The Hidden Benefits of Energy efficiency

Quantifying the Impact of Non-Energy Benefits When Energy Efficiency Measures Are Implemented in The EU Iron and Steel industry

Master Thesis

12 July 2021

Faisal Bin Abdulwahed
ID: 6419801
MSc Sustainable Development, E&M track
f.f.a.binabdulwahed@students.uu.nl

Wina Crijns-Graus
Thesis supervisor at Copernicus Institute,
w.h.j.graus@uu.nl

Universiteit Utrecht

Summary

EU Commission launched the EU climate action (2014) and European green deal to reinforce the climate and energy framework that includes the EU broad targets and the integrated strategic energy technology plan. Energy efficiency (EE) plays a key role in the ongoing efforts for a clean energy transition in the industry sector and for meeting the global climate and sustainability goals. So far, analyses of energy efficiency measures (EEMs) and technologies focus mostly on the direct energy saving potentials. Many of these energy efficiency measures provide additional benefits, known as non-energy benefits (NEBs). The steel sector rank first when it comes to CO2 emissions and second for energy consumption. To meet global energy and climate goals, emissions from the steel industry must fall by at least 50% by 2050. Steel directly accounts for 2.6 gigatons of CO2 emissions annually, responsible for 7% of energy sector CO2 emissions. Although current efforts have been taken to improve energy efficiency, there are future saving opportunities. Hence, the study aims to quantify the additional NEBs that are overlooked when implementing EEMs within the iron and steel sector.

Therefore, the research question is; *"To what extent can including NEBs increase the attractiveness of energy efficiency measures in the Iron and steel sector in the EU and to what degree can they be quantified?"*

The research develops upon the findings from the SEEnergies project. The study followed three main steps; identification and quantification, and measuring the impact of implementing NEBs. This research analysed the impact of implementing 20 new EEMs within the process of the steel industry in the scope of the EU. The NEBs were applied to three mitigating Best Available Technology's (BATs) scenarios, to construct different energy demand pathways for the EU industry. The quantified NEBs in this study were fossil fuel-saving, avoided air and avoided deaths caused by pollution. These indicators show significant benefits in each BAT scenario. The NEB indicator increases the significance of the benefit of recycling, showing a drastic impact on emission and fossil fuel reduction, as well as the indirect impact of deaths from emissions. the health and well-being indicator estimated 25,000 avoidable deaths for BAT high recycling and 12,000 for BAT incremental recycling for the EU27 in 2050. The limitation faced was the lack of available data to quantify other NEBs. Additional data should be collected by institutions to improve and streamline researchers' studies. Further research of the awareness of the importance's of NEBs is required and simpler developed quantification methods. Ultimately, the findings of this study highlighted the unnoticeable benefits of energy-saving, demonstrating the wide prospect for future research in the field of non-energy benefits.

Keywords: Non-Energy Benefits, Energy Efficiency Measures, Iron & Steel Industry, Best Available Technologies, Steel Recycling

Acknowledgements

I would like to express my gratitude to my supervisor, Dr Wina Crijns-Graus, who never ran out of patience, you provided me with constant support and guidance throughout the process of the thesis, I am forever grateful. Next, I would like to thank Katerina Kermeli, for all her support and always making time for answering all my technical questions. Finally, I would like to express my appreciation to my close family and friends, who provided me constant encouragement and love throughout the years of my studies.

Faisal Bin Abdulwahed
July, 2021

Table of Contents

Acronyms & Abbreviations 6

1. Introduction 7

1.1. Background 7

1.2. Iron and steel sub-sector 8

1.3. Knowledge gap 9

1.4. Research questions 10

2. Definitions and Scope 11

2.1. Non-energy benefits 11
  2.1.1. Societal level categorisation 13
  2.1.2. Non-Energy Benefits Quantification Tools 14

2.2. Iron and steel industry energy use and production in the EU 14
  2.2.1. Iron and Steel production process 16

2.3. Research Framework 19

2.3.1. Reading guide 20

3. Identification and Quantification of NEBs – Literature review 21

3.1. Exploring and Categorizing Non-Energy Benefits 21
  3.1.1 Frequently cited NEBs from literature 24

3.2. Observing Quantification Methods of NEBs 26

3.3 NEB Quantification impact on Investment decision 33

3.3. Indicators and Tools for Quantifying NEBs 34

4. Energy efficiency measures and indicators in the steel industry 35

5. Applying quantifiable NEBs to the BAT Reference scenarios. 39

5.1. Chosen NEBs Indicators and calculation methods 39
  5.1.1. Final Energy Saving 39
  5.1.2. Fossil fuel saving from energy saving potential 39
  5.1.3. GHG emission avoided from energy saving 40
  5.1.4. Local Air Pollution 41
  5.1.5. Health and well-being 42
  5.1.6. Avoided deaths from energy saving 42

5.2. Environmental benefits of energy efficiency 43
  5.2.1. Final energy demand 43
  5.2.2. Results of the Fossil fuel savings indicator 46
  5.2.3. Greenhouse Gases Emissions Avoided Indicator 47
  5.2.4. Air Pollution Avoided indicator 49

5.3. Social Benefit of Energy Efficiency 52
  5.3.1. Health and well-being indicator 52

6. Discussion 56

6.1. Contribution to literature 56
  6.1.1. Implementation of EEMs and NEBs in the BAT scenarios 56
  6.1.2. Steel Recycling Fuel Switch 56

6.2. Limitations and Assumptions 58
6.3. Recommendations for Further research 59

7. Conclusion 60

8. References 62

9. Appendix 67
9.1. Appendix - A 67
9.2. Appendix - B 82

Acronyms & Abbreviations

Term	**Description**
CO	Carbon monoxide
CO_2	Carbon dioxide
EE	Energy efficiency
EEM	Energy efficiency measures
BAT	Best available technology
NEBs	Non-energy benefits
NOx	Nitrogen oxides
TJ	Terajoule
PJ	Petajoule
PM2.5	Particulate matter with a diameter less than 2.5 µm
PM10	Particulate matter with a diameter less than 10 µm
SOx	Sulphur oxides
MtCO2	Megaton of carbon dioxide
Ktonne	Kiloton

1. Introduction

1.1. Background

In the last couple of years, efforts around the world to solve the climate crisis have increased through the introduction of new agreements. IPCC (2014) forecasted the global warming is on a trajectory of over 3°C, the warming of the planet can bring drastic changes causing uninhabitable areas around the world. Between 1990 to 2017 population has increased by 42% and final energy consumption grew by 50% and CO2 emissions by 58% (World Bank, 2020; IEA, 2020). Climate concern has led nations to develop treaties such as the Kyoto protocol in 1997 and the Paris agreement in 2016 in determination to reduce greenhouse gases (GHG) (UNFCC, 2016). The agreement required all nations to propose their national determined contribution (NDCs) that aims to limit the warming of the planet from 1.5°C to 2°C degrees.

The EU Commission launched the EU climate action (2014) and European green deal to reinforce the climate and energy framework that includes the EU broad targets and the integrated strategic energy technology (SET) plan set for the period 2021 – 2030. The key targets are; 40% cuts in greenhouse gas emissions (from 1990 levels), and at least 32.5% improvement in energy efficiency (European Commission, 2019). Private and public sectors have increased their efforts to take action in the reduction of greenhouse gases (GHG) emissions and energy consumption, although reports such as The Emission Gap released by the United Nations Environmental Program (UNEP) has shown investments and policies in energy efficiency projects are insufficient to reach the set targets of such agreements (UNEP, 2017).

the International Energy Agency (IEA) stated in the World Energy Outlook (WEO) 2016, energy efficiency (EE) needs to be at the core of any strategy to assurance secure, sustainable and inclusive economic growth. EE is one of the five core dimensions of the Energy Union, next to energy security, solidarity and trust; the internal energy market; decarbonization of the economy; and, innovation and competitiveness (European Commission, 2014b). Improving energy efficiency brings a variety of benefits such as reducing GHG, energy demand and overall cost. Renewable energy does help these objectives but improving efficiency is a more cost-effective and more immediate option to reduce fossil fuel use (López-Peña, 2012). Energy efficiency is increasingly recognized as a method to secure sustainable energy supply and promote the EU's competitiveness. Energy efficiency measures (EEM) have become recognized as a significant energy resource, as they avoid energy-use larger than any other supply-side resources through technical efficiency. From an investor point of view, EE options are not cost-effective enough when only energy savings are accounted as the benefit, while policymakers often rationalize EEM's by pointing to co-benefits.

a project such as Multiple benefits (M-benefits, 2018) and COMBI project (Combi-Project, 2015) for example, has collaborated with government organizations and private institutes to build a project that evaluates all the benefits that arise from EEM apart from energy savings benefits. The Co-benefits is also known as non-energy benefits (NEBs) such as the reduction of emission, health and economic benefits, and enhanced competitiveness can be much more significant than the cost of energy efficiency measures. They increase the attractiveness of energy efficiency investments and the prospect of gaining benefits other than energy savings (Pye & McKane, 2000, Zhang et al., 2016). Therefore, a strategic priority for the EU is to promote the principle of 'energy efficiency first' particularly in the industrial sector (European Commission, 2019).

The sector that can benefit the most from NEBs in the industrial sector because of the large potential for energy efficiency improvements. Since the industrial sector is responsible for roughly 54% of the world's total delivered energy, 36% of final energy consumption and 24% of total CO2; more than any other end-use sector (IEA,2017).

1.2. Iron and steel sub-sector

Steel is greatly embedded in our society as all construction relies on steel. Since 1970 global demand for steel has increased that's more than threefold and continues to rise as economies grow, urbanize, consume more goods and build up their infrastructure. It will also be an essential component for the energy transition, with wind turbines, solar panels, and electric vehicles all depending on it to varying degrees. (IEA, 2019). To meet future climate targets, the iron and steel (I&S) industry has to improve its resource and energy efficiency (Johansson & Söderström, 2010)

Among heavy industries, the iron and steel sector rank first when it comes to CO2 emissions and second for energy consumption. To meet global energy and climate goals, emissions from the steel industry must fall by at least 50% by 2050, with continuing declines towards zero emissions being pursued thereafter. I&S directly accounts for 2.6 gigatons of CO2 emissions annually, responsible for about 8% of global final energy demand and 7% of energy sector CO2 emissions. According to European Steel Association (EUROFER) is 2019, the European Union (EU) manufactures 16% of the global steel production, the second largest producers after Asia 72% (China 53.3%, India 5.9% Japan 5.9%) shares of production (EUROFER, 2020).

I&S sector is also the largest industrial consumer of coal, which provides 75% of its energy demand. As it is instrumental in the manufacturing process to produce steel from iron ore. The steel industry has for a long time held a strategic place in the EU economy, growth, and innovation. In contracts with other industrial sectors, energy consumption in I&S is expected to keep growing, and energy intensity is expected to only improve marginally with an increase in production (Nehlar, 2019). Energy efficiency benefits are commonly acknowledged in the I&S industry but only when directly linked to reducing costs savings. Steel manufacturers have not always chosen to implement EEM to achieve the most benefit; a survey study by OECD Steel Committee (2015), has shown that the I&S industry has a limiting internal investment, therefore reducing the implementation of EEM in the subsector.

Steel is one of the most recycled materials in the world. More steel is recycled every year than glass, aluminium paper and plastic combined steel has a potentially endless life cycle because it is easy to recover and practically 100% recyclable without any significant loss of quality. (Worldsteel, 2020). While iron ore is the source of around 70% of the metallic raw material inputs to steelmaking globally, the rest is supplied in the form of recycled steel scrap.

Therefore, the I&S sector has a significant potential to implementing EEMs that would have benefits to economic, social and environmental NEBs that would lead to a significant improvement to the EU energy efficiency target and increase the likelihood of stakeholders to increase their investments in energy efficiency-related projects within the industrial subsector. .

1.3. Knowledge gap

The IEA roadmap plans that the wide deployment of technology (electrification, hydrogen, carbon capture, use & storage (CCUS)) will increase between 2030 and 2050 to meet global energy and meet climate targets. Emissions from the I&S industry must fall by at least 50% by 2050, and the average CO2 emission intensity of steel production must decline by 60% by 2050 to achieve near-zero-emission (IEA, 2020). The efforts to reduce CO2 emissions within the I&S sector are ongoing, from governments and the private sector. Countries have already implemented policies to support improvements in energy efficiency, some producers have set goals for more carbon-neutral steelmaking by 2050 (ISO, 2020). Despite this, the sector's emissions continue to rise and greater ambition is needed. For instance, the energy intensity of modern blast furnaces is already approaching the practical minimum energy requirement. For inefficient equipment, the gap between current energy performance and best practice can be much greater, but with energy making up a significant proportion of production costs, there is already an incentive to replace the least efficient process units.

There have been studied of identifying non-energy benefits in the steel industry. Worrell et al., (2003) paper explored the implications change of evaluating energy efficiency technologies in the steel industry in the US from reviewing case studies. Their findings show by including productivity co-benefits in a model increases cost-effectiveness potential for energy efficiency improvements. Worrell et al., (2002), suggested future work into emerging industrial technologies and the quantification of non-energy. Although current efforts have been taken to improve energy efficiency, there are future saving opportunities as stated by Nehler (2016). To overcome barriers future studies should investigate NEBs related to a particular process or NEBs to specific energy efficiency measures for better precision (Nehler, 2016).

The objective of this research is to continue the investigation from previous literature on the additional benefits that arise from implementing energy efficiency measures, particularly when applied in an energy-intensive industry. Future research is suggested from most NEBs topics and emphasizes the need for improving quantification methods. Hence this research will identify and quantify possible NEBs from efficiency measures of the iron and steel sector, and beyond, together with the implementation of the best available technologies (BAT) and recycling the NEBs can benefit more promptly.

1.4. Research questions

“To what extent can including NEBs increase the attractiveness of energy efficiency measures in the Iron and steel sector in the EU and to what degree can they be quantified?”

1. “What is the extent of research in the topic of NEBs and which NEBs can be identified and quantified?”

2. “What are the identified energy efficiency measures in the iron and steel sector and what is their potential?”

3. “What are the results of the quantified NEBs taking into account different recycling scenarios?”

Answering sub-question 1, will first explore the findings on the NEBs topic by reviewing literature and present findings from relevant research papers, this includes the identification, categorization and quantification methods of NEBs. Frequency mentioned NEBs within the industrial sector and the methodological approaches done in the past will also be explored.

Sub-question 2, will explore the EEMs of the steel industry and elaborate on the data available for this study. The identified EEMs will give insight towards the NEBs that will be focused on, then the chosen indicators and methods for quantifying NEBs based on collected data will be presented.
Sub-questions 3 would show the quantifiable finding of different benefits compared to three BAT scenarios of different rates of recycling, which will show how the outcomes of measured NEB have a different level of benefits that vary in each scenario.

2. Definitions and Scope

In this chapter, the theory and definitions and background knowledge and literature that form the basis of the current research, together with the scope of analysis are provided.

2.1. Non-energy benefits

According to the Energy Efficiency Directive 2012/27/EC, energy benefits or savings are the amounts of saved energy determined by measuring or estimating consumption before and after implementation of an energy efficiency measure, whilst ensuring normalization for external conditions that affect energy consumption (The European Parliament and the Council of the European Union, 2012). NEBs impacts are those associated with efficiency activities other than direct energy and demand savings. Non-energy benefits are the additional effects of implementing EEM's. The impacts of NEBs can either be positive or negative. These benefits have been studied and observed by many depending on their respective applications, e.g. (IEA, 2012; Lilly and Pearson, 1999; Mills and Rosenfeld, 1996; Pye and McKane, 2000; Ürge- Vorsatz et al., 2009). IEA (2012) has denoted all the terms as multiple benefits which cover by all societal levels. Similar concepts are presented in research as non-energy benefits, by (Lilly and Pearson, 1999; Pye and McKane, 2000; Finman and Laitner, 2001), productivity benefits (Worrell et al., 2003) and co-benefits Ürge-Vorsatz et al., 2009). Other terminology such as 'multiple impacts' 'co-benefits, and 'indirect benefits', all refer to the same concept, according to Skumatz (2014). However, the term non-energy benefits are the most commonly used in literature. Figure 1 demonstrates some of the common NEBs from energy efficiency improvements (IEA, 2019).

