Additional Impacts of Energy-Efficiency Measures

A Systemic Overview of their Implications across Societal, Ecological and Economic Dimensions

Ilieva, Lazaara Simeonova; Skov, Iva Ridjan; Mathiesen, Brian Vad; Maya-Drysdale, David William

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QUANTIFICATION OF SYNERGIES BETWEEN ENERGY EFFICIENCY FIRST PRINCIPLE AND RENEWABLE ENERGY SYSTEMS

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Additional Impacts of Energy-Efficiency Measures: A Systemic Overview of their Implications across Societal, Ecological and Economic Dimensions

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Aalborg Universitet (AAU), Denmark
Hogskolan i Halmstad (HU), Sweden
TEP Energy GmbH (TEP), Switzerland
Universiteit Utrecht (UU), Netherlands
Europa-Universität Flensburg (EUF), Germany
Katholieke Universiteit Leuven (KULeuven), Belgium
Norges Miljø- og Biovitenskapelige Universitet (NMBU), Norway
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Authors	Lazaara Simeonova Ilieva, AAU Iva Ridjan Skov, AAU Brian Vad Mathiesen, AAU
Reviewers	David Maya-Drysdale, AAU

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Executive Summary

Analyses of energy-efficiency measures typically tend to shed light on direct energy savings and the greenhouse gas (GHG) saving potentials, thereby overlooking the non-energy related impacts. This narrow valuation of energy efficiency (EE) measures can lead to a significant underestimation and underappreciation of EE investments, since, in many cases, taking into account additional impacts could reinforce drivers and counterbalance barriers to more energy efficiency investments. For this reason, it is argued that comprehensive energy efficiency assessments should broaden their scope to include non-energy related impacts as well.

Therefore, this report provides an overview of the additional impacts across the building, transport and industry sectors, in order to create a more holistic picture of the non-energy related effects of EE measures for the future European energy system. Although there are numerous ways to categorise additional impacts, they are discussed here in terms of their effects within and across socio-economic, geo-political and ecological dimensions, as well as their relevance and magnitude within and across the building, transport, and industry sectors. In this way, we maintain a systemic perspective on the non-energy related role energy efficiency can play in Europe's energy transition and sustainability agenda.

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Acronyms & Abbreviations

Term	Description
CO	Carbon monoxide
CO_2	Carbon dioxide
EE	Energy Efficiency
EEFP	Energy Efficiency First Principle
IEA	International Energy Agency
GDP	Gross Domestic Product
GHG	Greenhouse gas
MEBs	Multiple Energy Benefits
NEBs	Non-Energy Benefits
NO_x	Nitrogen oxides
$PM_{2.5}$	Particulate matter with a diameter less than 2.5 µm
PM_{10}	Particulate matter with a diameter less than 10 µm
SO_x	Sulphur oxides

1 Introduction

The sEEnergies project is based on the concept of Energy Efficiency First Principle (EEFP), aiming to identify energy efficiency potentials based on which the future European energy system should be designed. Thus far, analyses of energy-efficiency measures typically tend to shed light on direct energy savings and the greenhouse gas (GHG) saving potentials, thereby overlooking the non-energy related impacts. This narrow valuation of energy efficiency (EE) measures can lead to a significant underestimation and underappreciation of EE investments (IEA, 2014), since, in many cases, taking into account additional impacts could reinforce drivers and counterbalance barriers to more energy efficiency investments (Rasmussen, 2017; Cagno et al., 2019). For this reason, it is argued that comprehensive energy efficiency assessments should broaden their scope to include non-energy related impacts as well. The sEEnergies project has therefore discussed, analysed, and, in some cases, quantified non-energy related impacts of energy-efficiency measures within the building, transport, and industry sectors (Reiter et al., 2021; Næss et al., 2021; Kermeli & Crijns-Graus, 2021, respectively).

In the literature, Non-Energy Benefits (NEBs) or Multiple Energy Benefits (MEBs) refer to impacts of EE measures not related to energy savings, which can play a significant role in influencing EE investments (Cagno et al., 2019). Besides positive impacts, in some cases, trade-offs between non-energy related impacts and energy savings can occur. Such rebound effects are thus equally important to consider as non-energy benefits, albeit often challenging to measure and quantify. Thus, we use the term 'additional impacts' in order to avoid the normative connotation of 'non-energy benefits' and extend its scope to include both positive as well as negative impacts.

For the building sector, Reiter et al. (2021) assessed additional impacts of EE measures such as comfort and productivity improvements due to better insulated windows and ventilation systems, reductions in noise and air pollution due to building envelope improvements, reductions in GHG emissions through the replacement of fuel-based heating systems, as well as economic impacts, which showed increases in GDP, employment, disposable income, and asset values. Additionally, comprehensive building refurbishment measures including all envelope components (e.g., walls, windows and roof or basement) were shown to result in the largest turnovers, which varied based on the building age and standard that influences the necessary additional insulation material needed to achieve specific energy savings.

The measures of the Energy-efficiency scenario for the transportation sector were found to produce a large number of environmental and social impacts in addition to their intended impacts in terms of energy saving. Substantial positive impacts were shown in terms of reduced greenhouse gas emissions and reduced air pollution, as well as reduced conversion of natural areas, farmland and areas for hiking, skiing and other kinds of area-demanding outdoor life. The strategies for urban spatial development and infrastructure construction also generated substantial positive effects in terms of lower material consumption. Rebound effects were also taken into account, such as likely reductions in energy gains through improved vehicle technology. Furthermore, through its halt in motorway construction, intensified urban rail and metro construction and travel demand management measures, the Energy-efficiency scenario was estimated to enhance the competitiveness of public transit substantially, and its provision of better infrastructure for walking and cycling was found to bring considerable positive health effects.

For the industry sector, the additional impact analysis was conducted for two industrial sectors, the iron and steel and the cement industries. The wide uptake of EE and recycling measures in the EU, especially the increased use of scrap in the iron and steel industry, was estimated, in 2050, to avoid up to 50,000 deaths and generate increased productivities of about 30%.

In the following report, we will provide an overview of the additional impacts considered in Reiter et al. (2021), Næss et al. (2021), and Kermeli & Crijns-Graus (2021), and introduce a cross-sectoral, systemic perspective on health impacts informed by results of D6.3. This creates a more holistic picture of the non-energy related effects of EE measures for the future European energy system. Although there are numerous ways to categorise additional impacts (see Cagno et al., 2019), we have chosen to discuss them here in terms of their effects within and across socio-economic, geo-political and ecological dimensions, as well as their relevance and magnitude within and across the building, transport, and industry sectors. In this way, we maintain a systemic perspective on the non-energy related role energy efficiency can play in Europe's energy transition and sustainability agenda.

Through this systemic perspective, the impacts that are discussed and analysed in the following sections relate to greenhouse gas (GHG) emissions, air, noise, and water pollution, material consumption, land use, employment, working environment conditions, quality of life, gross domestic product (GDP), energy security and energy prices. Across the three sectors, it was found that energy efficiency measures can have positive impacts in terms of reduced GHG emissions, air and noise pollution, and material consumption, which bring significant implications on European societies, economies, and environments related to climate change, human health, biodiversity, among others. Synergistic effects were shown regarding the simultaneous implementation of certain measures, for example, implementing economic instruments for transportation demand management, such as road pricing and parking fees (Wangsness et al., 2018) and simultaneously increasing transit's competitiveness compared to car travel through improvements in urban rail, metro, walking and cycling infrastructure (Mogridge, 1997; Næss et al., 2001; Engebretsen et al., 2015) will likely contribute to even higher reductions in urban car driving and its resulting emissions of greenhouse gases, air and noise pollutants.

