry relationship within an economy i.e. quantifying how much output of an industry is used as an input to other industry (Ürge-Vorsatz et al. 2015). The input-output table can be extended with environmental impacts as well but it cannot monetize or quantify itself (Miller and Blair 2009). Moreover, input-output models are more basic than CGE models as they cannot address the substitution effect or the additionality (Ürge-Vorsatz et al. 2015). It is important to note that the macroeconomic impacts are different in nature compared to the health and productivity benefits and hence, macro-economic models, such as computable general equilibrium (CGE) or partial equilibrium models are not a good choice to evaluate productivity impact.

The bottom-up engineering modelling features a large number of energy techniques to estimate the partial effect of energy policies on the economy (Böhringer & Rutherford 2008). However, this kind of modelling does not consider macroeconomic impacts. Bottom-up models, such as long range energy alternative planning (LEAP) modelling is widely used for assessment of impacts. LEAP is rather an engineering model than an economic model. LEAP usually follows partially equilibrium modelling which means it usually focuses on a single sector (Ürge-Vorsatz et al. 2015). Furthermore, LEAP model does not have the facility to evaluate productivity impact of energy efficiency measure.

Apart from the top-down and bottom-up models, there are two other types of modelling approaches: hybrid modelling and integrated models or integrated assessment modelling (IAM). The hybrid models although incorporate the responsiveness of bottom-up models and the technological richness of top-down models, they are not yet fully equipped to incorporate all the responses of energy efficiency measures, such as indoor air quality etc., which make them less relevant in the context of this dissertation. Similarly, though IAMs incorporate both socio-economic and scientific aspects of climate change policies but IAM models have mostly focused on the supply side. Thus, IAM can be used to evaluate the environmental impact of energy efficiency policies but they are not suited for productivity quantification.

Thus to summarize, in this section the most used methods to quantify the multiple impacts are discussed. These methods have their own limitations due to which there exists a gap for a systematic method to quantify any impact of energy efficiency measures. Table 12 lists the limitations of these methods below:

Table 12: Summary of the most common methodologies used to assess multiple impacts

Name of method	**Limitations**
Cost-Benefit Analysis and cost effectiveness analysis	Monetization of impacts is not always possible and if an impact is not monetised then it would not be incorporated in a CBA or CEA.
Energy Conservation Supply Curve or Marginal Abatement Cost Curve	Mostly calculated for direct cost savings and GHG reduction cost.
Multi-criteria Analysis	Subjectivity of weighting (if done) with no real scientific/disciplinary basis
Integrated Assessment Models	Highly simplified
Computable General Equilibrium models	Mainly focus on market
Input-Output models	No behavioural characteristics of agents
Partial equilibrium analysis	Lack of focus on macroeconomic interactions
Cost of illness	The extent of health loss is determined on the basis of treatment cost of the disease. Thus, it is often the case that COI method underestimate/overestimate the value of health loss.
Dose/exposure-response model	Requires many micro data which may not hold true at the population level. In addition for many of the diseases, the exposure and response extent are not yet clear.

Source: Adapted from (Ürge-Vorsatz et al. 2015)

In addition to the points mentioned in table 12, also these methods (except dose-response method) are not able to capture the overlaps between the impacts and without understanding the overlaps, a quantification of impacts may lead to double counting

Ideally, a decision on energy-related investment or policy should be taken based on potential full cost and benefits (both anticipated and unanticipated) associated with the policy or investment, but this practically never takes place due to the absence of mature methodology (Ürge-Vorsatz et al. 2014). As discussed in the beginning of section 4.2, cost benefit or cost effectiveness analysis only typically includes direct cost and benefit. There are few studies which estimated single impact by using various methodologies such as conservation cost curves, control group survey etc. Few of the studies with different quantification methodologies are described below to explain the other methodological challenges related to quantification of impacts. For instance, Worrell et al 2003 study evaluate the relationship between energy efficiency measures and productivity by reviewing over 70 case studies in the industrial sector. The authors have proposed a suitable method to incorporate productivity benefits of energy efficiency measures into an economic assessment. This paper explores the implications of including input/raw material productivity benefits into the economic assessment with the help of a study on the iron and steel industry in the US. In this study the evaluation of impact is done based on investor's perspective which followed the steps below:

1. Identify the input/raw material productivity benefits.
2. Quantify productivity benefits as much as possible in the most direct terms.
3. Make rational assumptions to translate the benefits into cost impacts.
4. Calculate cost impacts of productivity benefits.
5. Lastly, incorporate the cost value into the cost calculations by using bottom-up energy conservation supply curves (CSCs).

By following these above mentioned steps, these authors demonstrates that including productivity benefits into economic assessment can result in double benefit, compared to the analysis excluding productivity impact. Though in this study the authors argued about proper identification of benefits but it lacks to provide a systematic methodology to identify the benefits of energy policies. Also this study only quantifies the direct productivity benefits. This study shows that even with direct productivity benefits, a systematic identification is required. Worrnell et al 2003 study identifies the benefits by reviewing other literature.

Literature review is probably the most popular way to establish a relationship between energy efficiency measures and their effects. However, another way of finding the linkages between energy efficiency measures and their impacts is to conduct a control group survey. Through the control group survey the identification of impacts becomes evident and afterwards the value of impacts needs to be estimated. For example, Fisk and Rosenfeld 1997 study shows the economic incentives in investing in buildings. They provide quantitative evidence on how indoor environment can significantly influence labour productivity. For the US, the authors have estimated "potential annual savings and productivity gains of $6 billion to $19 billion from reduced respiratory disease respectively and $1 billion to $4 billion from reduced allergies and asthma". This proves the significance of the indoor air quality effect on worker's productivity. In fact, Fisk and Rosenfeld monetize the direct productivity gains due to investment in building operation and as per their case study, $12 billion to $125 billion can be gained from direct improvements in worker performance which are unrelated to health (Fisk, and Rosenfeld 1997).

Both Wornell et al and Fisk et al studies are sector specific studies where two different techniques were used to identify the effects of energy efficiency measure. Fisk et al 1997 study evaluates labour productivity by assessing few aspects of productivity, such as absenteeism and health care cost, whereas Wornell et al 2003 study reviews the existing literature and estimated input productivity by using CSC method. Thus, these methodologies could not be used for any sector other than the specified sector. However, both of these studies have a common first step to start with, which is the identification of the impact pathways.

Urge-Vorstaz et al 2016 paper talks about the general challenges of quantification of impacts. All three studies mentioned above provide a direction in assessment of multiple impacts but before doing the assessment of impact, it is important to clarify whether the impacts are worth enough to be assessed or in other words, the magnitude of the impacts need to be understood before assessment. The magnitude in this dissertation can be understood by reviewing literature where the impacts are already quantified.

The existing literature as described in chapter 2, 3, and in the beginning of chapter 4, suggest two key rationales behind not including all the benefits:

1. Most of the consequences of energy efficiency measures are not well-understood and thus, most of the times they are not incorporated into any kind of modelling or decision-making analysis such as cost-benefit analysis. Even majority of the models are not technically equipped enough to quantify all the impacts specially health and productivity impacts.
2. Even if there is a sufficient research on the different indirect benefits of sustainable energy policy, it is often the case that not all the indirect benefits can be quantified and hence they are usually not included in a decision making policy. The partial reason behind not quantifying all the impacts is a lack of methodology.

This lack of methodology to quantify and identify the multiple impacts would underestimate any energy efficiency policy. Even though few of the individual impacts have been estimated in few of the studies (for example, see (Fisk, and Rosenfeld 1997; Schweitzer and Tonn 2002),but these studies do not discuss the challenges of quantifying and integrating the individually estimated impacts into a total value (Urge-Vorstaz et al. 2016). One of the biggest challenges in the estimation of impacts is its interaction with other impacts. More precisely, some of the multiple impacts of energy efficiency measure overlap with each other which may cause double counting error. Thus, special care must be taken while quantifying these impacts in order to avoid double counting; otherwise, it may overestimate or underestimate the results. In addition to the risk of double counting, there is another risk of partial counting of an impact which results in biases. More precisely, if only a part of the multiple impacts is assessed then it may result in biases (Urge-Vorsatz et al. 2016). For example, only assessing positive effects and avoiding negative effects (such as adverse side effect, transaction cost, hidden cost etc. of a policy) would mislead us. However, as it is mentioned in Urge-Vorsatz et al. 2016 paper "a comprehensive identification of the multiple impacts needs a systematic approach" and as it is discussed in the methodological review in section 4.2, the existing methodologies such as cost of illness, MCA models are not suitable to assess productivity impact.

4.2 Challenges related to quantification of multiple impacts

Apart from identification of impact pathways, there are other challenges in quantifying the impacts. In order to accurately quantify the multiple impacts of energy efficiency, the challenges related to quantification need to be identified. Urge-Vorsatz et al 2016 study identifies few such key challenges (namely additionality, baseline, perspective, context dependency, perspective, scale and distributional impact) to the evaluation of the impacts of energy efficiency measures and also proposes possible solutions to address these challenges. The key problem identified in this dissertation is the lack of a comprehensive methodology which shows all the interactions and overlaps among impacts. In addition to the absence of a systematic methodology, there are few key factors as discussed above which make quantification of multiple impacts more difficult. These challenges are discussed in the following section:

1. **Additionality and baseline:** It is important to understand that the impact or the portion of impact quantified and accounted in a decision-making analysis is additional

compared to the baseline. For policy design, it is necessary to account only the additional impact in order to avoid over-estimation since the size of the impact would depend on the factors like additionality and baseline. An appropriate selection of baseline is the first step and then only the additional value needs to be taken into account. The value of impact depends on selection of type of baseline. There are two types of baselines: static and dynamic. The degree to which a baseline is static or dynamic, would have implications in terms of which impacts can be considered additional in order to avoid over-estimation. Also, it needs to be seen whether energy efficiency policy is itself additional compared to the baseline. In order to check that, one needs to constantly check whether the impact meets any of the three layers of additionality:

i. Additionality of the clean energy action/policy: Sometimes the energy efficiency measure is itself an additionality compared to the baseline and thus any effects of that policy would be automatically considered as additional.
ii. Additionality of the impact: Impacts only additional to the baseline should be considered during policy evaluation. The values of impacts should be compared with alternative ways to achieve the same impact.
iii. Additionality compared to alternatives: Any impact of energy efficiency investment needs to be compared to all the potential alternative investments.

Thus, before impact evaluation the baseline needs to be selected and then impact should meet one of these with these layers of additionality. Then only accurate evaluation of the impact is possible.

2. **Double counting:** As it is discussed in the previous section, multiple impacts are not distinct and independent in nature and often they may overlap with each other. Without understanding these overlaps if quantification is done then there is a possibility to

commit a double count of impacts. This double counting of impact would overestimate the policy. The double counting of impact is more prone to occur during impact aggregation. However, impacts such as labour productivity which has several aspects may lead to double accounting if not defined clearly (Chatterjee and Urge-Vorstaz 2018). Thus, a careful assessment is required to evaluate impacts.

The issue of double counting mostly arises when different impacts are aggregated. However, it may also arise when a single impact has several aspects (for example productivity) and each of the aspects needs to be aggregated in order to get a complete figure of the impact. Therefore, even with single impact a thorough identification is required in order to avoid double counting.

3. **Perspective:** Evaluation of impacts may vary as per the evaluation perspective. For instance, an impact may have a different value when it is calculated keeping societal perspective than evaluating from investors perspective. For investor, the crucial issue is whether the impact can maximize the revenue/profit whereas for society, societal welfare is important. The impact value may differ depending on the perspective. That is why a ‘standing' is important while doing a cost-benefit analysis of any policy.
4. **Context dependency**: Context can be broadly defined as the variables which provide background of a particular policy (Ürge-Vorsatz et al. 2016). These contexts are not directly related to the aim of the policy but they influence the policy outcome. For example, Urge-Vorsatz et al. 2010 study found that deep renovation programs in buildings would have intense employment effect only if external (EU) funds were used to pay for the retrofits. If the source of funding comes from loan then employment impact is much smaller from these programs. These kind of contexts need to be identified and understood during the policy and impact evaluation.

5. **Distributional impact:** The value of total impact not necessarily shows the effect on society or economy. For instance, any decision making analysis, such as cost-benefit analysis does not consider the difference between marginal utilities of income across different income groups, but only considers the total value. More precisely, due to retrofitting at a local level, less energy is required than pre-retrofitting condition, thus, less energy would be produced which would result in less energy import. This chain effect is not bounded by local level but it goes at the national scale and benefits the country.
6. **Scale:** Multiple impact assessment depends also on the scale of the impact-meaning, the size of the impact may also depend on the geographic scope of the impact. The impact also concerns on whose benefits should be counted. The appropriate scale of analysis depends on the type of multiple impacts assessed (Chatterjee et al. 2018). In other words, it can be said that the scale of analysis is context dependent. Thus, it is recommended that both geographical and temporal unit of analysis are precisely chosen in order to conduct a non-bias analysis.

Table 13 summarizes these challenges and possible solutions.

Table 13: Few quantification challenges and proposed solutions

Methodological challenges to the assessment of multiple impacts	**Recommended line of action**
Baseline, additionality and context dependency	The baseline needs to be as dynamic as possible in order to accurately quantify the incremental value of the impact. Moreover, as much as possible variables needs to be considered in the baseline and in the impact pathway maps as well as in the scenarios. A dynamic baseline would tackle the issue of additionality and a careful assessment of impact identification would tackle the issue of context dependency.
Distributional aspects	The distributional effects would be addressed very precisely especially by explain the pre-existing inequalities, and then the role of impact addressing these pre-existing inequalities. As per the identification of inequalities, quantification

Methodological challenges to the assessment of multiple impacts	**Recommended line of action**
	methods would address them through some adjustment factors.
Perspectives	Perspectives depends on priorities and the decision maker who is deciding the priorities such as investors/end-users or government. In social studies or for a national policy maker, the societal perspective would be prioritised.
Scale	Evaluate the impacts at national level first then analyze the possibility of transboundary issue

Source: Adapted from Ürge -Vorsatz et al 2016

4.3 Discussing the dissertation methodological framework:

To deal with these critical challenges of quantification of impact and also to address the shortcomings of methodology (discussed in section 4.1) as much as possible, this PhD dissertation proposes the following steps:

1. Identify the sequence chain of impacts explicitly- i.e. how the improved energy efficiency measure results in productivity change,
2. Identify the causal effects of an impact i.e. whether the impact results in another impact,
3. Quantify each of the effects on productivity in a physical unit,
4. Scenario analysis i.e. defining scenarios as per research design and then quantify the impact for all the scenarios, and
5. Monetize the incremental physical value which shows the effect of installing energy efficiency measure specifically.

As it can be seen from literature review and discussions throughout this dissertation that identification of impact pathway towards productivity is really crucial and without a systemic identification, impact can be undervalued hence it produces less significant results. Thus, in order to identify the pathway of the impacts from an improved energy efficiency measure, this methodological framework uses impact pathway approach. This approach decomposes all the chains of the effects starting from implementing an energy efficiency policy. In the following sub-section details of impact pathway approach are discussed:

4.3.1 Impact pathway approach

The concept of impact pathway is first proposed in ExternE project and then it is demonstrated in the context of multiple impacts, in Ürge-Vorsatz et al.'s 2014 paper "Measuring the Co-Benefits of Climate Change Mitigation". Previously, impact pathway approach has been applied for multiple purposes such as doing analysis of the influence of biofuel production in global markets, finding the environmental impact of large dams or investigating the links between health performance indicator and globalization (Brismar 2004; Cornia, Rosignoli, and Tiberti 2008; Huang et al. 2012; Ürge-Vorsatz et al. 2016).

ExternE project defines impact pathway as "the sequence of events linking a 'burden' to an 'impact" (European Commission 1995). In other words, impact pathway methodology follows a sequential path towards the impact. Impact pathway is a bottom-up approach where benefits and costs are estimated by following the pathway from the sequential causal chain (European Commission 1995). The first illustration of impact pathway done in the ExternE project was based on the source pollutant emissions via quality changes of air, soil and water (*ExternE* 1995). Figure 6 shows the first impact pathway derivation done in the ExternE project.

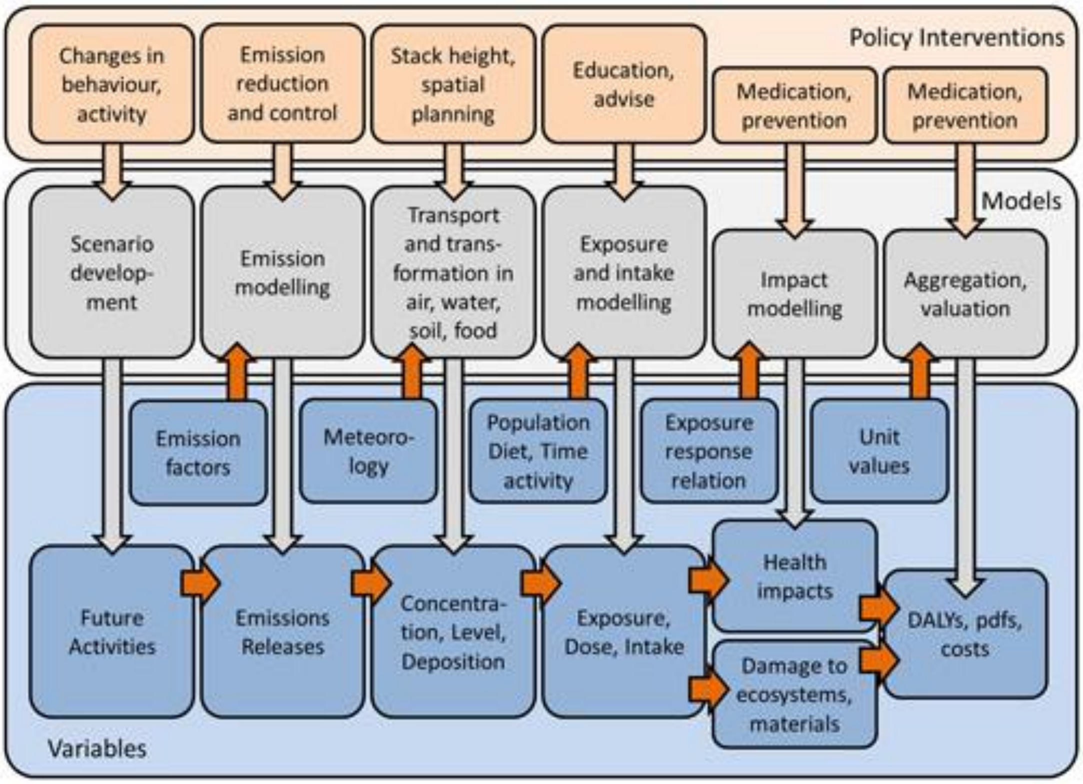


Figure 6: Impact pathway map used in Extern project

Source: (ExternE 2014).

However, we need an elaborate impact pathway map which is only dedicated to productivity assessment. This way the micro interactions of productivity assessment can be enabled.

4.3.1.1 Characteristics of impact pathway approach

There are three key strengths of using this approach namely transparency, consistency and marginal analysis (European Commission 1995). Each of these advantages is discussed individually below in the context of my dissertation context:

1. **Transparency**: Impact pathway approach precisely shows the impacts and their casual chain. Hence, it provides transparency in the time of calculation. Furthermore, uncertainties associated with impacts and their results can also be understood from the impact pathway.

In the context of multiple impacts of energy efficiency there could be mainly three kinds of uncertainties found, i.e. a) few of the impacts and their sequential chain may not yet be fully understood or acknowledged, b) As stated in Urge-Vorsatz et al 2014 paper “for analytical purpose, when operating with distinct individual impact may hide complex relation. For example, renewables and energy efficiency reduce air pollution, which decreases health care costs versus a baseline and may release public resources that can be invested or spent on alternative uses and further enhance employment or gross domestic product levels”, c) for few of the impacts the quantification methodology is not yet ready hence it cannot be incorporated into a decision making analysis such as cost-benefit analysis. Through impact pathway approach these uncertainties can be identified easily while drawing the impact pathway maps.

2. **Consistency**: This approach allows valid comparison between different impacts by considering all the context dependency and distributional aspects. Details of these factors are discussed in the beginning of section 4.2.
3. **Marginal analysis:** Impact pathway approach analyses the impacts on a marginal basis hence, only the incremental effects of energy efficiency are considered in this approach. The impact pathway maps are designed to see the effects which can be resulted due to the implementing efficiency measures. This marginal analysis of effects tests the additionality criteria and hence ensures the inclusion of only incremental effects. Thus, this approach also avoids the chances of any biasness as well.

4.3.1.2 Impact pathway map for building sector:

As discussed in the previous section, impact pathway map decomposes the chain of effects which starts at implementing an energy efficiency measure/action and it ends at the “impact receptor or welfare endpoint, i.e. the impact that directly affects utility” (Ürge-Vorsatz et al. 2016). The key aim of impact pathway approach is to explicitly identify the causal chain of impacts and detect the factors which enable or hamper the impact occurrence (Ürge-Vorsatz et al. 2014; Ürge-Vorsatz et al. 2016)

For building sector, only one energy efficiency measure is considered i.e. HVAC system with proper building shell as discussed in chapter 3. In deep retrofit type buildings i.e. deep retrofitted buildings, passive houses and nearly zero energy buildings, mechanical HVAC system is always installed along with heat-recovery system and high insulation level. The deep retrofit type buildings have by definition airtight building envelope.

In this section, it is shown that if improved HVAC system installed in a full airtight building (here building means both kinds of building sectors i.e. residential and tertiary) then how it is leading towards labour productivity. Each of these pathways such as how better ventilation improves health etc. is already discussed in chapter 3 with scientific references. Now for further steps towards quantification, these impact pathways of productivity impacts are shown through impact pathway map:

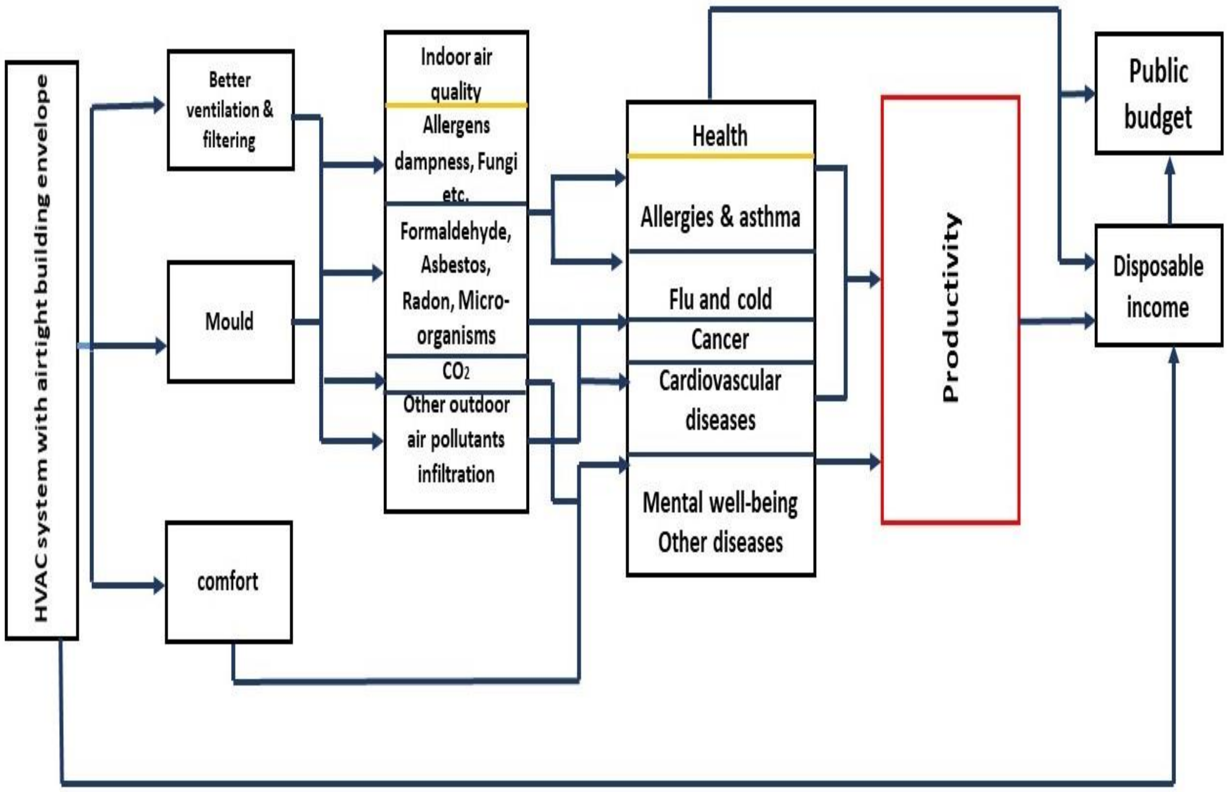


Figure 7: Impact pathway for building sector implementing building related energy efficiency measure

Source: (Chatterjee , and Urge-Vorsatz 2018)

Figure 7 decomposes the chain of effects of the building sector. For example, when improved HVAC system is installed with airtight building envelope then there are three primary consequences: better ventilation and filtering in the building, mould reduction, and comfort level enhancement where comfort includes all kinds of comforts such as thermal comfort and acoustic comfort. These three impacts (ventilation, mould, and comfort) have further consequences mainly related to indoor air quality. For instance, due to improved ventilation and filtering, the concentration of indoor air pollutants, mainly bio-aerosols such as particulate, spores etc. reduces inside the building atmosphere. Reduction in indoor air pollutant concentration improves indoor air quality. The improved indoor air quality transfers into health impact i.e. less allergy and respiratory related diseases. These health impacts ultimately lead to productivity improvement by avoiding sick days and increasing work performance. Here, one point needs to be noted that mould reduction is not significantly correlated with air exchange rate i.e. there would be a minimum health gain from mould exposure reduction by having an HVAC system. However, further mould growth can be prevented by installing HVAC system but for the pre-existing mould, the only option is to remove it.

Here, the macroeconomic impacts such as public budget and disposable income are mentioned in the impact pathway to indicate the fact that productivity impacts would further lead to other impacts. All the other impacts resulting from productivity are not within the scope of this study and hence not discussed. There could be other impacts as well apart from productivity impact, but this impact pathway map (figure 7) is designed to enable the pathway towards productivity, hence other impacts resulting from HVAC with airtight building envelope or other impacts resulting from productivity are not discussed here.

4.3.1.3 Impact pathway map for transport sector:

For transport sector, this study is considering only one energy efficiency measure i.e. modal shift towards active transportation. Similar to figure 7, each of these pathways of modal shift towards active transportation is already discussed in chapter 3 with scientific references. Now for further steps towards quantification, the impact pathway map decomposes the chain of effects of opting for modal shift towards active transportation.

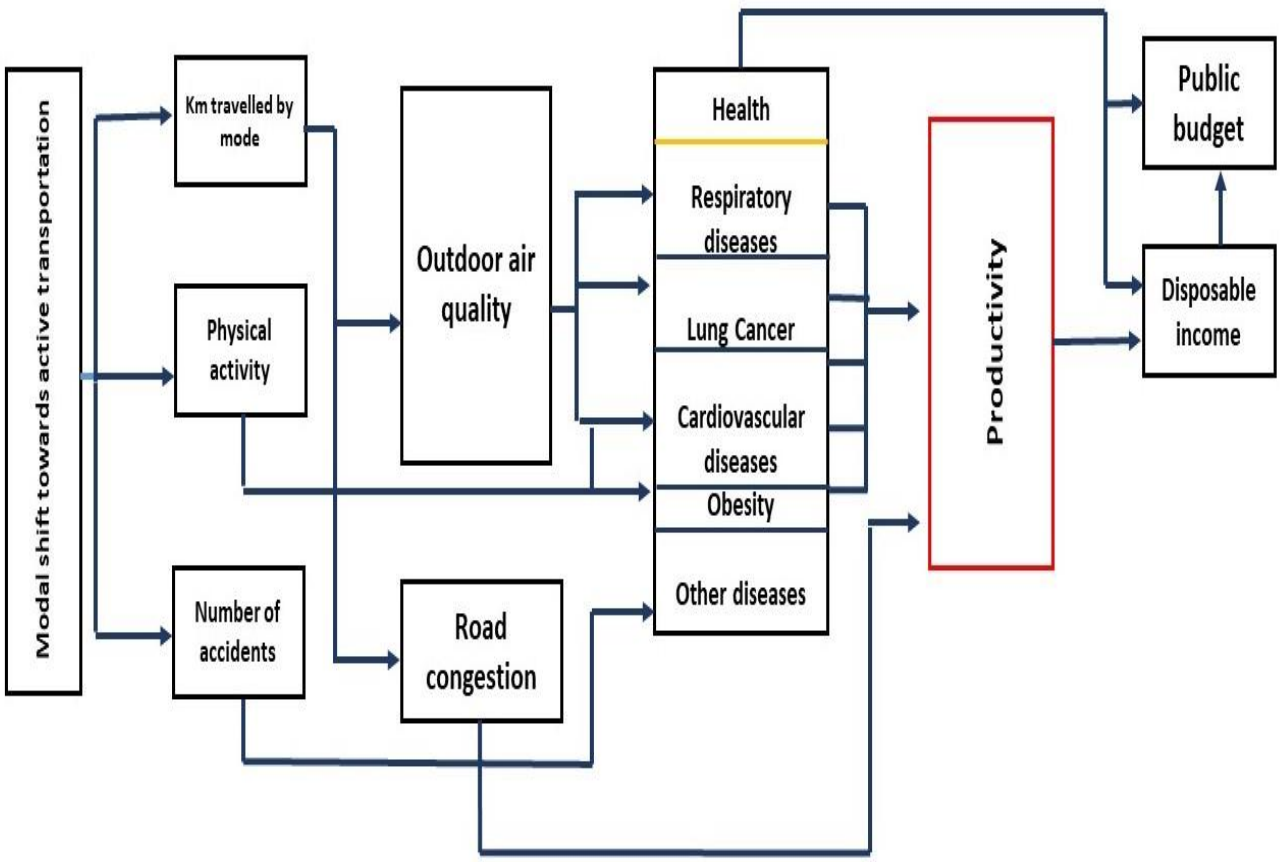


Figure 8: Impact pathway for transport sector implementing building related energy efficiency measure

Source: (Chatterjee & Urge-Vorstaz 2018)

Similar to figure 7, figure 8 also decomposes the chain of effects for transport related energy efficiency measure. After implementation of relevant energy efficiency actions, the primary consequences, such as reduced energy consumption, physical activity have been translated into productivity through saved travel time, outdoor air quality and health (Künzli et al. 2000; Katsouyanni 2003). For example, due to modal shift towards the active transportation, the primary consequences are physical activity, % kilometre travelled, physical activity and number of accidents. These consequences have further effects on productivity through health. Some are being physically active what leads to increased productivity and having less outdoor exposure leading to improvement in health. Some of the impacts are directly translating productivity, such as avoided congestion. Due to shift in active transportation, there would be less traffic congestion and hence traffic time can be saved. Then, saved traffic time can be spent by working and/or on other activities (Graham 2006).