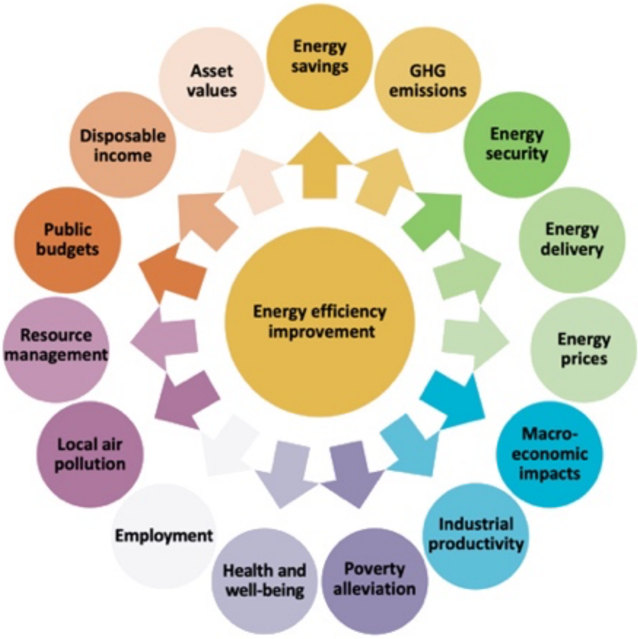

Figure 1 non-energy benefits of energy efficiency improvements (IEA, 2019)

Perceived non-energy benefits that have been sighted in earlier literature on the subject have been reported on three levels; as an outcome of energy efficiency in general; as the additional effects of energy efficiency measures for an energy-using process or technology; or as the particular non-energy benefits of specific energy efficiency measures as shown in figure 2(Nehler, 2016).

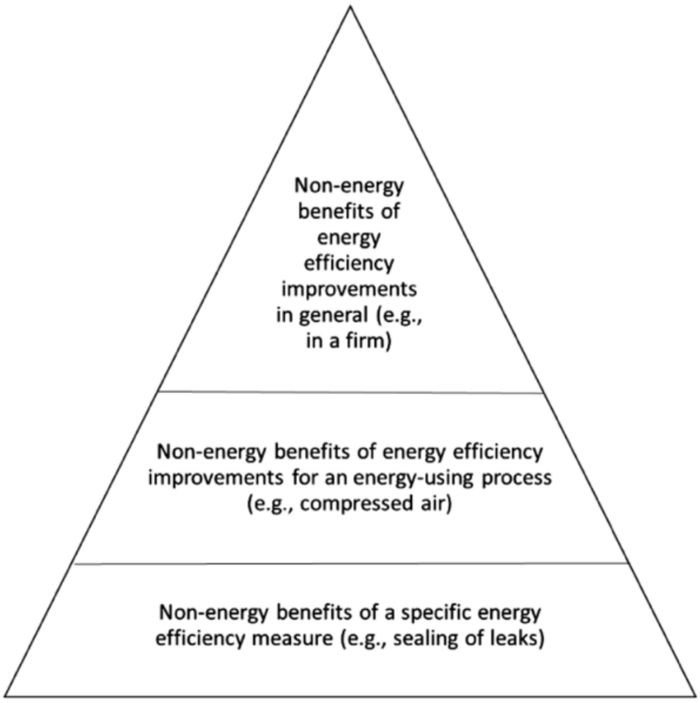

Figure 2: Non-energy benefit divided by the level of energy efficiency measures (Nehler, 2016)

the importance of the characteristics of energy efficiency measures has been recognised by Trianni et al. (2014). The classification shares similar features with the classification scheme mentioned by Fleiter et al. (2012), such as payback time and implementation cost. Trianni et al. (2014) have presented categorised attributes that characterise the industrial energy efficiency improvements, as seen in table 1.

Table 1 attributes of industrial energy efficiency measures, according to Trianni et al. (2014)

Characteristics	*Attributes*
Economic	Payback time, implementation cost
Energy	Resource stream, amount of saved energy
Environmental	Emission reduction, waste reduction
Production-related	Productivity, operation and maintenance, working environment
Implementation-related	Saving strategy, activity type, ease of implementation, the likelihood of success/acceptance, corporate involvement, distance to core business
Interaction-related attributes	Indirect effects

Based on IEA (2019), the macroeconomic impacts of energy efficiency are driven by two types of effects associated with EEM: I) investment effects, which is the result of increased investment in EE goods and services, and ii) cost/energy reduction demand effects. Investing in EE goods and services is the first step taken as part of EEM that would lead to the second step – realising energy efficiency savings from the goods/services. This brings out a collection of the direct and indirect effects that make macroeconomic impacts; this is demonstrated in figure 3. For instance, if investments are taken place (investment effect) then this can affect employment (macroeconomic impact). If energy security is improved (energy demand reduction effects) this can affect energy prices and so on.

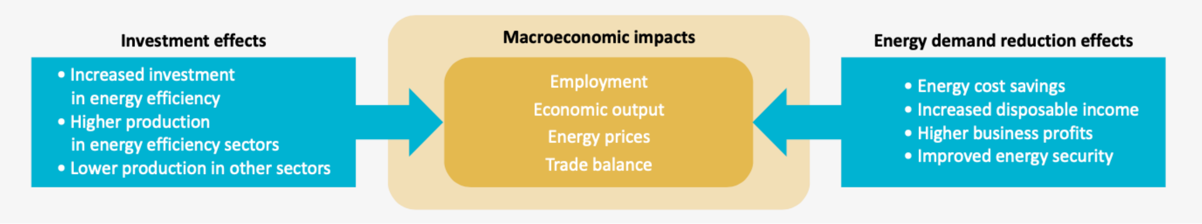

Figure 3: Energy demand reduction effects; Macroeconomic impacts are driven by investment effect and energy demand reduction effect (IEA, 2019).

2.1.1. Societal level categorisation

The IEA (2012) report covers the improvements of energy efficiency measures and uses the term 'multiple benefits' for all related benefits, and has categorised the NEBs by dividing them into four societal levels; individual, sectoral, national and international (IEA, 2012)as seen on figure 4. From an industry perspective, the Individual level refers to firms benefits (e.g., well-being, health impacts, increase disposable income), and the sectoral level refers to the benefits of a sector (e.g. industrial productivity, increase asset values). The national benefits refer to larger macroeconomic impacts (e.g., energy security, employment creation and economic output). The international level covers larger impacts, such as greenhouse gas emission mitigation and lower energy price (IEA, 2012, Rasmussen, 2014).

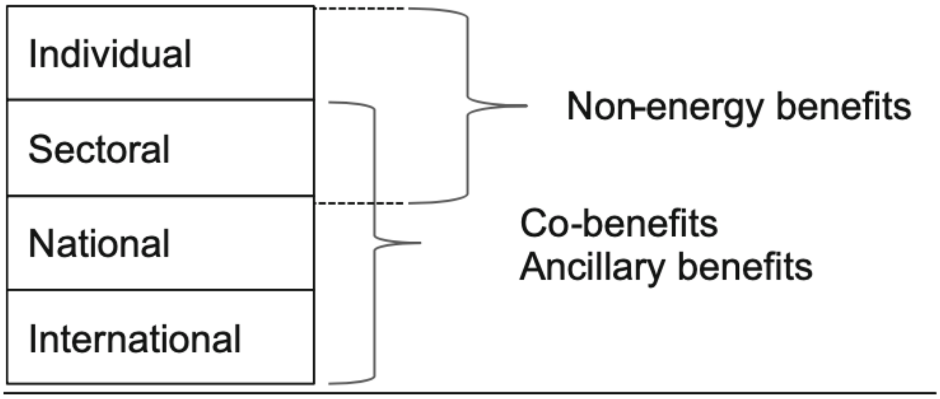

Figure 4: benefits terms by societal level.

2.1.2. Non-Energy Benefits Quantification Tools

The COMBI project (Calculating and operationalizing the multiple benefits of energy efficiency) categorised the NEBs into five categories; emission, resources, social welfare, macro-economy and energy system, which allow for a broader range of overlooked NEBs compared to other literature, this includes NEBs such as 'effect on health', 'disposable income', 'public finance' and 'energy security. The objective of the project is to provide a comprehensive overview of the existing benefits in Europe for policymakers, evaluators and the interested public (Naess-Schmidt et al., 2015). The project was launched in 2018 under the Horizon 2020 programme funded by the EU to quantify major multiple impacts of energy efficiency potential beyond existing policies scenarios and to make the research findings accessible (Mzavanadze, 2018).

In addition, another project supported by the Horizon 2020 programme European commission is Odyssee-MURE that began in 2015. The project is managed by Enerdata and Fraunhofer databases, in combination their databases contain energy efficiency indicators and impact evaluation of all measures at a national level or EU international level. Odyssee-MURE's objective is to provide a comprehensive database for monitoring energy efficiency trends and evaluate policy measures within the EU, partnered with more than 30 European countries to gather information on EE trends and policy impacts. Their analysis simplified NEBs to three groups; environmental, economic and social. the first group comprises direct aspects of efficiency e.g. energy saving, emission reduction. The second includes macro-economic impacts of the growth of the economy e.g. innovation and GDP impact. The third covers social benefits such as health, well-being and employment (odyssey-MURE, 2020).

However, some of these methods incorporate more qualitative indicators that can be subjective more than quantitative. While the studies have created theoretically valid approaches, data availability and qualitative methods determine their applicability be deemed useful in practice.

Given the above, the perspective of this research will follow a few selected NEBs from figure 1 and falls under the second tire of figure 2 since the EEMs in the steel sector are improvements in the process of each product level. The focus is on environmental and economic characteristics based on what can be quantified within the iron and steel sector. the quantification methods and tools that will be analysed and applied in the study is subject to the data collection stage.

2.2. Iron and steel industry energy use and production in the EU

The EU is the second-largest producer of steel in the world, its total output is 177 million tons of steel per year. This accounts for 16% of global output (IEA,2019). The I&S sector is worth €170 billion euros in Gross Value Added to the EU economy every year and currently has 500 production sites spread out across 22 EU Member States (Eurofer, 2020). the steel industry is one of the most energy-intensive industries; the subsector has the potential to increase energy savings and reduce carbon dioxide emissions through EEM (worldsteel, 2020). The value of the producers of crude steel is shown in the appendix.

Manufacturing metal is the largest energy-consuming compared to all industrial products (IEA, 2017). The intensities of the manufacturing subsectors; energy consumption per value-added, vary significantly, as shown in figure 4. Within manufacturing, basic metals are the most energy-intensive subsectors. With steel being highly recyclable, there is room for the larger implementation of energy efficiency measures and technologies in the subsector to reduce the production of new steel.

Steel production from scrap requires around one-eighth of the energy that produced from iron ore – mainly in the form of electricity, rather than coal for production from iron ore although most fuel consumed in the industry is coal as seen in figure 5. However higher recycling rates are required in steel production since scrap recycling cannot fulfil the sector's raw material input requirements alone because steel production today is higher than when the products that are currently being recycled were produced. Recycling alone cannot be relied upon to reduce emissions from the sector to the extent needed to meet climate goals. hence, higher energy efficiency measures/technologies need to be adopted alongside the uptake in the recycling process (IEA, 2020).

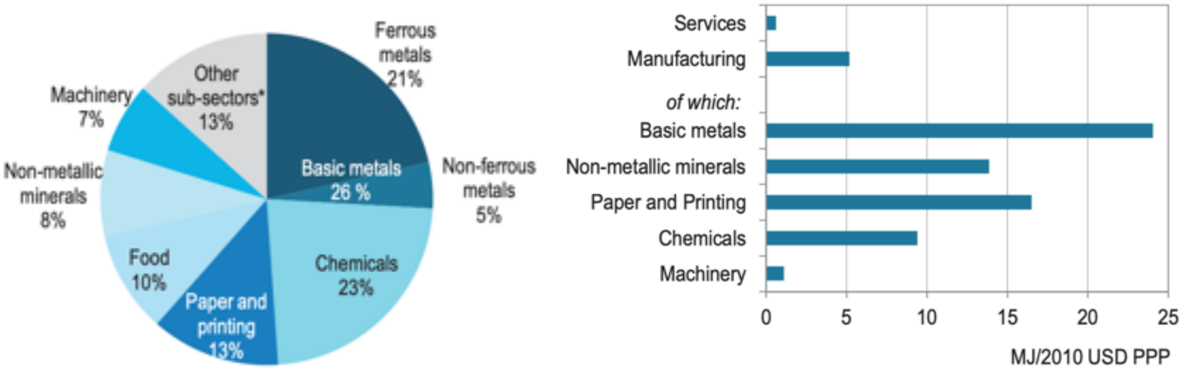

Figure 5 (left). manufacturing energy consumption by subsector; (right) Manufacturing and services intensities (IEA, 2017)

Steel production in the EU adopts different routes with differing technologies. Production processes can be broadly distinguished by two main routes; integrated blast furnace (BF)-basic oxygen furnace (BOF) route (integrated route) and the electric arc furnace (EAF) route (scrap route). BF-BOF are used for iron ore as the base that accounts for 50% of BOF steel cost and EAF is used for scraps which represent 75% of steel cost. BOF is self-sufficient in energy where the raw material is about 70% liquid hot metal from the BF. In the EU BF-BOF are primarily used for steelmaking and EAF are used via secondary routes. Thousands of different graded steels are produced through this process in a range of qualities. In 2019 it was recorded that the production share of crude steel in EU28 was 60.2% BF/BOF route and 39.2% EAF route (Steel Institute, STAhl, 2016).

The energy intensity of state-of-the-art blast furnaces is already approaching the practical minimum energy requirement. For inefficient equipment, the gap between current energy performance and best practice can be much larger, but with energy making up a significant proportion of production costs, there is already an incentive to replace the least efficient process units. Improvements in operational efficiency, including enhanced process control and predictive maintenance strategies, together with the implementation of the best available technologies contribute around 20% of cumulative emissions savings in the sustainable Development Scenario (IEA, 2020).

Conversely, scrap-based EAF production relies primarily on electricity and has a much lower emission intensity. The route results in only about 0.04 t CO2/t of crude steel produced on a direct emissions basis, as a result of a small amount of coal or gas use and from the production (IEA, 2020). Based on the current global average CO2 intensity of electricity generation, the scrap-based EAF route results in an additional 0.3 t CO2/t in indirect emissions. These can be achieved through measures such as maximising operational energy efficiency and by employing BATs.