Further socio-economic impacts were shown across all three sectors in terms of net job creation, related to manufacturing, construction, operation and maintenance work, training for EE related stakeholders, as well as energy performance certification and energy management services. Positive impacts were also estimated on working conditions and employee performance, where EE measures that generated health benefits, such as reduced noise pollution, were translated to the working environment. For example, the reduction in noise pollution, implied by a halt in motorway and airport expansion as well as measures that reduce car traffic volume, can translate to positive impacts on employees' concentration levels, productivity, and creativity. Furthermore, several studies (Brutus, Javadian & Panaccio, 2017; Cyclescheme, 2021; Quist et al., 2018; Ma & Ye, 2019) have shown that active commuting (walking or cycling) to work can increase concentration, improve memory, and enhance higher order thinking.

Across the three sectors, EE measures were shown to have varying impacts on (human) quality of life and livability. In the context of urban areas, the additional health and socio-economic impacts, resulting from reductions in air, noise, water and soil pollution, GHG emissions, material extraction, and landscape fragmentation and destruction, as well as the socio-economic implications of employment growth and employee performance, contribute to a 'livable space' that ensures a healthy environment and guarantees good job opportunities for residents. However, negative implications can arise from increased property and rental prices when buildings are refurbished, ultimately driving gentrification of urban areas (Rice et al., 2020), as well as from urban densification that can incur societal issues, such as lack of safety. Nevertheless, a synergistic effect can be expected when reductions in travel time allow for more leisure time in tandem with increases in recreational and mobility opportunities as well as disposable income.

Reductions in the use of fossil fuels were also shown across the three sectors, which not only impacts GHG emissions and air pollution, but also stabilises energy prices and the dependence on other countries' economies (Gamtessa & Olani, 2018). Efficiency measures that reduce energy usage can also help to alleviate potential trade imbalances and help to limit exposure to geopolitical tensions and volatile energy markets. Overall, EE measures were found to have substantial implications for European societies, economies and environments, the majority of which were positive. Nevertheless, taking into account rebound effects and possible trade-offs or distributional effects showed that EE measures must be implemented in tandem with economic and policy instruments, which are briefly considered below, and which will be thoroughly discussed in D6.4.

The structure of the report is as follows: Section 2 outlines the methodological considerations taken in WP 1, 2, 3, and 6 for the assessment of additional impacts of energy efficiency measures. Section 3 provides an overview of the EE measures proposed for each sector, followed by the analysis of non-energy related impacts of EE measures within and across the building, transport, and industry sectors, as well as the energy system as a whole, and their implications across societal, ecological, and economic dimensions. Lastly, Section 4 presents the main conclusions.

2 Methodological Considerations

In this section, we give an overview of the methodological considerations taken in WP 1, 2, 3, and 6 for the assessment of additional impacts of energy efficiency measures. We bring forward the methods used to analyse and measure these impacts, including the relevant indicators, calculation approaches, parameter definitions, as well as data availability and other analytical limitations. We highlight the most consequential boundary conditions of the sectoral assessments (building, transport, and industry), and those that were an outcome of the energy system perspective. Finally, we point out important areas for further research, ranging from modelling improvements to needed empirical studies.

2.1 Buildings Sector

In the buildings sector, the quantification of non-energy related measures and impacts is difficult as e.g., monetary or health impacts are difficult to quantify, either due to a lack of available empirical data or a lack of significant results of respective studies. However, as Skumatz et al. (2000) have shown, the additional impacts can add up to the level of efficiency gains and therefore significantly improve the profitability of related refurbishment measures. In general terms, the buildings sector is more homogeneous regarding efficiency measures, efficiency gains and potential impacts compared to e.g., the industry sector, and therefore, the potential non-energy related impacts can be described and partially quantified for all EU countries. Additionally, one also needs to consider potential rebound effects, limiting the effects of energy efficiency measures. Furthermore, under circumstances, a trade-off between social and economic benefits and energy savings can occur (IEA, 2012). Therefore, rebound effects are just as important to consider as non-energy benefits.

For the estimation of the non-energy impacts of EE in the EU building stock we base our calculation on available research and use the quantification of the useful energy demand form the FORECAST model (Fleiter et al. 2017). We group the non-energy impacts into three categories which are “economic impacts”, “social impacts” and “rebound effects” (Reiter et al. 2021).

With this approach, only some additional impacts can be quantified based on the limited information available from the energy demand model. Besides the information on investments in refurbishment measures and efficiency gains, we use the approach and equations described in Reuter et al. 2020 to quantify building-related non-energy impacts. Based on the data at hand, we were able to quantify the additional economic turnover based on the different refurbishment measures for all European countries and as the dataset is available, further analyses can be conducted on country level. We also derive first insights into the split-incentive problem, with the respective shares of the investments need to be carried by either the building owner and landlord or the tenants, respectively. It is more difficult to estimate further important impacts such as health impacts or other social impacts, as the available data is not sufficient for further insights, as will be explained in the following.

Regarding health impacts, the emissions from burning fossil fuels and related particle matter are relevant as they can influence the number of avoided deaths from decreased pollution. However, as the model results were calculated for the useful energy demand only which occurs within the building, relevant information on the use of e.g., different heating technologies was not part of the model output but will be provided within work package six. Therefore, the model results cannot be used to estimate the pathway for declining fossil emissions.

For other health or comfort levels, the available data and modelling approach is not suitable for further quantifications.

2.2 Transport Sector

The transport sector is highly complex with several different transport purposes and numerous modes of transport. Many of the studies related to transport and mobility relate to single cases and it is a challenge to transform the results into something applicable on a European scale. Two scenarios have been developed in the project: the Business-as-usual scenario and the Energy-efficiency scenario. The Energy-efficiency scenario includes a combination of the following strategies and measures:

- Energy-efficient urban spatial development
- Halt in motorway construction
- Halt in airport expansions
- Improved infrastructure for walking and cycling
- Economic instruments for transportation demand management
- Other demand management measures
- Energy-efficient vehicle technology

Each of the strategies and measures have additional environmental and/or social impacts. A literature study comprising of both peer-reviewed articles in international journals and grey literature were carried out to qualify the additional impacts of the strategies and measures. When possible, the specific impact was both described in general terms and by giving a case example. Each impact was assessed whether it was a substantial impact, considerable impact, moderate impact, or ambiguous impact. It was also assessed whether it was possible to quantify a given impact at either EU/EFTA scale or for individual project cases or cities. In total 72 non-energy impacts of the Energy-efficiency scenario were described. However, most of these were considered not quantifiable at either EU/EFTA scale or project/city scale due to lack of reliable, specific data.

Based on the data from D2.1 (Report on the Energy efficiency potentials in the transport sector by analysing the three main strategies for lowering energy use within the transportation sector), we estimated that the energy-efficient urban spatial development will save about 8950 km2 of land in the EU/EFTA area from being converted in the period 2050. The proposed halt in motorway construction will save about 4400 km^2 of land in the EU/EFTA area from being converted in the period 2020 – 2050.