Similar to the building sector, the macroeconomic impacts, such as public budget and disposable income are mentioned in figure 8 to indicate the fact that productivity impacts would further lead to other impacts. This impact pathway map (figure 8) is designed to enable the pathway towards productivity, hence other impacts resulting from modal shift towards active transportation or other impacts resulting from productivity are not discussed here.

4.3.2 Productivity indicators

Impact pathway maps identify (refer to figure 7 and 8) all the interactions between all the impacts and also explain the causal effects of energy efficiency measure. However, since labour productivity incorporates many aspects, it needs to be specified which aspect of labour productivity is influenced by improved energy efficiency measure in order to estimate productivity impacts precisely. Studies have been using different indicators to measure labour productivity loss but as Sennett's 2002 study rightly mentioned that "productivity is particularly difficult to calculate, due in part to the lack of standard metrics". Thus, a set of indicators/metrics is required which define different aspects of labour productivity relevant to energy efficiency measure. This dissertation defines three indicators of productivity namely: change in active days, workforce performance improvement and improved earning ability.

4.3.2.1 Change in active days:

Active days can be affected by being sick. In other words, sick days result in reduction in active days. Sick day is a linear combination of absenteeism (absent from work due to BRI) and presenteeism where presenteeism can be defined as working with illness or working despite being ill (Caverley, Cunningham, and MacGregor 2007; Mattke et al. 2007). For instance, a person might work slower than usual with respiratory diseases or make mistakes in work while suffering from the symptoms of his illness. In this dissertation, both absenteeism and presenteeism refer to the loss of productivity resulting from indoor exposure-related health problems such as asthma, cardiovascular diseases and mental well-being. These diseases affect both quantity and quality of work (Paul 2004). Both absenteeism and presenteeism estimate the morbidity of working population i.e. number of days of suffering from building-related illness (BRI) by the working population. However, many of the BRI affect mortality of the whole population. Mortality cannot be measured through sick days. Thus, the DALY indicator is used to estimate both mortality as well as morbidity along with sick days to provide a complete understanding of the severity of indoor exposure to the pollutants. The time saved from road congestion is calculated to measure the effects related to modal shift towards active transportation. In the following section each of these aspects of active days are described:

4.3.2.1.1 Avoided sick days

Absenteeism

Absenteeism due to illness is a rising concern for both the employees and as well as the employers. Many work days get wasted due to BRI (Fisk, and Rosenfeld 1997; Jones 1999; Arnetz et al. 2003). Most of the studies (see (Fisk 2002; Chapman, et al. 2009) etc.) estimated the cost of indoor exposure by measuring the absenteeism and health care expenditure but among these two, only absenteeism indicates productivity loss. The intensity of absenteeism due to BRI could be huge. For instance, the study by Fisk 2000 estimated that the cost of annual lost days due to sick building syndrome in the US would be as high as $34 billion (Fisk 2000).

Absenteeism days have been used as an indicator for many other types of research as well such as to evaluate health promotion programs, to evaluate vaccination programs etc. (Golaszewski, et al. 1992; Milton et al. 2000). In this study, absenteeism gain is used as an indicator of productivity gain from energy efficiency measures. As it is discussed in the previous section, one of the key reason behind this poor indoor air quality is inadequate air exchange rate inside the building and lack of filtration system (Asikainen et al. 2016). Installing an efficient HVAC system with filtration in an air tight building can reduce up to 58% of global burden of disease at EU-26 level (Hänninen and Asikainen 2013). Studies suggest that proper ventilation rate i.e. more than 12 L/s per person can reduce sick days by 1.2-1.9 days per person per year (Milton et al. 2000; Mudarri, and Fisk 2007). Thus, this reduction of sick days of 1.2 to 1.9 days per person per year can be considered as productivity gain per person per year due to the energy efficiency action.

There could be other factors as well for absenteeism days apart from indoor air quality, such as factors like job demand, shift work, work environment etc. are found to be correlated with absenteeism days (Aguirre, and Foret 1994; Milton et al. 2000). In this dissertation, I would estimate absenteeism only due to indoor exposure.

Presenteeism

As discussed in the beginning of section 4.2.2, presenteeism can be defined as working through illness (Dew, Keefe, and Small 2005). The loss of productivity through presenteeism is not small compare to absenteeism. For instance, according to a report by the Institute for Employment (2016), in Europe the average days of presenteeism are 3.1 per person per year (Garrow 2016). Lamb et al 2006 estimated the productivity loss of 3.2 hours due to presenteeism in an 8 hours work day. Chang et al. 2016 study estimated that prevention of outdoor pollutant infiltration can save $19.5 billion in labour cost by avoiding presenteeism in a packing company in the USA. Diseases such as allergic rhinitis or common cold have found to be associated with presenteeism and these diseases can be caused due to poor indoor air quality (Beer 2014). However, presenteeism can be resulted due to other diseases as well. In addition to the disease induced presenteeism, presenteeism due to illness may increase the risk of having an ill health because inadequate recuperation may lead to further acute health problems (McEwen 1998).

Similar to absenteeism, there could be several other factors such as unemployment in the country, personal factors (family issues, physical disability etc.), job security, nature of the job, along with illness affecting an employee's presenteeism but in this study only estimate presenteeism due to BRI (Aronsson, and Gustafsson 2005; Hafner et al. 2015).

4.3.2.1.2 Disability adjusted life years (DALY) gain

Absenteeism and presenteeism indicators both measure morbidity of the working population. These indicators mostly measure acute diseases whereas there are many chronic diseases caused by poor indoor environment. For instance, 23% of lung cancer is caused due to indoor exposure to pollutants (Hänninen and Asikainen 2013). Due to lack of absenteeism and presenteeism data for this particular disease, the number of active days gain/loss cannot be measured. In addition to this data unavailability, diseases such as lung cancer and cardiovascular disease caused by indoor exposure have an impact on the human life span i.e. these diseases do not only affect working days but also affect life expectancy. Absenteeism and presenteeism can only be measured for the working population. This implies the necessity for another indicator to be able to measure not only the acute diseases, but also chronic diseases as well for the whole population exposed to the indoor exposures because, the indoor exposure to pollutants affects the nonworking population in the same extent if not more. For example, people such as senior citizens or even children whose immunity level is lower compare to the young population, the effect of indoor exposure would be at least same if not higher. By definition, productivity is measured only for people who are in the labour force but, as discussed earlier section 3.2.3, the health risks from indoor exposure to pollutants would affect the social productivity for the non-working population. Thus, this dissertation includes disability adjusted life years (DALY) to measure the health impact for the whole population.

DALY was first proposed in 1990 in the global burden of disease study to measure the overall disease burden in different countries (Murray, et al. 2013). DALY calculates both mortality and morbidity of the entire population. To be precise, DALY measures premature mortality and disability for people who are living in health states less than the ideal health (WHO 2017). Mathematically it can be expressed as

$$DALY = YLL + YLD$$

YLL=Years of life lost due to premature mortality
YLD=Years of life lost due to disability

where YLL represents years of life lost due to premature mortality and YLD represents years of life lost due to disability. YLL can be expressed mathematically as

$$YLL = N \times L$$

N= Number of deaths
L=Standard life expectancy at age of death in years.

The mathematical equation of YLD can be written as

$$YLD = P \times DW$$

P=Number of prevalent cases
DW=disability weight expectancy at age of death in years.

where P is the number of prevalent cases and DW is disability weight (WHO 2017). The disability weight reflects the severity of a disease on a scale from 0 (perfect health) to 1(equivalent to death).

4.3.2.1.3 Time saved from road congestion/active time

Most of the countries in Europe have experienced a substantial increase in car ownership and as a consequence to this, road congestion has been increasing. Thus, policy makers are exploring options to reduce road congestion, with modal shift towards non-motorized transport as one option. Studies (see (Dixon, 1996; Litman, and Colman, 2001; Bovy and Salomon, 2002;Sælensminde, 2004;Davis, 2010) show that the modal shift towards active transportation such as walking, cycling and public transport have the potential to reduce road congestion during peak hours.

The time spent in traffic can result in work time loss which affects productivity. But active modes of transportation do not only reduce traffic congestion but also have other important benefits related to health and safety. Several studies have shown that greater use of motor vehicles may have negative health impact due to road accident, exposure to air pollution and physical inactivity (see (Elvik 2009; Fuller et al. 2013; Strauss et al. 2014). Physical inactivity is one of the key risk factors for global mortality because it may cause several diseases such as cardiovascular disease, obesity etc (WHO 2010). Walking and cycling would increase the physical metabolism of a person by reducing the risk of diseases such as obesity and cardiovascular disease. Exposure to outdoor air polution emitted from cars, and physical inactivity can result in both absenteeism and presenteeism days (Trubka et al. 2010). In this study, the modal shift towards active transportation related impacts are analyzed from three standpoints:

1. Modal shift towards active transportation can reduce road congestion for the existing drivers during peak hours. In other words, travel time can be saved which is often

claimed as the greatest benefit of transport projects and saved travel time may result in enhanced earning opportunity (Litman 2015).

2. Individuals who are opting for the modal shift would gain health related benefits by being physically active. Also, there could be some negative health effects for the active transporter due to excess exposure of the outdoor pollutants.
3. Society as a whole would have less air and noise pollution after the modal shift.

The health impacts of active transporation can be measured through absenteeism, presenteeism and DALY, but for the congestion-related time saving, we need a separate equation.

This study also acknowledges the fact that a person can spend their saved travel time from traffic by not working but being socially productive, for instance, taking care of family and friends and/or being involved in other socially productive activities.

4.3.2.2 Workforce performance improvement:

Workforce performance can be defined as labour input by the entire workforce by per unit of time and workforce can be defined as an total working population at the workplace. We estimate the workforce performance gain mainly through the quantity of labour input but poor indoor air quality can also affect the quality of work (Wargocki, et al. 2000). Several case studies (such as (Seppänen et al. 1999; Wargocki et al. 2000; Singh 2005) show how indoor air quality and thermal comfort can influence a person’s performance. By working in deep retrofitted buildings, employees have a better work performance compared to working in non-retrofitted buildings (Wargocki, et al. 2000;Singh 2005;Singh et al 2010). This improvement in performance does not only benefit the employees but also the employer by improving the labour input efficiency which maximizes the profit.

There are mainly three reasons behind this improvement in performance which are discussed below:

1. **Reduction in mental disorder:** Improvement in indoor air quality helps reducing mental stress which results in more labour input. Singh et al (2010) show that workers after moving into an energy efficient building gained additional 2.02 work hours annually per person because workers were feeling less mental stress. These additional working hours can certainly be considered as productivity gain per person. One of the possible reason behind feeling less mental stress could be that a worker is constantly exposed to the fresh air which replenishes attention and boosts up the energy to work (Singh et al. 2010; Ryan et al. 2010).
2. **Improvement in mental health conditions:** Thermal comfort helps improving a person's concentration ability which improves the work performance (Wargocki, et al. 2000). Wargocki et al 2000 estimated 1.7% improvement in productivity (mainly quality of work) after controlling the room temperature within 21-25˚C. In deep retrofit type buildings, an adequate temperature is always maintained throughout the day with the help of mechanical ventilation systems, airtight envelope and temperature control system (Eskom 2015).
3. **Better concentration ability:** As discussed in chapter 3, concentration ability may be hindered by certain symptoms such as eye irritation (eye tears and eye blinking), skin irritation and thus affects the work performance (Mølhave, Bach, and Pedersen 1986). Mould and fungi growth can be stopped by improving the building shell and by implementing stringent air filtration (Singh 2005). In the deep retrofit type buildings with HVAC system, constant fresh air intake is ensured which prevents further mould and fungi growth and during building shell improvement the existing moulds are being removed as a part of the retrofitting process (Bonetta, et al. 2010).

These three factors are related to mental well-being or better concentration ability. Improvement in any of these three factors would enhance the work performance.

4.3.2.3 *Earning ability*

Earning ability consists of two aspects, future income earning ability and present earning opportunity. The future income ability may be affected by the lack of education (Caroli, Greenan, and Guellec 2001). Number of years of schooling determines the type of jobs in the future and thus, if a child misses school days due to illness then it would impact his/her future earning ability (Acemoglu, 1996). In fact, as discussed earlier in chapter 3, that excessive absence from school may disrupt a child's learning process and could be one of the causes for dropping out from school eventually. It is seen that children who have asthma, are more absent from school compared to their healthy classmates (Moonie et al. 2006). Studies (see (Garrett et al. 1999; Kolarik, et al. 2008) show that children who are exposed to air pollutants, are prone to have several respiratory diseases and allergies. Thus, it is safe to claim that the children living in poor building conditions would have more respiratory diseases and allergies compared to other children living in good building conditions.

The caring need for sick children at home also affects the present earning ability of the parents, taking days off from work. Even, if the parents go to work despite their child being sick then there could be a chance of presenteeism i.e. productivity loss despite being present at work due to anxiousness about their sick child. Lamb et al 2006 estimated that employees, who cared for their ill child, were absent for 3.68 days/year and were unproductive for 3.55 hours in an 8 hours work day.

To summarize, this indicator of productivity is mainly concerned with two issues:

1. Impact on future earning ability due to loss of school days because of building related disease.
2. Parents absenteeism due to taking care of their sick child and presenteeism due to mental anxiety. As discussed above, mental anxiety here only accounts anxiety due to thinking about sickness of the child.

Presenteeism and absenteeism are measured in active days but the active days measure presenteeism and absenteeism due to own illness. The earning ability indicator measures these two due to taking care of their sick child. Also, similar to other indicators in this study, the earning ability would be measured only due to building-related illness.

4.3.3 Impact pathway maps discussing the productivity indicators:

Previously in section 4.3.1, impact pathway maps (refer to figure 7 and 8) describe the linkages between energy efficiency measure and productivity. Both of the impact pathway maps show how energy efficiency measures stimulate productivity but in order to measure productivity, we need to understand how the energy efficiency measures stimulate different aspects of productivity. By knowing that, it would be easier to determine the productivity measure. Since different indicators of productivity have already been discussed in the previous section, we can now redraw the impact pathway maps specifying different productivity indicators.

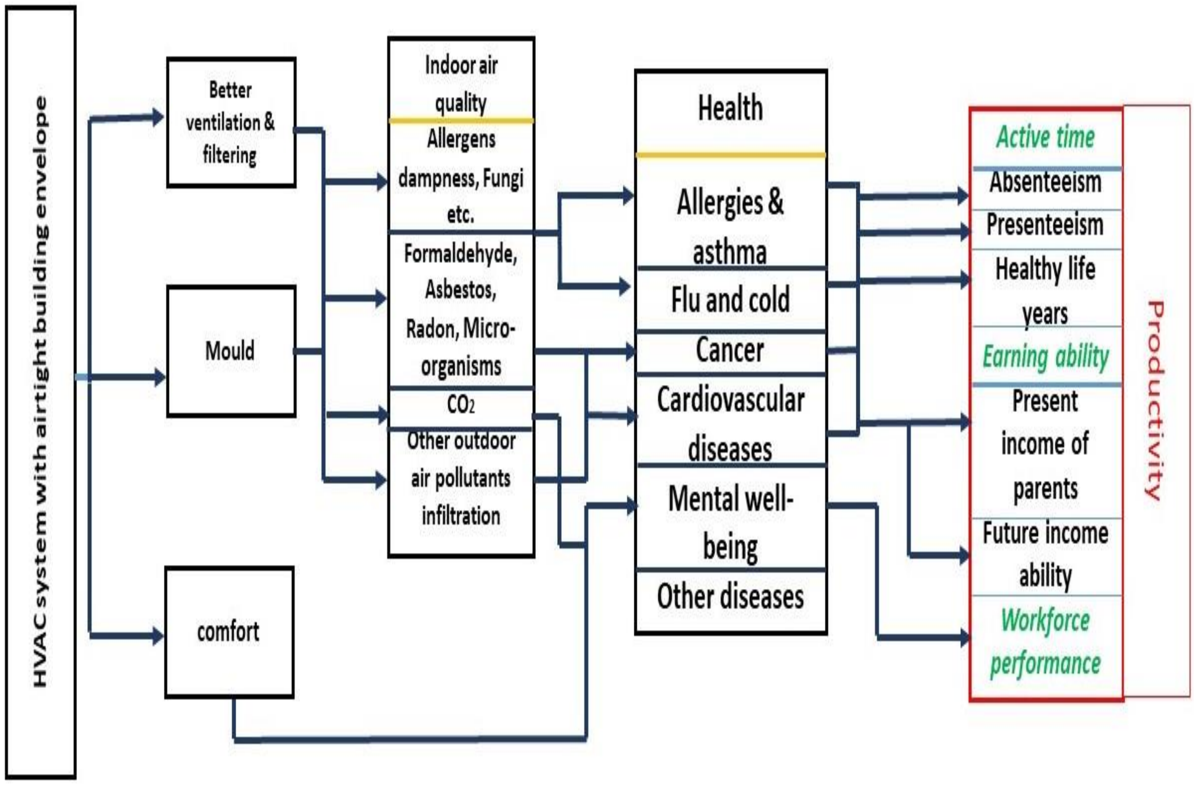


Figure 9: Impact pathway map of HVAC energy efficiency measure in building sector specifying productivity indicator

Source: (Chatterjee & Urge-Vorstaz 2018)

Similar to figure 7, figure 9 shows how energy efficiency measure leads towards different aspect of productivity. For instance, after HVAC system installation with proper building shell, there are three primary consequences such as better ventilation, mould reduction and comfort level enhancement. These three impacts have further consequences on indoor air quality. It means that the indoor air quality improves and the improved indoor air transfers into health impact. This improved indoor air quality reduces allergy and respiratory related diseases. This health impacts ultimately lead to productivity impact by gaining more active work days, higher work performance and earning ability by avoiding building related disease and also by having a better building condition.

Similarly, for modal shift towards active transportation measure, an impact map can be redone specifying the productivity indicators.

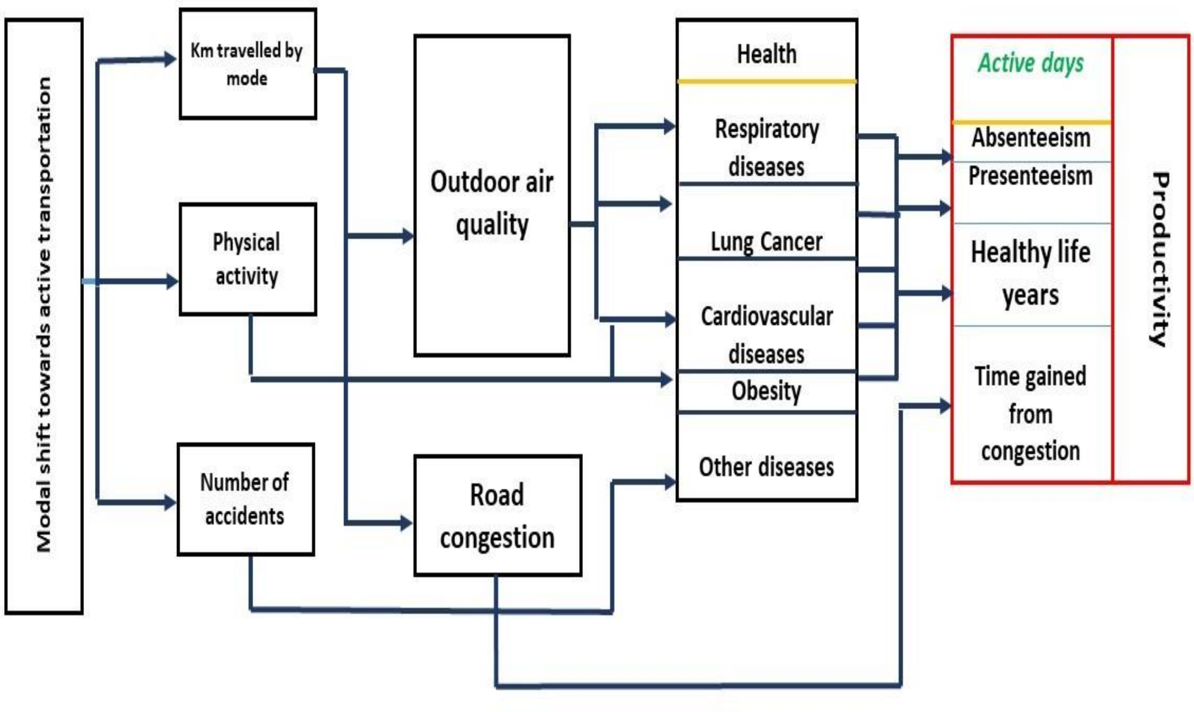


Figure 10: Impact pathway map of modal shift towards active transportation specifying productivity indicator

Source: (Chatterjee & Urge-Vorstaz 2018)

Similar to figure 8, figure 10 decomposes the chain of effects for transport sector energy efficiency measure leading towards different aspect of productivity. After opting for modal shift, the primary consequences are fewer kilometers traveled by transportation mode, being more physically active, and fewer number of accidents. These effects further translate into other effects such as less outdoor pollution and less road congestion. These effects then result in productivity gain by gaining more active days and more active time. Active days result of having less outdoor exposure and active time is a result of having less road congestion.

4.3.3.1 Strengths of systematic identification:

Figure 11 and 12 depict a systematic causal relation of productivity starting from implementing an energy efficiency measure. The rationale behind using impact pathway approach is to clearly understand the interactions among impacts. Urge-Vorstaz et al 2016 paper analyses impact pathway approach and as per the authors, impact pathway methodology framework enables "a) a systematic accounting for the various multiple impacts and thus it reduces the risk of excluding any impacts, b) a systematic and precise calculation of the multiple impacts through the identification of the detailed steps and distinct effects; (c) the minimization of over- and undercounting". These three key advantages analyzed in Urge-Vorstaz et al 2016 paper have further implications from estimation of impact perspective. For instance, 'systematic accounting' also helps us to understand the causal relationship between the impacts and it gives an idea on what portion of impact should be considered during the impact evaluation. For example, if someone wants to see the effects of energy efficiency measures from macroeconomic perspective then one needs to consider only the effects of productivity improvement on public budget via disposable income (refer to figure 7 and 8) and calculate the effect of import dependency reduction due to energy savings from energy efficiency measure.

Each arrow of impact pathway map indicates a distinct effect of impact which also somehow clarifies the valuation methodology (Ürge-Vorsatz, et al. 2016). For example, the arrow from congestion to active time loss represents opportunity to work loss which requires a separate valuation methodology (refer to figure 12). Furthermore, this systematic approach gives a detailed view of impacts by disaggregating the impacts and their interactions. For instance, air quality is disaggregated into several air pollutants that actually cause several diseases. Different air pollutants causes different diseases and affect productivity. For example, air pollutants like allergens and fungi cause diseases, such as asthma, cold and flu, allergy and air pollutants like radon and formaldehyde cause diseases like lung and liver cancer. These micro interactions are systematically illustrated through impact maps which help us to understand the diverse effects of the energy efficiency measures.

To summarize, the following benefits can be obtained by using impact pathway approach:

1. Impact pathway method enables a more systematic accounting and thus it reduces the risk of not accounting any impacts/sub-impacts.
2. This method identifies the detailed steps and distinct effects of the impacts which help to have a precise calculation.
3. Systematic accounting and detailed identification of impacts reduce the risk of over or under estimation of the impacts. For instance, increase in comfort level improves mental well-being which improves the workforce productivity. But, increase in comfort level has no interacting with active days or earning ability. Thus, the effects of comfort level can only be measured through the workforce performance indicator.

4.3.4 Functional formulation of productivity indicators

As discussed in chapter 2, the productivity of energy efficiency measures results in wellbeing/welfare enhancement. Most of the productivity indicators studied here are enhancing well-being by improving health condition and well-being often refer to overall standard of living in financial and material ways (Liberty Fund 2012). Cross-national studies show that "more encompassing welfare states, aiming for more social and gender equality, almost always perform better across a range of well-being measures" (Heins, and Deeming 2015).

As discussed in section 2.1.6, this dissertation postulates a two layer framework where national well-being is explained by individual subjective well-being with respect to more work time opportunity through improvement in health and less time spent in road congestion. Healthy life implies more productive years and hence, healthy life also indicates enhanced earning opportunity (Van Praag, Frijters, and Ferrer-i-Carbonell 2003). By following similar logic, the three basic indicators of productivity impact of this study namely active days, workforce performance and earning ability are mostly related to human health. Health improvement has positive effect on economic well-being because health reflects the constituent of well-being (Dasgupta and & Weale 1992). Alternatively, active time loss from road congestion has a direct impact on economic well-being since active time loss implies loss of working opportunity which further implies loss of economic well-being. However, time saved from congestion would not be considered within the health economics framework. Time saved from congestion basically follows the time allocation principle of economics. In the time allocation principle, utility maximization is subject to time constraint which implies that time is given or constant and utility can be maximized subject to time.

As discussed in chapter three, there are four key indicators of productivity studied in this research i.e. active days, workforce performance, earning ability and active time. For each of these indicators the theoretical framework is discussed below:

Functional formulation of change in active days:

As discussed, the number of avoided active days lost is a linear combination of days with avoided absenteeism and days with avoided presenteeism. Both absenteeism and presenteeism have a positive correlation with indoor exposure. Indoor air quality deteriorates not only due to the presence of indoor air pollutants but, also when outdoor air pollutants contaminate indoor air (Jones 1999; Fisk 2000). Outdoor air pollutants (such as, PM2.5, pollen and VOC) infiltrate in the indoor atmosphere mainly through the building envelope leakages and through ventilation (Hänninen and Asikainen 2013). This dual presence of indoor and outdoor pollutants can cause several diseases such as asthma, cold, flu, cardiovascular disease and cancer (Jones 1999; Fisk 2000; Hänninen and Asikainen 2013).

Thus, Absenteeism (similarly for Presenteeism Pr so not shown separately) Ab can be expressed as a function of indoor air pollutant (P1), outdoor air pollutants (P2) i.e.

$$Ab = Ab\,(P1, P2) \qquad \text{Equation 1}$$

Indoor air pollutant concentration depends mainly on the air circulation rate. Air circulation is basically determined by the ventilation rate (Hänninen and Asikainen 2013). In other words, if air circulation rate increases then indoor pollutant concentration decreases. Thus, indoor air pollutant can be expressed as a function of rate of ventilation i.e.

$$P1 = P1\,(V) \qquad \text{Equation 2}$$

where, V is the rate of ventilation and $\Delta P1/\Delta V<0$, which implies that if the rate of ventilation rises then indoor air pollutant concentration would fall and vice versa.

Alternatively, outdoor air pollutant concentration in indoor environment mainly depends on the building filtration system (Asikainen, et al. 2012; Hänninen and Asikainen 2013). Outdoor pollutants infiltrate indoor through cracks and ventilation. Thus, outdoor air pollutant infiltration can be expressed as a function of building filtration installation i.e.

$$P2 = P2(F) \qquad \text{Equation 3}$$

where, F represent filter installation and$\Delta P2/\Delta F<0$, which means that if there is filter installed in a building then outdoor air concentration in indoor environment would decrease.

On the contrary, both ventilation and filtration installing may have negative health effects if the buildings are not completely airtight. For complete airtightness certain level of building envelope criteria needs to be maintained. Thus, airtightness is mandatory before installing HVAC system in order to gain health benefits. The country specific technical details of airtight building envelope are discussed in chapter 5.