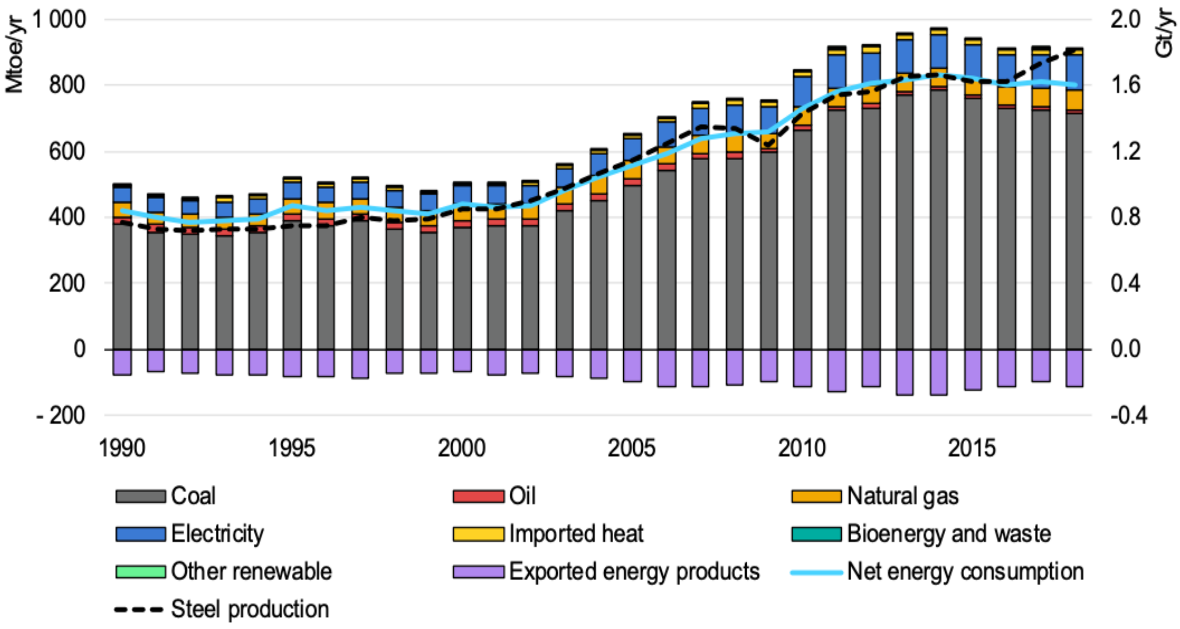

Figure 6: Final energy consumption in the steel industry, IEA analysis based on IEA (2020a), World Energy Balances, World Steel Association Steel Statistical Yearbook.

2.2.1. Iron and Steel production process

The EU produces a total of 157.5 ktonne of crude steel in 2019. The top produces are Germany, Italy, France, Spain, Netherlands. which make up more than 55% of the EU’s total (Eurofer, 2020). The production of steel has processing stages that carry out various configurations depending on the product mixes, raw material and energy supply. The two manufacturing routes dominating steel proception are blast furnace-basic oxygen furnace (BF-BOF) process – figure 7 illustrates the products routes (Carpenter, A. 2012).

Where iron ores are reduced with coke in the BF which results in pig iron (hot metal), this step undergoes a reduction process where it is separated from oxygen by carbon. It's combined with oxygen and forms CO2. Consequently, carbon is necessary and this is why emissions are unavoidable in the process. The next step is BOF and it's required since iron is brittle and not easily formable, so oxygen is blown on the liquid iron to burn unwanted elements (Worldsteel, 2021). Recycled metal known as scrap can also be reliquidated in the BOF. The second route is mini-mills based on the electric arc furnaces (EAF) process where the iron input is typically from scrap, cast iron and direct reduced iron (Carpenter, A. 2012). EAFs can produce many types of steel, from metal for basic products like reinforcing bars to stainless alloyed steel. Lastly, in both route's liquid steel is then cast and rolled to finished steel. As of 2019, the EU27 has a total of 49 BF-BOF and 133 EAF. EAF production has grown while BF-BOF production has been steady - shown in figure 10 between 2010 - 2019. The latter is still the most widely used but largely due to the limitation ins scrap metal available (EUROFER, 2020).

Energy consumption and CO2 emissions vary based on the steel product, which influences the CO2 that can be reduced. For instance, scrap recycling reduces energy consumption and direct CO2 emission by a factor of 2 to 4 (Gielen et al., 2008). Based on the power mix and fuel mix of each route will generate different CO2 emissions – coal produces more CO2 than natural gas due to its higher emission factor, whereas renewable energy sources produce zero direct emissions. Hence each country has a different value of power generation that directly influence the amount of CO2 emitted. The potential of energy efficiency improvements depends on the production route, energy and carbon intensity fuel and electricity (EUROFER,2020).

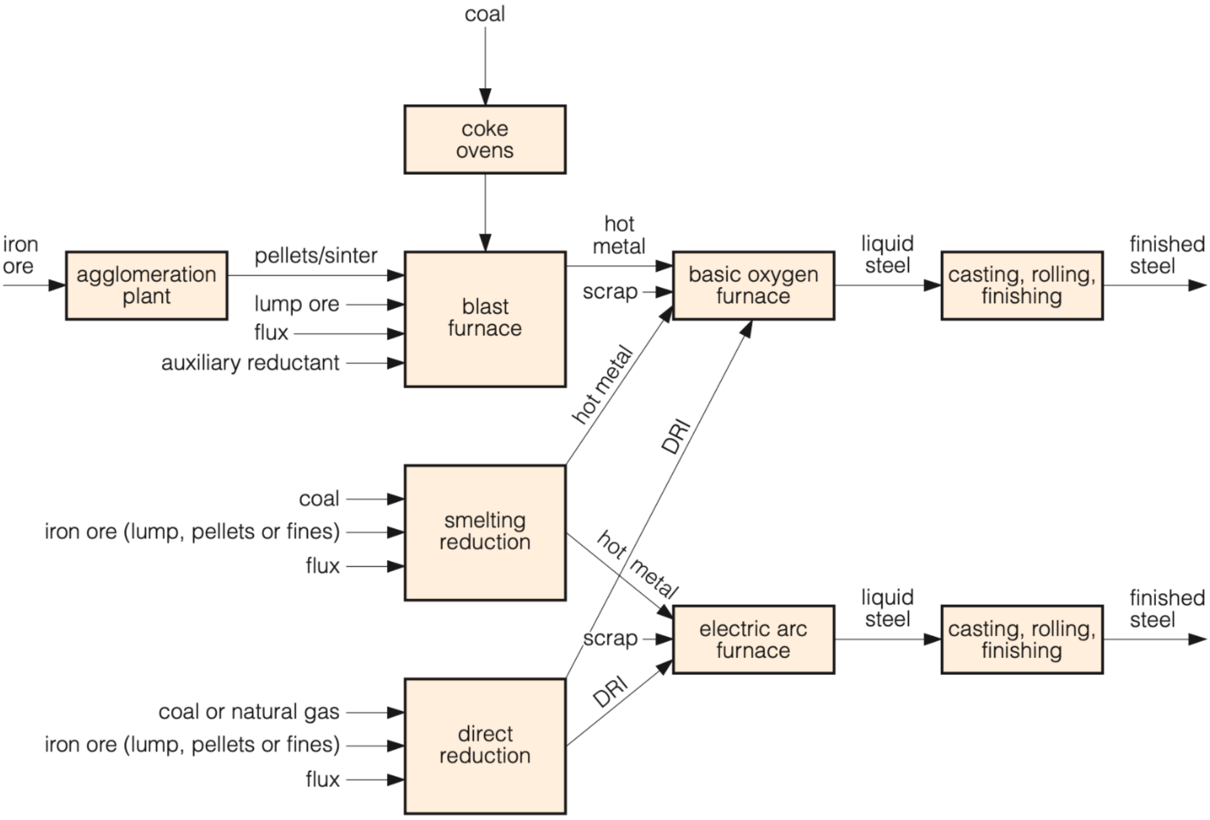

Figure 7: The major iron and steel production routes (Carpenter, A. 2012)

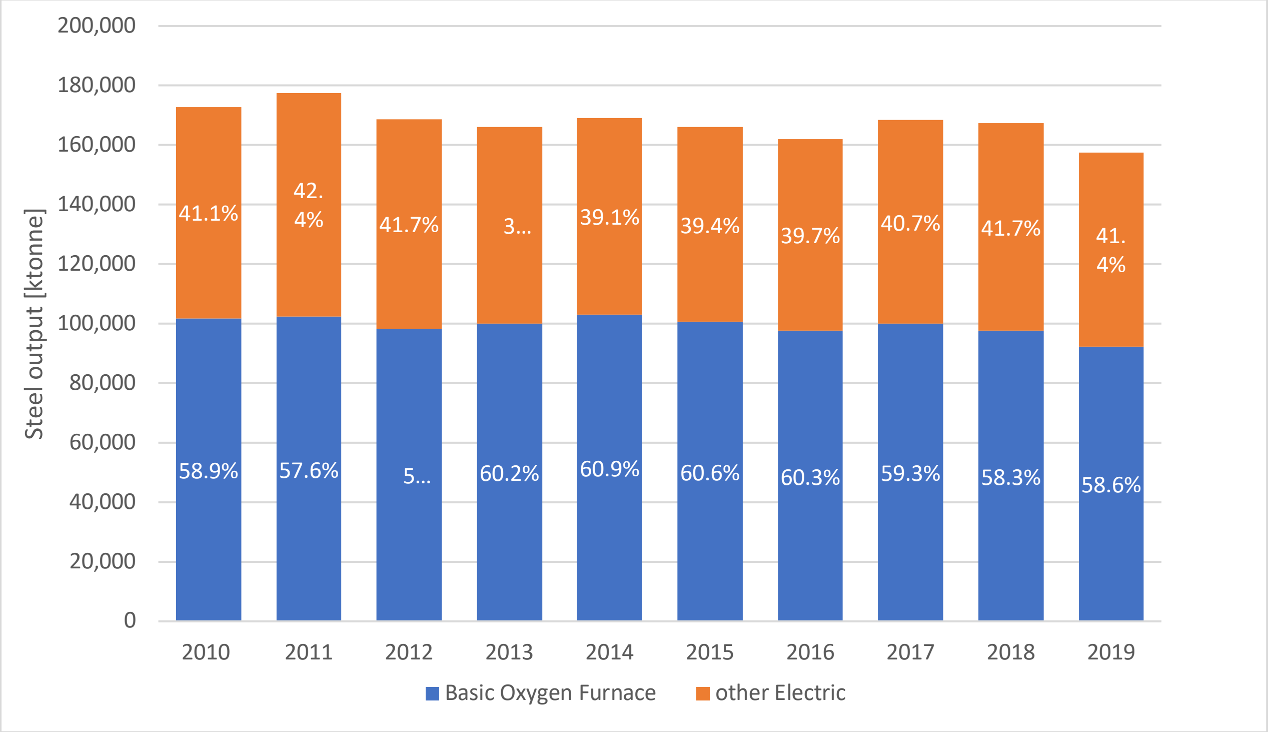

Figure 8: EU28 steel output by production route; BF-BOF and EAF, (EUROFER,2020).

2.3. Research Framework

the steps that the study will follow is explained in the following figure 9. It is coloured coded foe each sub-question with the two main steps they trail. The following section explains the steps further.

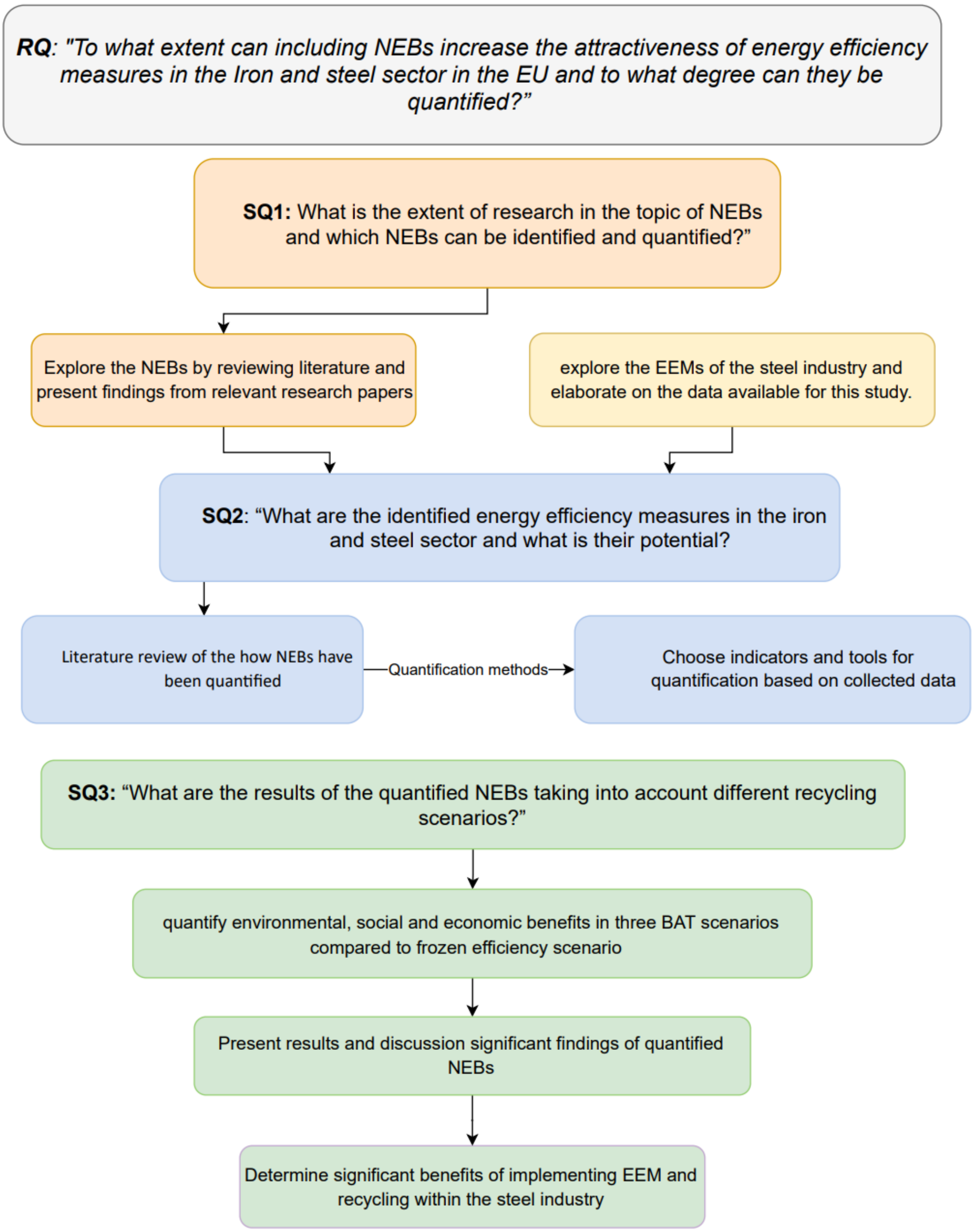

Figure 9: Methodology framework of the research.

2.3.1. Reading guide

The following sub-questions will build upon the background information discussed in previous sections. Literature reviews, methodology and results will be used to expand upon each of these sub-questions. Section 3 covers identification, categorisation and quantification methods from previous studies of NEBs, via the findings from the in-depth literature review, highlighting the main finding from past studies such as the most frequent NEBs cited. Section 4 answers sub-question 2, identifying the EEMs from the SEEnergies project and the data collected for the study is described. Then the chosen indicators and quantifying methods are presented. Next, chapter 5 will answer sub-question 3. the findings will be analysed in three BAT scenarios, the findings for the research are presented in graphs and tables for each NEB indicator. Furthermore, chapter 6 and 7, concludes the study with a discussion and conclusion chapters, showing the research contribution to literature, limitation faced and recommendation for future work.

3. Identification and Quantification of NEBs – Literature review

This chapter answers the sub-question *1 What is the extent of research in the topic of NEBs and which NEBs can be identified and quantified?* This section comprises of a extensive literature review of the topic of NEBs and the identification and quantification methods found in literature. This was done to identify and describe the benefits related to EEMs of in the steel sector. The review was performed to identify existing categorizations or frameworks associated with NEBs. This was accomplished to have a general picture and a benchmark of the benefits that can be implemented in steel sector.

3.1. Exploring and Categorizing Non-Energy Benefits

literature was collected on the topic of non-energy benefits (NEBs) to begin the assessment of identifying and categorizing relevant NEBs within the steel industrial sector. The assessment of literature is to shine a light on previous research that has been conducted on the topic to determine the approach of the research and barriers that were faced. The literature database that used are Google Scholar, Scopas and Web of Science, as they are primarily science-based, but includes social science literature. the results were sorted by the number of citations in each database. The keywords were non-energy benefits, co-benefits, and ancillary benefits, with the constraint on topics related to ‘Energy efficiency measures’ and ‘Industry/industrial sector; iron and steel’, which includes articles that are journals and conference papers. The search was in the titles, abstracts and keywords.