The Energy efficient urban spatial development, the halt in motorway construction and the improved infrastructure for walking and cycling will lead to the replacement of trips depending on external energy to trips depending on your own body's energy. This will not only reduce air pollution but also have a positive health impact as one of the largest killers in Europe is the lack of exercise. The World Health organization (WHO) have developed a tool for calculating the impacts of increased walking and cycling, see HEAT (2021). Until now the tool has been used on simple cases. It is probably not impossible to translate data from the sEEnergies project into input data for the WHO-based tool, but it is a far too demanding task for being carried out within the frame of the existing sEEnergies project.

2.3 Industry Sector

The industry sector is complex with many different industrial processes used to manufacture a variety of industrial goods. Except for the cross-cutting EE measures/technologies, such as improvements in motors, fans, pumps, steam supply systems etc., that are largely common across most industries and that will have similar non-energy impacts across industrial sectors, there are EE measures/technologies that are industry and technology specific. For the latter type of measures, the non-energy impacts will also be industry and technology specific. Some can reduce the noise level inside the factory and the need for maintenance, others can reduce employment, while others can increase industrial productivity or limit material consumption. This strong diversity makes the individual/sectoral impacts difficult to quantify for the entire EU industry.

For the estimation of the non-energy impacts of EE in the EU industries two approaches were used. With the first approach, the aim was to quantify all the economic, social, and environmental impacts that can be directly linked to EE potentials identified in Kermeli and Crijns-Graus (2020). For this, the methods identified and presented in Reuter et al. (2020) were used after making certain adjustments. The analysis from Reuter et al. (2020) was chosen due to its i) simplicity, most methods are non-data and non-modelling intensive that directly link the direct energy savings potentials to the non-energy impacts of EE and ii) ability to show the additional impacts for the whole EU industry, although the impacts are also calculated at a more disaggregated level (per industrial sub-sector, EE measure and EU country).

The second approach used is industry, technology, and measure specific. Initially all EE measures with significant non-energy impacts were identified for two industries, the cement and the iron and steel industries. This approach relied on available literature concerning details on Energy Efficiency, primarily technical reports, case studies and scientific articles.

Regarding the health impacts of energy efficiency, this analysis assessed the number of avoided deaths from decreased pollution. The focus was on two pollutants, $PM_{2.5}$ and NO_x that are generated from burning fuels in industries. The health impact of other pollutants, such as ground-level ozone (O_3) was not estimated, its impact however is expected to be lower than that of $PM_{2.5}$ and NO_x (EEA, 2020d).

For the estimation of the CO, NO_x, SO_x, $PM_{2.5}$ and PM_{10} pollutants avoided, a Tier 1 method was used, which was based on energy consumption data and default emission factors per energy carrier. For more accurate results, a Tier 2 or 3 method should be used that considers the types of technologies employed in the different industries and that also takes into account the level of pollution control. In this analysis, the fuels consumed in blast furnaces, coke ovens and for industry own use was also included in the pollutant calculations. This is in contrast to the EEA analysis where the emissions from coke ovens are reported in the transformation sector (EEA, 2016a).

2.4 Recommendations for Further Research

Estimating the additional impacts of energy efficiency measures across the building, transport, and industry sectors requires further research in terms of both quantitative and qualitative assessments. For example, qualitative studies on the implications of EE measures on human livability and quality of life are needed in order to further extend the valuation of EE measures and thereby contribute to a more holistic programme value that exceeds the monetary value of energy savings. Particularly for measures that induce explicit changes in the socio-material fabric of cities, such as the dense urban spatial development, contextualised research programmes can provide important insights into the implications such measures have on e.g., urban vibrancy, social equity, safety and health.

Additionally, further research is needed that addresses current gaps in available data on both European and country scales. For example, the impacts of workplace location on intra-metropolitan transport volumes and the shares of different modes of transport were not quantified for the transport sector due to the lack of European-scale spatial dataset on jobs distribution. Furthermore, datasets on emission factors for alternative fuels in transport and industry, e.g., ammonia as marine fuel, are largely missing given their niche applications.

3 Results

In this section, we give an overview of the non-energy related impacts of EE measures within and across the building, transport, and industry sectors, as well as the energy system as a whole, and their implications across societal, ecological, and economic dimensions. The EE measures proposed for each sector are summarised below.

3.1 Overview of Energy Efficiency Measures for Each Sector

For the building sector, 15 combinations of energy efficiency measures were applied to four different building-envelope components, namely walls, windows, roof and basement, and 10 residential building typologies, separated in two building types (single-family houses and multi-family houses) and 5 building construction periods (before 1961, 1961-1990, 1991-2008, 2009-2020, after 2020). Table 1 below shows the energy-refurbishment measures, including the different levels of efficiency (low, medium, high, etc.) that relate to U-values for the different components. Six energy carriers were considered, namely gas, oil, wood, coal, electricity, and district heating.

Table 1. Envelope-refurbishment measure packages.

ID_Packages	Energy-refurbishment measures
1	Façade painting
2	Refurbishing only windows (low)
3	Refurbishing window and walls (low)
4	Refurbishing windows, walls, and roof (medium)
5	Refurbishing windows, walls, roof, and floor (high)
6	Building on package 5, windows, walls, roof, and floor (higher)
7	Building on package 5, windows, walls, roof, and floor (highest)
8	Building on package 5, windows, walls, roof, and floor ("passivhouse")
9	Refurbishing windows (high); roof (higher)
10	Refurbishing only walls (low)
11	Refurbishing windows (higher)
12	Refurbishing windows and walls (higher)
13	Refurbishing windows (medium); roof (medium); floor (high)
14	Refurbishing windows, roof, and floor (higher)
15	Refurbishing roof (medium); floor (high)
16	Refurbishing roof and floor (highest)

For the transport sector, the energy efficiency measures were broken down in terms of three main strategies, namely, (1) technological advancements, through which each separate mode of transport is made more energy efficient, (2) reduction in the movement of goods and persons, and (3) modal shifts from energy-intensive to more energy efficient modes of transport. The energy-efficient vehicle technology measures applied in the assessment of additional impacts was based on the electrification + scenario, as it showed the greatest benefits in terms of energy savings and reduction of CO_2 emissions on, through extensive electrification of road and air transport and development of Electric Road Systems (ERS). The other EE measures include energy efficient urban spatial development (defined by higher urban population density and shorter residential distance to the main centre), replacement of motorway construction and airport expansion with surface transit improvements, improvements in walking, cycling, and railroad infrastructure, economic instruments for transportation demand management, and other demand management strategies, such as car-sharing and privileged lanes for EE vehicles.

For the industry sector, recycling, material, and energy efficiency measures along with innovative and fuel-switching measures were analysed across five sub-sectors, namely non-metallic minerals, non-ferrous minerals, iron and steel, pulp and paper, and chemicals. The non-energy impacts analysis was limited to two industrial sectors, the iron and steel and the cement industries, whose respective EE measures and technologies are listed in Table 2 below.

Table 2. Energy efficiency and technology measures for iron and steel, and cement industries.