Similar to absenteeism, both presenteeism and healthy life years of life loss are also a function of P1 and P2 because of the same logic discussed above.

Therefore, given the definition of active days (AD), we can write

$$AD = AD\,(P1\,(V), P2(F)\,) \qquad \text{Equation 4}$$

i.e. active days loss depends on the rate of ventilation and filtration system of a building.

Also, $\Delta AD/\Delta V<0$, $\Delta AD/\Delta F<0$ which implies that an increase in the rate of ventilation and installation of filtration system, active days loss would decrease and vice versa. In order to estimate the value of an active day impact due to change in ventilation rate and filtration installation, the values of $\Delta AD/\Delta V$ and $\Delta AD/\Delta F$ need to be known. These figures would show how much health gain and hence productivity gain can be achieved by installing ventilation and filtration with deep building retrofitting. Deep renovation is required in order to not only to save energy but also to remove the existing mould which cannot be removed by ventilation or filtration. Furthermore, deep renovation ensures complete airtightness which prevents infiltration of outdoor air pollutants. Therefore, along with installation of improved HVAC system and filtration system, deep renovation/retrofit of the building is required in order to minimize the adverse health impacts and hence productivity impact due BRI.

Ideally, it is important to know the functional form for equations (1, 2 and 4) and also information on 1) change in ventilation and filtration of buildings, 2).P1, 3).P2 , 4) disease specific AD (i.e. presenteeism and absenteeism data) to carry out a regression analysis to derive ΔAD/ΔV and ΔAD/ΔF. Since functional forms need more physical measurement data this remains outside the purview of this study. Thus, instead, the value of ΔAD/ΔV can be found from literature. These disease specific values found in literature are mostly in DALY form i.e. after installing of ventilation and filtration how many healthy life years can be saved. As discussed in chapter 3, DALY measures years of healthy life years loss due to disability which is basically a health impact measure (Murray and Acharya 1997). Thus, in this dissertation the values of equation 1, 2 and 3 are taken from Hanninen et al study (2013) as a proxy figure which estimate change in DALY due to change in ventilation and filtration.

Functional formulation of workforce performance:

Studies have shown that the workforce performance have improved at a significant rate in an energy efficient workplace compare to a non-energy efficient/non-retrofit commercial building and the key reasons for this improvement in performance are thermal comfort and ventilation rate (Wargocki et al. 2000; Singh 2005). Workforce performance does not only depend on health condition but it also depends on thermal comfort and ventilation rate. Thus, it can be functionally expressed as

$WKP = WKP\ (TC, V)$ *Equation 5*

Also, $\frac{\Delta WKP}{\Delta TC} > 0, \frac{\Delta WKP}{\Delta V} > 0,$ which implies if thermal comfort and ventilation rate increases then workforce performance would also increase and vice versa. These factors have a joint effect on workforce performance. These rates of change in performance due to change in thermal comfort and ventilation rate show how much performance gain and hence productivity gain can be achieved by commercial building retrofitting. The thermal comfort level maximizes with the temperature from 21 to 25 degree, temperature more than 25 degree may reduce the performance level (Wargocki, et al. 1999). Hence, mathematically $\frac{\Delta WKP}{\Delta TC} > 0$ up to 25 degree C. For temperature above 25 degree C this equation does not hold true.

Functional formulation of earning ability:

As discussed in chapter two, earning ability refers to the future earning ability of the children and present earning ability of the parent of the sick child. Studies show that the children who have asthma, are more absent from school compared to their healthy (with no asthma) classmates and more absenteeism in school may have an impact on future earning ability (Bloom, Canning, and Sevilla 2001; Moonie et al. 2006).

Thus, similar to active days loss earning ability depends on indoor and outdoor air pollutants. Therefore, functionally we can express this dependence as;

$EA_F = EA_F(SCH)$ *and* $EA_P = EA_P\ (SCH)$ *Equation 6*

where EA_F and EA_P represent earning ability in future and earning ability in present respectively. SCH denotes the number of school days loss. EA_F should be measured for the children's future earning ability whereas EA_P should be measured for the parent's present earning ability due to child care.

Also, $\Delta EA_F/\Delta SCH < 0$, $\Delta EA_P/\Delta SCH < 0$ which implies that a decrease in number of missing school days, both future and present earning ability would increase and vice versa. Here, the number of school days missed is related to the rate of ventilation and filtration.

In order to estimate the value of earning ability impact due to change in number of school days, the values of $\Delta EA_F/\Delta SCH$ and $\Delta EA_P/\Delta SCH$ need to be known. These figures would show how much health gain can be achieved for children by building retrofitting.

Functional formulation of time saved from congestion:

Studies show that traffic congestion affects working time which ultimately impacts on a person's productive time (Brownstone et al. 2003; Tavasszy, and Meijeren 2011). This dissertation also acknowledges the fact that a person can spend their saved travel time by not working.

In this dissertation, only modal shift towards active transportation is considered an energy efficiency measure in the transport sector. Modal shift towards active transportation results in less road congestion and by avoiding road congestion, travel time can be saved which is often claimed as the greatest benefit of transport projects (Litman 2015). The other aspect of active transportation is health improvement.

Therefore, active time loss (ATL) can be expressed functionally as

ATL = ATL (TSC) Equation 7

where $\frac{\Delta ATL}{\Delta TSC} > 0$ which implies less time spent in congestion results in less active time loss and vice versa. In addition, active transportation results in physical activity which improves the health condition. Here, TSC represents total time spent in congestion. The modal shift towards active transportation also improves the health condition by being physically active and hence by reducing the risk of obesity and cardiovascular diseases.

Thus to summarise, each of the functional form of the indicators explains the key influencing factors and the basic data needed for each indicator. This functional form can thus, be further developed into concrete equations in order to quantify the effect on productivity due to implementing improved energy efficiency measures. The functional form of indicators provide a fair understanding of the basis of the productivity indicators and hence, it provides the basis of the equations of the indicators. In the following section, equations of each of the productivity aspects are discussed.

4.3.5 Equations for impact quantification

Exposure to indoor air pollutants can cause several building-related diseases such as asthma, cold and flu, cancer, cardiovascular diseases and these diseases affect productivity. To quantify the productivity indicators due to these building-related diseases and the modal shift, we need to understand the interactions between productivity indicators and all other impacts as per the impact pathway maps. Each arrow in the impact pathway maps represent a distinct effect and thus a distinct calculation. Therefore, for each of these arrows towards productivity indicators, we would need a distinct method/equation to quantify them.

In order to compare the magnitudes of outcomes, a common metric such as monetization is required. Monetization is a popular way of converting different units into a uniform unit i.e. money. However, monetization is criticised conceptually on many grounds such as valuing different impacts which are considered as 'priceless' or the monetary values are dependent on monetization techniques (Luck, et al., 2012). In addition, for many impacts, such as health and ecosystem, controversial methodologies for monetization are applied. Many decisions are made based on the trade-off between non-market benefits, such as health, eco-system against other benefits or costs (Stiglitz, Sen, and Fitoussi, 2009; Ürge-Vorsatz et al. 2016). Thus, to mitigate the concerns and uncertainties regarding monetization of impacts, this study presents the physical values as well as the monetized values for all the indicators.

As discussed in section 4.3.2, the three key aspects of labour productivity measure are: active days, workforce performance and earning ability. These three indicators are sector specific and also energy efficiency action specific which means not all the impacts can be calculated for all the sectors. Thus, table 14 below shows the productivity indicators with their relevant sectors:

Table 14: Productivity indicators and their relevant sectors

Productivity indicators	Sector
Active days gain	Residential building, tertiary building, Transport sector
Workforce performance gains	Tertiary buildings,
Earning ability	Residential buildings, tertiary building (mainly schools)

Source: Own elaboration

As discussed earlier, all of these three indicators intend to measure productivity but these indicators are measuring different aspects of productivity. The method to quantify each of these components of productivity is defined below.

4.3.5.1 Equations to measure change in active day

Active days consist of the four following indicators:

1. Absenteeism
2. Presenteeism
3. DALY
4. Time saved from road congestion/Active time

Among the above-mentioned four indicators, absenteeism and presenteeism measure the acute disease-related immediate effects. Sick days can be mathematically expressed as

SD= Ab+Pr, where SD implies sick days, Ab is absenteeism and Pr is presenteeism.

Mathematically avoided absenteeism (Ab) can be expressed as

$$\sum_{V=1}^{4}\sum_{i=0}^{p} Ab_{Xv}^{ri} = \sum_{v=0}^{4}\sum_{i=0}^{p}\{(AVS \times ri) \times X_v\} \text{ ....Equation 8}$$

i determines type of retrofits
v determines type of disease
ri= working population lives in type i residential buildings
AVS= Average sick leave taken per person in a year due to illness
X_v= Percentage of sick leave taken due to disease v in a year

where i determines types of retrofitting and v determines types of diseases.

Here, *ri* represents working population who live in type *i* residential buildings. For example, r_0 is the working population living in non-retrofitted buildings, r_1 is the population living in low retrofitted buildings, r_2 is the population living in medium retrofitted buildings ,r_3 is the population living in deep retrofitted buildings, r_4 is the population living in new nearly zero energy buildings and r_p is the population living in passive houses . X_v is the percentage of sick leave taken due to disease v in a year. Here the value of v determines types of diseases. For example, X_0 represents asthma, X_1 represents cold and flu, X_2 represents cardiovascular disease, X_3 represents allergy disease and X_4 represents cancer. *AVS* shows average sick leave taken per person in a year due to illness.

Similarly, avoided absenteeism can be calculated for tertiary buildings i.e.

$$\sum_{v=1}^{4} \sum_{i=0}^{p} \boldsymbol{Ab}_{Xv}^{ti} = \sum_{v=1}^{4} \sum_{i=0}^{p} \{(\boldsymbol{AVS} \times \boldsymbol{t_i}) \times \boldsymbol{X_v}\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 9}$$

Ab=Absenteeism days
AVS= Average sick leave taken per person in a year due to illness
t_i = population working in type i tertiary buildings
Xv= Percentage of sick leave taken due to disease v in a year

where t_i represents population working in type i tertiary buildings.

Avoided presenteeism (Pr) can be expressed mathematically as

$$\sum_{v=0}^{4} \sum_{i=0}^{p} \boldsymbol{Pr}_{Xv}^{ri} = \sum_{v=0}^{4} \sum_{i=0}^{p} \{(\boldsymbol{AVP} \times \boldsymbol{ri}) \times \boldsymbol{P_v} \times \mu_v\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 10}$$

Pr= Presenteeism days
AVP= Average number of presenteeism days taken per person per year
μ_v= Value productivity loss at work due to specific diseases
Pv=Percentage of presenteeism days due to v type of disease in a year

Here, *AVP* represents the average number of presenteeism days taken per person per year and μ_v represents the value productivity loss at work due to specific diseases. Again, *v* determines types of diseases and P_v is the percentage of presenteeism days due to *v* type of disease in a year. For instance, μ_0 represents productivity loss due to asthma, μ_1 represents cold and flu, μ_2 represents cardiovascular disease, μ_3 represents allergy and μ_4 represents cancer.

In order to calculate sick days due to different building related diseases, we need to know total sick days taken due to different diseases. For example, if we want to know sick days due to asthma in a country, we need to know total sick leaves taken from work due to asthma and total days present at work with asthma in a country. However, the data on total sick leaves due to specific diseases are not readily available. Therefore, we have to calculate total sick leaves taken for different diseases per country by using the absenteeism and presenteeism equations.

Using the equations below, total avoided sick days taken per country per year can be calculated.

$$\sum_{v=0}^{4}\sum_{i=0}^{p} \boldsymbol{AD_{Xv}^{riti}} = \sum_{v=1}^{4}\sum_{i=0}^{p}[\{\boldsymbol{SD_{Xv}^{riti}} \times (\boldsymbol{1} - \boldsymbol{CF_{vi}})\} \times \boldsymbol{TSF_t}] \quad \text{..............} \quad \textit{Equation 11}$$

$\boldsymbol{AD_{Xv}^{riti}}$=Active days loss due to building related-illness per year of working adult population of each type of retrofitted buildings.
SD_{Xv}^{riti}= Sick days taken due to illness per year of the working adult population
CF_{vi}= Diseases specific conversion factor shows how much health gain/loss can be achieved from each retrofit types of buildings
TSF_t= Time spent factor in tertiary buildings

where *i* determines the type of retrofitting and *v* determines the types of diseases. Here, *r* represents residential building sector and *t* represents tertiary building sector. $\boldsymbol{AD_{Xv}^{riti}}$ represents active days loss due to building related-illness per year of working adult population of each type of retrofitted buildings.

SD_{Xv}^{riti} represents sick days taken due to illness per year of the working adult population. For instance, r_0 is the working population living in non-retrofitted buildings, r_1 is the population living in low retrofitted buildings, r_2 is the population living in medium retrofitted buildings ,r_3 is the population living in deep retrofitted buildings and r_p is the population living in passive houses. Similarly, t_0 is the population working in non-retrofitted buildings and so on.

Conversion factor shows how much health gain/loss can be achieved from each retrofit types of buildings for different building-related diseases. For a few retrofit types such as for zero, low, light and medium retrofitted type of buildings, the overall health impact can be even negative i.e. loss of health since these type of retrofitted buildings do not have complete airtightness and mechanical ventilation systems (as per COMBI input data assumptions). Initially, these type of buildings may provide some sort of thermal comfort and health benefits (as suggested in Chapman et al 2009 study) due to higher insulation level compare to its previous state, but in the long run, the high insulation level can cause mould growth and also increase the radon exposure level due to which the overall health state can get affected. We need evidence to show how much negative impact can be caused by residing or working in these type of buildings. In other words, we need the value of conversion factor for these type of buildings which is not found in any literature. Thus, for these types of buildings, in this study I have assumed that the value of conversion factor would be zero i.e. neither the positive nor the negative health impact is assumed. Alternatively, the deep retrofit type buildings ensure complete airtightness with proper air exchange rate and thus, in these types of buildings, there would be health related benefits. Therefore, for these types of buildings, the value of conversion factor would be positive.

TSF_t is time spent factor i.e. time spent in tertiary buildings. Personal exposure to indoor pollutants is largely determined by the time spent indoor (Schweizer, et al., 2007). On an average, both in the USA and Canada, a person spent 16.1 hours/day at home, though this indoor time varies across location and age-group (Brasche, and Bischof 2005). The Healthvent project only gives us the health gain factor from residential buildings. However, this time spent factor does not only determine the extent of indoor exposure but it also helps estimate the building sector specific health gains. For example, a person may work in a non-retrofitted tertiary building but lives in a retrofitted residential building. In that case, maximum health benefits would not be achieved from retrofitting as the person would still be exposed to poor indoor air quality at their workplace. Therefore, it is crucial to have an exposure time factor in order to calculate residential and tertiary sector specific productivity gain. In this study, TSF is used to provide an estimate of health gain from installing energy efficiency measures in both residential and tertiary sectors. In this study, the value of TSFt is estimated on the assumption that an employed person would spend 8 hours/day at workplace which is 33% time of a day. Thus the value of TSFt would be 33%. Only for cold and flu disease TSFt is assumed to be 50% due to the contagious nature of cold and flu. Since there is no other way to estimate the sector specific effect of productivity of an improved energy efficiency measure, this study has assumed the values of TSF based on rough calculation of average time spent at tertiary building per person.

Therefore, DALY gain in this study can be expressed mathematically as;

$\sum_{v=0}^{4}\sum_{i=0}^{p} \boldsymbol{AD_{Xv}^{ri}} = \sum_{v=1}^{4}\sum_{i=0}^{p}(\boldsymbol{DALY_{Xv}^{ri}} \times (\mathbf{1} - \boldsymbol{CF_v}))]$ .... *Equation 12*

where AD is active days loss due to BRI per year in i type of retrofitted buildings.

CF implies conversion factor.

The value for conversion factor is derived from Hanninen et al 2013 study.

Time saved from congestion and transport-related outdoor pollution induced active days loss:

Mathematically active days can be expressed as:

$$\boldsymbol{AD_C = [(TTL \times Ri) - \{(TTL \times Ri) \times TS\}]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textit{Equation 13}$$

ADc=Active time gain from congestion
TTL= Travel time loss due to traffic congestion per driver in a year
Ri= average number of drivers stuck in traffic congestion during peak hours per year
TS= travel time saved factor due to modal shift towards active transportation

where AD_c defines active days gain by avoiding congestion, TTL represents travel time loss due to traffic congestion per driver in a year and R_i is the average number of drivers stuck in traffic congestion during peak hours per year. TS is the travel time saved factor due to the modal shift towards active transportation. The value of TS is calculated from De Hartog, Boogaard, et al. 2010 study where the rate of modal shift towards active transportation is equal to road congestion reduction rate and from COMBI input data, the rate of modal shift can be calculated. For example, in Hungary the modal shift percentage in the efficient scenario is 4.1% compared to the reference scenario. Thus, the value of TS for Hungary would be 4.1%.

The other part of active days of transport sector come from health gain aspect by being physically active and also by avoiding outdoor pollution. This aspect of active days can be mathematically expressed as:

$$\sum_{v=0}^{4} AD_{Xv}^{c} = \sum_{v=0}^{4} (DALY_{Xv} \times (1 - CF_v)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textit{Equation 14}$$

here AD^c_{Xv} is the gain in active days by avoiding outdoor pollution or being physically active and v is the type of diseases as mentioned in the previous section. The outdoor pollution induced type of diseases are same as indoor pollution induced type of disease. Hence, Xv holds the same meaning like building sector related disease. Conversion factor shows how much health gain can be achieved by opting for modal shift towards active transportation.

Also, the sick days aspect of outdoor air pollution from transport sector can be measured by using the equation below:

$$\sum_{v=0}^{4} AD_{Xv}^{c} = \sum_{v=0}^{4}\{SD_{Xv}^{c} \times (1 - CF_v)\} \quad \text{.................................} \quad \textit{Equation 15}$$

where, AD^{c}_{Xv} is the active days from transport and v is the type of diseases.

The health aspect of modal shift could not be measured in this dissertation due to data and methodological constraints. Further details are discussed in chapter 7.

4.3.5.2 Equation to measure workforce performance:

In this study, workforce performance measures the enhancement of performance due to better work environment and comfort level. This measurement excludes performance loss due to illness, hence the chances of double counting the productivity indicators are minimised. By using the following equation, workforce performance can be measured:

$$\sum_{i=0}^{p} \boldsymbol{WKPti} = \sum_{i=0}^{p}\{\,(\boldsymbol{AVH} \times \boldsymbol{t_i}) + \left((\boldsymbol{AVH} \times \boldsymbol{t_i}) \times \boldsymbol{PI}\right)\} \quad \text{.............................} \quad \textit{Equation 16}$$

WKP_{ti}= Workforce performance in different types of tertiary retrofitted buildings
AVH= Average annual hours actually worked per worker
ti= working population in different types of tertiary retrofitted buildings.
PI= implies productivity improvement per hour in a year due to improvement in mental well-being

Where, WKP_{ti} represents workforce performance in different types of tertiary retrofitted buildings, AVH represents average annual hours actually worked per worker and t_i represents working population in different types of tertiary retrofitted buildings. Similar to AD_{ti} , t_0 is the population working in tertiary non-retrofitted buildingst_1 is the population working in tertiary low retrofitted buildings, t_2 is the population working in medium retrofitted buildings , t_3 is the population working in deep retrofitted buildings, t_4 is the population working in nearly zero energy buildings and t_p is the population working in passive-houses. PI implies productivity improvement per hour in a year due to improvement in mental well-being.

4.3.5.3 Equation to measure earning ability

Children's health related effects due to indoor exposure can be measured through active days indicator specifically through DALY. However, DALY does not measure future earning ability due to indoor exposure related health impacts and absenteeism and presenteeism of a parent due to child's illness. The earning ability indicator estimates these two specific aspects.

Earning ability from loss of school days can be mathematically expressed as:

$$\boldsymbol{EA} = \sum(\boldsymbol{PAI} \times \boldsymbol{SL}) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \quad \textit{Equation 17}$$

where EA implies future earning ability, *PAI* implies present average income of an individual in a year and *SL* is the skill loss factor due to loss of school days. Skill loss mainly occurs by having less education that is obtained by not attending school.

The other aspect of earning ability is loss of work days of parents due to care-giving of their sick child. Mathematically this aspect can be expressed as similar to the active days formulae i.e.

$$\sum_{v=0}^{4}\sum_{i=0}^{p} \boldsymbol{AD}_{Xv}^{riti} = \sum_{v=1}^{4}\sum_{i=0}^{p}[\{\boldsymbol{SCH}_{Xv}^{riti} \times (\mathbf{1} - \boldsymbol{CF}_{vi})\} \times \boldsymbol{TSF}_{t}] \;\ldots\ldots\ldots\ldots \quad \textit{Equation 18}$$

SCH= Sick days taken by the child from school due to illness
CF_{vi}= Value of health gain factor
TSF_i = Time spent factor

Where *SCH* implies sick days taken by the child from school due to illness and *ti* would imply specifically school buildings.

Due to data and methodological issues, earning ability could not be calculated in this dissertation. The further details are discussed in chapter 7.

4.3.6 Scenario analysis- definition of scenarios and its assumptions:

Multiple impacts are better compared across different scenarios than assessment models (Ürge-Vorsatz, et al. 2016). Quantification of impacts in different scenarios can provide useful insights which can be helpful in designing a sustainable energy policy. More precisely, scenario analysis provides a good understanding of the future trends based on present data. However, the objective of scenario analysis is not to predict the future accurately rather to provide a description of future subject to some underlying assumptions related to social and environmental processes (UNEP 2004) . By following similar logic, this dissertation estimates productivity impact with the help of two different scenarios to understand its magnitude. This dissertation takes two scenarios: reference and efficient scenario and both of these scenarios are defined according to the COMBI project. The reference scenario is derived from a baseline scenario which is based on existing EU legislation. In other words, reference scenario assumes the same growth rate and policies in 2030 as it is in 2015. The efficiency scenario is assumed to be consisted of ambitious assumptions on technology implementation following more ambitious policies till 2030. The COMBI efficiency scenario is quite similar to EUCO+33 scenario in EU's energy efficiency directive (COMBI 2018).

The building sector scenarios are defined on a basis of a decomposition approach. There are three factors which have defined these scenarios: activity levels, structural shifts and energy efficiency measure. Activity level refers to the number of buildings for the residential building sector, value added or square meter floor area in the tertiary building sectors and vehiclekilometres for transport sector (COMBI D2.2 report, 2018). Structural determinants are consists of shares of building types (single, multi-family, high-rise) in the residential sector, the activity shares of the different subsectors (offices, health care, education etc.) in the tertiary sector; and the share of private versus public transport (COMBI D2.2 report, 2018). For building sector, the population for the base year for each country are obtained from EUROSTAT and population and number of different type of buildings projection are made based on PRIME reference scenario (COMBI 2.3 Annex report). In COMBI scenarios, a distinction is made in case of new buildings by differentiating current building standards (until 2020), nearly zero buildings NZEBs (from 2020 onwards as per EU rule) and passive houses (Couder 2018). Furthermore, different types of retrofitted buildings are classified as low, medium, and deep. These types of new buildings and retrofitted buildings determine the magnitude of productivity impact hence, different annual share of these types of buildings in reference and efficient scenarios actually determines the magnitude of the impact. In COMBI as well as in this dissertation, annual retrofit rates are assumed to be 2.5% in 2030 in the reference scenario and 3.0% in the efficiency scenario. More building sector-related assumptions are discussed in chapter 5, section 5.3.2.

For transport sector, the scenarios are based on a decomposition analysis which incorporates changes in activity levels, structural shifts and energy efficiency measures (COMBI, D2.3 report, annex). For this study, the most important factor is structural shift (or in other words modal shift) related assumptions. The scenarios distinguish between slow mode of transport such as walking, cycling and also motorised mode such as motorized two-wheelers (moped, motorcycle), cars and public transport. Public transport includes bus or coach, two separate modes of rail transport (light rail and passenger train) (COMBI, D2.3 report, annex). The rate of modal shift is assumed by having different growth levels for different transport modes.

Similar to building sector, more transport sector specific assumptions are discussed in chapter 5, section 5.3.2.

4.4 Summary of the chapter:

The methodological framework of this dissertation has four key components:

- Identification of the chain of impacts (see sections 4.3.1 and 4.3.3) - Identification of impacts resulting from specific improved energy efficiency measures needs to be explicit to not only to have the complete overview but also to understand the causal effects of an impact i.e. whether the impact results in another impact.
- Definition of metrics to quantify productivity impact (see section 4.3.2) - After identification of causal effects leading to productivity impact, each of the metrics needs to be defined accordingly in order to quantify productivity impact rigorously.
- Quantification of productivity impact (see section 4.3.4, 4.3.5, and 4.3.6) - Equations for each of the metrics need to be developed to quantify productivity impact resulting from specific energy efficiency measure. The results of these metrics would be considered in physical unit (non-monetized unit).
- Monetization of impact (see section 4.3.5) - As per the physical value, monetization of each of the metrics would be done.

For each of the components mentioned above a specific method is used in this dissertation. The need for a new methodological framework comes from the lack of a mature methodology to quantify productivity or any other impacts rigorously. In other words, different existing methods need to be studied in order to understand the need of a new methodological framework. Each of the methods has its own limitations. Moreover, the challenges of the impact quantification need to be discussed thoroughly before discussing the modelling needs.

CHAPTER 5: DATA AND ASSUMPTIONS

"It is a capital mistake to theorize before one has data"

Arthur Conan Doyle

5.1 An overview of the data sources:

This chapter discusses the data required for the dissertation methodology and sources of the data. Listing both the data and data requirement provide a more in-depth understanding of the methodology. However, along with the data requirement and data sources, this chapter also provides the methodological and data-related assumptions of this dissertation. This chapter plays a crucial role by providing an in-depth understanding of the methodology which also helps in achieving the research objective.

This dissertation's methodology requires intensive data and most of the time, these data are not easily found. In addition, data requirement of this dissertation is such that no single source can provide the entire data needed for the methodology. Hence, this dissertation has relied mainly on five key data sources. Each of these data sources is discussed below briefly to provide an understanding of the intensive data needs of this dissertation:

COMBI project: As discussed in chapter 1 and 4, COMBI project input data (see project report D2.1, annex: https://combi-project.eu/downloads/project-reports) is a major data source of this dissertation. Mainly three types of data are used from the COMBI project:

1) Scenario description and their assumptions;
2) Country-specific population data in the different scenario- more precisely, number of people living and working in the different type of buildings in two scenarios (reference and efficiency scenario);
3) The number of people using a different mode of transportation in two different scenarios in both of the countries.

The population in two different scenarios and number of different retrofit type buildings are estimated in COMBI based on the PRIME scenario. These types of scenario data are not available in EUROSTAT or any other open sources. PRIME is an EU system model which is widely used for defining scenarios. The more detail parameter specific data sources are discussed in section 5.3.

HealthVent project: This dissertation uses Healthvent project data for mainly one parameter i.e. the health gain value of staying in deep retrofitted buildings. Similar to COMBI, healthvent project is also an EU project under the EU health programme (https://www.rehva.eu/eu-projects/completed-projects/healthvent.html).

Organisation for Economic Co-operation and Development (OECD) data source: This study has relied on OECD data for mainly country-specific sick leave data and actual labour input data. These OECD data sources data are available online (https://data.oecd.org/).

EUROSTAT: This dissertation uses EUROSTAT data mainly for country-specific daily wage data and also to strengthen some of the arguments of this dissertation.

Apart from the above mention sources, this dissertation also uses various scientific literature for some key data points. By intensive review of relevant literature, this dissertation uses many components of the dissertation model from various literature. Parameter specific literature source is discussed in section 5.3. Apart from the methodological framework, the scientific literature is widely cited throughout this dissertation for several purposes for example, to understand the concept of co-benefits, to understand the methodological gap in estimating of co-benefits etc.

5.2 Parameter specific data sources:

As discussed in chapter 4, section 4.3.5, each and every equation has different data requirements and since these data needs vary from one equation to another, it is not possible to have these data from a single source. Thus, it is important to list down these different data sources as per the parameter.