Each keyword varied the number of results in each database, the highest being non-energy benefits, followed by co-benefits then ancillary. Search strings were added to the search to reduce the risk of excluding relevant papers. Hence the terms ‘indirect benefits and ‘multiple benefits’ are terms used to also describe non-energy benefits. Using these terms resulted in more relevant articles on the topic (Cooremans 2011), the chosen timeframe was from 1999 onwards.

The abstract of each paper was thoroughly read, if the keywords were found to be applicable with the aim of the research, the paper is then considered necessary to the study. Using the chosen benefit terms resulted in overlap with many articles. Several papers were not available as full text due to their restriction to access or are not available online, hence they were excluded from the study.

Finally, a total of 104 papers were deemed relevant and were then read. The scientific articles and reports were narrowed down further by reviewing and comparing the aim of the research and methodology which aligned most to the research questions. The analysis of the literature was narrowed down to a total of 39 papers – table 2. which are the most relevant to energy efficiency measures and non-energy benefits in the industrial sector except for case studies regarding NEBs within the building sector. The findings of the literature are detailed in the following section, starting with the categorisation of NEBs from previous studies and the number the benefits mentioned in studies. This gives insight into what types of NEBs are present in the I&S industry and their frequency in research studies.

Table 2: literature of chosen publication in the field of non-energy benefits in industry, including region of study and publication type.

	Author, year	**Industry**	**Region**	**Type of Publication**
1	Lilly & Pearson, 1999	Iron & Steel	USA	Conference
2	Pye and McKane, 2000	Iron & Steel	USA	Journal
3	Skumatz et al. 2000	Multiple	USA	Conference
4	Finman & Laitner, 2001	Multiple	Multiple	Conference

5	Worrell et al., 2002	Iron & Steel	USA	Journal
6	Worrell et al., 2003	Iron & Steel	USA	Journal
7	Loftnes, 2003	Buling Retrofits	USA	Conference
8	Hall & Roth, 2004	Multiple	USA	Conference
9	Skumatz & Gardner, 2005	Multiple	USA	Journal
10	Lung et al., 2005	Multiple	USA	Conference
11	Bement and Skumatz, 2007	Multiple	USA	Journal
12	Mills et al, 2008	Buldings	USA	Conference
13	Ürge-Vorsatz et al., 2009	buildings	USA	Journal
14	Naess-Schmidt et al.	building - Multiple	EU	Conference
15	Bunse et al. 2010	Multiple	Multiple	conference
16	Fleiter et al., 2012	pulp and paper	EU	Journal
17	Willoughby et al., 2012	Glass	China	Conference
18	Woodroof & Capehart 2012	Multiple	Multiple	Conference
19	Larsen et al., 2012	buldings	USA	Conference
20	Hasanbeigi et al., 2013	Cement	China	Journal
21	yang et al., 2013	Cement	China	Journal
22	Gudbjerg et a 2014	LECA products	EU	Conference
23	Roser et al., 2014	Multiple	EU	Conference
24	Russell et al., 2015	Multiple	USA	Report
25	Naess-Schmidt et al., 2015	Multiple	EU	Conference
26	Rasmussen , 2015	Multiple	Multiple	Journal
27	Cagno et al., 2016	Non-metal fabrications	EU	Conference
28	Ürge-Vorsatz et al, 2016	multiple	EU	Conference
29	Wang et al., 2016	Coal fired power plant	China	Journal
30	Thema et al., 2016	Multiple	EU	Journal
31	Rasmussen & Nehler, 2016	Multiple	EU	Conference
32	Thema et al., 2017	Multiple	EU	Journal
33	Doyle & Cosgrove	Compressed Air System	EU	Journal
34	Nehler et al., 2018	Compressed Air System	EU	Journal
35	Zhou et al., 2018	water - energy nexus	China	Journal
36	Mzavanadze et al., 2018	multiple	EU	Conference
37	Chatterjee & Ürge-Vorsatz	HVAC	EU	Conference
38	Trianni et al, 2020	Compressed Air System	EU	Journal
39	Reuter et al, 2020	Multiple	EU	Journal

The Reviewed literature reveals that the term NEBs are mainly used within the field of energy efficiency for the building sector and the industrial sector, respectively. However, the review mostly focuses on the industrial sector benefits; specifically, iron and steel. Nevertheless, there have been efforts to categorise the industrial NEBs, in literature by many authors in the past two decades. Table A in the appendix - lists the frequent mentioned NEBs in industrial energy efficiency and their efforts of categorisation. This includes other non-literature; EIA (2012) and ODYSEE-MURE project and COMBI projects which are online databases/tools.

Ürge-Vorsatz et al. (2009) categorised NEBs into five categories; health effect, economic effect, ecological effect, service provision benefits and social effect. Lilly and Pearson (1999) identified the NEBs in the industrial sector to reduced cost for maintenance and operation together with reduced emissions. Others include improved productivity, higher product quality, increase reliability, improved worker safety and reduced waste (Pye and McKane 2000; Finman and Laitner 2001, Worrell et al. 2003). Skumatz et al (2000) categorised the NEBs in the building sector in relation to the type of measure e.g. 'water measure', 'lighting measure'.

Coleman (2011), explored the link between NEBs and competitive advantage, therefore reorganised the categories into three groups; cost, value and risk. Examples are such as, the reduction of product waste and lowering cooling requirements are an example of cost benefits. As for value benefit, an example is improving product quality and improve public image. In the risk category, reducing emission benefit and decreasing liability are linked (Cooremans 2011). These findings show the variety of possible NEBs that result from implementing energy efficiency measures, as they play a crucial role in increasing the attractions of energy efficiency measures.

Moreover, the most prominent categorisation recurrent in the literature that has been cited numerous times is by Finman & Laitner (2001) and Worrell et al. (2003). The NEBs are divided by type of benefit which simplifies the categorisation of each benefit. Table 3 demonstrates the six NEB categories; waste, emission, operational and maintenance, production, work environment and others. Each category includes the most mentioned and reoccurring NEBs in industrial energy efficiency.

Table 3: categorisation summary of non-energy benefits within industrial (Finman and Laitner, 2001, Worrell et al. 2003).

Waste	Emission	Operational & Maintenance
Use of waste fuels, heat, gas Reduced product waste Reduced wastewater Reduced hazardous waste Materials reduction	Reduced dust emissions Reduced Air pollutants; CO, CO2, NOx, SOx emissions, PM2.5, PM10 Fossil fuel savings	Reduced need for engineering controls Lowered cooling requirements Increased facility reliability Reduced wear and tear on equipment/machinery Reductions in labour requirements
Production	**Working Environment**	**Other**
Increased product output/yields Improved equipment performance shorter process cycle times Improved product quality/purity Increased reliability in production.	Reduced need for personal protective equipment Improved lighting Reduced noise levels Improved temperature control Improved air quality.	Decreased liability Improved public image Delaying or Reducing capital expenditures Additional space Improved worker morale

The chosen 39 papers were thoroughly re-read and the NEBs mentioned in each study were counted and categorised using by Finman and Laitner, (2001), Worrell et al. (2003) categorisation method, the EEMs were also counted but not categorised, as demonstrated in in Appendix A. Counting the benefits of each study demonstrations what NEBs are mostly covered in literature regarding NEBs in the industrial sector. The table also shows whether the studies have adequate quantification methods of NEBs included in the study. this step is supplementary exercise to find the most value in terms of which NEBs are identified and quantified in the industrial sector in terms of studies found in literature, to demonstrate the most frequent mentioned NEBs in industry that are the most significance when quantified.

3.1.1 Frequently cited NEBs from literature

The most frequent NEBs mentioned were then highlighted from literature, the list seen in table 4 narrows the reoccurring benefits and combine ones with similar terminology to establish a shortlist of most identified NEBs authors have cited in their studies, classifying them like the most vital NEBs in industry. Even benefits in the same category need to be distinguished from one and other since the same type of benefit may still have different characteristics, therefore the need for quantifying the benefits is stressed (McKane 2000, Worrell et al. 2003). In the following section, the shortlisted NEBs will be further examined by linking them to indicators, which will enable NEBs to be translated into quantifiable and possibly monetary values to be included in energy efficiency and financial evaluations, thereby increase the chances for investments in energy efficiency.

Table 4: Most frequent mentioned non-energy benefits in each category from 39 studies.

Category	*Non-energy benefits*
Productivity	Increased productivity
	Reduced production costs
	Improved product quality
	Improved equipment performance
Operation & Maintenance	Reduced need for maintenance
	Improved operation
	Increase equipment lifetime
	material reduction
Work environment	Improve work safety and mortality
	Reduce noise
	Improve lighting
	Improve air quality
	Improve temperature control
Emissions	Reduce emissions
	Reduced costs of environmental compliance
	Reduce air pollutants
Waste	Use of waste fuel
	reduce product waste
	Reuse of waste
Other	Improve public image
	Energy system & security
	Environmental penalties
	Decreased liability

Table 5 continued: Number of NEB count per category

NEB Category	Count	Mean
Production	67	1.7
Operations & maintenance	56	1.4
Work Environment	52	1.3
Waste	31	0.8
Emission/Environment	45	1.1
Other	38	1.0

In can be concluded that the categorisation methods in literature have a lot of overlapping with one and other, and refer back to a few studies such as Worrell et al., (2002) and Finman and Laitner, 2001, as their papers are highly cited. There are a number of NEBs identified and partially quantified, although NEBs still have a number of different names and categorisation, they all fall under the same three environmental, social and economic co-benefits perspectives.

3.2. Observing Quantification Methods of NEBs

This chapter covers the quantification methods found in the literature in depth (time perspective, research design and methods of data collection). The research methodology has been analysed to have a better understanding of the different approaches taken in the chosen publication. This provides an overview of the data collection, research design, quantification potential and timeframe perspective in the field of NEBs within the industry. This can be seen in table 5.

Time perspective

In analysing the articles, the time perspective has shown to be vital to the study, whether the evaluation of the NEBs happened before or after the implementation of measures as seen in table 6. Almost half of the studies had only an ex-post time perspective (48%), meaning the additional effect of energy efficiency measures were evaluated after the implementation of the measures. About 26% of the articles took an ex-ante time perspective i.e. these are studies that suggest models, methods and calculations measure and forecast the impact of NEBs savings for investments. Some studies include both time perspectives this makes up 28% of the reviewed articles. Various methods have been applied to forecast NEBs impacts on future measures. Gudbjerg et al (2014) created databases gathering information regarding NEBs and used them as a tool to enable the presence of NEBs in new EEM plans.
Lung et al. (2005), Cagno et al. (2016), both included am ex-ante and ex-post perspective in their analysis, they first classified future measures of NEBs then used calculations such as net present value, payback period, cost/benefit ratio and conservation supply curve. These evaluation methods are reoccurring with most research using an ex-ante perspective (Lilly & Pearson; 1999 Worrell et al. 2003; Fleiter et al., 2012; Ürge-Vorsatz et al, 2016).

Research design

As for the research design, the most common research design are case studies to evaluate observed non-energy benefits. The number of cases varies from one to and other, ranging from 2 to 62 cases. Some comprise of comparing different firms in an industry, such as glass and other compare a certain energy efficiency measure between several sub-industries (Nehler et al., 2018). Most cases evaluate energy efficiency projects or measures based on energy saving and non-energy benefits, emphasising economic evaluation (Naess-Schmidt et al., 2015; Thema et al., 2016; Reuter et al, 2020). More recent dated literature evaluates several energy efficiencies measures, but also go beyond economic evaluation, such as Cagno et al (2016), and Ürge-Vorsatz et al, (2016) classified and categorise the benefits enabling further assessments. Another common method of research is through reviewing publications and case studies to compile the observed NEBs, as seen with the studies of (Bunse et al. (2010) and Trianni et al, (2020).

On the other hand, a few of the research designs have incorporated web-based tools with a case study to quantify the hypothesis of the study using available open-sourced data. This is seen in more recent literature due to more accessible data. An example is the research of Chatterjee & Ürge-Vorsatz (2018) who proposed a systematic methodological framework to quantify NEBs of productivity from energy efficiency improvements of reducing carbon dioxide emissions used COMBI web-based tool to measure two reference scenarios. This indicates that ex-ante perspectives are more suitable to research when databases are available and more importantly better quantification of NEBs from different perspectives are achievable.

Methods of data collection

The table also includes the methods of data collection in relation to observed NEBs, the studies mostly include interviews, questionnaires and surveys with firms. These methods of data collection are useful as they gather many qualitative data at one time, as long as the answers are honest. Rasmussen & Nehler, (2016) interviewed energy managers from different firms about their knowledge and experiences of NEBs regarding compressed air systems. Nehler et al., (2018) also applied questionnaires to study the perceived NEBs as outcomes of energy efficiency improvements.

Both studies revealed that the concept of NEBs was not clearly understood by the firms as they had different perceptions of NEBs (Rasmussen & Nehler, 2016); Nehler et al., 2018). Moreover, five studies do not specify the data collection process in detail, and only mention the number of cases of EEMs that were looked at, therefore, how the information of observed NEBs are ambiguous. This is observed numerous times in the non-selected literature and shows a pattern of uncertainty in the field of researching NEBs

Table 6: Methodological approach and data collection method applied in the observation of NEBs in the reviewed literature in industry and their time perspective. n/a—not available.

Authors	**Research design**	**Methods for data collection**	**Ex-Post/Ex-Ante Perspective**
Lilly & Pearson, 1999	Multiple case study	Interviews	Ex-Post/Ex-Ante
Pye and McKane, 2000	Multiple case study	-	Ex-Post
Finman & Laitner, 2001	Multiple case study	Reports/public data	Ex-Post
Skumatz et al. 2000	Multiple case study	Interviews	Ex-Post
Worrell et al., 2002	Literature review, Multiple case study	Literature review	Ex-Post
Worrell et al., 2003	Multiple case study	-	Ex-Post/Ex-Ante
Loftnes, 2003	Multiple case study	Public database	Ex-Post/Ex-Ante
Hall & Roth, 2003	Case study	Interviews	Ex-Post
Skumatz & Gardner, 2005	Case study	Interviews /Questionnaire	Ex-Post
Lung et al., 2005	Multiple case study	Interviews	Ex-Post/Ex-Ante
Bement and Skumatz, 2007	Multiple case study	Interviews	Ex-Post
Mills et al, 2008	Correlational research	Public database	Ex-Post
Ürge-Vorsatz et al., 2009	Quantification assessments/ Multiple case study	literature review	Ex-Post
Bunse et al. 2010	Case study, interviews	interviews	Ex-Post
Larsen et al., 2010	Multiple case study	-	Ex-Post
Naess-Schmidt et al. 2012	Case study, Interviews	Private database	Ex-Post
Fleiter et al., 2012	model-based assessment	Public database	Ex-Ante
Willoughby et al., 2012	Multiple case study	-	Ex-Post
Woodroof et al, 2012	Case study	Survey	Ex-Ante
Hasanbeigi et al., 2013	Case study	Literature review	Ex-Post/Ex-Ante
Yang et al., 2013	Multiple case study	literature review/Private data	Ex-Ante

Gudbjerg et a 2014	Multiple case study/web-based tool	Interviews	Ex-Post/Ex-Ante
Roser et al., 2014	Case study	Private data	Ex-Post/Ex-Ante
Russell et al., 2015	Multiple case study	literature review/Public data	Ex-Post
Naess-Schmidt et al., 2015	Case study/web-based tool	-	Ex-Post/Ex-Ante
Rasmussen, 2015	Multiple case study	Literature review	Ex-Post
Cagno et al., 2016	Literature review	Interviews	Ex-Post/Ex-Ante
Ürge-Vorsatz et al, 2016	Multiple case study	literature review/web-based tool	Ex-Ante
Wang et al., 2016	Literature review/case study	public database	Ex-Ante
Thema et al., 2016	Case study	Interviews	Ex-Ante
Rasmussen & Nehler, 2016	Case study/tool	Interviews/Questionnaire	Ex-Post
Thema et al., 2017	Case study/tool	Interviews	Ex-Post
Doyle & Cosgrove 2017	Case study/tool	-	Ex-Ante
Nehler et al., 2018	Case study	Interviews	Ex-post
Zhou et al., 2018	Case study/ Correlational	public database	Ex-Ante
Mzavanadze et al., 2018	Case study	literature review/web-based tool	Ex-Post/Ex-Ante
Chatterjee & Ürge-Vorsatz, 2018	Web-based tool	literature review/web-based tool	Ex-Post/Ex-Ante
Trianni et al, 2020	Literature review/case study	Literature review	Ex-Ante
Reuter et al, 2020	Literature review	Literature review	Ex-Ante

To dive further into the chosen literature, the methods for measurements, quantification, and monetisation of NEBs are looked into, and their approaches vary among studies. Table 8 a few of the reviewed the findings and describing the different approaches the studies have taken for a better understanding of the methods of quantifying and monetising and evaluations. The full table can be seen in Appendix - A.