Industrial sub-sector	Measures/Technologies
Iron and Steel	Programmed heating in coke oven
	Variable speed drive on coke oven gas compressors
	Coal moisture control
	Waste heat recovery blast furnace slag
	Top gas recovery turbine
	Moisture Removing Blowing Technique in Blast Furnace
	Injection of pulverized coal in BF
	Cogeneration (for the use of untapped coke oven gas, blast)
	Recovery of blast furnace gas
	Improved hot blast stove control
	Improved blast furnace control
	Recovery of BOF and sensible heat
	Scrap preheating
	Converting the furnace operation to ultra-high power (UHP)
	Improved process control in EAF
	Recuperative or regenerative burner
	Endless Hot Rolling of Steel Sheets
	Process control in hot rolling
	Variable speed drives for flue gas control, pumps, fans
	Energy monitoring and management systems
Cement	Improved Raw Mill Blending
	Use of High-Pressure Roller Presses
	High Efficiency Classifiers
	Raw Meal Process Control
	Energy Management and Control Systems
	Kiln Combustion System Improvements
	Indirect Firing
	Oxygen Enrichment Technology
	Preheater Shell Heat Loss Reduction
	Conversion to Grate Cooler
	Optimize Grate Cooler
	Low-Pressure Drop Suspension Preheaters
	Heat Recovery for Power Generation (ORC)
	Increase Preheater Stages (from 5 to 6)
	Addition of Precalciner or Upgrade
	Conversion of Long DryKiln to Preheater Precalciner

Industrial sub-sector	Measures/Technologies
	Use of Fly Ash, Blast Furnace Slag in Clinker (15% substitution)
	Biomass and Waste
	Energy Management and Process Control
	Replace Ball Mills with VRMs
	High-Efficiency Classifiers
	High-Efficiency Motors
	Adjustable Speed Drives

3.2 Impacts on Greenhouse Gas Emissions

Across the three sectors, building, transport, and industry, it was found that energy efficiency measures can have a positive impact in terms of reduced greenhouse gas (GHG) emissions. For the building sector, the improved insulation of the building envelope showed reductions in the heat demand and thereby reductions in greenhouse gas emissions. Additionally, reductions in GHG emissions could also be achieved through the replacement of fuel-based heating systems. It is important to note that the impact of such measures must take into consideration the direct as well as indirect emissions of the building. A shift in emissions can occur from the direct use of fossil fuel energy to the use of electricity (EEA, 2021a). Therefore, a key priority must be meeting the energy demand of buildings by production of renewable energies or decarbonised energy. Furthermore, reductions of GHG emissions from the building stock can be achieved through measures that extend beyond building operation and consider the full life cycle of buildings (Röck et al., 2020). In this way, emissions arising from the manufacturing and processing of building materials, i.e., from the construction industry, are also brought into focus via the notion of 'embodied' GHG emissions.

Similarly, in the transport sector, measures related to the halt in motorway construction and airport expansion can also reduce the GHG emissions embodied in the construction materials. This impact, however, relates more directly to the analysis of industrial measures, which will be further discussed below. It is important to note that although the CO_2 emissions related to the construction phase are important to take into account, the emissions of the operation phase are substantially greater. The induced demand of constructing a new road generates a significant rise in emissions associated to the use phase, i.e., the total emissions of the induced traffic. The transport sector assessment analyses the impact of EE transport measures on GHG emissions in terms of avoided road and air traffic volume as well as technology improvements. In fact, Næss et al. (2021) estimate that within the EU/EFTA area and in the absence of vehicle and aircraft technology improvement, the reduced energy use for transportation due to halt in motorway construction and airport expansion gives a reduction over the period 2020-2050 of 1400 million and 1300 million tons of CO_2, respectively, compared to the Business-as-usual scenario[1]. Adjusting for vehicle technology improvement, the reduction is estimated at 480 million tons, while, for aircraft technology improvement, the estimated reduction is 780 million tons. Moreover, avoiding the construction of new motorways and airport expansions would also avoid encroachments on forests or bogland, where the construction process would reduce sequestering capacity and/or release carbon (Honningsøy & Solvang, 2020). This impact, which was estimated to avoid about 4400 km^2 of land conversion resulting from motorway construction[2], coupled with the

[1] All quantified estimations mentioned from this point forward are taken over the period 2020-2050, compared to the Business-as-usual scenario – exceptions will be explicitly stated.

[2] This impact was not considered possible to quantify at either the EU/EFTA scale or for individual infrastructure project cases.

impact of the energy-efficient urban spatial development on land conversion (estimated to be about 8950 km^2), could further reduce GHG emissions.

In addition to stopping motorway construction and airport expansion, the remaining transport EE measures were also found to reduce GHG emissions. For example, the reduction in motorised transportation, effectuated by the energy-efficient urban spatial development, implies further reductions in GHG emissions. Specifically, within the EU/EFTA area and in the absence of vehicle technology improvement, the more concentrated urban development in the energy efficiency scenario was estimated to give a reduction of 370 million tons of CO_2 (Eurostat, 2020; Næss et al., 2020a; Williams, 2012); while adjusting for vehicle technology improvement gives an estimated reduction of 125 million tons of CO_2. EE measures that further reduce car and air traffic, such as improved rail, metro, walking and cycling infrastructures as well as flight taxes, road and parking pricing, and car-sharing systems, give an overall impact on GHG emissions that is considerably positive. In fact, economic instruments for transportation demand management alone give an estimated reduction of 2000 million tons of CO_2 in the absence of aircraft and surface vehicle technology improvement.

Reduction in GHG emissions was also found to be an estimated impact of industrial energy efficiency measures related to reductions in fuel combustion and coke demand. For example, injection of natural gas or pulverised oil in blast furnaces can reduce coke demand, and thereby induce reductions in CO_2 emissions. Specifically, the CO_2 emissions that can be saved in 2050 from increased energy efficiency and recycling were estimated at about 60 million tons.

The estimated reductions in GHG emissions from energy efficiency measures across the three sectors are highly relevant for societies, economies, and the environment. The most substantial impact of reducing GHG emissions is its significant contribution to mitigating climate change. According to the IPCC (2021), greenhouse gases produced by human activities is the largest contributor to global warming and to limit warming to 1.5°C or even 2°C will require immediate and large-scale reductions GHG emissions. Along with the impact on average temperature, the continued increase of GHG emissions has profound implications on precipitation, sea-level rise, ocean acidification as well as the frequency and magnitude of extreme events, with major consequences for natural and human systems (CBD, 2012). Pressing environmental and socio-economic concerns relate to biodiversity loss, species extinction, and degradation of vital ecosystem services, such as air and water purification, food production, and global nutrient and carbon cycles. Increases in the number of heat-related deaths have been recorded, especially in Southern and Central Europe where heat waves, forest fires and droughts have been occurring more frequently, while Northern Europe has seen more extreme cases of rainfall and flooding (Naumann et al., 2020). Such damage to property and infrastructure as well as human health imposes severe socio-economic costs. Thus, the reductions in GHG emissions from EE measures across the three sectors pose significant and imperative social, environmental, and economic benefits for the 28 Member states.

3.3 Impacts on Air Pollution

It was also found that, across the three sectors, building, transport, and industry, energy efficiency measures can have a positive impact in terms of reduced air pollution. For the building sector, these measures included improvements in building ventilation and heating systems, where inadequate ventilation and fossil heating systems are the primary causes of indoor air pollution and outdoor air quality can be enhanced by reducing the burning of volatile content solid fuels (Spiru & Simona, 2017).