Data sources for absenteeism and presenteeism: In Chapter 4-section 4.3.5.1, the equations for absenteeism and presenteeism are described. In order to calculate absenteeism the following data are required and, the data sources are mentioned with the data points in the table below:

Table 15: Absenteeism data and their sources

Absenteeism data	Data Source
Average sick days taken per person per year per country	OECD,2017 (Database: Absence from work due to illness, URL: http://stats.oecd.org/index.aspx?queryid=30123)
Number of working population who live in non-retrofitted buildings per year per country ($\boldsymbol{r_0}$) and number of workers working in non-retrofitted tertiary buildings (t_0)	COMBI 2018, D2.3 Annex report
Number of working population who live in low retrofitted buildings per year per country ($\boldsymbol{r_1}$) and number of working population who work in low retrofitted buildings per year per country ($\boldsymbol{t_1}$)	COMBI 2018, D2.3 Annex report
Number of working population who live in medium retrofitted buildings per year per country ($\boldsymbol{r_2}$) and number of working population who work in medium retrofitted buildings per year per country ($\boldsymbol{t_2}$)	COMBI 2018, D2.3 Annex report
Number of working population who live in deep retrofitted buildings per year per country ($\boldsymbol{r_3}$) and number of working population who work in deep retrofitted buildings per year per country ($\boldsymbol{t_3}$)	COMBI 2018, D2.3 Annex report
Number of working population who live in new nearly zero energy buildings per year per country ($\boldsymbol{r_4}$) and number of working population who work in new nearly zero energy buildings per year per country ($\boldsymbol{t_4}$)	COMBI 2018, D2.3 Annex report
Number of working population who live in	COMBI 2018, D2.3 Annex report

Absenteeism data	Data Source
passive houses per year per country ($\boldsymbol{r_p}$) and number of working population who work in passive houses per year per country ($\boldsymbol{t_p}$)	
Percentage of sick leave taken due to asthma among total sick leave taken by working population per year	(Alexopoulos, and Burdorf 2001) –It is a Europe based study with sample size of around 400 workers (both blue and white collar workers)
Percentage of sick leave taken due to cold and flu among total sick leave taken by working population per year	(Alexopoulos, and Burdorf 2001)
Percentage of sick leave taken due to allergies among total sick leave taken by working population per year	(Lamb et al. 2006)- It is a US based study with the sample size of 8267 employees to calculate the economies losses due to presenteeism and absenteeism.
Percentage of sick leave taken due to cardiovascular disease among total sick leave taken by working population per year	(Price 2004)- This study has reviewed literature on the effects of heart diseases on working population.

Similarly, in order to calculate presenteeism the following data are required and also the data sources are mentioned with the data points in the table below:

Table 16: Presenteeism data and their sources

Presenteeism data	Data Source
Average number of presenteeism days taken per person per year in Europe	(Garrow 2016)- It is a Europe based study on presenteeism. This report is obtained http://www.employment-studies.co.uk/system/files/resources/files/507_0.pdf
Percentage of presenteeism days taken due to disease asthma (Pv)	(Johns 2010)- This study reviews literature on presenteeism to conduct a meta-analysis to show the significance of presentism at workplace.
Percentage of presenteeism days taken due to disease cold and flu (Pv)	(Johns 2010)

Percentage of presenteeism days taken due to disease allergies (Pv)	(Lamb, et al. 2006)
Value of μ i.e. the productivity loss factor due to disease V	(Lamb, et al. 2006)

Source: Own elaboration

For presenteeism since the country-specific figures could not be found, the average presenteeism days within Europe i.e. 3.1 days/person, year is used for both the countries (Garrow 2016). However, for absenteeism, country-specific sick leave data are available. Here, one noteworthy point is that not every disease is caused by indoor or outdoor pollution. There could be some sick leaves which are taken due to other reasons than pollution such as due to muscular pain or due to an accident. Thus, this dissertation only considers diseases which can be caused due to indoor pollution, outdoor pollution and dampness. One issue arises during this course of research, that is disease-specific sick leaves and presenteeism data are not readily available. Therefore, different literature is reviewed in order to find out the usual percentage of sick leave taken due to the diseases caused by indoor pollution, outdoor pollution, and dampness as discussed in chapter 3, section 3.2.1.1. Table 17 shows below these data:

Table 17: Percentage of absenteeism and presenteeism for different diseases

	Percentage of Absenteeism	**Source of the absenteeism data**	**Percentage of Presenteeism**	**Source of the presenteeism data**
Asthma	14%	(Alexopoulos and Burdorf ,2001)	17%	(Johns 2010)
Allergy	20%	(Lamb, et al. 2006)		(Lamb, et al. 2006)
Cold and flu	19%	(Alexopoulos and Burdorf ,2001)	17%	(Johns 2010)
Cardiovascular diseases	6%	(Price 2004)	10%	(Price 2004)
Total	59%		44%	

Source: Own elaboration (data extracted from different literature)

As it can be seen from table 17, the total percentage of absenteeism and presenteeism is not adding up to 100% which shows that there are other diseases due to which absenteeism and presenteeism can occur. For allergy and asthma the presenteeism percentage is merged because it is reported that 17% presenteeism days are due to allergy and asthma together (Lamb, et al. 2006). The diseases mentioned in table 17 can be caused by some other reasons apart from indoor exposure to pollutants. Thus, the conversion factor of this dissertation's methodology would make sure that this dissertation only accounts for the diseases caused due to indoor exposure.

Moreover, this dissertation acknowledges the fact that presenteeism days do not mean the loss of entire work day. In other words, 1 day of presenteeism does not mean 1 day of work loss. Thus, for asthma, cold and flu the presenteeism time is assumed 2.3 hours a work day which is 8 hours (Lamb, et al. 2006). This implies 29% of productivity loss due to presenteeism for asthma, cold and flu.

Both avoided sick days and healthy life years saved are the outcomes of installing an improved HVAC system with airtight building envelope and both of them are calculated based on how many diseases specific disability would reduce due to improved HVAC installation and airtightness. The disease-specific disability reduction rate is taken from the healthvent project which assumes a 90% reduction in radon, carbon monoxide and secondhand smoke, 50% reduction in VOC and dampness exposure, and 25% reduction in particulate matter (PM2.5) due to ventilation installation and controlling VOC and particulate matter exposure (Hanninen et al 2013). More precisely, based on these pollutant reduction rates, the disability rate is calculated in the healthvent project. The healthvent project estimates disease-specific health gain factor for each type of scenarios and those scenarios can be compared with the retrofit scenarios. The health gain factors are given in the form of the percentage of reduction in DALY due to change in ventilation, filtration and pollutant source control. Table 18 shows the values of health gain under different scenarios as per the healthvent project.

Table 18: Values of burden of diseases from Healthvent project

	Diseases	Baseline DALY (Total DALY / million pop)	Scenario 1 ventilation only	Scenario 2 filtration only	Scenario 3 optimal control
Germany	Asthma and allergies	467	402	333	201
	Cardiovascular diseases	2298	869	1263	1280
	Lung (trachea & Bronchus) cancer	838	1648	679	387
	COPD	462	323	259	254
Hungary	Asthma and allergies	271	215	175	129
	Cardiovascular diseases	5376	3691	2718	3352
	Lung (trachea & Bronchus) cancer	2571	2882	2165	1142
	COPD	768	530	406	467

Source: Healthvent project

Hanninen et al 2013 study describes scenario 1 as ventilation scenario i.e. only with optimum ventilation rate how much health gain can be achieved. Scenario 2 shows that only with proper filtration installed keeping other factors constant how much health gain can be achieved. Lastly, 3rd scenario shows how much health gain can be achieved by controlling the pollutant sources technically along with optimum ventilation rate. The baseline DALY in the healthvent project is taken from the WHO 2010 burden of disease database.

As discussed in the previous paragraph and in table 18, the health gain factors from each scenario are given in DALY which directly cannot be used in our model. Thus, in order to get the value of our conversion factor, the percentage reduction of DALY compared to baseline can be used as the value of the conversion factor. Table 19 shows the reduction potential or the potential of conversion factor for both Germany and Hungary for different scenarios compared to the baseline which is calculated from table 18.

Table 19: Percentage reduction of burden of diseases under different scenario

	Diseases	Scenario 1 (DALY reduction percentage)	Scenario 2 (DALY reduction percentage)	Scenario 3 (DALY reduction percentage)
Germany	Asthma and allergies	14%	29%	57%
	Cardiovascular diseases	62%	45%	44%
	Lung (trachea & Bronchus) cancer	96% (increase)	54%	53%
	COPD	30%	44%	45%
Hungary	Asthma and allergies	21%	35%	52%
	Cardiovascular diseases	31%	49%	38%
	Lung (trachea & Bronchus) cancer	12% (increase)	16%	55%
	COPD	31%	47%	39%

Source: Own calculation (based on healthvent project data)

For this dissertation, scenario 3 i.e. source control with optimum ventilation rate results are used as a value of conversion factor. The source control scenario shows health gain from optimum ventilation rate in a full airtight building with sources of pollutants (such as VOC, radon, PM 2.5, CO, and dampness) controlled using technical measures such as removing existing building shell, using CO sensor alarm system etc. These results of percentage reduction in DALY from source control scenario are used for certain types of buildings such as deep retrofit, zero energy buildings, and passive houses where deep renovations of buildings ensure full airtightness. Hence minimum infiltration of outdoor pollutants and presence of mechanical HVAC system ensures constant air supply.

This dissertation assumes the same reduction percentage for cold and flu disease like asthma and allergy since no reduction percentage data is available for cold and flu. However, in order to be theoretically consistent- meaning considering the contagious nature of cold and flu disease, the value of TSF is higher in the tertiary buildings for cold and flu disease. In tertiary buildings, the possibility of getting a cold and flu is more compared to the residential building due to the higher population presence in tertiary buildings. Thus, for the residential sector, the reduction rate of cold and flu is assumed to be half of the reduction rate of asthma and allergy.

As it can be seen from table 17 and 18 that the main source of population data is Coulder 2018 study and to provide a more in-depth picture, table 20 and 21 presents all the population data for both residential building sector as well as for the tertiary building sector:

Table 20: Working population living in different type of buildings in different scenarios in the year 2030

Type of buildings/Country, Scenario	**Hungary**		**Germany**	
	Reference scenario	Efficient Scenario	Reference scenario	Efficient Scenario
Working adults living in surviving non-retrofitted dwellings (in million)	1.9	1.6	28.5	23.5
Working adults living in light (shallow) retrofitted dwellings (in million)	0.03	0.06	1.6	3.5
Working adults living in medium retrofitted dwellings (in million)	0.1	0.2	2.1	4.1
Working adults living in deep retrofitted dwellings (in million)	0.2	0.4	1.2	2.3
Working adults living in new dwellings - minimum required standard 2015-2020 (in million)	0.6	0.6	0.9	0.9
Working adults living in new nZEB dwellings (in million)	1.1	0.7	4.8	3.1
Working adults living in new Passive House dwellings (in million)	1	1.4	3.8	5.5
Total working population (in million)	4.4		42.9	

Source: Own elaboration (data extracted from Couder 2018, D 2.3 report)

Table 21: population working in different type of tertiary buildings in different scenarios in the year 2030

Type of buildings/Country, Scenario	**Hungary**		**Germany**	
	Reference scenario	Efficient Scenario	Reference scenario	Efficient Scenario
Working adults in surviving non-retrofitted dwellings (in million)	2.3	1.9	24.7	21.9
Working adults in light (shallow) retrofitted dwellings (in million)	0.25	0.42	1.4	1.7
Working adults in medium retrofitted dwellings (in million)	0.91	0.14	0.50	0.64
Working adults in deep retrofitted dwellings (in million)	0.11	0.30	0.38	2.8
Working adults in new dwellings - minimum required standard 2015-2020 (in million)	0.66	0.66	0.68	0.68
Working adults in new nZEB dwellings (in million)	0.57	0.35	6	3.8
Working adults in new Passive House dwellings (in million)	0.10	0.32	1.1	3.4
Total working population (in million)	3.5		34.8	

Source: Own elaboration (data extracted from Couder 2018, D 2.3 report)

From table 21 and 22, it can be seen that for both tertiary and residential buildings, the stock of NZEB is less in the efficient scenario. The reason behind it is that from 2020 onward, there are two alternatives: NZEB buildings or Passive House (PH) buildings, where Passive House buildings are assumed to be more energy efficient than NZEBs because of higher insulation standards. Thus, in the efficiency scenario, COMBI building stock model assumes that more NZEB buildings are converting into passive houses.

Data and their sources for workforce performance: As discussed in chapter 4, section 4.3.5.2, for workforce productivity the following data are gathered from different sources:

Table 22: Workforce performance data and their sources

Data	**Data Source**
Average annual hours actually worked per worker per country	OECD 2017 (Database: Actual hours of work data, URL: https://stats.oecd.org/Index.aspx?DataSetCode=AVE_HRS)
Number of people who work in t1 buildings per year per country	COMBI 2018, D2.3 Annex report
Number of people who work in t2 buildings per year per country	COMBI 2018, D2.3 Annex report
Number of people who work in t3 buildings per year per country	COMBI 2018, D2.3 Annex report
Value of productivity improvement factor	(Singh et al. 2010) - It is a US (in Lansing, Michigan) based study with 262 sample size on effects of green office buildings on employee's health and productivity.

Source: Own elaboration

For workforce performance metric there are three key data point: 1) population data working in the different type of tertiary buildings, 2) performance enhancement factor due to improved building condition and 3) actual annual hours worked per worker. The average annual hours actually worked per worker data is basically derived by dividing the total number of hours worked over the year with the average number of people in employment (OECD 2017).These three data are collected from three different sources as discussed in table 22 above. The population data is already presented in table 21 and the other two data points are presented in chapter 6, section 6.4.

Data and their sources for time saved from congestion: For active time metric or time saved from congestion metric, data requirement are the given below:

Table 23: Time saved from congestion data requirement

Data	Data Source
Number of drivers stuck in traffic during peak hours per country per year	COMBI 2018- D2.3 Annex report
Average Hours wasted in traffic in 2015	(INRIX 2017), Traffic scorecard report- INRIX scorecard is used to conduct research on urban mobility and this report reported global congestion situations (URL:http://inrix.com/scorecard/)
Travel saved factor	(De Hartog et al. 2010; COMBI 2018)

Source: Own elaboration

As it can be seen from table 23 that for time saved from congestion metric, there are three key data points and similar to workforce performance, these three key data points come from three different sources. As discussed in chapter 4, the travel saved factor is calculated from the modal shift rate towards active transportation. Hence, in the table below data for these key variables are presented:

Table 24: Key data for calculation of time saved for congestion metric

	Germany	Hungary	Data source
Average wasted hours in traffic/driver, year	38	5	INRIX 2017,Traffic scorecard report, (URL:http://inrix.com/scorecard/)
Passengers stuck in peak hours traffic using cars in the year 2030	19,351	1,074	COMBI 2018- D2.3 Annex report
Modal shift rate towards active transportation	2.7%	3.9%	COMBI 2018- D2.3 Annex report

To summarize, this section lists-down all the data required for the productivity metrics mentioned in chapter 4, section 4.3.2. Some of the data are taken from literature, while some of them are taken from project COMBI. This section shows how data-intensive productivity impact is. This could be one of the reasons why productivity impact has not been measured so rigorously till now. Along with the methodology and its data, like any empirical study, this dissertation has also some key assumptions which are discussed in the next section.

5.3 Assumptions:

5.3.1 Assumptions of methods:

Like every empirical study, this study also has to assume a certain number of things to simplify the study in view of the time and resource constraints:

1. Ceteris paribus prevails. Without ceteris paribus, it would be too complex to calculate the productivity impact of improved energy efficiency measure as there could be other factors which can influence productivity.
2. The HVAC system needs to be properly maintained. Otherwise, the health effect would be minimal since then HVAC could itself be a source of indoor air pollutants.
3. HVAC system would be installed with a few other system control measures such as temperature control, and sensors etc. to monitor the indoor air quality properly.
4. Radon safe constructions are assumed in radon-prone areas.
5. Since this study projects the productivity gain values in the year 2030, the average sick leave data/ per person and presenteeism data are assumed to remain the same as for 2014/2015 data. For instance, the average sick leave taken in Hungary in the year 2015 was 7.9 days/per person and it is assumed that in the year 2030 also the average sick leave taken would be the same. For presenteeism days since country-specific presenteeism days are not available, the average presenteeism days for Europe are taken

for both the countries. Also, the average presenteeism days are considered to be the same for 2015.

6. The health gain factor is calculated from the healthvent study's source control scenario. This scenario controls the exposure by several technical measures such as a sensor, removal of existing building shell etc. This study also talks about HVAC system installation with system control which includes a sensor and thermostat etc. Thus, the result of source control scenario of the healthvent project is close to this study and hence it is used as a conversion factor.
7. As discussed in chapter 4, section 4.3.5.1, the value of TSF is assume to be 33% in order to be theoretically consistent. More precisely, people spent 8 hours a day at work place, and indoor exposure to pollutants depends on the amount of time expose to the pollutants. Thus, to calculate the effects of improved energy efficiency measure in tertiary building sectors, the value of TSF is assumed to be 33%.
8. Before modal shift towards active transportation, there are some pre-requirements which are assumed to be maintained. Pre-requirements such as proper cycling and walking on road need to be there while cyclers are maintaining proper safety measures etc.
9. The marginal utility of leisure is equal to the marginal utility of income. This assumption is made for monetization of active time loss due to road congestion.
10. For monetization of impacts especially active days, it is assumed that the number of working days is 22 days in a month in order to calculate the daily wage.

5.3.2 Assumption of scenario:

As discussed in chapter 4, methodology of this dissertation consists of two scenarios: reference and efficient and as per the scenario the number of different type of buildings varies. There are mainly four types of retrofitted residential buildings i.e. non-retrofitted, light retrofitted, medium retrofitted and deep retrofitted. Apart from retrofitting types, there are also passive houses and nearly zero energy buildings (NZEB), which give equivalent benefits compared to deep retrofitted buildings. In efficient scenario, the number of deep retrofit type buildings such as passive houses, NZEB, and deep retrofit type buildings is assumed to be higher compared to the number of buildings in reference scenario. However, in this dissertation, the population residing or working in these type of buildings are more important than the number of buildings. However, the basic understanding of assumptions is required to understand how these different type of retrofit levels are determined. Thus, in the section below for each country a different retrofit specification-related assumption is discussed:

5.3.2.1 Types of retrofits of residential building sector in Germany

In Germany, different types of retrofitting require different classifications. Below classifications details are discussed for each type of residential retrofitted buildings in Germany. These classification details are from the COMBI project building classification data (COMBI 2018). Also, these retrofit types are defined taking Berlin as an example for the whole Germany.

Light retrofit:

1) **Light envelop:** Building envelope light retrofitting consist of 10 cm external insulation in the wall, 16 cm of added roof insulation and 5 cm of basement insulation. In the basement insulation, 5 cm of thermal insulation needs to be added below the slab in contact with the basement. For roof insulation, the 15 cm of external thermal insulation needs to be added over the last slab in contact with unconditional space.
2) **Light windows:** In case of light retrofitting of windows triple glass with argon cavity (16mm) and a low-e glass need to be installed.
3) **Light cooling:** Solar shading external window blinds - fixed slat angle - manual control (setpoint 500W/m2 in summer) night cooling and natural extra ventilation in summer

(automatic control to open windows) - automatic control through differential temperature.

4) **Heat recovery and ventilation:** Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Medium retrofit:

1) **Medium envelope:** Medium retrofit consists of 15cm wall insulation along with external insulation, 20cm roof insulation along with a thermal insulation layer over the last slab in contact with unconditioned space, 10 cm basement insulation and lastly, installation of a layer of thermal insulation below the slab in contact with the basement.
2) **Medium windows:** Triple glass with argon cavity (16mm) and a low-e glass are installed in medium retrofit.
3) **Medium cooling:** Solar shading External window blinds - fixed slat angle - manual control (setpoint 500W/m2 in summer). Night cooling Natural extra ventilation in summer (automatic control to open windows) - automatic control through differential temperature.
4) **Heat recovery and ventilation:** Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Deep retrofitting:

1) **Deep envelope:** Deep envelope retrofit consists of 20cm wall insulation - external insulation (EIFS System) with 30cm roof insulation, an additional thermal insulation layer over the last slab in contact with unconditioned space, 15cm basement insulation along with a layer of thermal insulation below the slab in contact with the basement.

2) **Deep windows:** Triple glass with argon cavity (18mm) and a low-e glass.

3) **Deep cooling:** Solar shading with external window blinds is present in deep cooling. Also, fixed slat angle with manual control and night cooling with natural extra ventilation in summer (automatic control to open windows) - automatic control through differential temperature is present.

4) **Deep heat recovery:** Heat recovery and mechanical ventilation are present.

5.3.2.3.2 Types of retrofits of tertiary building sector in Germany

For tertiary buildings, the retrofitting specifications vary since the population density is much higher in commercial buildings compared to residential buildings. In addition, tertiary buildings are usually larger than residential buildings, which requires a greater safety and structural construction (Architecture lab 2014).

Therefore, in the section below, specifications of different types of retrofit are discussed for tertiary buildings of Hungary and Germany as per COMBI project data.

For tertiary buildings in Germany, the retrofit types are defined as follows:

Light retrofit:

Light envelope: Light envelope includes wall External insulation (EIFS System): 10 cm of roof insulation, 10 cm of insulation basement layer and 5 cm insulation in the inner of the floor slabs or frameworks is installed.

Light windows: External/internal window blinds - fixed slat angle - automation control is present.

Light cooling: External window blinds - block beam solar - automation control.

Heat recovery and ventilation: Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Medium retrofit:

Medium envelope: Medium envelope includes Wall External insulation (EIFS System): 30 cm of roof insulation, 30 cm of insulation basement layer and 15 cm of insulation in the inner of the floor slabs or frameworks is installed.

Medium windows: External/internal window blinds, fixed slat angle and automation control are present.

Medium cooling: External window blinds - block beam solar - automation control is present.

Heat recovery and ventilation: Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Deep retrofit

Deep envelope: Deep envelope involves wall External insulation (EIFS System), 30 cm roof insulation, 30 cm of an insulation layer on the basement, and 15 cm insulation in the inner of the floor slabs or frameworks is installed.

Deep windows; External/internal window blinds, fixed slat angle, and automation control are present.

Deep cooling: External window blinds, block beam solar, and automation control are present.

Deep heat recovery: Heat recovery and mechanical ventilation are present.

The above description of assumptions of different retrofit levels is taken from COMBI 2018 study. Most of the description of assumptions holds true for the German tertiary buildings as well. The only difference in the tertiary building assumptions is that the insulation level is more in deep-retrofitted buildings compared to the residential deep-retrofitted buildings. For instance, for tertiary building sector, 30cm of external insulation is assumed along with 30cm of roof insulation. Whereas for the residential building sector the external insulation level is assumed to be 20cm.

As discussed at the beginning of this section, the building stocks are not important or required for the methodology. However, as per these descriptions of assumptions, building stock percentage would provide an in-depth picture of the scenarios. Thus, table 25 below shows the percentages of different type of retrofitted residential and tertiary buildings in Germany in the year 2030:

Table 25: Percentage of different retrofitted residential and tertiary buildings in Germany in the year 2030

	Residential building stock		**Tertiary building stock**	
	Reference scenario	**Efficiency scenario**	**Reference scenario**	**Efficiency scenario**
Percentage of non-retrofitted dwellings	66%	55%	71%	63%
Percentage of light retrofitted dwellings	4%	8%	4%	5%
Percentage of medium retrofitted dwellings	5%	10%	1%	2%
Percentage of deep retrofitted dwellings	3%	5%	1%	8%
Percentage of new dwellings minimum required standard 2015-2020	2%	2%	2%	2%
Percentage of NZEB dwellings	11%	7%	17%	11%
Percentage of Passive House dwellings	9%	13%	3%	10%

Total building stock (in million)	48.8		0.65	

Source: Own elaboration (data calculated from COMBI 2018, D2.4 annex report)

5.3.2.2 Types of retrofits of residential building sector in Hungary

Similar to Germany, the assumptions of different retrofit types are defined for Hungary considering Budapest as an example for retrofit classification. In the paragraph below, details of retrofitting in Hungary are given;

Light retrofitting:

1) **Light envelope:** Light retrofit envelope consists of 10cm wall insulation, external insulation (EIFS System), 15cm roof insulation with an additional thermal insulation layer over the last slab in contact with unconditioned space, and 5cm basement insulation along with a layer of thermal insulation installed below the slab in contact with the basement.
2) **Light windows**: Double glass with air cavity (16mm) and a low-e glass are installed.
3) **Light cooling:** Solar shading with external window blinds is installed with manual control (setpoint 500W/m2 in summer). Night cooling and night ventilation are absent.
4) **Heat recovery and ventilation:** Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Medium retrofit:

1) **Medium envelope:** Medium building envelope consists of 20cm wall insulation with external insulation (EIFS System), 30cm roof insulation with an additional thermal insulation layer over the last slab in contact with unconditioned space, and 15cm basement insulation. Lastly, a layer of thermal insulation below the slab in contact with the basement is installed.

2) **Medium windows**: Double glass with air cavity (16mm) and a low-e glass are installed.
3) **Medium cooling:** Solar shading with external window blinds is installed with manual control (setpoint 500W/m2 in summer). Night cooling and night ventilation are absent.
4) **Heat recovery and ventilation:** Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Deep retrofit:

1) **Deep envelope:** Deep envelope consists of 20cm wall insulation with external insulation (EIFS System), 30cm roof insulation with an additional thermal insulation layer over the last slab in contact with unconditioned space and 15cm basement insulation. Lastly, a layer of thermal insulation below the slab in contact with the basement is installed.
2) **Deep windows:** Triple glass with argon cavity (16mm) and a low-e glass.
3) **Deep cooling:** Solar shading, external and window blinds with manual control (set point 500W/m2 in summer) are in place.
4) **Deep heat recovery:** Heat recovery and mechanical ventilation system are present.

5.3.2.3 Types of retrofits of tertiary building sector in Hungary

Similarly, for Hungary the classifications for different types of retrofits in tertiary buildings are defined as:

Light retrofitting:

Light envelope: Light envelope involves wall renovation of the exterior layer, roof renovation of the exterior layer but no renovation to the basement.

Light windows: Replace old window with new one.

Light cooling: Solar shading and external/internal window blinds with automation control is present. Night cooling and night ventilation are present.

Heat recovery and ventilation: Heat recovery and mechanical ventilation system are not present. For ventilation, instead of mechanical, natural ventilation is used.

Medium retrofit:

Medium envelope: Medium envelopes include wall external insulation (EIFS System), 5 cm roof of insulation, 10 cm of insulation layer on the basement, and 5 cm insulation in the outer of the floor slabs or frameworks is installed.

Medium windows: External/internal window blinds, fixed slat angle, and automation control are present.

Medium cooling: External window blinds - block beam solar, and automation control are present.

Medium heat recovery: Heat recovery and mechanical ventilation are present.

Deep retrofit:

Deep envelope: Deep envelope includes wall insulation (EIFS System), 25 cm roof insulation, 30 cm of insulation layer on the basement, and 15 cm insulation in the outer of the floor slabs or frameworks is installed.

Deep windows: External/internal window blinds - fixed slat angle - automation control are present.

Deep cooling: External window blinds - block beam solar - automation control are present.

Deep heat recovery: Heat recovery and mechanical ventilation are present.

Similar to German tertiary sector, Hungarian tertiary sector has also more tight insulation level compared to the residential sector. More precisely, the wall insulation is 25cm in deep retrofit type tertiary buildings whereas in case of deep-retrofit type residential building, the wall insulation is 20cm. Within the table below, the percentages of different type of retrofitted residential and tertiary buildings in Hungary in the year 2030 are shown:

Table 26: Percentage of different retrofitted residential and tertiary buildings in Hungary in the year 2030

	Residential building stock		**Tertiary building stock**	
	Reference scenario	**Efficiency scenario**	**Reference scenario**	**Efficiency scenario**
Percentage of non-retrofitted dwellings	43%	36%	66%	54%
Percentage of light retrofitted dwellings	1%	1%	7%	12%
Percentage of medium retrofitted dwellings	3%	5%	3%	4%
Percentage of deep retrofitted dwellings	4%	9%	3%	9%
Percentage of new dwellings minimum required standard 2015-2020	1%	1%	2%	2%
Percentage of NZEB dwellings	25%	15%	16%	10%
Percentage of Passive House dwellings	23%	33%	3%	9%
Total building stock (in million)	7.1		0.04	

Source: Own elaboration (data calculated from COMBI 2018, D2.4 annex report)

With various data sources and research steps discussed so far in this chapter, it is best to present all these different research design of productivity quantification through a schematic diagram.