The majority of papers stress that the quantifiability of NEBs is the most important aspect, but many benefits are difficult or almost impossible to quantify and monetise than others. For example, Lilly and Pearson (2001) and Nehler and Rasmussen (2016) easily managed to quantify NEBs related to the operation and maintenance but had difficulty for NEBs in the work environment category. Benefits in the emission category are more straightforward to measure since CO2 emissions are well documented in some cases Ürge-Vorsatz et al., (2009) Many authors have done interviews and questioners to estimate the value of the benefit, hence why many studies have taken an ex-post time perspective with certain benefits. The papers by Bement and Skumatz, (2007) Thema et al., (2016) Nehler et al., (2018) all conducted interviews or surveys for evaluating NEBs value. Bement and Skumatz (2007) related the values of the benefits to energy savings to create multipliers for types of measures. However, finding from the interviews of firms reveal that counting and measuring benefits can be time-consuming and was not a priority for the firms (Thema et al., 2016, Nehler et al,.2018).

Quantification matrix

Another example is Rasmussen (2014) classification framework based on the timeframe in relation to quantifiability, the benefits are structured in short-term and long-term Some benefits are easier to quantify than others, finding a method of assessing the levels is needed when approaching measures and impacts to understand the decision-making aspect better to focus on. Plotting NEBs into this matrix can help identify those that are easiest to quantify and most likely to deliver in a short time frame (IEA, 2015). A remaining challenge is that some EEM impacts are less tangible and therefore more difficult to quantity. These challenging impacts to quantify falling the 'low' zone on the matrix, since estimating the values are less feasible. The matrix example is seen in figure 10 (Rasmussen, J., 2014).

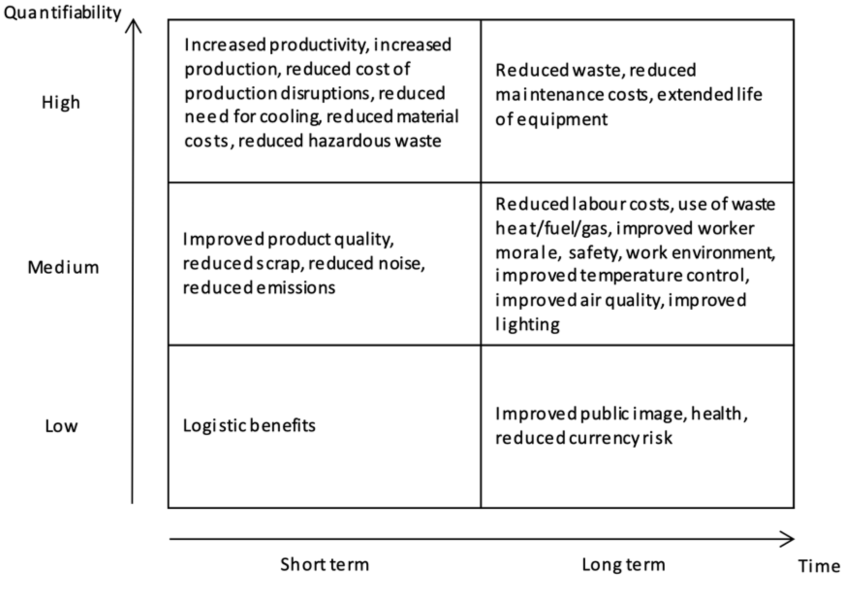

Figure 10: Matrix classifying industrial benefits in terms of quantifiability and time horizon (Rasmussen, J. 2014)

Table 7: Methods applied in the quantification and monetization of non-energy benefits and evaluation potential in the reviewed literature in in industry. n/a- not available, NVP- Net Present Value, PBP – Payback period, CBR – Cost Benefit Ration, LCOE – Levelized Cost of Energy, IRR – Initial rate of return, CSC – Conservation supply curve, CCE –Cost of conserved energy, CBA – Cost benefit analysis,

Authors	**Methods for Quantification or Monetization**	**Methods Applied to Evaluate the Potential**
Pye and McKane, 2000	n/a	NPV, PBP, IRR
Skumatz et al. 2000	Relative to the energy savings, Multiplier	n/a
Worrell et al., 2002	Classification of the NEBs based on their importance to the firm	Identification of the NEBs which can act as drivers
Worrell et al., 2003	n/a	CSC, CCE, BPB
Hall & Roth, 2003	Analysis of interview questions	NEB ranking based on importance
Bement and Skumatz, 2007	Assessment of willingness to pay/willingness to accept through interviews	CBA, Questionnaire
Ürge-Vorsatz et al., 2009	Review finding from literature	Cost-benefit assessment-based decision-making frameworks
Yang et al., 2013	MACCs with and without considering the NEBs from avoided environmental impacts	MACC is used to rank mitigation options along with the marginal costs to identify the least costly approach
Rasmussen, 2015	Framework illustrates a matrix of time frame and the level of quantifiability	Quantifiability of the categorised NEB (long term, short term)
Wang et al., 2016	Quantification of health benefits under different scenarios for the coal-fired power sector	Intake Fraction method is incorporated into Energy CSC
Rasmussen & Nehler, 2016	Classification of non-energy benefits as costs and revenues	Framework based on time frame and quantifiability to enable the inclusion of non-energy benefits in the investment process
Thema et al., 2017	Impact indicators of Energy system, Power reliability and Energy security related impacts in macroeconomics	Assessment of macroeconomic impacts using gross capacity margin, value of lost load

Nehler et al., 2018	n/a	Ranking based on non-energy benefits’ importance as drivers
Mzavanadze et al., 2018	impact pathway for avoiding air pollution using Drivers-Pressures-State-Impact-Response	Modelling of air pollution impacts via impact pathway approach using GAINS model
Reuter et al, 2020	Calculation approaches for evaluated indicators for NEBs	Setting indicators to evaluate NEBs

3.3 NEB Quantification impact on Investment decision

The following section gives a insight into investment decisions making from case studies in the literature. Evidence from Pye and McKane, (2000) research shows that investment in industrial energy efficiency projects may have a positive impact on the company in the sector for their economy. To enhance the investments in energy efficiency improvements, non-energy benefits should be quantified and monetised to fully understand the potential they include within the investment calculation project (Pye and McKane, 2000). Finman and Laitner (2001) acknowledged that NEBs have to be considered and assigned a monetary value, when possible, for the full potential of energy efficiency investment can be reached. Their study analysed 77 case studies to get an indication of the value of the benefits and 52 of the cases were deemed quantifiable and monetizable. Resulting in cutting back the payback period from 4.2 to 1.9 years.

In addition, in an investigation of 70 industrial case studies, Worrell et al., (2003) identified the productivity benefits which were quantified as far as possible. The cost savings of the results showed a ranging between 0.03% to 70% of total savings when NEBs were included. By incorporating NEBs into the cost supply curve, a decrease of 31% in the payback period is identified. Moreover, in Hall and Roth (2003) study of 74 businesses, they found that monetised NEBs were worth more than two times the energy savings per year. hence, the results show the financial potential of the additional benefits when quantified and monetised (Hall and Roth, 2003; Nehler, 2018). An average of 3 NEBs out of 10 was quantified for each energy efficiency measure, therefore, there are limits to the benefits that can be quantifiable or monetizable in each category (Hall and Roth, 2003). This can be seen further in the research by Laitner et al (2001) and Lung et al (2005), the study shows that non-energy benefits of production, operation and maintenance, could be quantified more than work environment benefits since they are more difficult to monetize due to the lack of indicators and collected data from firms. Omitting non-energy benefits from the evaluation of energy efficiency investments may result in an understatement of the financial potential for an energy efficiency investment measure (Nehler, 2018).

Finding from reviewed literature stresses the importance of quantifying and monetizing the NEBs to incorporate them into investments calculation. Quantifying the benefits would result in increased cost reduction and higher energy saving which will thereby contribute to a better decision on energy efficiency investment. Emerging evidence to data reveals the scope of potential value impacts for reducing cost and increasing value and lessening risks in the sector. Though, there is a lack of consistent methodology throughout literature for identifying, quantify, monetising benefits. o determine each EEMs improvement in terms of, energy saving, GHG emission avoided are compared to the annual investment cost. a conservation supply curve (CSC) is used to investigate the technical and economic potential of individual measures and technologies of energy efficiency. The findings would give insight to which EEM improvement has the largest CO2 abetment and energy saving compared to cost. Thus, influencing the decision-making phase for stakeholders for energy efficiency improvements and amplify the importance to identifying and quantifying NEBs within the industry. the following section gives a better insight to investment decisions making from case studies in literature.

Evidence from Pye and McKane, (2000) research shows that investment in the industrial energy efficiency projects may have a positive impact for company in the sector for their economy. To enhance the investments in energy efficiency improvements, non-energy benefits should be quantified and monetised to fully understand the potential they include within the investment calculation project (Pye and McKane, 2000). Finman and Laitner (2001) acknowledged that NEBs have to be considered and assigned monetary value, when possible, for the full potential of energy efficiency investment can be reached. Their study analysed 77 case studies to get an indication of the value of the benefits and 52 of the cases were deemed quantifiable and monetizable. Resulting in cutting back the payback period from 4.2 to 1.9 years.

In addition, in an investigation of 70 industrial case studies, Worrell et al., (2003) identified the productivity benefits which were quantified as far as possible. The cost savings of the results showed a ranging between 0.03% to 70% of total savings when NEBs were included. By incorporating NEBs into cost supply curve, a decrease of 31% in the payback period is identified. Moreover, in Hall and Roth (2003) study of 74 businesses, they found that monetised NEBs were worth more than two times the energy savings per year. hence, the results show the financial potential of the additional benefits when quantified and monetised (Hall and Roth, 2003; Nehler, 2018). An average of 3 NEBs out of 10 were quantified for each energy efficiency measure, therefore, there are limits to the benefits that can be quantifiable or monetizable in each category (Hall and Roth, 2003). This can be seen further in the research by Laitner et al (2001) and Lung et al (2005), the study shows that non-energy benefits of production, operation and maintenance, could be quantified more than work environment benefits, since they are more difficult to monetize due to the lack of indicators and collected data from firms. Omitting non-energy benefits from evaluation of energy efficiency investments may result in an understatement of the financial potential for an energy efficiency investment measure (Nehler, 2018).

Finding from reviewed literature stresses the importance of quantifying and monetizing the NEBs to incorporate them into investments calculation. Quantifying the benefits would result in increasing cost reduction and higher energy saving which will thereby contribute to better decision on energy efficiency investment. Emerging evidence to data reveals the scope of potential value impacts for reducing cost and increasing value and lessening risks in the sector. Though, there is a lack of consistent methodology throughout literature for identifying, quantify, monetising benefits.

3.3. Indicators and Tools for Quantifying NEBs

Based on the findings from the literature review, the only study that had viable quantification methods is Reuter et al. (2020) who built upon COMBI (COMBI Project, 2021) and M-benefits (M-Benefits, 2021) indicators to unify the different aspects with a more holistic view and qualitative approach on the energy efficiency benefits in one framework to make the benefits in quantitative terms to be less scattered and easier to assess. Hence the study developed a toolbox indicator that presents different aspects of energy savings in a simple manner to be more comprehensible (Reuter et al., 2017a). Referring the NEBs to both direct energies saving from EEM as well benefits from social, economic impacts (Reuter et al. 2020). Table 8 lists the indicators, Reuter et al. (2020) findings These indicators are grouped into three main categories:

- Environmental impacts: include the direct effects of EE on primary/ final energy consumption, the mitigation of GHG and local emissions.
- Social impacts are defined as direct effects of EE on energy poverty alleviation, health and well-being and disposable household income.
- Economic impacts comprise EE impacts on economic growth, employment, competitiveness and energy security.

Table 8: Set of indicators for the quantification of multiple benefits of energy efficiency Reuter et al. (2020).

CATEGORY	SUB-CATEGORY	INDICATOR
ENVIRONMENTAL	**Energy/Resource Management**	
	Energy savings	Annual energy savings (top-down/bottom-up)
	Savings of fossil fuels	Annual fossil fuels saved due to EE
	Impacts on RES targets	Lowering of RES targets due to EE
	Global and Local Pollutants	
	GHG savings	Annual CO2 savings linked to energy savings
	Local air pollution	Avoided local pollutants from PM2.5, PM10, NOx (incl. from electricity/heat generation)
SOICAL	**Energy Poverty**	
	Alleviation of energy poverty	Reduction of energy cost shares in disposable incomes as a consequence of energy savings
	Quality of life	
	Health and well-being	Externalities linked to health impacts
	Disposable household income	Changes in energy cost share in disposable HH income due to EE
ECONOMIC	**Innovation/Competitiveness**	
	Innovation impacts	Revealed Patent Advantage (RPA)
	Competitiveness	Revealed Comparative Advantage (RCA)
	Turnover of EE goods	Investments linked to energy savings
	Macro-economic	
	Impact on GDP	Impacts of Energy savings on GDP growth
	Employment effects	Additional FTE linked to energy savings
	Potential impact on energy prices	Lower energy prices based on price elasticities
	Impact on public budgets	Additional income tax revenue from employment based on energy savings
	Micro-economic	
	(Industrial) productivity	Change of productivity due to lowered cost
	Asset value	Change in asset value of commercial buildings due to EE benefits
	Energy Security /Energy Delivery	
	Energy security 1	Lower import dependency
	Energy security 2	Larger supplier diversity (Herfindahl-Hirschmann-Index)
	Impact on integration of RES	A Demand response potential by country

4. Energy efficiency measures and indicators in the steel industry

This section answers sub-questions “What are the identified energy efficiency measures in the iron and steel sector and what is their potential?”. The energy efficiency measures in the steel industry are identified and presented.

The European Union’s Horizon 2020 Research and Innovation Program have funded a number of projects such as SEEnergies, M-benefits, and COMBI projects. Horizon 2020 is a financial instrument implementing the Innovation Union, aimed to secure Europe global competitiveness. The SEEnergies project aim is to quantify and operationalize the potential for energy efficiency in multiple sectors to develop innovative and holistic energy efficient approaches in their models. Their report analysis the industrial sector latest EU projections for the development of energy demand up to 2050 (European Commission, 2019).