For the transport sector, all the measures were found to generate reductions in overall emissions of pollutants mainly by reducing car travel and shifting from fossil-based vehicle technologies to a more electrified transport sector. Although the impact on air pollution of each EE measure was not considered quantifiable, it can be expected that the simultaneous implementation of these measures will give a synergistic effect. For example, implementing economic instruments for transportation demand management, such as road pricing and parking fees (Wangsness et al., 2018) and simultaneously increasing transit's competitiveness compared to car travel through improvements in urban rail, metro, walking and cycling infrastructure (Mogridge, 1997; Næss et al., 2001; Engebretsen et al., 2015) will likely contribute to even higher reductions in urban car driving and its resulting emissions of air pollutants. Further, the reductions in urban car driving coupled with the implementation of car-sharing systems can reduce land-use for parking and thereby open space for intra-urban green areas, which have shown reductive effects on concentrations of air-borne particulate matter (PM) (Selmi et al., 2016; Diener & Mudu, 2021). Although, some measures are estimated to counteract these impacts, such as the rebound effect caused by increased energy-efficiency gained through improved vehicle technology and the increased concentration of emissions via inner-city densification, the overall impact on air pollution is considerably positive.

Reduction in concentrations of pollutants ($PM_{2.5}$, PM_{10}, CO, NO_x, and SO_x) was also found to be an estimated impact of industrial energy efficiency measures related to reductions in fuel combustion. It was calculated that the 2050 CO emissions could decrease by about 1,000 ktonnes, SO_x emissions by about 790 ktonnes, NO_x by about 400 ktonnes, PM_{10} by about 140 ktonnes and finally $PM_{2.5}$ by about 130 ktonnes (Kermeli & Crijns-Graus, 2021).

The estimated reductions in concentrations of air-borne pollutants, such as NOx, CO and PM, from energy efficiency measures are highly relevant for societies, economies, and the environment. In particular, air pollution is a significant risk factor for human health, ranging from respiratory system impairments to premature mortality (Sicard et al., 2021). In fact, the European Environment Agency (EEA) estimates that, in 2019, approximately 307,000 premature deaths were attributed to fine particulate matter ($PM_{2.5}$) in the 27 EU Member States and 40,400 premature deaths linked to Nitrogen dioxide (NO_2) (EEA, 2021b). Air pollution has also been identified as a major environmental issue, causing considerable damage to terrestrial ecosystems, vegetation, and biodiversity (Mills et al., 2011; Sicard et al., 2016; EEA, 2021b). These health and environmental risks also translate to direct and indirect costs related to labour productivity, agricultural crop yields and health expenditures (OECD, 2016). In D6.3 (Energy Efficiency Roadmap Europe: A cost-effective and energy efficient strategy for decarbonizing Europe), the socio-economic costs of health impacts, analysed in terms of air pollution, were estimated and compared across all three sectors on an EU level. Total health costs related to SO_2, NO_x, and $PM_{2.5}$ emissions, reduced to approximately 71 billion EUR/year in sEEnergies EU2050, from approximately 299 billion EUR/year in 2015 and 154 billion EUR/year in the PRIMES 2050 Baseline. Therefore, if the energy efficiency measures of the sEEnergies EU2050 scenario are implemented throughout Europe, there will be savings of approximately 228 billion EUR in 2050.

The reductions in air pollution from EE measures across the three sectors pose significant social, environmental and economic benefits for the 28 Member states. For example, for the industry sector, it was estimated that the wide of adoption of energy efficiency measures and recycling in 2050 will prevent 48,000 and 2,700 premature deaths due to the avoided $PM_{2.5}$ and NO_x emissions, respectively. (Kermeli & Crijns-Graus, 2021). In addition, synergistic health impacts can be achieved from EE measures in the transport sector, whereby improvements in air quality are coupled with a rise in walking and cycling via infrastructure improvements.

3.4 Impacts on Noise Pollution

For all three sectors, Reiter et al. (2021), Næss et al. (2021), and Kermeli & Crijns-Graus (2021), found that EE measures can have a positive impact on noise pollution. Refurbishments of the building envelope resulted in reductions in indoor noise pollution, since the capacity of insulation materials to reduce thermal transmission correlates with their ability to absorb outdoor noise (Pisello et al., 2016). For the transport sector, the results showed similar findings to the impacts on air pollution, where EE measures that reduced car travel and replaced fossil-based vehicle technologies with a more electrified transport sector led to reductions in noise pollution. In addition to the noise related to car traffic, the noise pollution resulting from infrastructure construction was also accounted for. Hence, halting motorway and airport construction was estimated to give further reductions in noise pollution. Although the improvements of rail and metro infrastructure resulted in some noise pollution from the construction sites, it was found that improved rail and metro networks can reduce car driving and thereby offer long-term reductions in noise pollution from car traffic. Additionally, despite the increased concentration of noise pollution via inner-city densification, the overall impact of EE measures on noise pollution was found to be considerably positive.

For the industry sector, reduction in noise pollution was also found as an additional benefit of EE measures, assessed in terms of its impact on the working environment. Within the iron and steel industry, for example, it was calculated that the installation of a Comelt furnace could reduce the noise level by up to 15 dB(A) in addition to improving air quality.

The estimated reductions in noise pollution can have relevant implications for human health and the environment. According to the EEA (2020b), more than 100 million people within Europe are exposed to long-term noise levels that can have negative implications on their health, especially in terms of quality of life and mental health. In fact, the EEA (2020b) found that, in Europe, long-exposure to environmental noise is estimated to cause 12,000 premature deaths and contribute to 48,000 new cases of ischaemic heart disease per year, with an estimated 12,500 schoolchildren suffering from learning impairment as a result of aircraft noise. These threats also extend to terrestrial, aquatic and coastal wildlife, where anthropogenic noise can adversely affect species' communication, use of space, and reproduction (Sordello et al., 2019).

Although improvements in building envelopes would help alleviate the negative consequences of noise pollution for humans, the fundamental issues to address relate to the noise levels of road, railway, and aircraft traffic as well as industrial sites, with several studies (EEA, 2020b; Khomenko et al., 2022) identifying transport as the most widespread source of noise pollution. In fact, after fine particulate matter pollution, noise caused by transport is estimated as the second most significant cause of ill health in Western Europe (EEA, 2020b; Hänninen et al., 2014). Long-term exposure to road traffic noise has been found to cause an increase in heart rate, blood pressure, vasoconstriction, as well as release of stress hormones, which can eventually lead to cardiovascular disease, depression and anxiety disorders (Khomenko et al., 2020). According to a recent study, conducted by the Barcelona Institute for Global Health, across 749 cities in 25 European countries (ibid.), nearly 60 million adults are subjected to unhealthy levels of road traffic noise and an estimated 3608 deaths from IHD could be prevented annually with compliance of the World Health Organisation noise-level guidelines.

Across the three sectors, several EE measures that lead to reductions in noise pollution also generate reductions in emissions of air pollutants and greenhouse gases. This can be seen in the transport sector, for example, where measures reducing car traffic produce simultaneous reductions in GHG emissions as well as air and noise pollution. Although these impacts are discussed and analysed separately in the present report, it is important to note that their estimated effects and implications for European societies, economies and ecologies are not discrete. The related societal benefits are deeply entangled in dynamic socio-economic, political and ecological processes that must be accounted for in policy design. Eco-gentrification studies have shown that the pursuit of low-carbon cities unfolds several shifts in urbanisation related to displacement and way of life (Rice et al., 2020), which in turn can lead to substantial distributional effects (Vona, 2021) and rebound effects. For example, studies have shown that more affluent residents have much larger carbon footprints due to their consumption, despite reductions in transportation and building energy emissions (Rice et al., 2020). Thus, EE measures should be implemented in tandem with economic and policy instruments that can offset such effects, such as energy tax schemes, emissions targets and behavioural instruments related to consumption patterns (Freire-González & Ho, 2022). The most effective policy design and policy mix, however, is highly contingent on local contexts and existing strategies, and must therefore be carefully curated on a country level (ibid.).