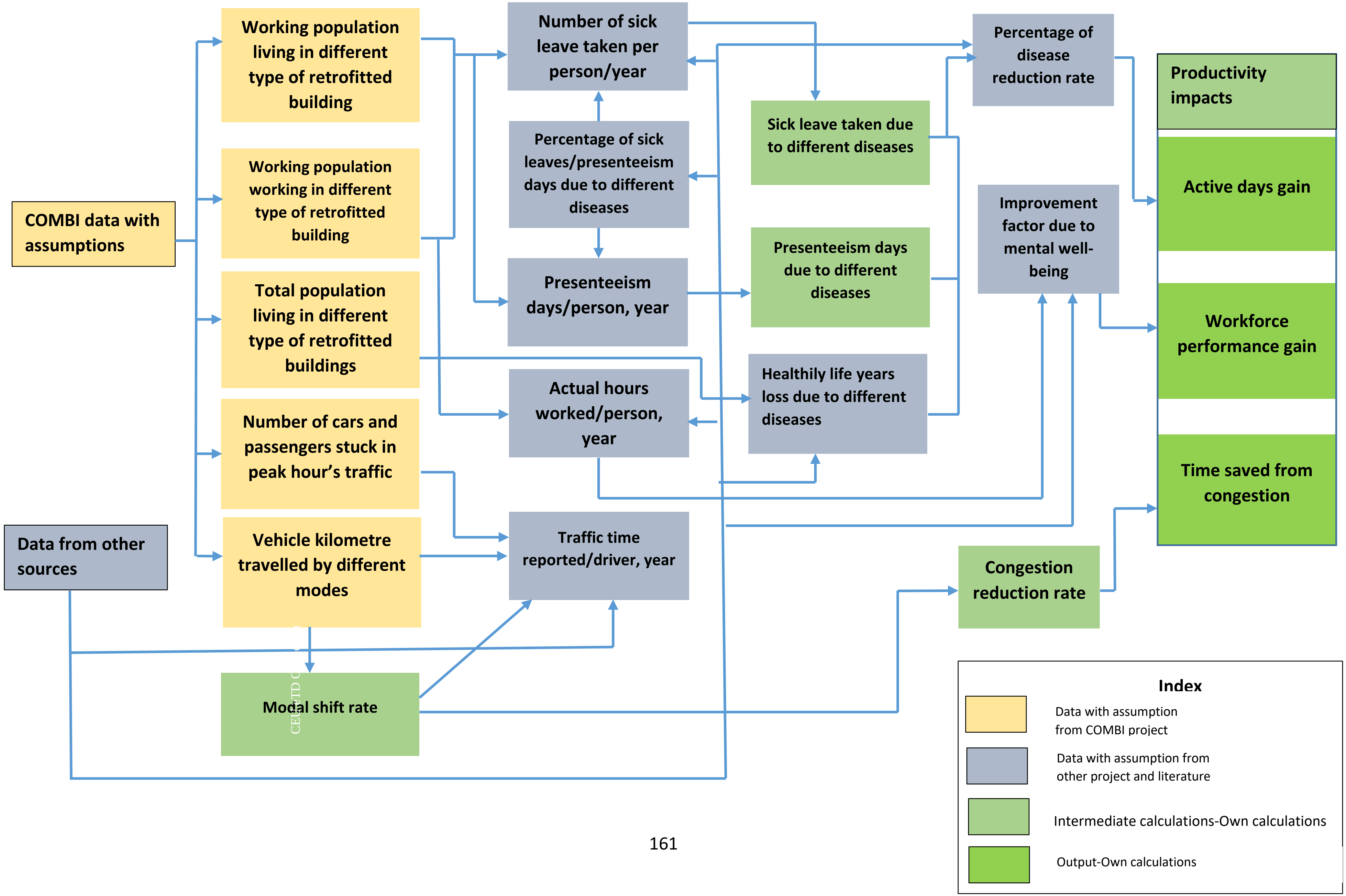

COMBI data with assumptions
Data from other sources
Working population living in different type of retrofitted building
Working population working in different type of retrofitted building
Total population living in different type of retrofitted buildings
Number of cars and passengers stuck in peak hour's traffic
Vehicle kilometre travelled by different modes
Modal shift rate
Number of sick leave taken per person/year
Percentage of sick leaves/presenteeism days due to different diseases
Presenteeism days/person, year
Actual hours worked/person, year
Traffic time reported/driver, year
Sick leave taken due to different diseases
Presenteeism days due to different diseases
Healthily life years loss due to different diseases
Percentage of disease reduction rate
Improvement factor due to mental well-being
Congestion reduction rate
Productivity impacts
Active days gain
Workforce performance gain
Time saved from congestion
Index
Data with assumption from COMBI project
Data with assumption from other project and literature
Intermediate calculations-Own calculations
Output-Own calculations

Figure 11: Schematic diagram of research steps with different data sources and own calculations

The schematic diagram above does not only present different research steps and their data sources, but it also shows this dissertation's novelty in terms of intermediate calculations and in calculating the outputs. As it can be seen from the schematic diagram, the methodology of this dissertation is quite data intensive and most of the data are not readily available. Thus, some of the data are calculated (for example, sick leave taken due to different diseases) from various data sources. All these intermediate calculations and the final output are the novelty of this dissertation.

5.4 Summary of the chapter:

This chapter presented all the input data and intermediate calculations used in this dissertation. Input data are taken from different sources namely COMBI project data, healthvent project data, scientific literature, Eurostat, and OECD. The methodology of this dissertation is quite data intensive and hence, not all the data can be found readily. Thus, in some cases, proxy data are used with certain assumptions. Like every empirical study, this dissertation also has to assume certain points both for methods as well as for scenarios. Last but not the least, in order to provide a complete picture, a schematic diagram is developed to show the different data sources used and also the novelty of this dissertation.

CHAPTER 6: QUANTIFICATION AND MONETIZATION OF THE PRODUCTIVITY IMPACTS: PRESENTING RESULTS OF PRODUCTIVITY INDICATORS

"The alchemists in their search for gold discovered many other things of greater value."
Arthur Schopenhauer

6.1 Quantification and monetization of active days resulting from improved energy efficiency measures:

This chapter provides the evidence to fulfil the empirical research gap. It presents the value for each of the productivity indicators discussed in chapter 4. These indicators are calculated by using the scenario analysis. To be precise, by comparing the results from two scenarios, the magnitude of productivity impact of energy efficiency measure is calculated. Particularly, the difference between the efficient scenario and reference scenario is presented as productivity gain. The objective of this dissertation is not to provide precise estimates of productivity but to offer a general idea of the magnitude of productivity impact as an additional effect of energy efficiency measure.

As discussed in chapter 4, active days have three aspects which are resulted from the two analysed efficiency measures. Each of these aspects is calculated for both reference and efficient scenarios, and the difference between these two scenarios is presented as active days gain. For example, in case of avoided sick days, the total days loss is calculated for both the scenarios. Since in the efficient scenario, the number of days loss would be less due to more people living or working in deep retrofit-type buildings compared to the reference scenario, the difference between these two scenarios would basically show the number of days gain due to having more deep retrofitted buildings i.e. active days gain resulted from energy efficiency measure.

Results-avoided sick days: The number of avoided sick days is one of the key indicators of active days and it is calculated for both the residential and tertiary building sectors separately. More precisely, the effects of the HVAC system with an airtight building envelope on sick days are calculated separately for the tertiary and residential building sectors. In order to calculate the avoided sick days, equations 8, 9, 10 and 11 are used (refer to chapter 4, section 4.3.5.1). To explain it further, first, the disease-specific absenteeism and presenteeism (equation 8 and

9) are calculated for people living/working in each type of residential/tertiary buildings. Then, the disease-specific absenteeism and presenteeism are aggregated to calculate the disease-specific sick days for each type of retrofitted buildings. Lastly, the disease-specific sick days are aggregated and multiplied with the conversion factor (i.e. health effects due to living/working in the deep-retrofit type of buildings) for both the countries to calculate the country-specific avoided sick days.

These steps are followed for both the scenarios and the result presented as active days gain is an incremental effect-meaning, it is the difference between efficient and reference scenario. By following this process, the incremental gain shows that if the HVAC system with airtight building shell is installed in residential buildings then people in Germany can gain around 5 million days in the year 2030. Similarly, people in Hungary people can gain around 0.43 million days in the year 2030 by having the HVAC system with the airtight building envelope. However, in order to provide more country-specific insights, per capita active days gain is the most suitable way of representation. Therefore, figure 12 below presents the country-specific active days data at a per capita level:

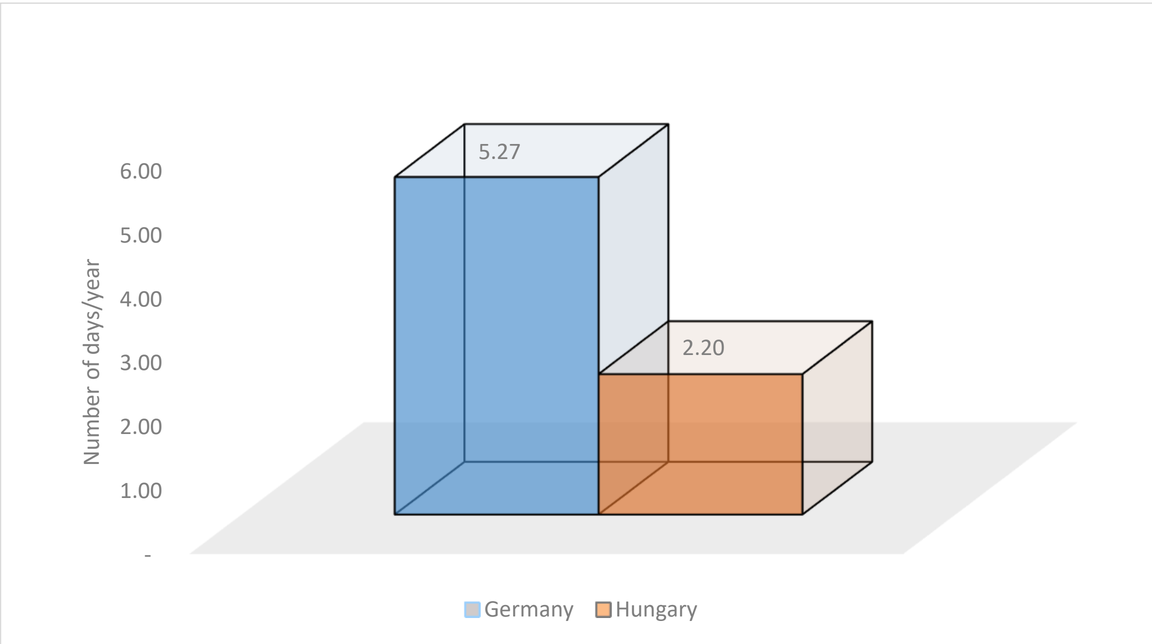


Figure 12: Avoided sick days/Active days gain in the year 2030/per person who has shifted to deep retrofit type residential buildings

Source: Own elaboration (dissertation data)

It is important to note that active days gain data are presented at per person scale in figure 12, where only those people are included who have shifted to deep retrofit type residential buildings as they are the only one who would enjoy the gain. Instead, dividing the total avoided sick days by total working population would have underestimated the per capita scale. Thus, the use of per capita scale in this dissertation only includes people who have shifted to deep retrofit type residential buildings.

The total number of sick days loss and active days gain by avoided sick days is presented in table 27 below for both of the scenarios:

Table 27: Sick days in different scenarios due to residential building-related illness

	Active days loss in reference scenario (in million)	**Active days loss in efficient scenario (in million)**	**Active (difference between two scenarios) days gain (in million)**	**Active days gain/Per person (number of days)**
Germany	357.9	352.1	5.8	5.2
Hungary	14.4	13.9	0.4	2.2

Source: Own elaboration (dissertation data)

Similar to residential buildings, if tertiary buildings also have the HVAC system with airtight building envelope then Germany can gain around 5 million days in the year 2030 and Hungary can gain 0.20 million days in the year 2030. As it is discussed in the above paragraph that data are best represented at per capita level. Hence, figure 13 below shows the country-specific per capita active days gain by installing HVAC system with proper building shell in tertiary building sector:

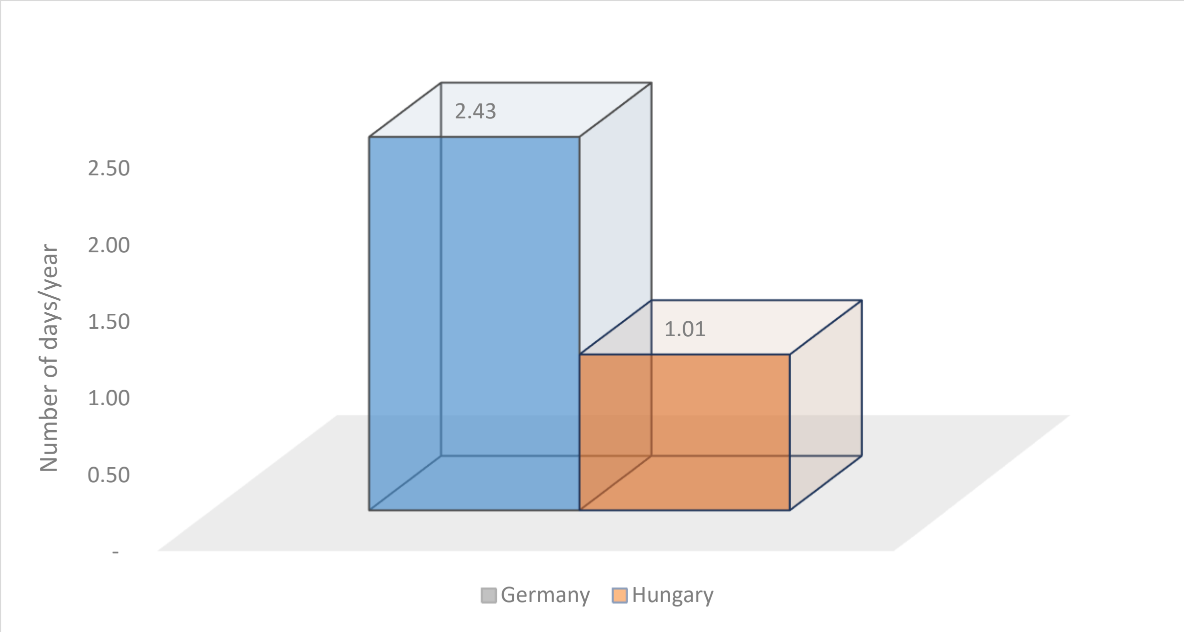


Figure 13: Avoided sick days/Active days gain in the year 2030/per person who has shifted to deep retrofit type tertiary buildings

The total number of sick days loss and active days gain by avoided sick days are presented in table 28 below for both scenarios:

Table 28: Sick days in different scenarios due to tertiary building-related illness

	Active days loss in reference scenario (in million)	**Active days loss in efficient scenario (in million)**	**Active (difference between two scenarios) days gain (in million)**	**Active days gain/Per person (number of days)**
Germany	133.9	128.2	5.8	2.4
Hungary	6.3	6.1	0.2	1.0

Source: Own elaboration (dissertation data)

Monetization of sick days: Monetization of any health effect is greatly debated and its methods have certain shortfalls (Luck et al 2012). For instance, most of the ecosystem-related impacts are monetized using the "willingness to pay" (WTP) approach which basically reflects people's preference for environmental goods and services (Söderholm and Sundqvist 2003). However, the use of the WTP approach can cause an underestimation because people may be unaware of the actual costs of the damage. The details of these methodologies are already discussed in chapter 4, section 4.2. In this dissertation, however, avoided sick days are calculated only for the working population and it is calculated based on the sick leaves and presenteeism days. Thus, this study uses country-specific daily net wage as a proxy value to monetize the avoided sick days.

The monetization of active days gain is calculated by multiplying avoided sick days with daily wage and daily net income is calculated by dividing monthly net income with the number of working days in a month i.e. 22 days. The daily net income is not readily available for both the countries but the monthly net income data is available for both countries. The country-specific monthly net income data is extracted from Eurostat database (Eurostats- http://appsso.eurostat.ec.europa.eu). As per Eurostat 2014 net monthly income database, the monthly net income for Germany and Hungary are 3045 and 811 Euro respectively. Calculated from the net monthly income, the net daily income would be 138 and 37 Euro for Germany and Hungary respectively.

Thus using these monetary units, Germany and Hungary have a potential of gaining 331 million and 5 million Euros/year respectively, by having airtight residential buildings with HVAC system. These monetary gains are calculated assuming that the wage in 2030 of these two countries would remain the same as in 2015, and thus these monetary figures are somewhat undervalued as they do not incorporate the rate of inflation. Similar to the residential sector, the tertiary building related active days gain can also be calculated by following the same process i.e. the number of active days gains multiplied by daily net income and daily net income is calculated by dividing monthly net income with the number of working days in a month i.e. 22 days. Germany and Hungary can gain 332 million and 2 million Euro/year respectively by having more airtight tertiary buildings with HVAC system and proper building shell. At per capita scale, Germany and Hungary can gain around 730 and 81 Euro/ year respectively by having more deep retrofit-type residential buildings. Similarly, for tertiary building sector at per capita scale, Germany and Hungary can gain 337 and 37 Euro/ year respectively.

Analysis of the result of avoided sick days gain: The active days gain is bigger in Germany compared to Hungary because Germany has taken more sick leaves compared to Hungary. In Germany, the average sick leaves taken annually were 18.3 days/person which are also quite high above the average EU sick leaves. The average sick leave taken within EU-28 is of around 10.62 days/per person annually (OECD database of compensated sick leave). Whereas, in Hungary, the annual sick leaves are 7.9 days/person. These sick leave data are compensated sick leave data- meaning sick leaves which are compensated by the government, or the employer. Similar to Germany, for Hungary also compensated sick leave data is used to calculate avoided sick leaves. One key reason behind Germany’s high sick leaves is probably a well-design social security system for the employees. As per the German labour law, in case of sick leaves, the employer is obliged to pay the full wage for up to six weeks under the act on the continuing of remuneration (Entgeltfortzahlungsgesetz, EntgFG) and after six weeks, the health insurance covers 70% of one‘s gross salary in case of long-term sickness (Kraemer 2017). Moreover, termination of employment contract while an employee is on sick leave is prohibited unless an unlawful conduct is detected (Kraemer 2017). Thus, employees take sick leaves in case of sickness without worrying about financial security or job security. On the contrary, the Hungarian labour code dictates to pay 70% salary in case of a sick leave (Kiss et al. 2017). Thus, compared to Germany, the compensated sick leave taken in Hungary is lower due to the finacial insecurity.

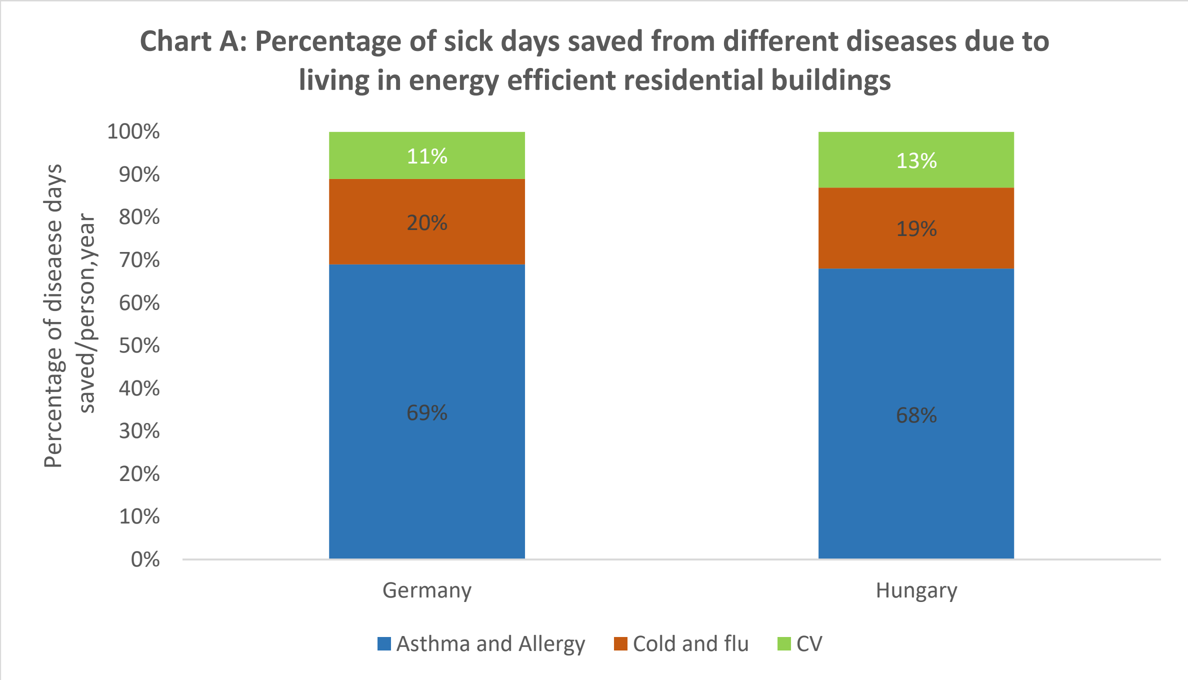
However, the concern here is that irrespective of the strength of the social security systems, both Hungary and Germany are losing many days because of sickness. One possible reason for the high number of sick days could be that 95% of the German residential buildings were non-retrofitted until 2015 and a similar trend can be seen for tertiary building sector i.e. 97% of the

German tertiary buildings were non-retrofitted (COMBI 2018, D2.3 annex report). In Hungary, 97% of the residential buildings and 96% of the tertiary buildings were non-retrofitted until 2015 (COMBI 2018, D2.3 annex report). This high number of non-retrofitted buildings might have resulted in poor indoor air quality and thus more frequent sickness.

Thus, health effects due to the installation of energy efficiency measure has become significant. Instead of absolute gain, if the relative gain is considered then the results look more significant for both the countries:

- Before the implementation of energy efficiency measure, the active days loss (combination of absenteeism and presenteeism) in Germany was 21.4 days, person/year. However, after implementation of energy efficiency measures i.e. HVAC system with airtight building envelopes in both residential as well as in the tertiary sector, total active days gain is 7.7 days, including active days gain in both residential and tertiary building sector. This gain accounts for around 36% savings of active days loss, that is, 36% active days can be gained by implementing energy efficiency measures in both residential and tertiary building sector in Germany.
- Similarly, in Hungary, the active days loss (combination of absenteeism and presenteeism) was 11 days/person/year and among these days total 3.21 active days are saved by implementing energy efficiency measures in the building sector which accounts for around 29% of active days savings. Thus, in relative terms as well, Germany is gaining more active days compared to Hungary. Though in absolute terms, per capita days saved in Hungary do not look big but in relative terms, 29% seems quite significant considering the fact that not all the sick leaves are taken due to indoor exposure to pollutants.

Now, in order to have an in-depth analysis, the disease-specific avoided days should be considered. Figure 14 below presents the percentages of sick days saved from three diseases after installing energy efficiency measures in both residential and tertiary building sector:



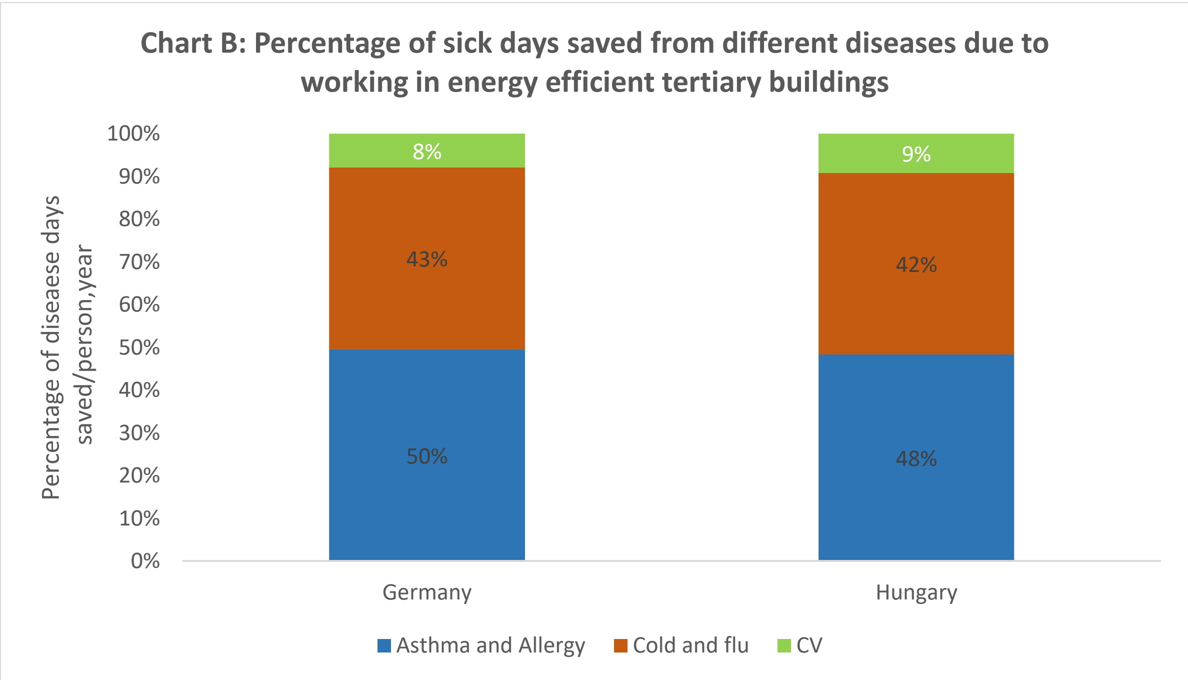


Figure 14: Disease specific active days gain for each country in the year 2030 after installing energy efficiency measure in residential and tertiary buildings

Source: Own elaboration (dissertation calculation)

Both charts A and B in figure 14 represent 100% as the total sick days saved from installing improved HVAC system with airtight building envelope-meaning, 5.2 days for Germany and 2.2 days for Hungary in the residential building sector and 2.4 for Germany and 1.0 for Hungary in the tertiary building sector. The sick days savings from cold and flu is actually higher for both Germany and Hungary compared to their cold and flu-related gain from the residential building sector. There are mainly two reasons behind this:

- Cold and flu disease can be contagious and there is a higher possibility to spread from tertiary buildings since more people work there. Thus, considering the contagious nature of this disease, the TSF is assumed to be higher for cold and flu as discussed in chapter 4, section 4.3.5, compared to other diseases. For diseases apart from cold and flu, the TSF factor is minimizing the effect as per the time spent in the tertiary buildings.
- More people shift to the deep retrofit-type tertiary buildings compared to the residential buildings. For instance, in Germany around 2 million more working people are moving to the deep retrofit type of buildings in the efficiency scenario, whereas in the residential sector, 1 million more working population are moving to the deep retrofit type residential buildings (COMBI 2018, D2.3 Annex report). Thus, the incremental gain is much higher in the tertiary sector. In Hungary, almost 0.19 million more people are working as well as residing in the deep retrofit type tertiary buildings and residential buildings respectively. Though in Hungary, the population shifts in the deep retrofit-type buildings are almost the same for the residential and tertiary building sectors, but due to the higher value of TSF for cold and flu disease, Hungary's percentage of saved sick days from cold and flu is higher for the tertiary sector compared to its residential sector.

From table 28 and figures 12 and 13, it is clear that Germany is gaining more active days compared to Hungary. Though this dissertation's objective is not to compare between these two countries but to provide an analysis of the results, it offers few more possible explanation of this higher active days gain in Germany. One of the reasons behind Germany's high active days gain is already explained at the beginning of this section i.e. use of compensated sick leave. Apart from using compensated sick leave, there are other explanations as well behind this gain, such as:

1. In Germany, the reduction rate of asthma and allergy due to the installation of HVAC system with airtight building shell is 57% and the reduction rate of cardiovascular diseases reduction rate is 44% (refer to table 19, chapter 5). Both of these reduction rates are above the average compared to EU-26 reduction potential (Healthvent project data). The average reduction potential at the EU- 26 is 40% for cardiovascular diseases and 55% for asthma and allergy (healthvent project data). Whereas in Hungary, the reduction rate of asthma and allergy due to installation of HVAC system with proper building shell is 52% and the same for cardiovascular diseases reduction rate is 38% (Healthvent project data). These reduction factors are calculated based on the assumption that HVAC system with airtight building envelope can result in 90% reduction in radon, carbon monoxide and second-hand smoke, 50% reduction in VOC and dampness exposure, and 25% reduction in particulate matter (PM2.5) (Asikainen, et al. 2016). These reduction rates of pollutants are assumed the same for both Germany and Hungary.
2. In the efficiency scenario, 17% and 7% more German residential buildings and tertiary buildings respectively are retrofitted in the deep retrofit type or passive house standard compared to the reference scenario. Whereas, in Hungary, 9% and 5% of the residential and tertiary buildings respectively are retrofitted in the deep retrofit type or passive house standard compared to the reference scenario. Thus, it is quite natural that more

people would gain productivity in Germany compared to Hungary, since fewer buildings are retrofitted in the deep retrofit type/passive house standard in Hungary.

3. Since country-specific presenteeism data is not available, the average presenteeism data which is 3.1 days/person annually, is used for both the countries. As a result, a country with a higher population tends to gain higher active days. Since the social security system in Hungary is not as good as the system in Germany, it is possible that presenteeism days are much higher in Hungary. Thus, country-specific survey is required to find out the presenteeism days for Hungary.

Results- healthy life years gain: As discussed in chapter 3 and 4, there could be other diseases - both chronic and acute - which can be caused due to indoor exposure. Moreover, avoided sick days are calculated only for the working population and DALY calculates healthy life years for the entire population including people who are not in the labour market. Equation 12 is used (see chapter 4, section 4.3.5.1) to calculate DALY saving or healthy life years gained by installing improved energy efficiency measures. The result shows that if the improved HVAC system with an airtight building envelope is installed in the residential building sector then Germany and Hungary could gain 1870 and 3849 healthy life years/million population in a year, respectively.