One of SEEnergies publication by Crijns-Graus & Kermeli, (2020), uses multiple reference scenario in European Commission (2016) includes final energy demand projection per industrial sub-sector and EU countries, with the addition of policies and market trends. The study constructed a frozen efficiency scenario that considers same structural changes as the reference scenario but with no energy efficiency improvements. As the main aim is to understand the impact of structural changes and energy efficiency in the total final energy projections (Crijns-Graus & Kermeli, 2020). Their study developed four mitigation references scenarios from the European Commission (2016), showing energy demand projections for 2030 and 2050 per industrial sub-sector industrial product and fuel types for EU28. The references scenario is three developed Best available technologies (BAT) scenarios, which have a varying degree of technology diffusion rates and technological innovations, constructed into different energy demand pathways for the EU industry. Therefore, due to the availability of the recently studied data from the SEEnergies project, this research follows the BAT reference scenarios that include 20 EE measures and technologies that are adopted in the manufacturing of steel products.

The following section lists the available data collected from the SEEnergies project following the data collected by Crijns-Graus & Kermeli (2020). The data obtainable from the SEEnergies project includes the BAT reference scenarios. Each measure has a saving potential based on the implementation rate of the EE measures for 2030 and 2050, which assumes the same amount of relative saving for each EU28 country. The available data used in this study are listed below. This data allows for quantitative measures of certain NEB indicators which are explained in the next chapter.

- 20 energy efficiency measures for steel products; BF-BOF steel, EAF steel, rolled steel, coke oven, pig iron.
- Production Projection of five products for EU27 country between 2015 – 2050.
- Implementation rate of the BAT for 2030 & 2050.
- Fuel Savings [GJ/tonne] of each measure.
- Electricity Savings [GJ/tonne] of each measure.
- Annualized Investment Cost in [€ /tonne] of each measure.
- Fuel energy consumption [TJ] of each product.
- Electricity energy consumption [TJ] of each product.
- Final energy consumption [TJ] of each product for Fuel and electricity.
- Fuel share and power mix: energy generation of each fuel type (IEA,2019).

- Three BAT scenarios; each with different recycling rate.

The reference scenarios are divided into three BAT scenarios with different rate of recycling rate.

- **BAT (no extra recycling):** Best Available Technologies are widely implemented, no increase in recycling rates is allowed.

- **BAT (incremental recycling):** Best available technologies are widely implemented; with current recycling trends continue.

- **BAT (high recycling):** Best available technologies are widely implemented, plus an increased uptake of recycling improvements (e.g., increase shares of steel production from scrap).

The BAT reference scenarios are a varying degree of EEMs and technologies with different diffusion rates to develop the energy demand pathways for the EU industry with decreased production rate. The recycling rates are implemented first and then the EEMs, for the simplicity of distinguishing EEMs implementation and investment cost outcomes due to recycling. recycling is not considered an EEMs its reduction can have a significant impact on the efficiency of material use. The BATs measures are then adopted with different reductions of energy demand according to the Energy Efficiency First Principle (EEFP) then the impact of energy demand from the technologies is quantified (Crijns-Graus & Kermeli, 2020). The references scenarios are based on the frozen efficiency scenarios, where the specific energy consumptions remain fixed since this provides a good basis to estimate the EEMs outcomes comparison to the frozen efficiency and for the results to be consistent.

Since each BAT scenarios have a different production rate due to the change in recycling rate, the amount of energy-saving potential [TJ] differs for each product. Hence, the quantifiable NEBs in this study is applied to all three BAT scenarios. Therefore, the results of the NEBs will be presented in each BAT scenario. Thus, the outcomes of implementing EEMs and quantifying NEBs are presented in each BAT scenario within the EU27. The findings will be further explored in section 4.1.

Table 9 list the EEMs of the BAT scenario, they include different areas of the steel process, such as processing recycled scraps in EAF steel, improving process control in pig iron and rolled steel production and carbon mitigation. The implementation rates of the BAT are relied on existing literature and SEEnergies project findings (Crijns-Graus & Kermeli, 2020). Each of the energy efficiency measures and technology for the iron and steel industry has a fixed maximum level of energy saving for both fuel type and implementation rate for 2030 and 2050, and investment costs. The BATs are applied to the energy consumption production of five iron and steel products; Coke, oven, pig iron, BF/BOF steel, EAF steel and rolled steel. The EEM fuel saving for each fuel is multiplied by the projected production of each product and by the implementation rate of 2030 and 2050 respectively. This results in the energy-saving potential for each fuel type (table 9) - these values are then used in each NEB indicator in chapter 6.

Table 9: Iron and steel BAT energy efficacy measures/technologies with 2030 & 2050 implementation rates, energy saving potential for fuel and electricity, and investment cost (SEEnergies; Crijns-Graus & Kermeli, 2020).

Product sEEnergies	Measure	Implementation rate 2030 (%)	Implementation rate 2050 (%)	Fuel Savings (GJ/tonne)	Electricity Savings (GJ/tonne)
Coke oven	Programmed heating in coke oven	50%	70%	0.16	0.0
Coke oven	Variable speed drive on coke oven gas compressors	50%	70%	0.01	0.0
Coke oven	Coal moisture control	50%	70%	0.33	0.0
pig iron	Waste heat recovery blast furnace slag	43%	80%	0.35	0.0
pig iron	Top gas recovery turbine	21%	29%	0.00	0.1
pig iron	Moisture Removing Blowing Technique in Blast Furnace	65%	75%	0.23	0.0
pig iron	Injection of pulverized coal in BF	45%	95%	0.64	0.0
pig iron	Cogeneration (for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills)	20%	50%	0.23	0.0
pig iron	Recovery of blast furnace gas	3%	5%	0.09	0.0
pig iron	Improved hot blast stove control	30%	45%	0.32	0.0
pig iron	Improved blast furnace control	25%	50%	0.32	0.0
BF/BOF steel	Recovery of BOF and sensible heat	10%	20%	0.56	0.0
EAF steel	Scrap preheating	25%	70%	0.15	0.4
EAF steel	Converting the furnace operation to ultra-high power (UHP) (Increasing the size of transformers)	45%	70%	0.11	0.0
EAF steel	Improving process control in EAF	40%	50%	0.24	0.1
Rolled Steel	Recuperative or regenerative burner	50%	60%	0.56	0.0
Rolled Steel	Endless Hot Rolling of Steel Sheets	14%	19%	0.36	0.0
Rolled Steel	Process control in hot rolling	50%	70%	0.30	0.0
pig iron	Variable speed drives for flue gas control, pumps, fans in integrated steel mills	15%	15%	0.00	0.03
pig iron	Energy monitoring and management systems	25%	50%	0.08	0.01

5. Applying quantifiable NEBs to the BAT Reference scenarios.

This section answers the sub-question 3; “What are the results of the quantified NEBs taking into account different recycling scenarios?”, following the findings SQ2 regarding identifying EEMs. Then, the calculation methods from section 3.3 are used to quantify the results. Next, data will be analysed and applied in the three BAT scenarios plus recycling rates per selected country. The results will be presented in three categories; environmental, social and exclude and economic benefits, due to a lack of data and time constraints. Each NEB covers the findings of the EU27 as well as Germany, Italy and Netherlands since they are one of the top producers of steel in Europe and each has different fuel sources that would give a varied range of findings. Comparing the selected countries would show more information regarding the fuel and power mix and how that can have an impact on the results of the NEB indicators. The following section explains in-depth the steps taken to quantify the NEBs.

5.1. Chosen NEBs Indicators and calculation methods

Reuter et al. (2020) established indicators for each NEB for quantification, with the objective to allow for simpler methods without the need for an extensive data model. The overview of the formulas developed in the study is all listed in Appendix - B. The chosen NEBs to quantify in this study is based on the findings from sub-question 1; the identification and categorisation narrow down the most frequently used NEBs in the industrial sector. A shortlist of NEBs are selected for quantification from the developed indicators of Rueter et al (2020), which have been modified based on the available data - the equation used in the study are as follow.

5.1.1. Final Energy Saving

Annual energy savings for fuel type is derived from the study of Crijns-Graus and Kermeli, (2020) developed for SEEnergies project. (Both types of fuel savings are available for EU28 countries). The energy saving is not an NEB however it an essential indicator to calculate the rest of the benefits.

5.1.2. Fossil fuel saving from energy saving potential

To calculate the fossil fuel saving from energy saving potential, the final energy saving of each energy efficiency measure is added upper steel product for years 2030 and 2050. Then, the fossil fuel saving from each source (coal, natural gas, and oil) are individually calculated – this is done for fuel and electricity, as they have different shares. Eq. 1 calculates the energy saving from fuel, by multiplying ESP by the fuel share of each source, which is then divided by the calorific value, expressing the results in ktonne of fossil fuel saving. Energy-saving from electricity (eq. 2) following slimier steps, however, includes an additional step of dividing power mix by the fixed conversation factor of electricity. The results are expressed in ktonne. Table 10 lists the conversion factor used for electricity generation for all countries.
Additionally, the fuel share and power mix of each country are listed in table (11 -12).

$$ES_{fossil} = \frac{ESP\ x\ FS}{cv} \qquad \text{(Eq. 1)}$$

$$ES_{elec.} = \frac{ESP\ x\ PM_j}{conv._j} \Big/ cv_j \qquad \text{(Eq. 2)}$$

Where ESfossil represents energy savings from fossil energy carrier j and ESelec. is energy saving from fossil fuel generated from electricity bot represented in (ktonne). ESP [TJ] represents energy saving potential of each steel product. FS is the fuel share of fossil energy carrier j. cv is the fixed calorific value of each fossil fuel carrier expressed in (TJ/kt). PM is the share of power mix which is fossil fuel generated from electricity. And finally, Conv. is the conversion factor of power plants for each carrier j.

Table 10: conversion factor for for elec. power mix

Conversion Factor	Shares
Coal	33%
Natural Gas	36%
Nuclear	33%
Oil	33%

5.1.3. GHG emission avoided from energy saving

Avoided emission CO2 is the amount of GHG saved from the indicator ‘Savings of Fossil Fuels’. Calculated per fuel type and fuel share (table 11) in MtCO2. Emissions from fuel (EMfuel) is calculated using (eq. 3) the total energy saving potential [TJ]. Emissions from electricity generation (EMelec) follows eq. (4), similar to the former equation but divided the power mix (table 12) and emission factor (table 11) by conversion factor of electricity generation plants. Values are divided by 10^9 to express the results in Megatonne of CO2 avoided [Mt CO2]. The analysis does not account for additional indirect emissions.

$$EM_{fuel,k} = \sum_j ESP_{final} \quad x\ FS_j\ x\ emf_j \qquad \text{(Eq. 3)}$$

$$EM_{elec.,k} = \sum_j ESP_{final} \quad x\ \left(\frac{PM\ x\ emf_j}{conv.}\right) \qquad \text{(Eq. 4)}$$

EMfuel avoided emissions from fuel per capita of pollutant k and EMelec avoided emissions from electricity per capita of pollutant k both measured in (MtCO2). ESP [TJ] represents energy saving potential of each steel product. emf [g/GJ] is the emission factor for each energy carrier j and pollutant k.

Table 11: shows the fuel share and for each selected county.

Fuel share	EU27	Germany	Italy	Netherlands
Coal	15%	77%	54%	89%
natural gas	23%	18%	38%	11%
oil	32%	5%	3%	0.17%

Table 12: power mix for each selected county.

Power mix	EU27	Germany	Italy	Netherlands
Coal	23%	30%	6%	16%
Wind	16%	20%	7%	9%
Natural gas	27%	15%	49%	59%
Nuclear	0%	12%	0%	0%
Solar PV	6%	8%	8%	4%
Biofuels	6%	7%	6%	3%
Hydro	26%	4%	16%	0.10%
Waste	0%	2%	2%	3%
Oil	2%	1%	4%	1%

5.1.4. Local Air Pollution

the air pollutants avoided from implementing the EEMs are NOx, SOx, PM10, PM2.5. They are calculated for both fuel and electricity as the other indicators using (eq. 5) and (eq. 6). The emission of the pollutants from fuel is calculated by multiplying the sum of ESP [TJ] by emission factor and fuel share, then divided by the population size of the selected county. As for emissions from electricity following the same formula however the emission factor and power mix are divided by conversion factor before its division by population size.

$$PE_{fuel,k} = \sum ESP_{fuel}\ x\ \frac{emf\ x\ FS}{pop} \qquad \text{(Eq. 5)}$$

$$PE_{elec.,k} = \sum ESP_{elec}\ x\ \left(\frac{emf\ x\ PM/conv.}{pop}\right) \qquad \text{(Eq. 6)}$$

PE$_{fuel}$ is the avoided emissions from fuel per capita of pollutant k. PE$_{elec}$ avoided emissions from electricity per capita of pollutant k expressed in [kg/cap]. emf [g/GJ] is the emission factor for each energy carrier j and pollutant k (table 13). pop refers to the population of each country. Local emissions are given in kilotons [ktonne] and as a relative value in kilogram per capita [kg/cap].

Table 13: emission factor per pollutant (EEA, 2016. 1.A2. Manufacturing industries and construction (combustion))

Unit:g/GJ	NOx	SOx	PM10	PM2.5	CO2

Solid fuels	175	900	117	108	931
Gaseous fuels	74	0.67	0.78	0.78	29
Liquid fuels	513	47	20	20	66

5.1.5. Health and well-being

Health benefits represent a more indirect effect of EE. Impacts on health are strongly related to local emissions, by reducing the energy consumption, a part of this air pollution can be avoided. Health and well-being benefits can be estimated by combining avoided local air pollution with premature mortality rates (Lelieveld et al., 2015).

$$EMIS_k = emf_{jk}\ x\ FEC_j \qquad \text{(Eq. 7)}$$

$$cf = {}^{EMIS}/_{av} \qquad \text{(Eq. 8)}$$

$$D = cf\ x\ deaths/1\ \mu gr/m3 \qquad \text{(Eq. 9)}$$

$$AD = D\ (fr.eff.) - D\ (ref\ eff.) \qquad \text{(Eq. 10)}$$

EMIS [Gg] emissions from pollutant k
Emf$_{jk}$ [g/GJ] is the emission factor for each energy carrier j and pollutant k.
FEC$_j$ [TJ] is the final energy consumption energy carrier j
Cf =concentration factor
av [10^9 m3] = air volume
AD= avoidable deaths

Where the AD =avoided deaths related to the pollutant i is calculated from the emission EM of the pollutant multiplied with the concentration factor cf and the corresponding change in pollutant concentration and population of the country (derived from EEA data (EEA, 2019)

5.1.6. Avoided deaths from energy saving

Health benefits represent a more indirect effect of EE. Impacts on health are strongly related to local emissions, by reducing energy consumption, a part of this air pollution can be avoided. This indicator follows four steps. First, using (eq. 7) the emission for each pollutant is calculated by multiplying the emission factor of each fuel type by final energy consumption per energy carrier j. Secondly, the concentration factor [cf] is measured by dividing the emission by the fixed air volume per country – (eq. 8) Next, the deaths from emission pollutants is measured by multiplying the concentration factor [cf] by the fixed value Deaths/(1 μgr/m3) per country using (eq. 9). Finally, the deaths avoided [AD] is subtracted by the frozen efficiency scenario compared to each reference's scenarios for both selected years – (eq. 10). The data of each county is seen in table 14. The data for concentration factors and deaths/(1 μgr/m3) are not available for SOX and PM10 therefore they are not calculated.

$$EMIS_k = emf_{jk}\ x\ FEC_j \qquad \text{(Eq. 7)}$$

$$cf = {}^{EMIS}/_{av} \qquad \text{(Eq. 8)}$$

$$D = cf\ x\ deaths/1\ \mu gr/m3 \qquad \text{(Eq. 9)}$$

$$AD = D\ (fr.eff.) - D\ (ref\ eff.) \qquad \text{(Eq. 10)}$$

EMIS [Gg] emissions from pollutant k. Emf_{jk} [g/GJ] is the emission factor for each energy carrier j and pollutant k.FEC_j [TJ] is the final energy consumption energy carrier j. av is the air volume [10^9 m3]. Fr. eff is the frozen efficiency scenario.