3.5 Impacts on Pollution of Watercourses, Soil and Groundwater

For the transport and industry sectors, several EE measures were also found to generate positive impacts related to pollution of watercourses, soil and groundwater. Specifically, the construction of motorways and airports has been identified as a significant source of contamination of soil, watercourses and groundwater (National Roads Authority (Ireland), 2008; Nunes et al., 2013). In addition, road runoff, a mix of exhaust and wear products from breaks, tires, and asphalt, has been identified as one of the most significant non-point sources of pollution in terrestrial and aquatic environments (Angermeier et al., 2004; Mooselu et al., 2022). In particualr, recent analytical and toxicological studies (Tian et al., 2020; Hiki et al., 2021) have identified 6PPD quinone, a ubiquitous tire rubber-derived chemical, as a direct cause of acute mortality in freshwater fish and crustacean species via stormwater runoff. Thus, in the Energy-efficiency scenario for transport, where motorway and airport construction are halted, considerably positive impacts were found with regard to water and soil pollution. Similarly, industrial EE measures that reduce wastewater, such as non-recovery coke ovens, and promote resource recycling, like waste injection in EAFs, were also found to contribute to reductions in water and soil pollution. The impact of building EE measures were not assessed in terms of water and soil pollution, however, a life cycle perspective on the materials used for refurbishing buildings can shed light on the sources of water and soil contaminants released during the different stages of the supply, manufacture, and installation of building envelope refurbishments. This however is beyond the scope of the present analysis.

Although these additional impacts were not quantified for either sector, the scope of their impact across environmental, societal, and economic dimensions can further highlight their value extending beyond energy savings. The pollution of waterways, groundwater and soil are intimately related and pose serious threats to human and non-human life. A significant proportion of surface and groundwater enters water bodies through soils; therefore, substances in soils may end up as pollutants in water bodies through diffuse pollution (Farmer, 2020). In addition, soil itself can pose a water pollution issue, by restricting light penetration to aquatic plants or covering substrates, which can damage fish spawning grounds (ibid.). According to the EEA, industry is reported to be a major contributor to soil contamination, with an estimated 2.5 million potentially contaminated sites across Europe and an estimated cost of € 6.5 billion per year for managing contaminated land (45% of which is estimated to come from public budgets) (EEA, 2020c). Furthermore, contaminated surface and groundwaters can limit access to a sufficient supply of safe water for maintaining public health (EEA & WHO, 2002). Thus, the reductions in water and soil pollution from EE measures across the transport and industry sectors pose significant social, environmental and economic benefits for Europe.

3.6 Impacts on Material Consumption

EE measures related to the building, transport, and industry sectors were found to have varying effects on material consumption. For example, building refurbishments would likely induce an increase in material consumption, such as windows and insulation materials, although the result data did not provide sufficient insights into the correlation between material needs and efficiency improvements of the building envelope (Reiter et al., 2021). Nevertheless, the impact of material consumption for the built environment is a central concern across Europe, where energy efficiency measures for a sustainable building stock are prioritised in tandem with circular economy and resource efficiency principles (European Commission, 2020).

On the other hand, in the transport sector, the energy efficient urban spatial development was estimated to have a considerably positive impact in terms of reduced material consumption. In particular, concentrated building types that require less outer surface area of the buildings and shorter networks of roads, pipes, cables, and sewers, characteristic of denser cities, contribute significantly to reductions in material consumption. Further reductions were also shown from the measures halting motorway and airport construction. Additionally, since the intensified railroad and metro construction in the EE scenario was restricted to metropolitan areas, the ensuing material consumption was estimated to be considerably smaller than the material consumption for motorway construction in the Business-as-usual scenario. Therefore, the overall impact of EE measures on material consumption, in the transport sector, is considerably positive. In addition, accounting for the related impacts of concentrated building types of higher density urban areas can provide a counterbalancing effect on the material consumption required for EE measures of the building stock.

Several industrial EE measures were also found to contribute to reductions in material consumption. For example, producing blended cements contributes to the effective utilisation of by-products generated in other industries, such as fly ash and blast furnace slag, thereby reducing consumption of raw materials for cement production. Similarly, in the iron and steel industry, waste injection in Electric Arc Furnaces would allow for greater resource recycling, decreasing the needs for coke and coal by 30%; while injection of plastic waste in Blast Furnaces was estimated to reduce coke demand, such that 1 tonne of coke can be replaced with 1.3 tonnes of plastic. Overall, measures related to improved material efficiency through recycling showed substantial effects on material consumption.

Reductions in material consumption can play a key role in alleviating the adverse consequences of material use on the environment and human societies. The activities associated with the extraction, processing, transport, consumption, and disposal of different material resources have varying implications on societies and environment, including, but not limited to, acidification, eutrophication, habitat alteration, biodiversity loss, aquatic and terrestrial ecotoxicity, climate change, and human toxicity (OECD, 2019). For example, the extraction of construction aggregate requires the complete removal of vegetation, topsoil, and subsoil, destroying existing wildlife and habitats, and posing significant threats to adjacent ecosystems and communities via increased levels of noise, air, and water pollution (Assefa & Gebregziabher, 2020). By taking into account the impacts associated with the entire life cycle of resource use, we see that EE measures that contribute to reductions in material use and allow for greater resource recycling can generate further reductions in air, water, soil and noise pollution, GHG emissions, and land-use (OECD, 2019).

3.7 Impacts on Land Use

Several EE measures in the transport sector showed reductions in the conversion of natural areas and farmland. In particular, the measures related to compact urban development and motorway and airport construction showed considerably positive impacts on land-use. The avoided land conversion resulting from stopping motorway construction and the energy-efficient urban spatial development was estimated to about 4400 km^2 and 8950 km^2, respectively. As mentioned earlier, these impacts on land-use have additional implications on air pollution and climate change, given the carbon sequestration capacity of forested areas and boglands, as well as the reductive effects of vegetation on concentrations of air-borne particulate matter (PM) (Selmi et al., 2016; Diener & Mudu, 2021). These implications further extend to concerns surrounding loss of biodiversity and biologically productive areas, which according to the IPBES (2019) are threatening to create unprecedented hunger and ecological collapses.

Taking into account the complexities of the socio-ecological system in which natural areas are situated, we see that there are significant benefits for human communities living near or within them, including effects on wellbeing, mental and physical health, access to natural resources, and cultural activities (Jones et al., 2020). Concepts like ecosystem services (West, 2015), human-nature connections (Ives et al., 2018) and biophilia (Wilson, 1993) aim to translate the deeply interconnected and multi-faceted roles of the environment and human society, serving as important valuation mechanisms for the protection and conservation of natural areas. Sustainable land use is thus a growing concern in Europe and across the world (EEA, 2016b). In fact, the EEA has identified the continued rates of urban sprawl as a major threat to sustainable land use, through three main processes, namely landscape transformation, degradation and fragmentation (ibid.). Landscape transformation refers to the loss of valuable habitats and agricultural soils, while landscape fragmentation refers to the partitioning of natural areas, which severely threatens the resilience of ecosystems (ibid.). In light of these implications, the EE measures proposed for the transport sector offer considerably positive effects with regards to reductions in land conversion.