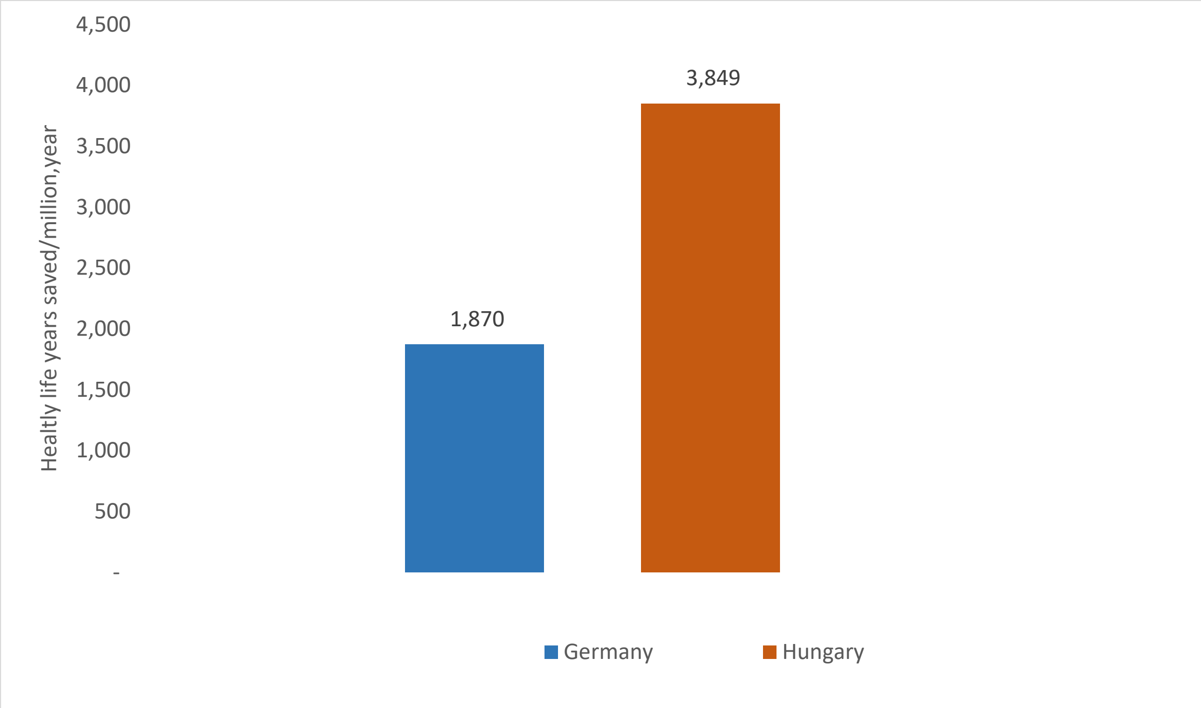


Figure 15: Disability adjusted life years saved in the year 2030/million population who have shifted to deep retrofitted type residential buildings

Source: Own elaboration (dissertation calculation)

From the DALY gain figure (see figure 15) it is observed that Hungary is having higher health benefits compared to Germany after moving to the deep retrofit-type residential buildings. In case of avoiding sick days, Germany has been the highest gainer compared to Hungary but when diseases such as lung cancer, chronic obstructive pulmonary disease (COPD) and cardiovascular disease-related mortalities are included, Hungary becomes the highest gainer. Figure 16 below presents the disease-specific life years saved for both the countries.

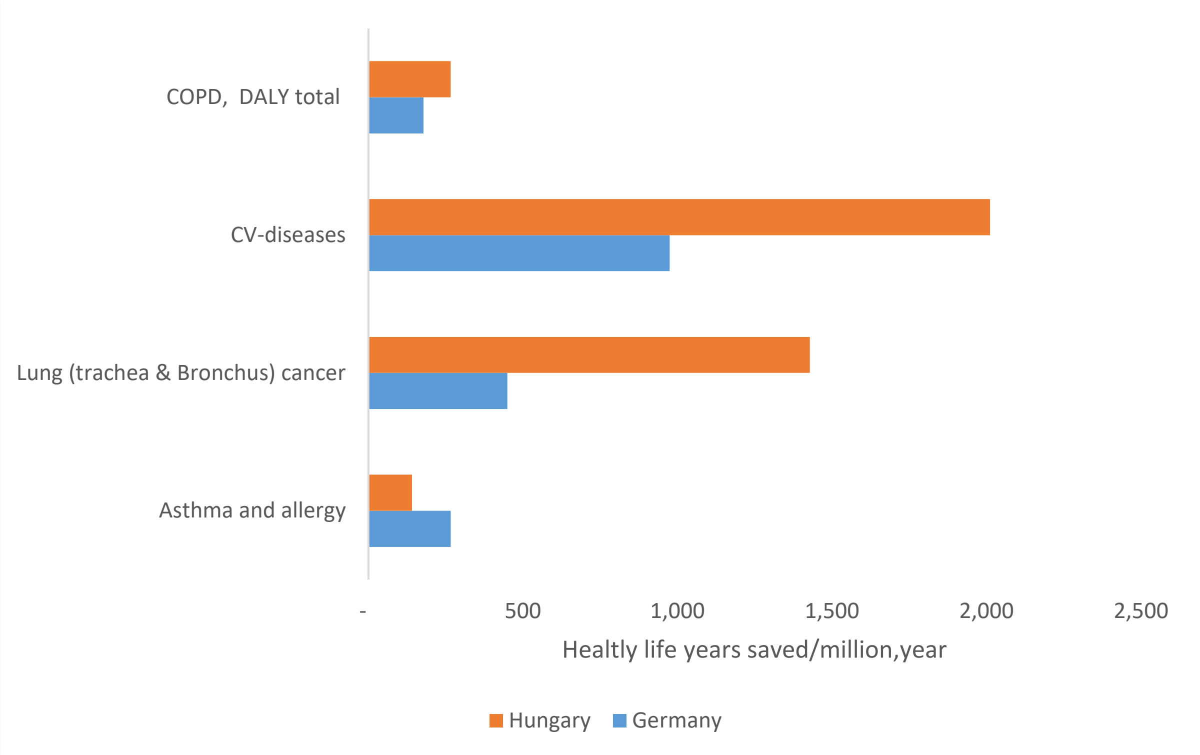


Figure 16: Disability adjusted life years saved /million population who have shifted to deep retrofitted type residential buildings, year from each diseases

From figure 16 it can be observed that apart from asthma and allergy, for all the other diseases Hungary gains more life years compared to Germany. The values of DALY in two scenarios are presented in the table below:

Table 29 : Disability adjusted life years in different scenario

Country	Total DALY in reference scenario (in years)	Total DALY in reference scenario (in years)	Total DALY gain (avoided DALY) (in years)	Percapita DALY gain (in years)
Germany	295,592	291,530	4,062	1,870
Hungary	65,898	64,241	1,657	3,849

Source: Own elaboration (dissertation calculation)

Monetization of DALY: The monetization of health impact is not easy and is controversial by nature. In case of avoided sick days, the sick days are monetized by multiplying with the daily wage. The critics of the monetization of DALY suggest that “human life is the ultimate example of a value that is not a commodity and does not have a price“ (Ackerman, and Heinzerling

2002). However, it needs to be understood that monetization of health indicators such as the value of statistical life (VSL) or DALY does not value an actual life, rather it values the amount of money that can be spent or the amount of money received/saved to avoid a certain type of health risks (Fiúza et al. 2006). If the health benefits are not quantified then these health benefits would simply be out of the cost-benefit accounting. Thus, to have accounts of the health benefits, such as DALY gain, one should monetize it.

This dissertation monetizes DALY by using the value of a life year (VOLY) estimates. Since healthy life years saved accounts life-saving of the senior age citizens as well, it is better to use the "value of a life year (VOLY) estimates per (avoided) death assuming that the group affected would have lived at least one more year" (Mzavanadze et al. 2018). The country-specific VOLY values are taken from the COMBI work package 5 report (https://combi-project.eu/wp-content/uploads/D5.4). The VOLY for Germany and Hungary are around 0.15 million and 34 thousand Euro respectively (Mzavanadze et al. 2018).

Therefore, multiplying these VOLY figures with years of life saved accounts for around 602 million Euro and 57 million Euro for Germany and Hungary respectively. At per capita level, Germany and Hungary can gain around 277 million Euro and 134 million Euro respectively.

Analysis of the result- Healthy life years saved: The possible explanations for this result are the following:

- Compared to Germany, one of the key reasons behind Hungary's high life years gain is the higher outdoor pollution concentration (mainly PM2.5) in Hungary (Hänninen and Asikainen 2013), (WHO 2016). More precisely, the PM 2.5 concentration in Hungary is 21 micrograms per cubic meter (ug/m3) annually which is the second highest in the European member states following Bulgaria, whereas in Germany the PM 2.5 concentration is 14 (ug/m3) annually (WHO 2016). Here, the DALY gain for Hungary has primarily resulted by avoiding indoor exposure-related lung cancer and cardiovascular diseases (as it can be seen in figure 16). By having an airtight building envelope, pollutants such as PM, VOC would infiltrate less in indoor and thus, cause less exposure to pollutants in indoor, result in higher DALY gain.

- As per the world cancer research Fund data, Hungary has the highest number of lung cancer cases in Europe (World Cancer Research International 2012). Thus, it is justified that Hungary has the higher per capita DALY gain mainly through savings of healthy life years from lung cancer by having more airtight buildings which prevents infiltration of the pollutants, mainly PM 2.5 along with VOC and radon exposure up to some extent. In Hungary, the cancer reduction percentage by avoiding these above mentioned pollutants is 55%, whereas the same in Germany is 53%.
- The baseline healthy life years lost due to lung cancer (lung cancer from indoor exposure to pollutants) are 838 years/million population and 2571 years/million population for Germany and Hungary respectively (Healthvent project data). The healthy life years lost due to cardiovascular diseases (cardiovascular diseases due to indoor exposure to pollutants) are 2298 years/million population and 5376 years/million population for Germany and Hungary respectively (Healthvent project data). These baseline data shows that both cancer and cardiovascular disease-related healthy life years loss are already higher in Hungary compared to Germany and thus, a reduction in disease risk is resulting in a higher gain (at the per capita level) in healthy life years for Hungary compared to Germany.

Results- time saved from congestion: Time saved from congestion is calculated based on the rate of modal shift. As discussed in the assumption section in chapter 5, the infrastructure (such as cycling and walking lane, public transport availability and connectivity etc.) for the modal shift is a pre-requisite for modal shift. In order to evaluate, equation 13 (refer to chapter 4, section 4.3.5.1) is used to calculate the time saved from congestion due to modal shift towards active transportation. The result shows that by opting for the modal shift towards active transportation, Germany can save 2.5 hours annually, per driver and Hungary can save 0.5 hours annually, per driver during the peak congestion. These traffic time saved figures reflect only time saved only during peaked congestion as discussed in Chapter 3, section 3.2.2.2.

Figure 17 below shows per-capita hours saved from congestion after modal shift towards active transportation:

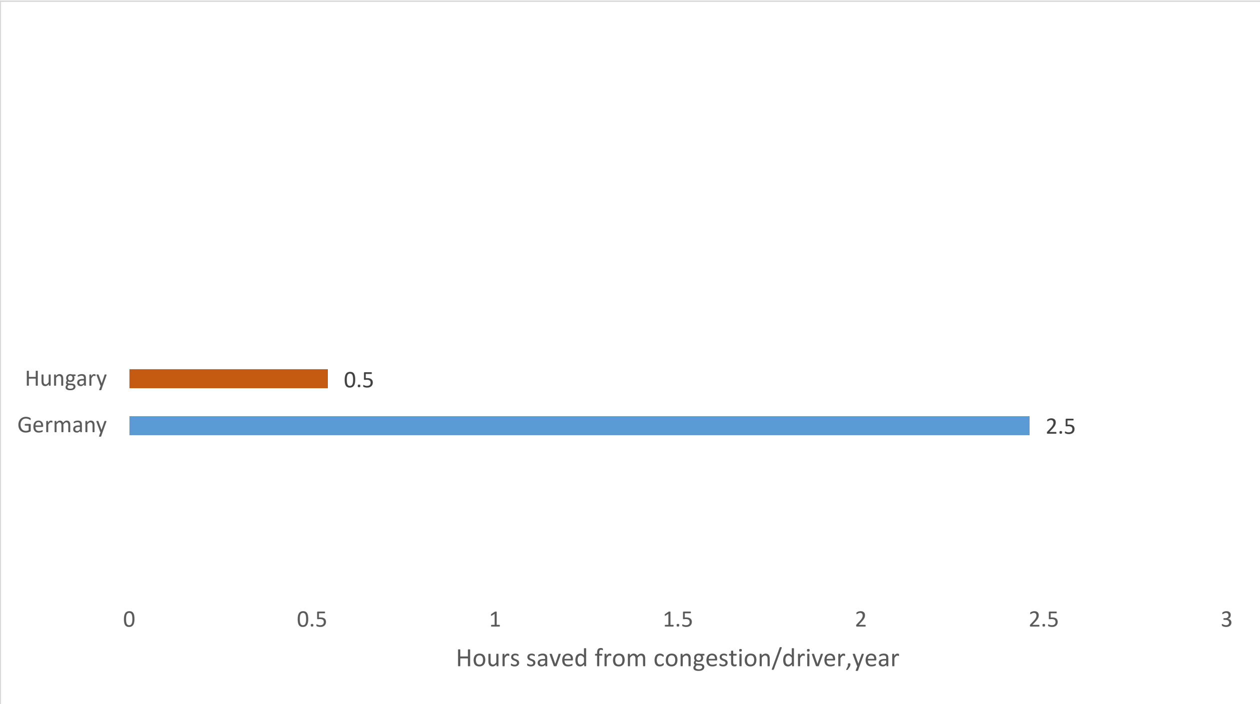


Figure 17: Active time saved in hours from road congestion in the year 2030/per driver

In absolute terms, these figures for both the countries are not high. The active days results in the different scenario are presented in table 30:

Table 30: Traffic congestion time loss during peak hours in different scenario

Country	**Congestion time reported/per driver,year(hour)**	**Total time spent in congestion in the reference scenario (in hours)**	**Total time spent in congestion in the efficient scenario(in hours)**	**Active time (Hours/year)**	**Active time /Driver, (Hours/year)**
Germany	38	763,139	715,516	47,623	2.5
Hungary	5	5,745	5,162	583	0.5

Source: Own elaboration (dissertation calculation, except congestion time reported data)

As discussed in chapter 5, the congestion time reported/per country data is collected from INRIX traffic scorecard and the rest of the data in table 30 are calculated using this dissertation's equation.

Monetization of time saved from congestion: Active time gain from congestion can be monetized as well by multiplying hours saved from congestion with the hourly wage. The mean hourly wage data is extracted from the Eurostat mean hourly wage database (http://ec.europa.eu/eurostat/web/labour-market/earnings/database). The mean hourly wage for Germany and Hungary are around 18 and 5 Euro respectively. By multiplying this wage with hours save, Germany and Hungary can save annually up to 0.8 million Euro and around 2.5 thousand Euro respectively, year by saving traffic time due to the modal shift.

Although it could be a case that all the drivers stuck in traffic jam may not be a worker or going to work thus, may not be accurate to use the hourly national wage to monetize. But, here the main objective to monetize the hours saved is to provide an estimate of the magnitude of the modal shift-related effect on congestion. A person though may not go to work or coming back from work even during peak hours, but with the saved travel time, the person can be socially productive. However, as these traffic hours include only the peak time data, it is highly likely that the majority of the passengers are office goers. Thus, hourly wage here is used as a proxy value to monetize the impact on all the drivers.

Analysis of the result –time saved from congestion: Congestion is not an issue for all the countries within the EU member states and thus, the time saved from congestion can be estimated only for those countries where congestion data is reported. Both Germany and Hungary reported their congestion time and hence their time gains are estimated in this dissertation. Although in absolute terms, the time savings is not much intuitive, but in relative terms, it can be quite significant. For instance, Hungary reported 5 hours/driver traffic time annually (INRIX traffic scorecard data-refer to chapter 5) and with the modal shift towards active transportation, Hungary can save 0.5 hours/driver annually. Thus, Hungary saves 11% of the congestion time by opting for modal shift. Similarly, Germany is reported to have 38 hours of traffic time/driver annually (INRIX traffic scorecard data-refer to chapter 5) and Germany saves 6% of the congestion time by opting for modal shift. Although in absolute figures, Germany is saving more hours compared to Hungary but Germany's reported congestion is also higher compared to Hungary. Thus, it is always recommended to see the relative savings than absolute savings since absolute savings depend on the country size. That means congestion time depends positively on a country's population of car drivers and higher number of car drivers would result in high congestion. Behind these relative high savings of congestion time, the possible reason could be that the modal shift incremental rate in Hungary would be 3.9% in 2030. That means 3.9% more trips are shifted towards active transportation in the efficiency scenario compared to the reference scenario. In Germany, the incremental rate would be 2.9% (COMBI 2018).Thus, due to this higher rate of modal shift in Hungary, the country is gaining more time from traffic relatively compared to Germany. Unfortunately, the different rates of modal shift rate in Germany and Hungary cannot be explained, since the COMBI modal shift model uses many external models to derive the modal shift scenarios.

These multiple models used (such as PRIME, EUCO, ITRAN and ASTRA) make the analysis of different modal shift rates difficult.

6.2 Quantification and monetization of workforce performance resulting from energy efficiency measure:

Working in a deep-retrofit type of building would not only reduce sick days but it also would have a positive impact on employee's performance. As discussed in chapter 4, workforce performance is a tertiary sector specific indicator which accounts for the additional gain in performance by having better mental well-being. Workforce performance does not consider absenteeism or presenteeism related workhour loss.

Results –workforce performance: Workforce performance is calculated by using equation 16 (refer to chapter 4, section 4.3.5.2). The result shows that by moving into deep retrofit-type of tertiary buildings, Hungary and Germany can gain annually around 0.4 million and 4 million working hours respectively. Workforce performance calculates the number of actual hours worked before and after the implementation of tertiary sector-specific energy efficiency measure. To present this data in a reader-friendly way, the actual hours of work are converted into the number of working days. Figure 17 shows the annual workforce performance improvements in working days in a country.

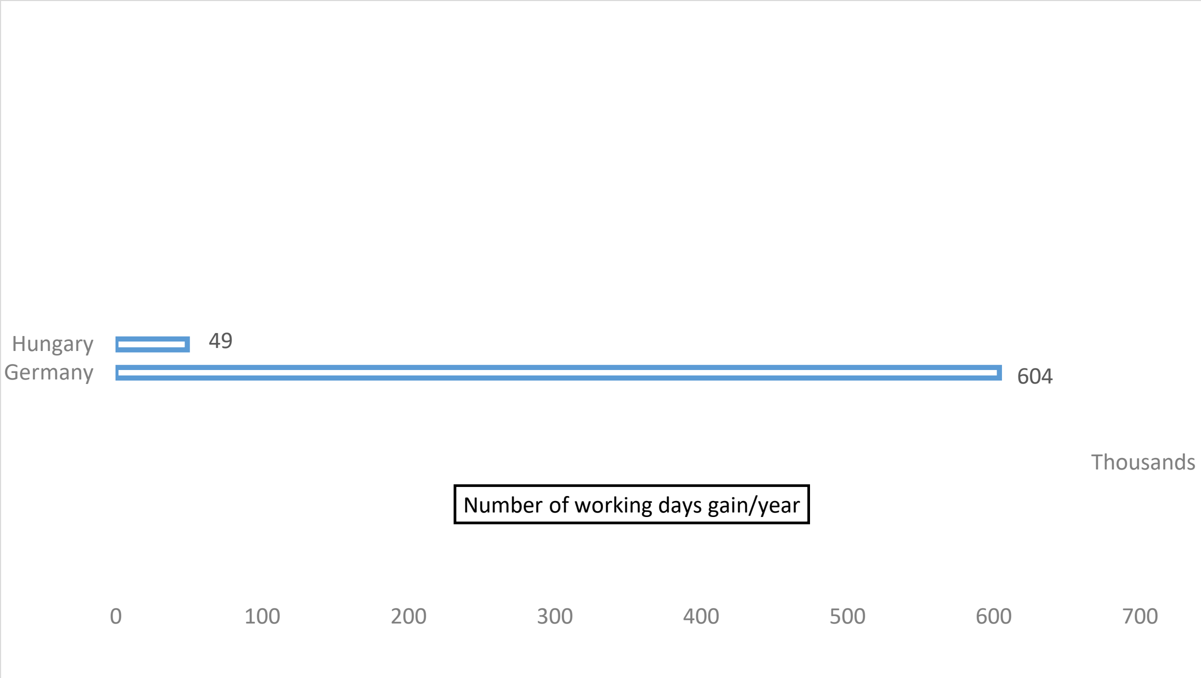


Figure 17: Number of working days gained/per (equivalent to workhours) country by improving mental well-being in the year 2030

These days gains are only due to only improvement in mental well-being. The workforce performance data or in other words, the labour input data in different scenarios are presented below:

Table 31: Labour input in actual hours working in two scenarios

Country	Actual hours workings (Hours/per person,year)	Total Actual hours workings in reference scenario (In billion)	Total Actual hours workings in efficient scenario (In billion)	Total work hours gain/year (In million)
Germany	1,363	46	46	4
Hungary	1,761	6	6	0.4

Source: Own elaboration (Dissertation data, except for actual hours working data)

As discussed in chapter 5, the actual hours working data for each country is sourced from the OECD database and the rest of the data are calculated by using the equations discussed in chapter 4, section 4.3.5.3.

Analysis of the result- workforce performance: In the case of workforce performance, since no country-specific data is available, I use a single productivity gain factor for both countries. My model requires a specific productivity gain factor i.e. what would be the effect on mental well-being due to the HVAC installation in complete airtight buildings. In this study, I estimated the actual hours of working in 2030 for each country after implementing the energy efficiency measure. Since the data I found is per worker's incremental work hour/year after shifting into `green buildings`. The performance enhancement factor is unique here as this factor only reflects the performance enhancement from improved mental well-being which is an addition to the presenteeism days avoided. This additional factor of performance enhancement is added with actual hours working values for each the countries. Thus, a country with higher workforce working in deep retrofit type buildings would have higher workforce performance gain. For instance, Germany has 7% more passive house standard tertiary buildings in the efficiency scenario compared to its reference scenario and also 7% more German workforce work in the deep-retrofit type of buildings compared to the reference scenario. Whereas in Hungary, there are 5% more passive house standard tertiary buildings in the efficiency scenario compared to its reference scenario and 6% more Hungarian workforce work in the deep-retrofit type buildings compared to the reference scenario. Thus, Germany would gain a higher workforce performance compared to Hungary after implementing an energy efficiency measure.

Monitization of workforce performance: Working days gain is simply calculated by dividing work hours gain from energy efficiency measure in the tertiary sector with usual working hours i.e. 8 hours. The work hours (days) gain by shifting into the deep retrofit type of tertiary buildings is presented here as work days gain to provide a more insightful overview of workforce performance impact. The workforce productivity gain can also be monetized by multiplying the number of annual working days gained/ year (equivalent to work hours) with daily wage similar to avoided sick days. To provide the potential for mental well-being, presentation of the monetary values of workforce performance is essential. Thus, by monetizing the workforce performance, the results show that Germany and Hungary can gain annually 34 million Euro/year and 0.60 million Euro/year respectively by gaining more productive work hours from improved mental well-being.

6.3 Summary of results:

Productivity is measured in this dissertation by quantifying different aspects of productivity which are resulted from sustainable energy measures. This study quantifies three indicators of labour productivity which are resulted from two sustainable energy measures namely: the improved HVAC system with an airtight building envelope and the modal shift towards active transportation. The three indicators are active days, workforce performance and earning ability. The earning ability could not be quantified due to the data constraints. The active days have three further aspects: avoided sick days, healthy life years gain and time saved from congestion.

Table 32 summarises the results and present both physical and monetary values of each productivity indicators for both Hungary and Germany:

Table 32: summary of results

Indicator	Germany	Hungary
Avoided sick days/year from residential building sector (In million days)	5.8	0.43
Per capita-avoided sick days gain/year from residential building sector	5.27	2.20
Avoided sick days in Euro (In million Euro/year)	802.6	15.9
Avoided sick days /year from tertiary building sector (In million days)	5.8	0.20

Indicator	Germany	Hungary
Per capita- avoided sick days from tertiary building sector	2.43	1.01
Avoided sick days in Euro (In million Euro/year)	805.5	7.2
Healthly life years gain (in years)	4062	1657
Per capita (per million) healthly life years gain (in years)	1,870	3,849
Monetization of total healthly life years (in million Euro)	602	57
Monetization of per capita healthly life years (in million Euro)	277	134
Workforce performance (Hours/year) (in million hours)	4.8	0.40
Workforce performance (equivalent to work days/year)	603,971	48,781
Monetary values (In million Euro/year)	85.9	1.8
Active time (Hours/year)	47,623	583
Active time gain/driver (Hours/year)	2.46	0.54
Monetary value (Euro/year)	846,735	2,706

Source: Own elaboration (dissertation calculation)

6.4 Sensitivity analysis:

6.4.1 Uncertainties and limitations:

Like any quantitative study, this study also has a certain number of uncertainties and limitations. The key uncertainties and limitations of this study are discussed here:

1) Technical optimization: In this dissertation, technical optimization plays a crucial role to estimate productivity impact. For example, as discussed in chapter 3 if the HVAC

system is not properly installed or properly maintained then it could be a source of pollutant itself. In this study, it is assumed that all the technical measures such as HVAC system are properly installed and maintained.

2) National average versus individual cases: The model used in this study estimate productivity by using national average data. However, it could be the case that individual case is higher/lower than average data. For instance, the reaction towards particulate matter exposure would vary among different individuals.

3) Value of conversion factor: In our model, the disease-specific DALY reduction percentage is used as a conversion factor or health gain factor to estimate active days gain indicator. However, the DALY reduction percentage may include both mortality and morbidity factors. These DALY reduction percentage data are taken from the Healthvent project and it is not clear what the proportion of mortality and morbidity factors in the DALY reduction percentage is. Thus, we have to assume the whole DALY reduction percentage as our conversion factor. However, since the active days gain indicator only consider acute diseases, the DALY reduction percentage would mostly contribute to morbidity.

4) The scenario analysis consists of a certain level of uncertainty for any future forecast. We may not be aware of all the effects of the system on human health and also any of the future economic conditions are unpredictable. Thus, we must rely on the assumption.

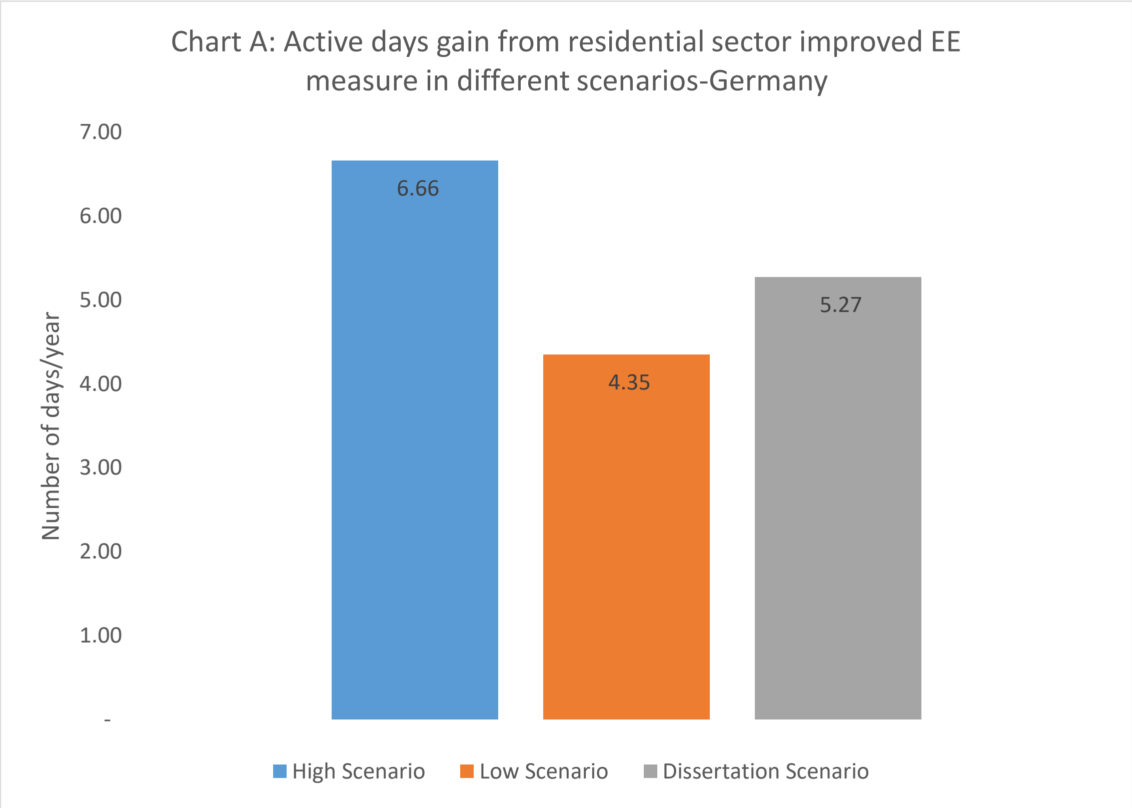
6.4.2 Test of parameters:

There are few important variables in this study whose values are subject to uncertainty. Thus, a sensitivity analysis is required to estimate the uncertainty range of this model. For sensitivity analysis, three key parameters namely conversion factor, performance improvement factor and traffic time saved factor which have a larger influence on the final results, are tested. Each of these parameters are discussed in the section below:

Conversion factor: As discussed earlier, the conversion factor shows how much health gain/loss can be achieved from each retrofit type of buildings. Health improvement only takes place if the buildings are completely airtight and HVAC systems with sensors are installed and maintained properly. If the HVAC system is not properly installed and/or not maintained properly then the intensity of health gains would vary.