Table 14: air volume and deaths deaths/(1 µgr/m3) for NOx and PM2.5 for each country.

	NOX		PM2.5	
Country	air volume (10^9 m3)	deaths/(1 µgr/m3)	air volume (10^9 m3)	deaths/(1 µgr/m3)
Germany	67.4	481.7	8.0	5130.1
Italy	33.4	517.4	10.4	3374.2
Netherlands	12.4	78.4	1.1	825.0
EU27 (80%)	171.06	947.84	38.0	9,051

Now that the methods for quantifying the chosen NEBs are established. The following section shows the results and findings of each NEB when applied in different BAT scenario, which emphasises the effect of the different recycling rates and how it can affect outcomes of the quantified benefits.

5.2. Environmental benefits of energy efficiency

The results presented in these following paragraphs are calculated using the methods described in section 4.1. The environmental non-energy benefits that are calculated are fossil fuels saving, CO2 emission avoided and air pollutants avoided from implementing the EEM within the three BAT scenarios; no extra recycling, incremental recycling, and high recycling.

5.2.1. Final energy demand

Figure 11 shows the final energy demand in the EU27 for the Iron and steel sector in the base year, frozen efficiency, and energy efficiency scenarios (BAT scenarios with recycling). In 2050 the energy-saving potential is 858 PJ for BAT - high recycling and decreases by 53% compared to BAT incremental recycling equalling 462 PJ. BAT– no extra recycling and BAT incremental recycling have a slower rate of improvement; energy demand decreases by 32% in 2030. In addition, pig iron is the highest energy-intense product out of the five, because of its a direct product from the BF-BOF route. EAF and Rolled Steel following second and third closely.

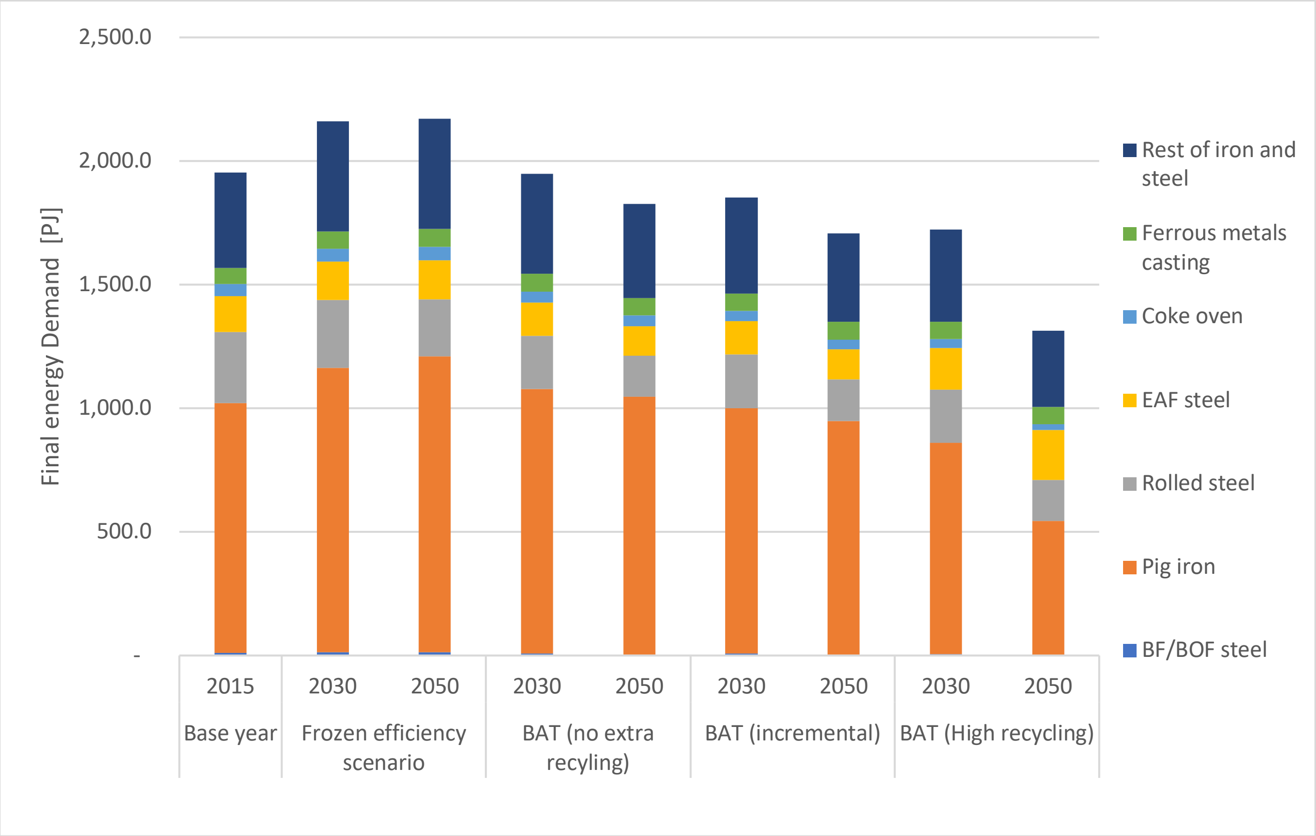

Figure 11: Final energy demand of EU27 in each scenario.

The following tables (15 – 16) demonstrates the colour scale of the finding from final energy demand per product, giving a better comparison of the energy demand of each product - Green to red; indicates less consumption to larger consumption compared to the frozen efficiency scenario. Main findings show little significant change of energy saving between the BAT no extra and BT incremental, in the five products with the exception of pig iron 8%. Although BAT high recycling drastically decreases consumption of BF-BOF and increases EAF in both 2030 and 2050. This is due to the impact of recycling since EAF is used to recycling scrap.

Table 15: Colour scaled Final Energy demand compared to frozen efficiency scenario of EU27 in 2030.

product	**BAT -no extra recycling**	**BAT incremental recycling**	**BAT high recycling**
BF/BOF steel	-43%	-43%	-52%
Pig iron	-7%	-14%	-26%
Rolled steel	-21%	-21%	-21%
EAF steel	-13%	-13%	9%
Coke oven	-15%	-21%	-32%
Rest of iron and steel	-9%	-13%	-16%

Table 16: Colour scaled Total Final Energy demand compared to frozen efficiency scenario of EU27 in 2050.

product	BAT -no extra recycling	BAT incremental recycling	BAT high recycling
BF/BOF steel	-86%	-86%	-92%
Pig iron	-13%	-21%	-55%
Rolled steel	-27%	-27%	-27%
EAF steel	-25%	-23%	27%
Coke oven	-21%	-28%	-59%
Rest of iron and steel	-14%	-19%	-31%

The following figure 11 shows the energy saving of each fuel type for the EU27 in 2030 and 2050. This shows that the EU27 has a large potential of saving from oil more than coal and natural gas. BAT – high recycling reinforces the point that it has a substantial saving due to recycling implementation.

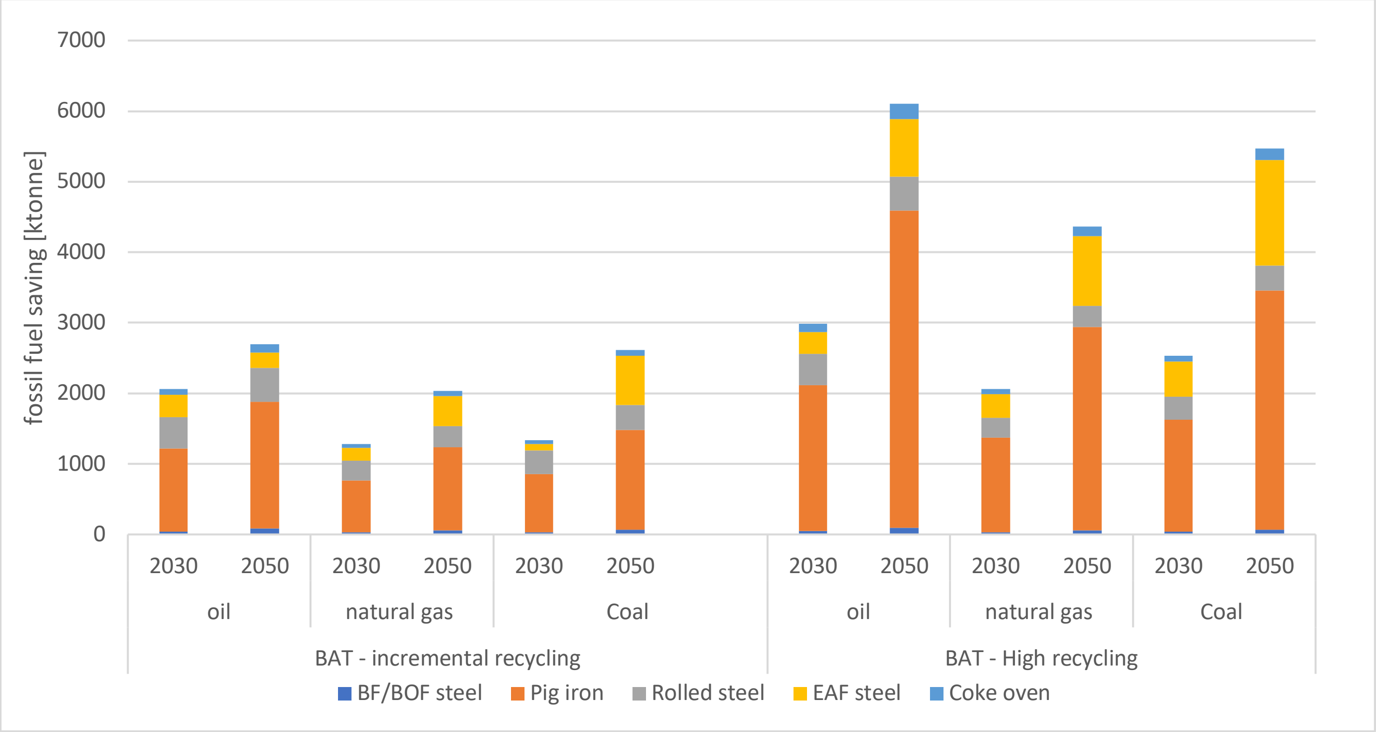

Figure 12: total energy saving [ktonne] of fuel type per product in EU27 2030 and 2050.

5.2.2. Results of the Fossil fuel savings indicator

Using the fossil fuel saving indicator, the value of savings is measured in [ktonne] of fossil fuel calculated for the Netherlands (NL), Italy, Germany and the whole of the EU27. Based on the fuel mix and power mix of each country. Figure 11– 12 shows the energy savings for both fuel and electricity for each BAT scenario in 2030 and 2050.

As shown in figure 12, the saving of fossil fuel has an increasing trend for fuel-saving for each country in both years in all BAT scenarios, Bat high recycling has the largest leap in savings as this scenario implements much-improved recycling rates. Germany savings shares in 2050 compared to the EU27 fossil fuel saving makes up 67% of the whole EU savings, 12% for the Netherlands and 11% for Italy. This makes up 90% of total EU27 savings from high recycling rates due to their high annual production rates of steel. Indicating 90% of saving for the EU comes from only three countries.

Moreover, the fossil fuel saving from electricity seen in Figure 13, reveals fewer savings from electricity as well as additional consumption of electricity seen in Germany and Italy in BAT-high recycling. This is a result of their increased rate of recycling through EAF production and less BF-BOF route. The EU27 shows a large saving potential from electricity, compared to the other countries. This is because the average electricity power mix of all the EU is much higher than Germany, Italy and the Netherlands, which rely more upon fossil fuel than electricity. In addition, the power mix of each country includes a share of renewable energy which reduces the electricity energy saving share. For example, Germany generates 20% wind and 16% nuclear and Italy generated 16% of hydropower which does not emit GHG emissions.

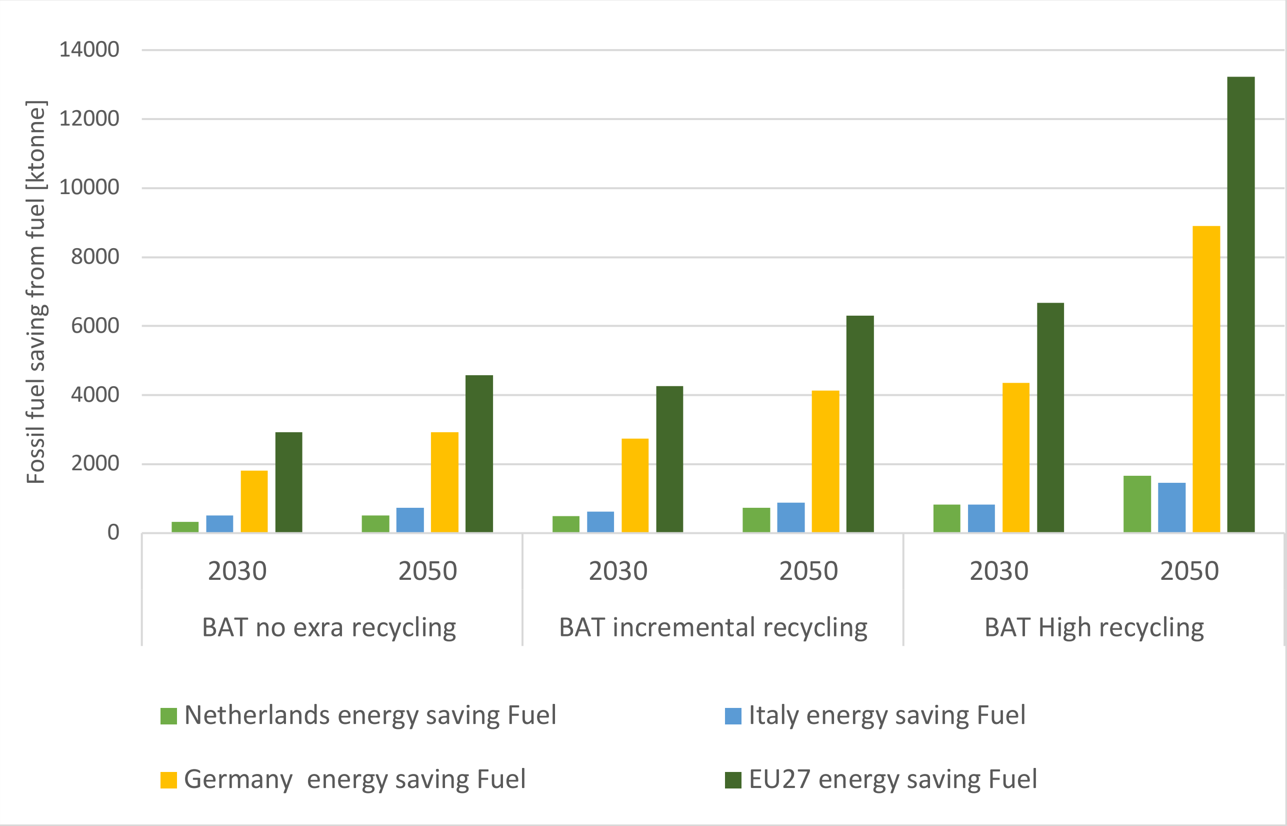

Figure 13:: Fossil fuels saving from fuel [ktonne] for the year 2030 and 2050 in each BAT scenario for selected regions.