Although impacts on land use were assessed only for the EE measures in the transport sector, the industrial measures that reduce material consumption could also influence land use. As discussed earlier, accounting for the different parts of the life cycle of resource use can show significant impacts on land use, especially during the extraction phase. For this reason, measures that reduce the need for raw material extraction through resource recycling, for example, can further reduce the destruction and fragmentation of natural areas.

3.8 Impacts on Employment

Across all three sectors, EE measures were found to have a positive impact on the creation of jobs. Building refurbishment measures were shown to lead to a net job creation, since RE and EE are more labour intensive in terms of electricity-generated or saved than traditional fossil-fuel generation (Blyth et al., 2014). In addition to construction work, other jobs resulting from investments in EE measures for the building sector can include manufacturing of energy efficient building materials (e.g. insulation and glass) and heating and cooling appliances, training in EE for related stakeholders in planning, production and services, as well as jobs related to energy performance certification and energy management services (MED-ENEC, 2013).

EE measures within the transport sector were also found to contribute to job creation. Improvements in cycling infrastructure, for example, can lead to cycling-related jobs in retail, wholesale and design (WHO, 2016), as well as jobs in relation to general tourism, administration and other cycling-related businesses. Technological improvements related to the electrification of vehicles can also lead to the creation of jobs in the electromobility value chain. According to the European Association of Electrical Contractors (AIE, n.d.), the jobs created by electromobility will offset those lost in automotive manufacturing, with many new jobs associated with the installation, operation, and maintenance of charging points as well as battery cell manufacturing. The AIE study demonstrates that electromobility can offer thousands more job opportunities for SMEs and local communities across Europe, ultimately creating a positive economic impact. Furthermore, a counterbalancing effect can be estimated in relation to construction jobs since, in the EE scenario, motorway and airport construction work is replaced with intensified railroad and metro construction as well as extensive improvements in cycling and walking infrastructure.

For the industry sector, EE measures can impact employment primarily by the following two mechanisms: i) investments in EE measures and technologies that can increase the employment in industries that supply the EE technologies and, ii) energy reductions that can decrease the employment in energy suppliers and distributors (Reuter et al., 2020). Nevertheless, Kermeli & Crijns-Graus (2021) showed a net increase in job creation and estimated that in 2030 and 2050 EE measures and increased recycling could generate 200,000 and 380,000 jobs, respectively.

Across all three sectors, further impacts on employment can be indirectly achieved through the increased disposable income generated by cost-effective EE measures that could be invested in productivity expansions and increases in employment. However, a potential rebound effect of increases in disposable income can occur when financial savings of reduced energy consumption are spent on other energy-consuming activities. From an energy perspective, this is a negative impact; however, in some cases, this can be seen to have positive implications for human well-being and quality of life. Furthermore, some studies (Lecca et al., 2014; Pollitt et al., 2017) have shown that increased income and spending on non-energy sectors have a greater economic impact than equivalent spendings on energy, ultimately confirming that a shift away from spending on energy goods is a beneficial consequence for European economies.

Net job creation can have further positive implications not only in terms of unemployment rates across Europe, but also in relation to the ratio of workers to pensioners. In particular, employment growth can play a key role in raising the worker to pensioner ratio, thereby lowering the cost of its social safety net (Garibaldi & Mauro, 2000). Furthermore, the additional income tax revenue from increased employment can also generate growth of public budgets for the 28 Member States.

3.9 Impacts on Working Environment and Employee Performance

In addition to generating employment growth, several EE measures were found to also improve working conditions for employees in office buildings and industrial plants. Specifically, building refurbishments related to improved insulation led to reductions in indoor air and noise pollution. As discussed earlier, these impacts imply health benefits (e.g., reduced illness and stress), which further translate to improved productivity when taken in the context of office buildings. In addition, reductions in overheating can also enhance employees' performance and thereby further contribute to productivity improvements.

Energy efficient transport measures were not explicitly assessed in terms of their potential impact on the working environment in Næss et al. (2021). However, based on earlier considerations of the health impacts of some EE measures in the transport sector, especially in relation to noise pollution, positive effects can be translated to the working environment. For example, the reduction in noise pollution, implied by a halt in motorway and airport expansion as well as measures that reduce car traffic volume, can translate to positive impacts on employees' concentration levels, productivity, and creativity. Ahlfeldt & Pietrostefani's (2019) extensive review of 180 studies on the economic effects of urban density shows that dense cities have a range of benefits including higher productivity and innovation. Furthermore, several studies (Brutus, Javadian & Panaccio, 2017; Cyclescheme, 2021; Quist et al., 2018; Ma & Ye, 2019) have shown that active commuting (walking or cycling) to work can increase concentration, improve memory, and enhance higher order thinking. Thus, EE transport measures that improve walking and cycling infrastructure could further imply positive impacts on employee performance.

For the industry sector, several additional impacts were found to generate positive effects on the working environment. For example, improved air quality was an estimated impact of several EE measures, relating to coke dry quenching, coke stabilisation quenching, emission optimised sintering, and the use of Comelt furnaces. Further effects on the working environment related to reduced noise and heat levels. Noise-induced hearing loss has been identified as a major by-product of noisy machinery and technological processes in industrial settings and is considered as one of the most common occupational health hazards (Pawlaczyk-Luszczynska et al., 2013). These risks carry significant costs with respect to workers' compensation as well as wider social costs due to decreased levels of productivity and damage to quality of life (ibid.).

Overall, improvements in the working environment and employee performance carry significant implications for European societies and economies. Increases in labour productivity allow organisations to produce greater output without increasing input levels, earn higher revenues, and ultimately generate higher GDP. Furthermore, improvements in working conditions and employee performance can also imply increased levels of job satisfaction, which can further generate positive impacts on mental health and wellbeing.

3.10 Impacts on Quality of Human Life

EE measures across the three sectors were shown to generate mostly positive effects on quality of human life and livability – concepts which describe the fundamental conditions of a decent life for all inhabitants of a city or community. These conditions include the numerous health impacts discussed above resulting from reductions in air, noise, water and soil pollution, GHG emissions, material extraction, and landscape fragmentation and destruction, as well as the socio-economic implications of employment growth and employee performance across all three sectors. In the context of urban areas, these additional health and socio-economic impacts contribute to a 'livable space' that ensures a healthy environment and guarantees good job opportunities for residents.

In addition to the reduced levels of air and noise pollution, increased thermal comfort, reduced moisture issues, and better safety were also found to be additional impacts of building refurbishments, particularly insulation measures. Furthermore, the intended energy savings in buildings also translate to increases in disposable income for tenants. This impact is particularly high for low-income households, where the relative change of disposable income due to EE measure in residential buildings can increase by up to 50% (Figus et al., 2017). Furthermore, more energy efficiency leads to better energy affordability and energy access, which in turn can lead to poverty alleviation (IEA, 2012; Ürge-Vorsatz et al., 2007). However, there are several factors that reduce the likelihood of these impacts, including the tenant-landlord dilemma, as discussed in Reiter et al. (2021), as well as the tendency for low-income households to be less likely to invest in renovation activities. Thus, EU Member States should develop effective combinations of regulatory measures, financial incentives and information tools to complement the implementation of EE measures across the building sector (see Reiter et al., 2021 for an overview of current policy programs on European and country levels addressing barriers to EE building measures). For example, several studies have emphasised the need for specific measures to target energy efficiency in buildings at low-income households in order to enhance the positive impacts on social welfare and income distribution (Pollitt et al., 2017; FEANTSA, n.d.).