In order to provide some sensitivity analysis to estimate the impact of unmaintained or poorly installed HVAC system, a different scenario with lower impact is estimated. This scenario is referred to as low scenario. If HVAC system is properly installed with proper sensors in an airtight building then people living/working in the building would gain a higher health benefits from this measure. Thus, another scenario with the highest impact is estimated. This dissertation refers to it as high scenario. Apart from these two scenarios impact, there is also my model scenario where the health benefits from a properly installed HVAC system in an airtight building is assumed with moderate impact. This scenario refers to it as the dissertation scenario. Comparing these three scenarios would provide an uncertainty range of values. These three scenarios discussed above are the same for avoided sick days, and healthy life years gain. The high scenario is assumed with a reduction of 100% radon, 75% reduction in carbon monoxide and second-hand smoke, and also 75% reduction rate in volatile organic compound (VOC) and dampness exposure. The low scenario is assumed with reduction of 80% radon exposure, 25% reduction in carbon monoxide and second-hand smoke, and 25% reduction in volatile organic compound (VOC) and dampness. Whereas the dissertation scenario assumes a 90% reduction in radon, carbon monoxide and second-hand smoke, 50% reduction in VOC and dampness exposure, and 25% reduction in particulate matter (PM2.5) (Asikainen et al. 2016).

Figure 18 below shows the Germany and Hungary's active days gain/ person who have shifted to deep retrofit type buildings in the year 2030 by installing HVAC system with airtight building envelope (energy efficiency measure-EE measure) in the residential building sector in these two countries.



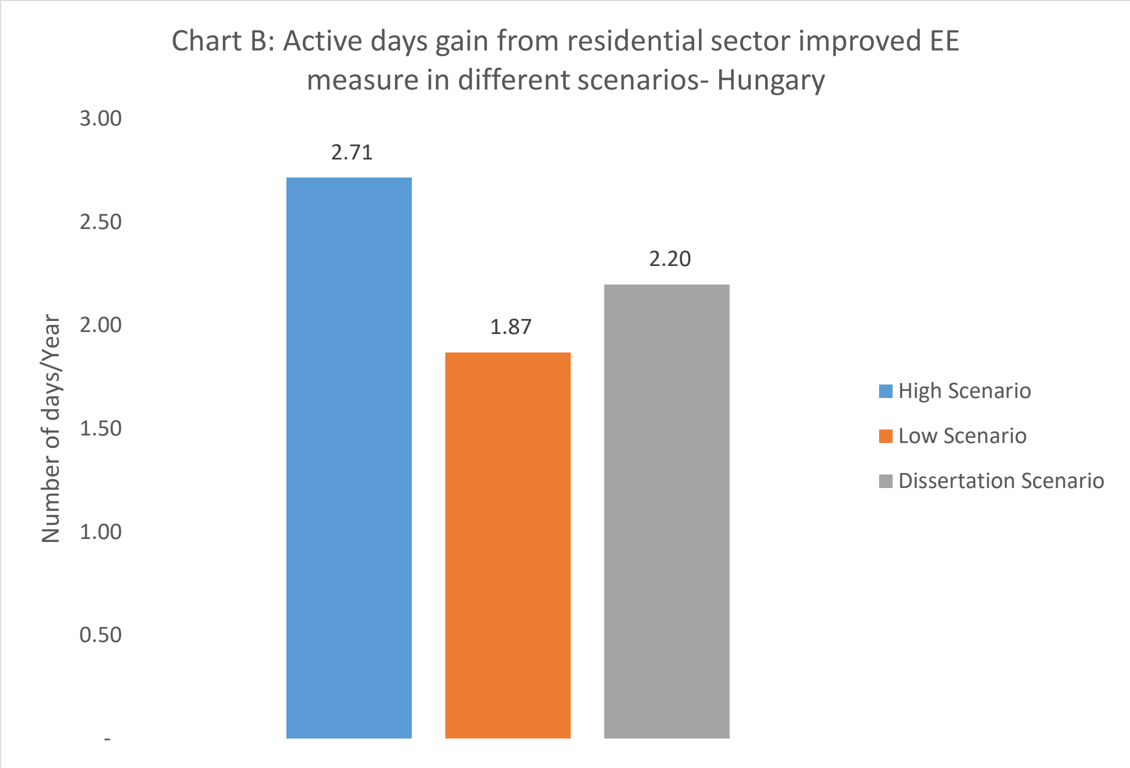
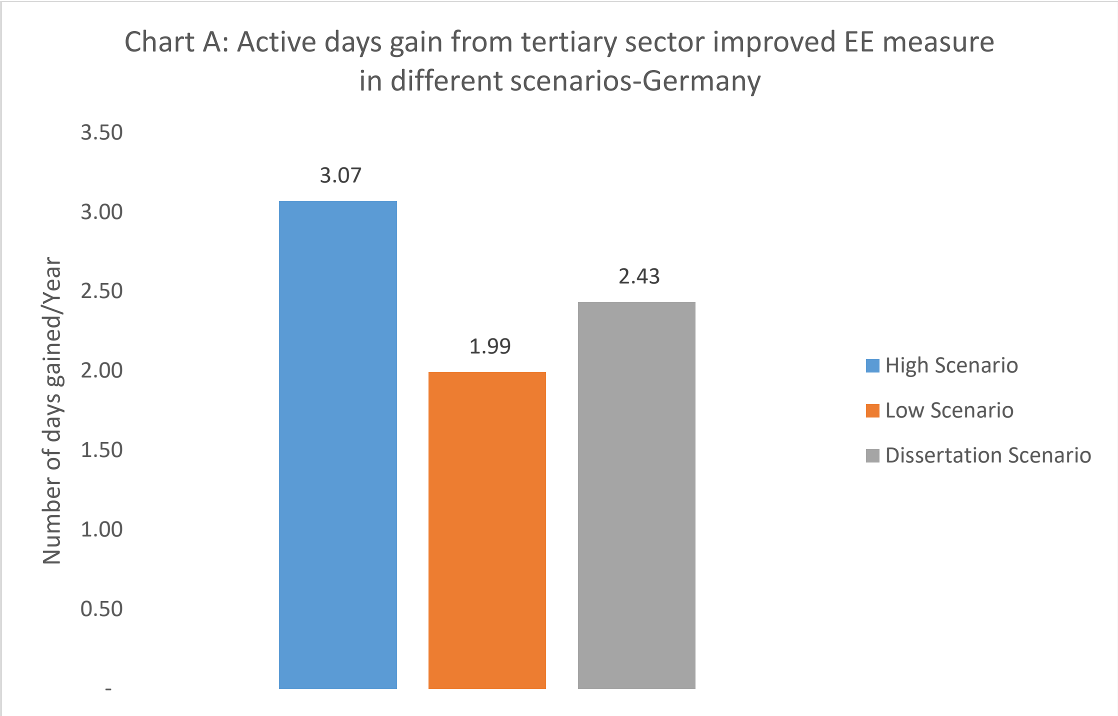


Figure 18: Active days gain in Germany and Hungary in the year 2030 by installing energy efficiency measure in the residential building sector in three different scenarios

As it can be seen from figure 18 that even the lowest possible impact of HVAC system has a significant productivity gain. The data for these three scenario's data are taken from the Healthvent project. Assuming these three scenarios, the range of productivity gain by avoiding sick days for Germany would be between 4.35-6.66 days/per person annually and for Hungary the same would be between 1.87-2.71 days/person, year. These ranges are valid for the residential building sector. Similarly, the uncertainty range can be seen in the tertiary building sector by comparing these three scenarios. Figure 19 shows below the range of uncertainties in the tertiary building sector by installing HVAC measure in both Germany and Hungary:



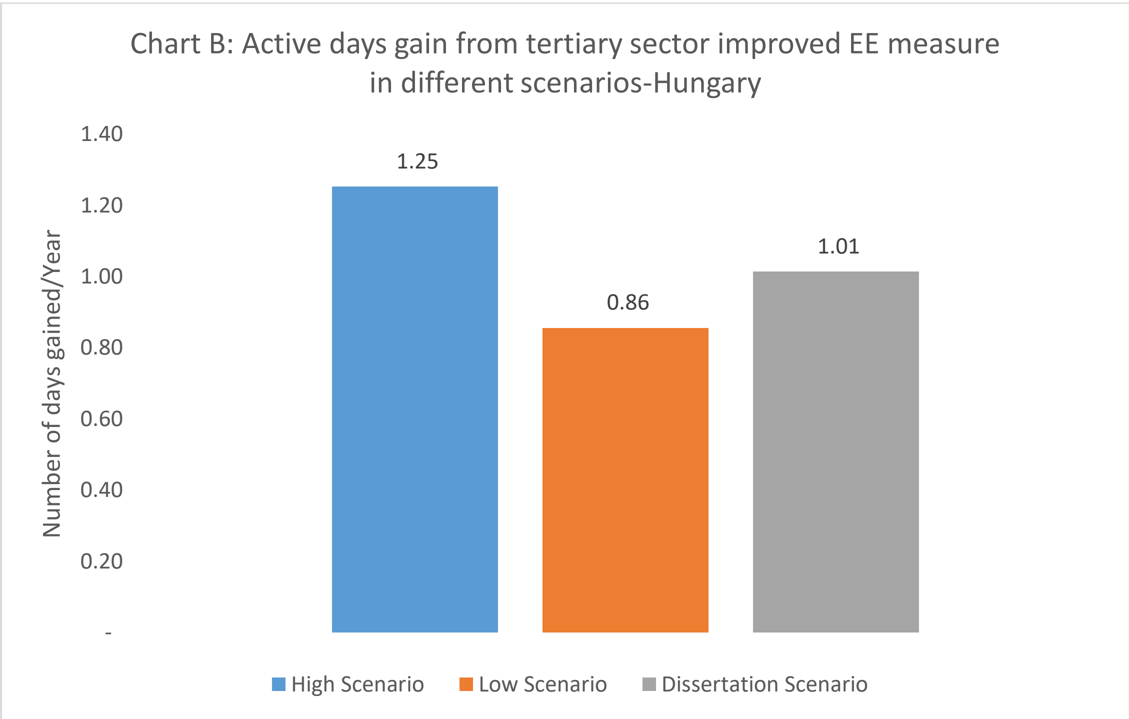
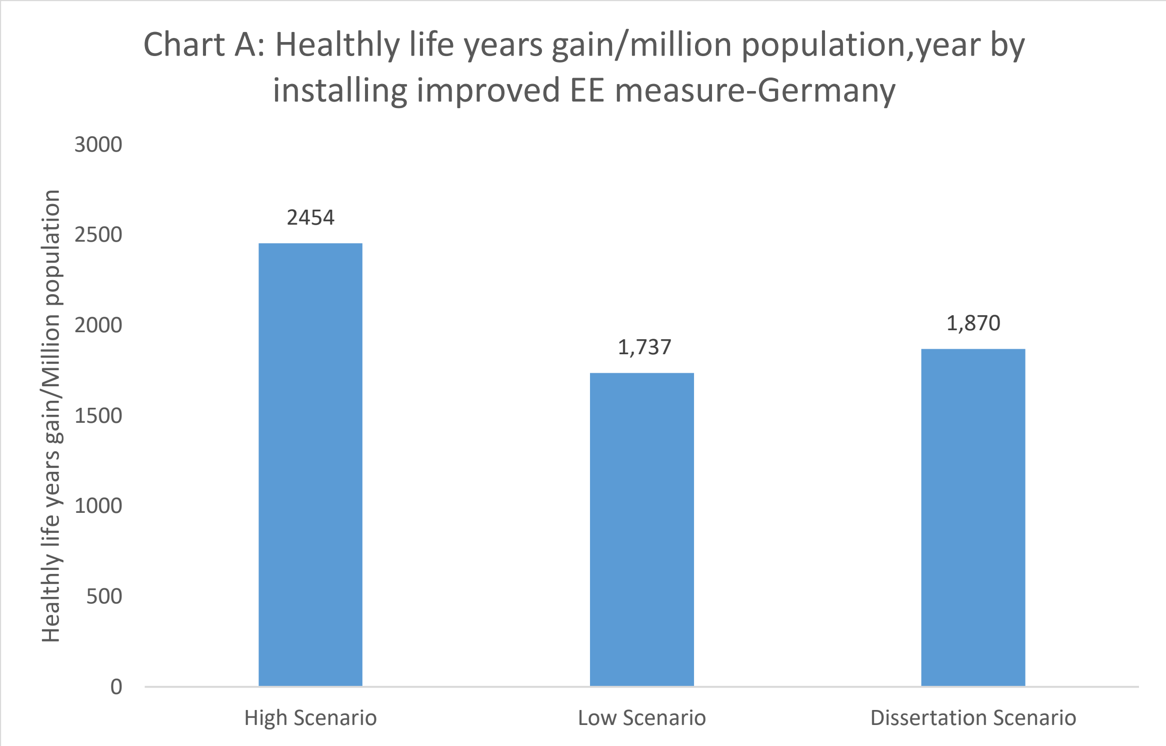


Figure 19: Active days gain in Germany and Hungary in the year 2030 by installing energy efficiency measure in the tertiary building sector in three different scenarios

In case of improved energy efficiency measure in tertiary buildings, the active days gain by avoiding sick days for Germany lies between 1.99-3.07 days per person per year and for Hungary it is between 0.86-1.25 days/person annually.

Similarly, also for DALY a sensitivity analysis can be conducted considering the same scenario definitions.



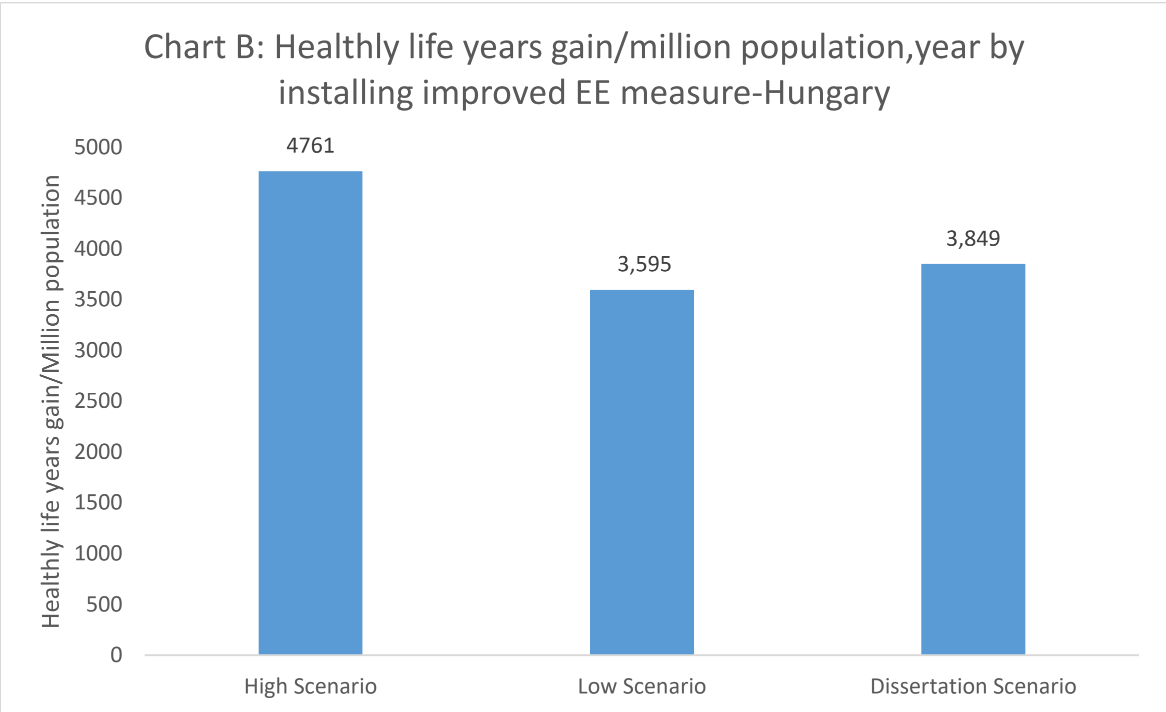


Figure 20: Healthy life years gain in Germany and Hungary by installing energy efficiency measure in the residential building sector in three different scenarios

As it can be seen that the healthy life years gain for Hungary is higher (lies between 4761- 3849 years/per million population) compared to Germany (lies between 2454- 1870 years/per million population).

The reduction rates of different diseases would be different under these three scenarios. For a better understanding, different reduction rates are presented in table 33:

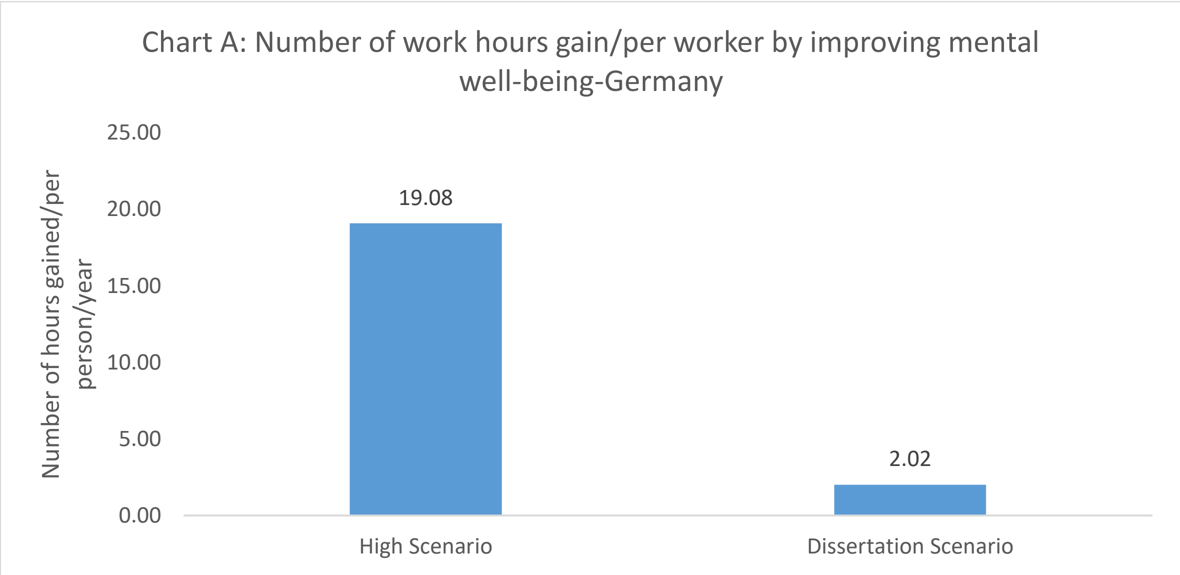
Table 33: Disease specific reduction rate under different scenarios

	Germany			**Hungary**		
	High Scenario	Low scenario	Dissertation scenario	High Scenario	Low scenario	Dissertation scenario
Asthma & allergy	72%	46%	57%	64%	43%	52%
Lung (trachea & Bronchus) cancer	70%	47%	54%	68%	48%	56%
COPD	60%	42%	45%	50%	37%	39%
Cardiovascular diseases	58%	43%	44%	47%	37%	38%

Source: Own elaboration (data extracted from the Healthvent project)

The disease reduction rate in the dissertation scenario is previously discussed and presented in section 6.1. These disease reduction rate data are taken from the Healthvent project where a dose-response model is used to calculate these reduction rates. These reduction rates show that even with the low scenario, the HVAC system with airtight building envelope can play a significant role in the improvement of health.

Performance improvement factor: As discussed, performance may enhance by reducing mental stress and anxiety. These reduction rates would vary as per the nature of the work. The uncertainty analysis for performance improvement factor mostly reflects this nature of job that impacts on productivity. More precisely, if the nature of the job is repetitive, such as proofreading, typing etc., then productivity gain would be much higher by working in a deep retrofit type of buildings. In this study, since we are calculating the workforce performance at the national level, it is difficult to consider the nature of the job. Hence, we have considered a factor for our model which is kind of mix of all kind of jobs such as managerial where the nature of the job is mostly not repetitive and support staffs where the jobs may be repetitive. However, if we consider mainly repetitive tasks then productivity gain would be much higher than 2.02 hours/per person annually. We call it to be dissertation scenario. Thus, as per Wargocki et al 2000 study, adequate ventilation rate at the workplace would improve the work performance by 1.4%. In this study, I use this factor as our source to find uncertainty range of workforce performance factor. We call it as high scenario. Figure 21 shows the productive hours gain by avoiding mental stress and disorder for both Germany and Hungary:



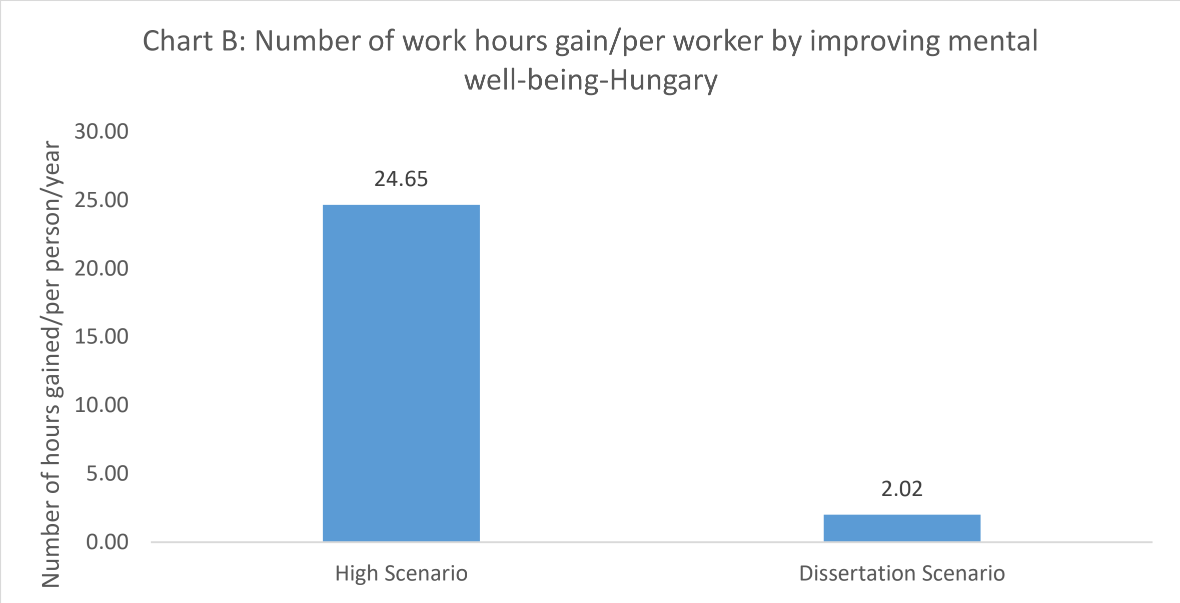


Figure 21: Work hours gain/per person in the year 2030 by installing HVAC system in the tertiary building sector

For both Germany and Hungary, the same performance improvement factor is used. The performance improvement factor's uncertainty range is presented here to show the range. The significant difference between these two scenarios mainly occurs due to the nature of the job and sample size. In the high scenario, the nature of the job is repetitive and requires less skill. In these kinds of jobs such as proofreading, logical reasoning etc. there remains a higher potential to enhance performance. Additionally, the sample size of Wargocki et al 2000 study was quite low- more precisely it was only 30, whereas in Singh et al 2010 study's sample size was 142. Despite this difference in sample size, this uncertainty analysis sheds a light on the huge potential for performance improvement through improving mental well-being by installing the HVAC system in an airtight tertiary building. Unfortunately, there is no data available for any other range of performance improvement by improving mental well-being through the HVAC system.

Traffic time saved factor: As discussed earlier in chapter 3 and 4, the value of TS is calculated from De Hartog et al. 2010 study where the rate of modal shift towards active transportation is equal to road congestion reduction rate and from COMBI input data, the rate of modal shift can be calculated. Hence, in this study, the rate of modal shift is equivalent to the rate of traffic congestion rate. Thus, in other words, traffic time saved factor would vary as per the country-specific modal shift towards active transportation rate. However, Cairns, et al 2004 study assumes a reduction rate of traffic congestion due to active transportation. This study found that 11% reduction in all traffic can be achieved nationwide by reducing car use in the UK. Thus, considering this traffic time saved factor referred here as the high scenario, it can be compared with the dissertation model's result which is referred to as dissertation scenario.

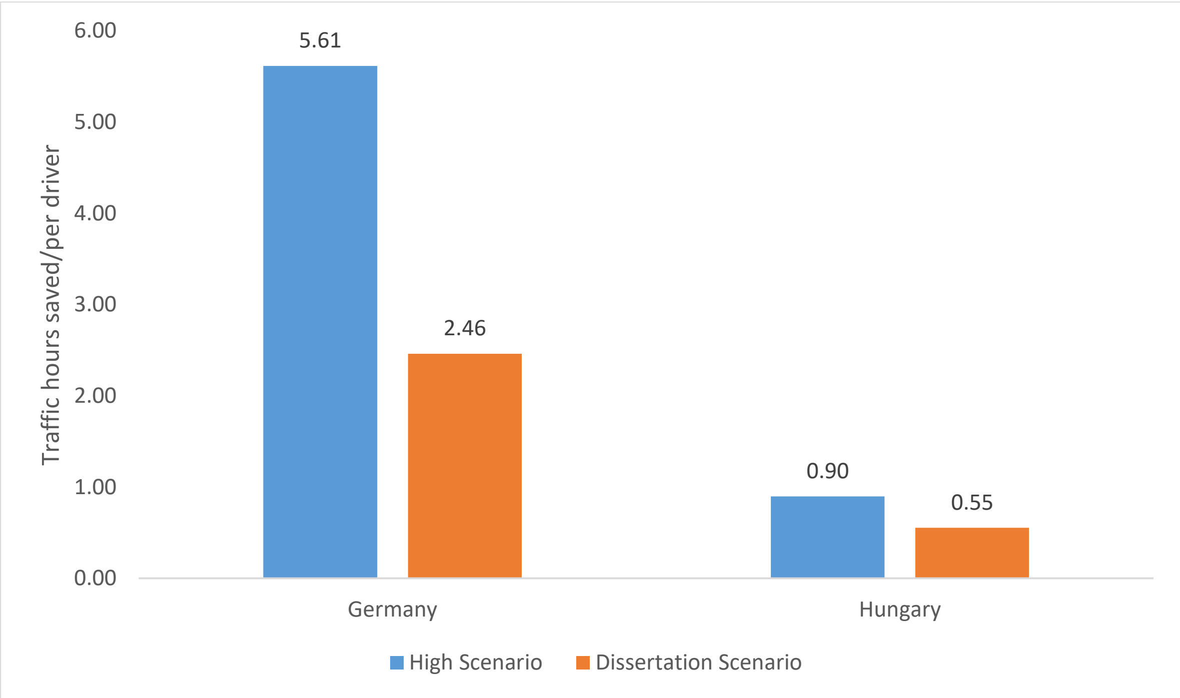


Figure 22: Traffic time saved per driver in the year 2030 for Germany and Hungary

In the case of high scenario, the UK's rate of congestion reduction is used for both Germany and Hungary. In the dissertation scenario, the country-specific traffic time saved factor is calculated from the modal shift towards active transportation rate. Thus, there remains difference between these two scenarios, which also shows the range of uncertainty. For instance, in Germany this range is between 2.5- 5.6 hours/ per driver and in Hungary the range is in between 0.5-0.9 hours/per driver on an average in the year 2030.

Thus, from this section, it can be concluded that even with low-performance range, there can be a significant impact of energy efficiency measure on productivity. The purpose of this dissertation is not to evaluate productivity impact accurately rather provide a magnitude of the impact, which can be obtained from implementing energy efficiency measure. With the help of the uncertainty analysis, this dissertation shows that even considering all the obstacles, the energy efficiency measures have a significantly positive effect on productivity. This positive magnitude of the energy efficiency measures also reflects what we were missing so far by not incorporating these multiple impacts of energy efficiency.

6.5 Summary of the chapter

The results for all the indicators of productivity impacts are presented and analyzed in this chapter. The results of this study are already summarized in table 31 and thus, in this section, the summary of results has not been presented. Like most of the empirical research, this study has also some uncertainties due to which a sensitivity analysis is conducted to show the sensitivity range. The sensitivity analysis shows that even with the lower range of data, the magnitude of productivity impacts is positive. In the next chapter, it can be discussed that how productivity impacts and why these impacts are important from a broader perspective.

CHAPTER 7: ANALYSIS OF THE POTENTIAL OF THE PRODUCTIVITY IMPACTS OF IMPROVED ENERGY EFFICIENCY MEASURES

"The aim of argument, or of discussion, should not be victory, but progress"

Joseph Joubert

7.1 Discussion about the importance of multiple impacts:

The benefits of sustainable energy policies go beyond energy cost savings. The benefits range from energy cost savings to improvement in health, productivity or even macroeconomic impacts (Ryan and Campbell 2012). However, these multiple impacts of energy policies do not get incorporated into a policy evaluation analysis. One of the key reason for not incorporating these impacts is the lack of a mature methodology to quantify these impacts (Ürge-Vorsatz et al. 2016). Thus, in order to fill this knowledge gap regarding quantification methodology, the aim of this study is to provide better tools and methods to quantify multiple impacts of sustainable climate policies which can assist to the discussion of the science of multiple impacts quantification.