Further negative implications can arise from increased property and rental prices when buildings are refurbished, which can be expected to be in the range of 3 to 5 % higher for higher performing buildings compared to low efficiency buildings (Fuerst et al., 2015; Khazal & Sønstebø, 2020), ultimately driving gentrification of urban areas (Rice et al., 2020). Thus, political attention must be extended to the challenges lying at the intersection of housing and energy policies. According to the European Federation of National Organizations Working with the Homeless (FEANTSA), the current form of the European Commission proposal for the Renovation Wave Strategy does not clearly outline the necessary instruments to explicitly recognise and address the social risks of building refurbishment measures (n.d.).

The most salient impacts on quality of life and livability derive from the EE measures of the transport sector, as they directly relate to changes in the urban fabric. In particular, the spatial densification measures coupled with improvements of public transit systems provide mobility and accessibility opportunities for residents unable to drive, reduce travel time for daily-life purposes, and facilitate easier everyday schedules. Nevertheless, the social impacts of denser cities are varying, with some studies showing that higher density incurs societal issues, such as lack of safety, and other studies arguing for the positive implications of denser urban areas on society, in terms of urban vibrancy and accessibility (see Berghauser Pont et al. (2021) for an extensive review and comparison of densification effects on sustainable urban development). Thus, it is crucial for urban design and planning strategies as well as policy programmes to address potentially adverse social impacts of urban densification. Several studies point to the need to conceptually expand the notion of the compact city beyond form, with heightened sensitivity toward co-evolutionary processes (Neuman, 2005; Rinkinen et al., 2021) and cultural sustainability (Skred & Berg, 2019).

Further, recreational opportunities that arise with the preservation of large and continuous non-developed areas, via dense and concentrated urban development, also contribute to the livability of urban areas. A synergistic effect can be expected when reductions in travel time allow for more leisure time in tandem with increases in recreational and mobility opportunities as well as disposable income. Furthermore, halt in motorway construction was found to have positive impacts on quality of life in terms of reduced traffic accidents and avoiding nuisances related to the construction phase.

The impact of industrial EE measures on quality of life and livability are highly dependent on the geographical distribution of plants. Investing in technologies that reduce emission concentrations of pollutants can contribute to improving the air quality of surrounding areas, while positive impacts on employment growth can further increase job opportunities for residents. Overall, EE measures across all three sectors carry considerably positive implications for European communities on both individual and societal levels.

3.11 Impact on GDP, Energy Security, and Energy Prices

EE measures across the sectors showed overall positive impacts on the gross domestic product (GDP), energy security and energy prices. On a national level, energy efficiency measures stock can influence GDP either positively or negatively, depending on whether energy commodities are produced domestically or being imported. Nevertheless, additional impacts on productivity and employment growth, as discussed above, can further induce increases of GDP. According to Figus et al. (2017), energy efficiency measures can increase the GDP such that household incomes profit more from this growth than from the efficiency improvement itself.

Furthermore, reductions in the use of fossil fuels were shown across the sectors. In addition to the impact this has on GHG emissions and air pollution, reducing the usage of fossil fuels can also stabilise energy prices and the dependence on other countries' economies (Gamtessa & Olani, 2018). However, other factors such as increasing demand for energy services due to overall economic growth could counteract positive impacts on energy prices. Furthermore, drops in energy prices may result in a rebound effect, by which energy consumption increases due to lowered prices. In addition, the reductions only in one end-use sector or one EU country will not have a prominent effect.

Overall reductions in energy demand can further reduce reliance on imports of oil, gas, and coal, thereby increasing energy security. Reducing energy imports through efficiency measures can also benefit national economies by reducing the need for supply and storage infrastructure and the related costs (IEA, 2014). Efficiency measures that reduce energy usage can help to alleviate potential trade imbalances and help to limit exposure to geopolitical tensions and volatile energy markets.

4 Conclusion

In the literature, Non-Energy Benefits (NEBs) or Multiple Energy Benefits (MEBs) refer to impacts of EE measures not related to energy savings, which can play a significant role in influencing EE investments (Cagno et al., 2019). Besides positive impacts, in some cases, trade-offs between non-energy related impacts and energy savings can occur. Such rebound effects are thus equally important to consider as non-energy benefits, albeit often challenging to measure and quantify. Thus, in this report, we have used use the term 'additional impacts' in order to avoid the normative connotation of 'non-energy benefits' and extend its scope to include both positive as well as negative impacts.

In order to create a more holistic picture of the non-energy related effects of EE measures for the future European energy system, we have provided an overview of the additional impacts considered in Reiter et al. (2021), Næss et al. (2021), and Kermeli & Crijns-Graus (2021), discussing them in terms of their effects within and across societal, environmental, and economic dimensions, as well as their relevance and magnitude within and across the building, transport, and industry sectors.

Across the three sectors, it was found that energy efficiency measures can have positive impacts in terms of reduced GHG emissions, air and noise pollution, and material consumption, which bring significant implications on European societies, economies, and environments related to climate change, human health, biodiversity, among others. Further socio-economic impacts were shown across all three sectors in terms of net job creation, related to manufacturing, construction, operation and maintenance work, training for EE related stakeholders, as well as energy performance certification and energy management services. Positive impacts were also estimated on working conditions and employee performance, where EE measures that generated health benefits, such as reduced noise pollution, were translated to the working environment. Across the three sectors, EE measures were shown to have varying impacts on (human) quality of life and livability. In the context of urban areas, the additional health and socio-economic impacts, resulting from reductions in air, noise, water and soil pollution, GHG emissions, material extraction, and landscape fragmentation and destruction, as well as the socio-economic implications of employment growth and employee performance, contribute to a 'livable space' that ensures a healthy environment and guarantees good job opportunities for residents. However, negative implications can arise from increased property and rental prices when buildings are refurbished, ultimately driving gentrification of urban areas (Rice et al., 2020), as well as from urban densification that can incur societal issues, such as lack of safety. Nevertheless, a synergistic effect can be expected when reductions in travel time allow for more leisure time in tandem with increases in recreational and mobility opportunities as well as disposable income.

Reductions in the use of fossil fuels were also shown across the three sectors, which not only impacts GHG emissions and air pollution, but also stabilises energy prices and the dependence on other countries' economies (Gamtessa & Olani, 2018). Efficiency measures that reduce energy usage were found to also help in alleviating potential trade imbalances and help to limit exposure to geopolitical tensions and volatile energy markets. Overall, EE measures were found to have substantial implications for European societies, economies and environments, the majority of which were positive. Nevertheless, taking into account rebound effects and possible trade-offs or distributional effects showed that EE measures must be implemented in tandem with economic and policy instruments, which will be thoroughly discussed in D6.4.

Ultimately, we have shown that considering the non-energy related impacts of EE measures brings to light a valuation frame that extends across societal, economic, and ecological dimensions, beyond energy and cost savings. This, in turn, can serve to influence EU policy makers and investments and increase understanding uptake of EE measures across the continent. However, the additional impacts or multiple benefits approach does not currently form the basis of formal decision-making processes, which are primarily concerned with financial costs and benefits (Fawcett & Killip, 2019). This report thus contributes to the emergent 'multiple benefits' framing of energy efficiency, providing a qualitative overview of the additional impacts of EE measures across the building, transport, and industry sectors. The saliency of different impacts hinges on the values and priorities of different stakeholders. Thus, we have aimed to provide a holistic overview that touches upon the various implications for the Member States and the future of Europe's energy transition and sustainability agenda.

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