Quantification of impacts is crucial not only to sell energy efficiency policies, but also the multiple impacts would be one of the outcomes of these policies. The inclusion of impacts into policy evaluation would make a stronger case for energy policies. Thus, not measuring the impacts would mean undervaluation of the natural potential of a policy. For instance, this dissertation takes two energy efficiency measures which lead to the productivity impact. Both of these measures have an immense potentiality to save energy usage and at the same time, they have an almost a direct impact on health and productivity. Therefore, implementing (or adopting) improved energy efficiency measures would not only mitigate climate change globally but at an individual level or at a societal level, it can be beneficial via the multiple impacts, for example, health and productivity impacts.

The research question of this study is how to quantify multiple impacts especially productivity impacts rigorously and by answering the research question, one of the key contributions of this dissertation is to provide a methodological framework to rigorously quantify multiple impacts. The methodological framework as discussed in chapter 4, has four key components:

1) Identification,
2) Quantification in diffrent scenarios,
3) Monetization, and
4) Assesssment of quantification.

Each of these components has contributed to the knowledge of impact quantification methodology. For instance, in order to conduct a systematic identification of the pathway to productivity, each step needs to be understood from implementing improved energy efficiency measures to productivity. Thus, for identification purpose, this dissertation uses an impact pathway approach which enables all the pathways leading towards productivity impacts. Similarly, for quantification purpose, this dissertation develops equations to quantify different aspects of productivity. These equations and their respective data are quite intense in nature as discussed in chapter 4 and 5. Each of these equations is contributing to the methods of labour productivity quantification. Finally, the assessment discusses the reasons behind the results and by doing so, the assessment shows the potential of productivity impacts.

With the methodological framework, it is easier to discuss the significance of multiple impacts especially the productivity impacts. Though labour productivity is mostly seen as an incentive to the investors only, this dissertation argues that productivity can go beyond the economic benefits. Moreover, since health is an input factor to productivity, there is an ethical responsibility for the policymaker to design sustainable energy policies through which state of health would also improve. Sustainable energy policies are mostly perceived as climate change mitigation techniques but this dissertation argues and also shows that the inclusion of multiple impacts can provide a multi-objective framework for the sustainable energy policies. Thus, the overall contribution of this research does not only limit itself to quantification, but it goes further representing the various economic as well as ethical side of these energy efficiency measures.

7.2 Productivity impacts in the context of well-being:

Productivity impact is one of the biggest multiple impacts as it can be seen in table 3 and table 11. However, so far only a few handful aspects of productivity is measured and productivity impacts are mostly seen as an incentive to the investors. This dissertation shows through numbers that productivity can be equally beneficial for the individual, especially when it involves health risks. More precisely, since health aspects are involved, productivity impacts are equally if not more lucrative for the individual as well as for the investors. For instance, as it is discussed in chapter 6, Hungary and Germany save/gain 29% and 36% of active days by avoiding sick days. These sick days savings would not only be beneficial for the investors but also for the individual who avoids certain health risks. Thus, these days gain lead to improvement in welfare and well-being.

Discussion of active days in the context of well-being: The scope of improved efficiency measures is quite big in European member states not only in terms of energy savings, but also in terms of labour productivity improvement. For instance, in Hungary, 70% of the burden of diseases due to indoor exposure can be caused due to outdoor pollutant exposure indoor (Hänninen, and Asikainen 2013). Whereas in Germany 64% of the burden of due to indoor exposure can be caused due to outdoor pollutant exposure indoor (Hänninen, and Asikainen 2013). Thus, installing improved energy efficiency measure in the building sector can save many healthy life years by mitigating indoor pollutants concentration and preventing outdoor pollutant infiltration inside. In this dissertation, although the HVAC system with an airtight building envelope helps in reducing exposure induced diseases by avoiding outdoor exposure, improved HVAC with an airtight building envelope does not directly mitigate outdoor pollution. However, installing energy efficiency measures indirectly save a significant amount of energy use which reduces the outdoor pollution concentration (Ürge-Vorsatz et al. 2007).

How much outdoor pollutant can be reduced that is beyond the scope of this dissertation but for future research endeavor, this topic should be explored in detail.

The results of active days gain by avoiding indoor exposure to pollutants may not be directly compared with other studies as there are methodological and geographical gap across different studies. For instance, Milton et al. 2000 study showed that proper rate of ventilation can save up to 1.2 to 1.9 days annually which accumulates to around 35% savings of sick leaves. However, this figure is only for office buildings in Massachusetts, USA, and this figure considers only ventilation rate related absenteeism. Whereas, this dissertation concerns both absenteeism and presenteeism resulting from indoor exposure at the national level. Furthermore, Milton et al. 2000 study analysed the sick leave savings based on 1994 US sick leave data which is different from what is used in this dissertation (compensated sick leave for each country). However, for both Hungary and Germany, the active days gain from tertiary building sector data are within the range of 1.0-2.5 days annual savings/per person which is more or less similar to Milton et al. 2000 study. However, one point needs to be mentioned that in this dissertation, active days incorporate both absenteeism and presenteeism whereas Milton et al 2000 study considers only absenteeism. The difference could be due to different geographical boundary and surely due to the difference in methodological approach. This dissertation uses the time spent factor to distinguish between residential and tertiary building effects. No literature is found on residential building-related per person active days gain. This dissertation makes the first attempt to estimate the active days due to residential sector renovation. Thus, to compare this dissertation‘s results on how many sick days can be saved, more control group field study needs to be conducted in both tertiary as well as in the residential building sector.

Apart from sick days, active days are also measured through DALY gain. Hänninen and Asikainen 2013 study (from healthvent project) measures DALY due to indoor exposure as well. As per Hänninen and Asikainen 2013 study, Germany and Hungary can save 1920 and 3960 DALY/million population respectively which is really close to the result of this dissertation. As per dissertation research, Germany and Hungary can save 1870 and 3849 DALY/ million population respectively. The figures may look quite close but actually, they are not since this dissertation refers per capita population as the population who have shifted to deep-retrofit type buildings. The difference between these two studies is due to the difference in methodology. More precisely, Hänninen and Asikainen 2013 study uses a dose-response model by assuming a certain percentage of the population exposed to the pollutants to calculate the DALY. Whereas this dissertation uses population in 2030 living in the different type of retrofitted buildings and then uses the reduction potential to the population. The reduction percentage or the health gain is assumed to be obtained only for people living in deep- retrofit type of buildings. Thus, normally, compared to whole population estimation, the population living in deep-retrofit type buildings would give a small number. However, due to a more detail scenario used in this dissertation compared to healthvent project, the contribution of this study is still significant.

Therefore to conclude, the active days either through avoided sick days or healthy life years gain, achieve a higher well-being by attaining both higher welfare and improved quality of life. More work days are available by avoiding sick days. By working more days, one can earn more and thus, achieve a higher welfare/economic well-being. Moreover, sick days avoidance is resulted from avoiding a certain type of diseases which improves the overall state of health and hence, quality of life improves.

Discussion of workforce performance in the context of well-being: As discussed in chapter 6, workforce performance improvement of a country mainly depends on how many people have shifted to the deep retrofit type of tertiary buildings. Here one of the concerns could have been the population factor. More precisely, the concern questions whether countries with higher population could have higher workforce performance gain since country-specific per capita gain is not available. However, from the dissertation data, it can be seen that 7% of the working population has shifted in the deep-retrofit type tertiary buildings in Germany and 6% of the working population has shifted in Hungary. Thus, despite having a huge difference in population between these two countries, the shift in population percentage is not relatively as high as the difference in total population. Here, the point is that only population may not play a crucial role but factors such as unemployment rate, retrofitting rate and overall growth of the economy can influence the result of this dissertation model. Thus, these factors apart from retrofit rate, are considered to be the same as 2015 for both of the countries.

Another key issue with the performance indicator is that it is not showing a significant amount- meaning gaining per person 2.02 hours annually may not be considered as significant. However if this dissertation shows that even with a small figure like 2.02 hours can prove to be a significant gain country wise. There are a couple of challenges to find performance enhancement indicators in this dissertation which are discussed below:

- Performance enhancement value should only have resulted from improved mental well-being. This figure should not consist of any effect due to presenteeism as it is already considered in the model through avoided sick days. Thus, finding value only due to improved mental well-being was not easy.
- The value of performance enhancement factor also depends on the nature of the job and since this dissertation is estimating performance at a national level, nature of the job has to be mixed- meaning all repetitive and non-repetitive jobs need to be considered. Otherwise, the results for this indicator could be biased. A detailed explanation with sensitivity analysis is provided earlier in chapter 6, section 6.4.2.

Considering these factors discussed above, no other studies could be found to compare this dissertation results. However, there is Wargocki et al 2000 study which showed a 1.4% increase in the work performance after shifting into a good retrofitted building. Thus, considering this result, a sensitivity analysis is conducted in chapter 6. The importance of the performance improvement indicator is crucial because it indicates that mental well-being is correlated with work performance and despite being physically fit, a poor mental well-being can cause lower performance. This study refers mental well-being improvement resulted from improved indoor air quality and building condition. Thus, improved mental well-being by improving building conditions can certainly improve the mental health and hence the quality of life.

Discussion of time saved from congestion in the context of well-being: Active time gain from congestion mainly depends on three factors:

1. Number of car users in peak hours
2. Number of people (in percentage) opting for modal shift towards active transportation
3. Time spent in traffic during peak hours

From the above mentioned three factors, number of car users and time spent in traffic are positively correlated i.e. if one of these goes up the other factor also moves in the same direction. Thus, the deciding factor of active time gain here is the number of people opting for the modal shift towards active transportation. In other words, modal shift percentage is the key deciding factor of active time gain. Thus, Hungary having 3.9% of modal shift rate towards active transportation achieves 11% reduction in congestion time during peak hours, while Germany having 2.7% of modal shift rate towards active transportation achieves 6% reduction in congestion time during peak hours. Therefore, this dissertation confirms the previous literature conclusion (see (Buis, and Wittink 2000; De Hartog et al. 2010) that a modal shift towards active transportation can reduce congestion significantly.

Time saved from congestion in this study only measures the time gain from peak hour's congestion. The car users' data is also for peak hours only. Active time only shows the savings from peak hours traffic time. However, the total time spent in transportation may remain the same over the year. One of the key reasons behind this could be the stability of annual travel time. More precisely, studies show that the time used in transportation is more or less stable per person (Petersen et al. 2009; Fleischer, and Tir 2016). One of the possible reasons behind this phenomenon is that people travel to a long destination for vacation, leisure etc. and thus, saved time from daily commute may not be spent in transport only (Fleischer and Tir 2016). Thus, it is important to note that this dissertation's intention is not to provide a magnitude on how much total travel time can be saved annually, rather it provides a magnitude of how much time spent in congestion can be saved during peak hours of traffic due to modal shift towards active transportation. Time-saving from congestion does not only result in less travel time and hence, more time for work/leisure, but it also reduces the disutility out of displeasure of being stuck in traffic. These saved time and reduced disutility improves the overall well-being of a person.

Modal shift towards active transportation has certain health effects as discussed in chapter 3. By using equations 14 and 15, the health effects of the modal shift towards active transportation can be measured. To measure the avoided sick days and healthy life years gain due to modal shift towards active transportation, the following data are required:

1. Country and disease-specific values of conversion factor which show the health gain factor by being physically active and by avoiding outdoor pollution for different diseases. This conversion factor of disease specific health gain should reflect both positive and negative health effects as discussed in chapter 3.
2. Number of people who have opted for modal shift towards active transportation. More precisely, country-specific modal shift percentage.

3. Age distribution of people who have opted for the modal shift in order to calculate the risk of accidents.
4. Disease-specific DALY, absenteeism and presenteeism data which are caused due to outdoor exposure.

The absenteeism and presenteeism data can still be calculated, but the other two data points i.e. the value of disease-specific conversion factor and age distribution of the people who have opted for the modal shift could not be found because the conversion factors need to be linked with the rate of modal shift. Since the value of conversion factors is not available, this dissertation would not be able to measure the health aspect of active transportation. However, in future, if the conversion factor data and age distribution data can be found, the health effects of active transportation can be measured easily by using the proposed equations. The health effects have a direct link with both the components of well-being. More precisely, if the net health condition improves then a person would be more productive and hence, achieve a higher welfare and, also health improvement further leads to achieving a higher quality of life (Lequiller and Blades 2014). The productivity aspect of modal shift has not been discussed in any other study this comprehensively yet. Thus, this dissertation starts this discussion on productivity aspects due to the modal shift towards active transportation by defining all the relevant aspects of labour productivity.

Discussion of earning ability in the context of well-being: Earning ability indicator can be measured by using equations 17 and 18 as discussed in chapter 4. However, in order to estimate earning ability, the following data are required:

1. Data on disease-specific school days loss for each member states
2. The value of SL i.e. percentage value of skill loss due to being absent from school in a year,
3. Country-specific average future income,

4. Value of health gain factor (CFvi) after retrofitting home /school

Since these data are not readily available, the earning ability indicator cannot be estimated. In order to estimate the earning ability gain, an econometric modelling needs to be used to determine the value of SL. Thus, for future research purpose, calculating earning ability can be a really good option. Although earning ability indicator could not be measured due to data and methodological constraints, the significance of earning ability is not less compared to the other indicators of productivity. To explain it further, one of the components of earning ability is the loss of future income opportunity of children due to illness. Any kind of health risk to children should be avoided not only because of there is an ethical side attached to it, but in addition, school days missed due to sickness also results in loss of human capital (Sachs and Malaney 2002). Thus, apart from improving quality of life, another aspect of accumulating human capital is attached to children's school days loss due to BRI. Moreover, by saving parent's absenteeism and presenteeism due to child care, acts similarly like active days achieving a higher well-being.

Further steps towards cost-benefit analysis (CBA): Now since productivity impact is quantified, the value of productivity can be incorporated into CBA. However, in order to conduct a CBA, the investment costs along with other values of impacts are required. Otherwise, the energy improvement measure would be undervalued. Thus, in order to evaluate an energy efficiency measure, other impacts resulting from it, need to be rigorously quantified as well and then only it can be incorporated into CBA. Partial analysis such as only incorporating productivity impact along with the investment cost i.e. cost for implementing the improved energy efficiency measure would not evaluate the full potential of the measure. While conducting a CBA, one needs to be very careful with the time period analysis. For example, if this dissertation results are incorporated into a CBA then, the cost of implementation of energy efficiency measure should be annual i.e. in a year as the benefits in this study is for a year. Otherwise, the comparison between cost and benefits would not fair. Another option would be to multiply the benefits with lifetime of the technology in order to have a valid comparison, For instance, the energy efficiency measures of the building sector has a life time of 25-30, then benefits from this study should be multiplied by life time of the energy efficiency measure in order to have a valid comparison.

7.3 Discussion on data and methodological challenges:

Like every quantitative study, this dissertation also has certain methodological limitations which are discussed in detail in chapter 5. As discussed in the methodological framework, the quantification of impacts needs to conducted in a careful and rigorous manner to avoid any kind of biases (i.e. incorporate both positive and negative impacts). However, the rigorous evaluation of impact is quite data intensive. In some cases, due to data unavailability, the impact cannot get quantified (e.g earning ability). On the contrary, in some cases, proxy data are used to calculate the impacts. For instance, in order to calculate avoided sick days, country-specific absenteeism data are taken from OECD portal named compensated sick leaves which actually underestimates the total sick leave taken. Another sick leave data is available at OECD portal named self-reported sick leaves. Theoretically, self-reported sick leave data should have been higher than compensated sick leave but this is not the case for Hungary. For Germany, self-reported sick leave data is not even available at the portal. Furthermore, in the year 2003, the annual per capita self-reported sick leaves for Hungary were 9.5 days and suddenly in 2009 they went down to 5.5 days and in 2014 they further went down to 3.2 days (OECD dataset of compensated sick leaves). The years in between 2003,2009 and 2014 data are missing. This kind of sudden drop in per-capita sick leave is suspicious and no significant rationale can be found to justify this sudden drop. Hence, self-reported sick leave data carries a bit of suspicion. Thus, to be on a safe side, compensated sick leave data is taken as a proxy data for actual sick leave taken which would be much higher because not all the sick leaves are compensated.

Similarly, proxy data are used for monetization techniques. Thus, by using proxy data where 'real data' is unavailable, the science of multiple impact evaluation develops significantly further.

For methodological challenges as discussed in chapter 4, section 4.3, this dissertation methodology deals with these challenges (baseline, context, and distributional impact) to quantify productivity impacts rigorously. In the section below a few examples of the solutions are discussed:

Context Dependency: Context can be referred to as some variables which provide a background for a particular policy or action, also influence the outcome of the policy or action (Urge-Vorstaz et al. 2016). Context dependencies usually include broader socio-economic settings such as cultural and behavioural attributes, environmental conditions, market conditions and much more. Since the focus of this dissertation is on actions rather than on policies, the wider policy context dependencies are out of the scope. For productivity research, we have identified the following context dependencies:

1. Road congestion is context dependent. More precisely, road congestion is a typical urban problem and in this dissertation, productivity impacts are estimated at a national level. Many of the countries do not have congestion. In productivity research, the country-specific road congestion data (congestion data is extracted from INRIX scorecard) is calculated from city level road congestion.
2. Outdoor air pollution level across countries causes several diseases such as cardiovascular diseases and cancer. These outdoor pollutants infiltrate indoor and hence countries with higher outdoor pollution would have more such diseases such as cancer or cardiovascular disease. That is why there is a strong need for filtration. For

productivity research, the data used in this study is from the healthvent project has already incorporated these outdoor pollutant factors.

Definition of system boundaries and distributional aspects: In any quantification method, it is a big challenge to find the appropriate system boundaries and to tackle the spill over effect because the evaluation of impacts depends on the scale and unit of analysis. For instance, to measure productivity impacts, it is important to know whether the productivity varies from rural to urban or whether some of the productivity impacts go beyond country boundaries. Also, the additional income due to productivity improvement would vary across different income groups.

However, due to data and resource constraints, distributional effects cannot be quantified. Productivity gain by shifting into deep retrofit type buildings can gain more work days and can save money from spending in medical expenditure. These savings utility would be different across different income groups because people in lower income group have a higher marginal utility of income. In other words, the utility of one additional income is more in lower income group compared to the higher income group. In order to estimate productivity impact at lower income group, we would need the following data:

1. How many people in the lower income group are shifting to deep retrofit type buildings (both residential and tertiary buildings)?
2. What are the different income levels and elasticities across different income groups?

If these above-mentioned data are available then in future it is possible to run a scenario analysis model to estimate the distributional impact.

Baseline: As it is discussed in chapter 4, selecting a dynamic baseline is really crucial for impact quantification. This dissertation uses project COMBI scenarios to evaluate impact and COMBI uses a detailed bottom-up stock model to calculate the reference scenario and efficiency scenario. COMBI uses this stock model by extrapolations of past developments and accounting for current policies (reference/baseline) and additional policies (efficiency) scenario (Chatterjee et al. 2018). Thus, it is safe to say that COMBI uses a dynamic baseline that incorporates existing EU policies. This also implies that substantial energy efficiency improvements are already incorporated in the baseline (Chatterjee et al. 2018).

7.4 Policy relevance

The main aim of this dissertation is to provide a methodology by using which multiple impacts can be quantified and hence can be taken into account in policy evaluation. The main purpose of this study is not to recommend any policy directly but rather to provide an idea about the magnitude of multiple impacts of improved energy efficiency measures. However, this study shows the importance of multiple impacts by taking productivity impact as an example and while doing so, this study also indicates the potentiality of any sustainable energy policy. The evaluation of any sustainable energy policy would be an under estimation without their impacts. For instance, the results of this dissertation show the significance of productivity impact and incorporating productivity impact into any decision-making analysis such as cost-benefit analysis or cost-effectiveness analysis or multi-criteria analysis would change the importance of energy policy. The common goal of any sustainable energy policy is to reduce the energy use and it has been the entry point for any policymaker. However, this study shows that even only the impacts can be an entry point for any policymaker to design a sustainable energy policy. In other words, sustainable energy policies are a well-fit in the European commission's multi-framework policy goal by considering all the impacts of the policies. By using this dissertation's proposed methodology, a policymaker can be able to quantify all the additional effects of a sustainable energy policy and incorporate them in a decision making the analysis. This would certainly change the evaluation overview of any sustainable energy policy. The evidence of this dissertation translates into a series of recommendations:

1. Existing sustainable energy policies and measures should be reassessed by incorporating all the additional effects especially productivity-related effects of any low-carbon techniques. Then a proper cost-benefit analysis could be done which would not underestimate the potentiality of the energy policy.
2. By seeing only the productivity values for both Hungary and Germany, it can be recommended to have more deep energy efficiency programs (like efficient scenario). Deep energy efficiency scenario results in reduction of the burden of diseases which has an ethical side attached to it since it is also related to health. More precisely, years of healthy life can be saved by opting for deep energy efficiency programs and health is a priority for every government.
3. In order to reduce the productivity loss results from presenteeism, the social leave policy for Hungary needs to be improved. Hungary can follow the social leave policy framework of Germany. The presenteeism days are not reported hence, the employer does not know how much work hours is actually lost. One possible example could be the actual work hours data for Germany and Hungary. As discussed in chapter 6, the annual work hours reported data per worker is less in Germany compared to Hungary. However, the per capita gross domestic product (GDP) in purchasing power standard is higher in Germany compared to Hungary (Eurostat data 2017).One possible reason behind having high work hours and still low per capita GDP could be presenteeism. Thus, a detailed study on country-specific presenteeism days should be conducted to understand the magnitude of presenteeism and hence productivity loss, which in turn would help the government to formulate an improved social policy.
4. As it is discussed during explaining distributional effects, the lower income group is also exposed to negative health effects from the buildings (due to the poor condition of buildings) and thus, having a deep energy efficiency measure can avoid such risk. The

gain of energy efficiency measure would be more among the lower income group due to the higher marginal utility of income among lower income group. However, the implementation cost of such energy efficiency measure in lower income group could be a barrier and thus, some welfare schemes are needed to uplift their living condition.

5. Adequate data and resources are required to quantify the net health impact of modal shift. Also, from the discussion of modal shift, it can also be said that policies promoting active transportation should be aggregative because the lower rate of active transportation may result in some negative health impact. The effect of modal shift towards active transportation on congestion time is quite significant, thus, for future research, the net health impact of active transportation needs to be calculated to get the complete picture.

7.5 Original contribution:

This dissertation has produced the following original contributions in the research field of co-benefit/multiple impacts of climate change mitigation policies:

In terms of evaluation methodology of multiple impacts, this dissertation offers:

- A systematic methodological framework which enables the causal relationship of different impacts leading towards productivity and by seeing the nature of the interaction, different aspects of labour productivity are defined.
- A set of indicators to measure labour productivity of improved energy efficiency measures. These indicators include several aspects such as presenteeism, future earning ability as well as time saved from road congestion which have not been incorporated before in any study in this comprehensive manner to measure the effect of an energy efficiency measure.

- Precise equations of productivity indicators fill-up the gap related to productivity of energy efficiency measure. Also, these equations advance the methodological knowledge of multiple impacts.
- Challenges-related to methodology such as double counting, additionality, scale, distributional effect are identified and solution or a set of solutions are proposed with the help of productivity impact to tackles these challenges.

In terms of geographical coverage, this dissertation contributes:

- So far no study has measured labour productivity impact of energy efficiency measures at national level this comprehensively. This dissertation measures different aspects of productivity for two specific European countries i.e. Hungary and Germany.
- An assessment behind this potentiality is given for both of these countries.

In terms of current knowledge and concept about multiple impacts and energy efficiency measures, it offers:

- Providing a comprehensive understanding of the role of energy efficiency measures, specifically the role of air tightness and ventilation in building sector and the role of active transportation in transport sector.
- The first ever evidence provided of labour productivity impacts at national level with a detailed assessment which shows the significance of energy efficiency measures. However, the scale/intensity of the measures may vary between these two countries. Nevertheless this dissertation shows a positive magnitude of productivity impacts.
- A concrete theoretical basis is described for the methodology as well as the productivity. In other words, this dissertation paints a broader picture with its theoretical background for the policy makers.

7.6 Future research avenues:

There are few aspects of this topic which cannot be studied in this dissertation due to resource constraints. These aspects can be divided into two broad categories: 1) Theoretical future research avenues, and 2) Methodological future research avenues. In the section below each of these categories is mentioned regarding potential future research on a priority basis:

1) **Theoretical future research avenues:**

- Labour productivity improves welfare and well-being. However, for future research, more details of ethics, economic well-being, welfare and productivity should be explored.
- More epidemic case studies are required to understand the relationship between indoor exposure and health in non-European as well as European countries so that it can be compared and well understood in details.
- Most of the results of this dissertation are based on single study data. Although this study does a sensitivity analysis, but more studies on quantification of productivity impact should be done in order to compare the results of different studies.

2) **Methodological future research avenues:**

- A countrywide workplace/household survey is required to understand the extent of presenteeism. This survey should also classify the different types of retrofitted buildings. Survey on presenteeism could fill in the data gap which further enables the potential of building related energy efficiency measures.
- This dissertation defines workforce performance quite extensively but due to data unavailability of performance enhancement factor, this dissertation uses a proxy value for this factor. Thus, a control group survey is required to measure at least the self-perceived performance improvement in terms of quantity of work.

- The intensity of indoor exposure on the children would be much more intense. However, since children's sick leave data are unavailable, this dissertation could not measure the earning ability aspect. Thus, a thorough survey on effect of indoor exposure on children needs to be conducted. On the other hand, country-wise econometric modelling study needs to be conducted to understand the effect of children's future income who are losing school days due to building-related illness.
- Active transportation can avoid a certain amount of outdoor exposure. However, there is no disease specific case study available which quantifies the net health impact (more precisely, how many sick days can be saved due to modal shift towards active transportation) in different scenarios. Thus, few disease specific case studies need to be conducted to contribute to the knowledge gap.

Conclusion:

The multiple impacts are often not considered in the policy evaluation due to the lack of mature quantification methodology, but this lack of methodology to quantify the impacts does not make them any less significant. Climate change policies do not only mitigate climate change but with the wide range of multiple impacts, it benefits the society and economy as well. Multiple impacts especially productivity impact of climate change policies can achieve a higher well-being by improving the standard of living and quality of life. Thus, climate change policies can fit in well in the multi-objective policy framework by mitigating climate change as well as by improving well-being.

Climate change policies such as sustainable energy policies can result in significant productivity improvement. A rigorous quantification of productivity impact can show the potential of sustainable energy policy. This dissertation's aim is to provide better methods to quantify multiple impacts rigorously. However, for a rigorous quantifying purpose, the pathway from a policy to its productivity impact needs to be understood with all the interactions. A detailed identification of impact resulting from the policy is the first step towards quantification. The different aspects of productivity have several stages and in order to understand and define them accurately, there is a need to understand the different aspects of productivity resulting from sustainable policy implementation. The quantification process consists of further methodological challenges such as additionality, baseline, context dependency and distributional effects. These challenges are important to be taken into account during an impact evaluation if not quantitatively then at least qualitatively.

This dissertation shows that the productivity impacts is a significant impact of energy efficiency measures. For instance, in Hungary and Germany, 3.21 and 7.7 days/person, year respectively can be gained by having more deep-retrofit type residential and tertiary buildings such as deep retrofitted buildings, passive houses, and nearly zero energy buildings. In addition, by improving the mental well-being Germany and Hungary can gain around 85 million euro/year and 1.8 million euro/year respectively. Moreover, 1870 and 3849 healthy life years/per million population can be gained/year in Germany and Hungary respectively by avoiding indoor exposure to pollutants. Last but not the least, this study also shows that by opting for modal shift, Germany and Hungary can gain 2.5 and 0.5 hours respectively from avoiding traffic congestion in a year. Therefore, this dissertation has concluded that labour productivity is economically and since, health is an input factor to productivity, it is also an ethically important impact to consider. The value of productivity impact would be greater if the sustainable policies are much more ambitious.

This dissertation contributes to the knowledge gap by defining productivity beyond work performance and hence by estimating productivity in a comprehensive way. This quantification of productivity impact would not only help the policymaker to include productivity in the decision making analysis while evaluating a policy, but also the quantification of productivity impact is so significant that it would provide an entry point apart from energy savings for the policymaker to design a sustainable energy policy. Moreover, while developing the methodological framework, this dissertation identifies several data and methods-related limitations which can be used as a future research agenda. However, even with the limitations of this methodological framework, the science of multiple impacts quantification progresses by identifying the data and method-related gaps. In regard to the quantification methodology, this dissertation has recommended that more impact specific studies should be conducted and keeping in mind the data-intensiveness of these kinds of methods, more case studies should be conducted.

Overall this dissertation concludes that all possible impacts of climate change policies should be quantified rigorously and should get incorporated in the policy decision making analysis in to order to analyse the potential of the policy accurately. The rigorous quantification of impacts is necessary in order to conclude the importance of the impact. Despite, the data and methodological issues, we have an improved methodological framework proposed by this dissertation which can quantify impacts. The limitations along with data gaps can be explored further as future research avenues.

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