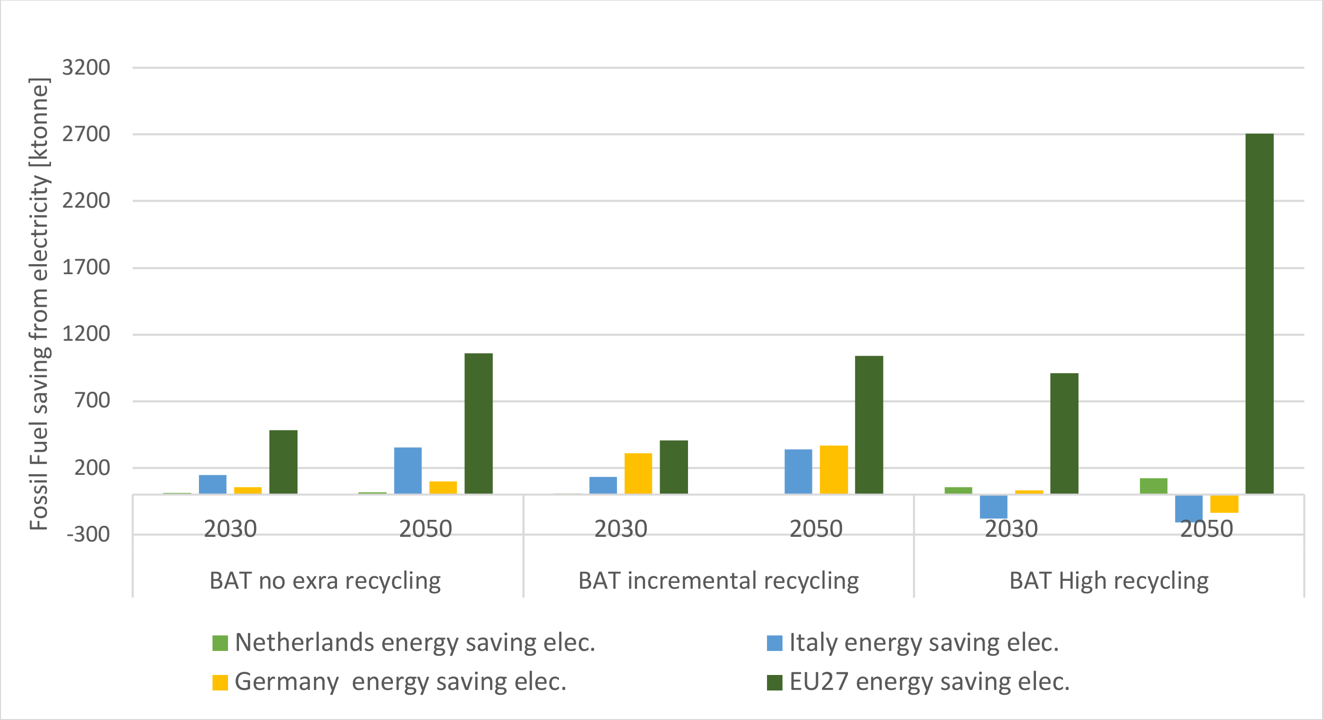

Figure 14: Fossil fuels saving from electricity [ktonne] for the year 2030 and 2050 in each BAT scenario for selected regions.

5.2.3. Greenhouse Gases Emissions Avoided Indicator

This indicator quantifies GHG emission - CO2 emissions avoided is calculated using the energy-saving, final energy consumption and fuel and power mix of each country. As seen in Figures 14 -15, the amount of CO2 that is possible to prevent when implementing the EEMs is significant, with recycling having a larger impact.

Germany has the largest emissions to avoided due to their 77% and 18% use of coal and natural gas in their fuel share. The EU27 has a much smaller number of avoided emissions compared to Germany since their fuel mix is an average of all the EU27 which consists of less coal (15%) and natural gas (23%). The Netherlands also has used a high share of coal (89%) in steel production therefore they have a higher potential to avoid emissions by implementing EEM and recycling. Italy, on the other hand, is the lowest out of the four countries, this is due to Italy's higher share of renewable energy and less coal use (6%) and natural gas (49%) than the rest. Yet their avoided emissions from electricity (figure 15) are very and negative in the high recycling scenario. CO2 emission avoided from electricity for the Netherlands is also minimal. Natural gas makes up most of the power mix of the Netherlands, which has a less emission factor compared to coal. Italy and Germany would consume more electricity in the high recycling BAT scenario due to the fuel switch to electricity and the recycling electricity consumption share, however the saving from electricity is very insignificant compared to fuel. The fuel switch of steel production will be further discussed in the following chapter.

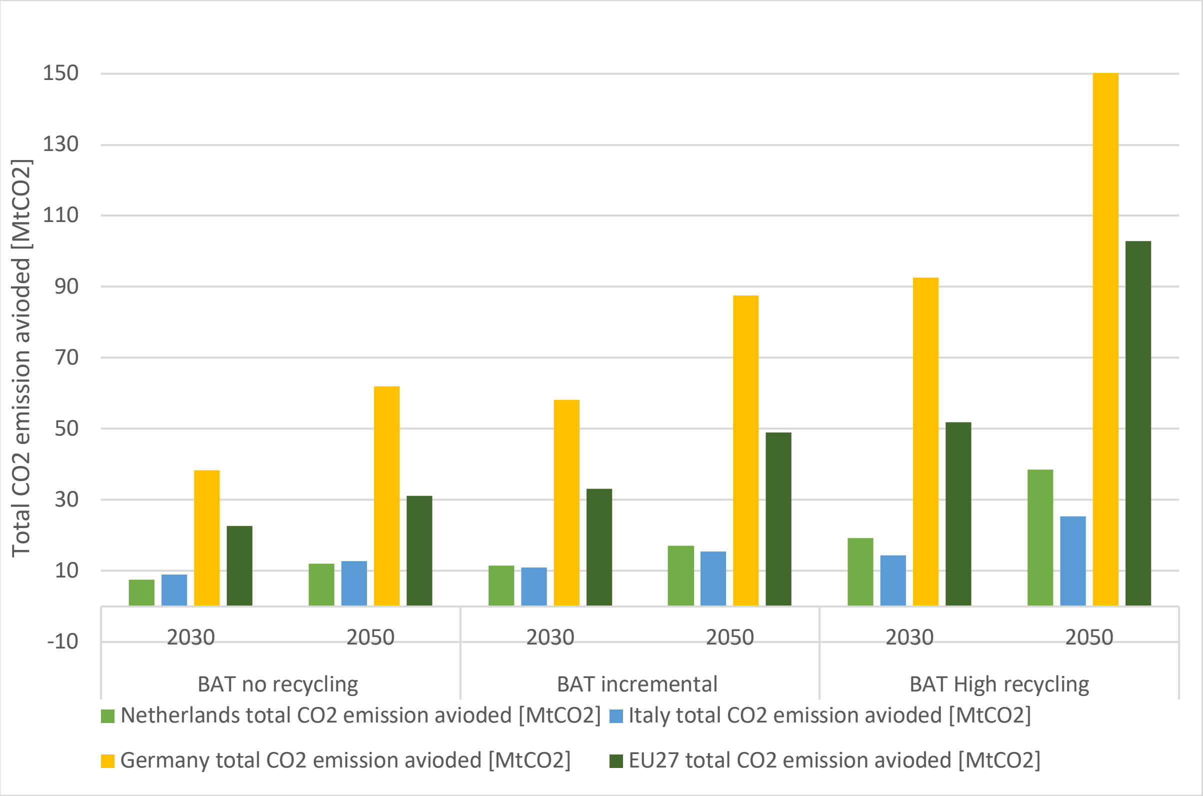

Figure 15: CO2 emissions avoided from fuel energy savings [MtCO2] in three Bat scenarios for 2030 and 2050.

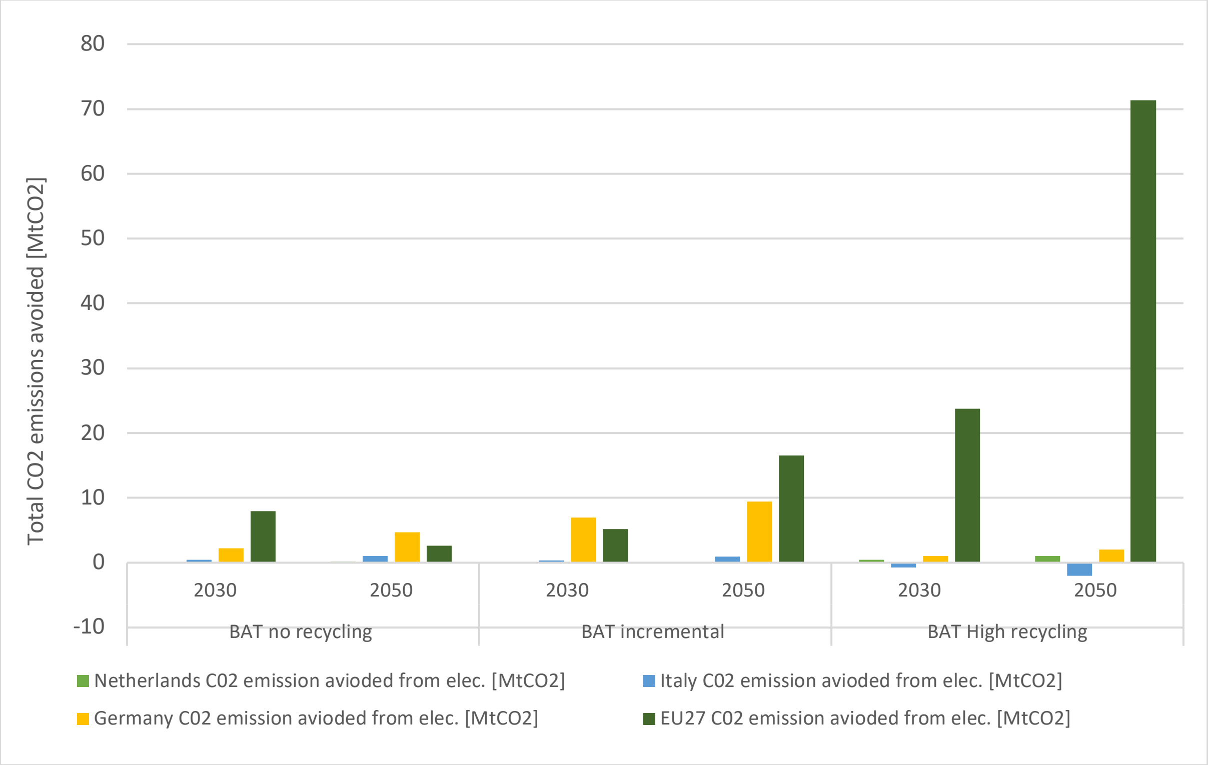

Figure 16: CO2 emissions avoided from electricity energy savings [MtCO2] in three Bat scenarios for 2030 and 2050.

5.2.4. Air Pollution Avoided indicator

Steel production has several impacts on the environment, including air emissions such as coke oven gas, naphthalene, ammonium compounds, crude light oil, sulphur and coke dust are released from coke ovens and other processes, however, the study only measures CO, SOx, NOx, PM2 due to data limitations. By implementing the EEM in each BAT recycling scenario the results show a varying number of pollutants avoided (Sox, NOx, PM2.5 and PM10) shown in figures 17-20. The results of the total emissions avoided is given in kg per capita (left axis) and in ktonne (right axis) for reach county in 2030 and 2050. The two Y-axis values correlate the impact of the population size in each country.

For all presented emissions EU27 has high rate of reduction in total ktonne however when measured compare to the dense population the emission avoidance per capita decreased as expected. But it is not the case for NOx, as the kg/cap is significant, this can be due to the large share of NOx concentration across the EU27 on average despite the population size.
The opposite is observed for Germany and the Netherlands, where both values relate in SOx, PM2.5 and PM10 except in NOx. As for the Italy's trends follow one and another.

The EEMs have a large impact on air pollutant SOx, PM2.5 and PM10 in impartial in the NL and Germany due to their large consumption of coal, hence the switch from BF-BOF to EAF would result in significant emissions reduction. As for the EU27, other than NOx the emissions reduction is less than the other countries, this is again due to the average fuel share of the EU27 having less coal and natural has share than Germany and the Netherlands and a much larger population. Even though Italy is the second-largest producer of steel their emissions avoided is much smaller. This shows the effect of the fuel share playing a role again and the production route and size of the sector (steel production/capita).

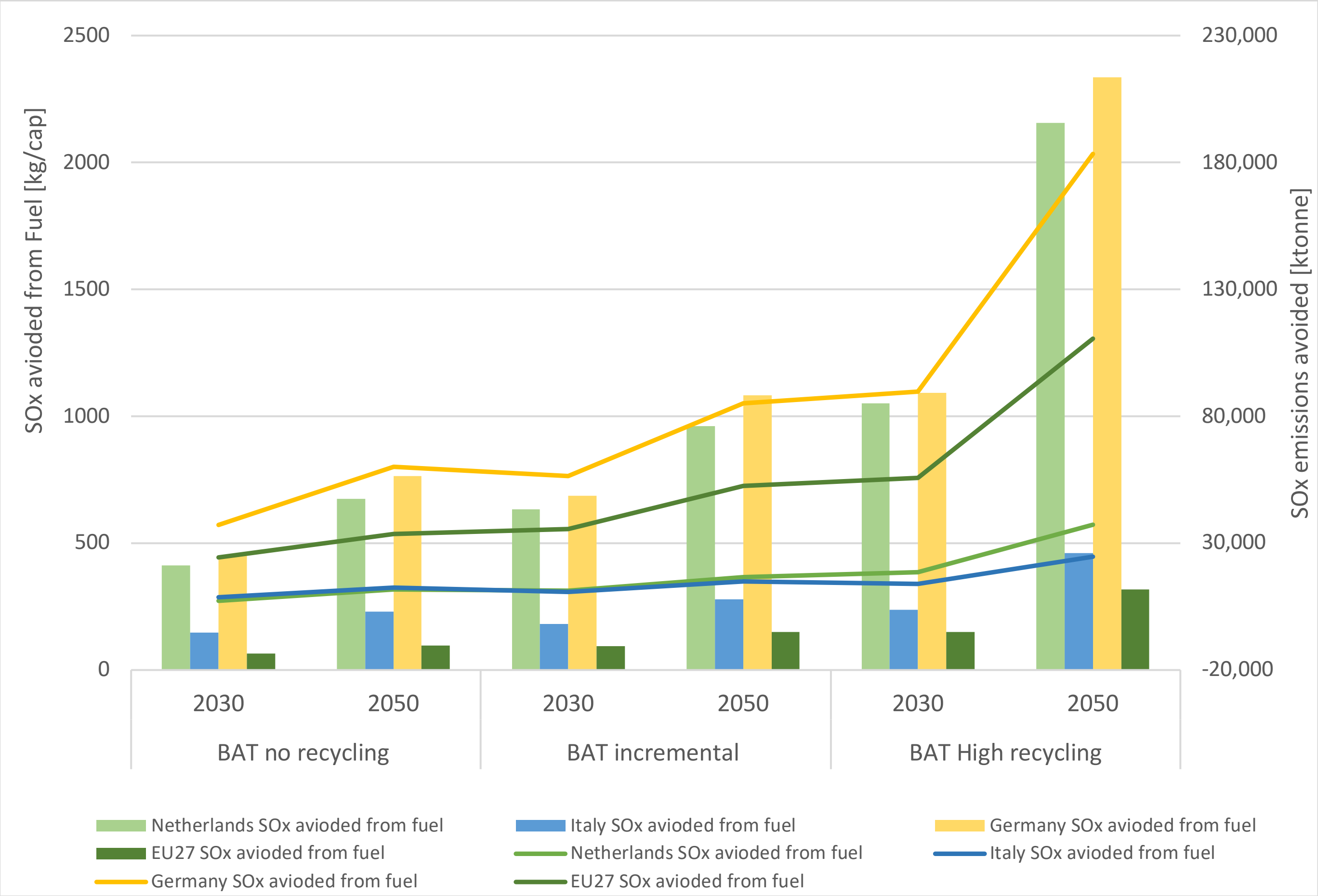

Figure 17: Total Sox emissions avoided from fossil fuel by implementing EEMs in three BAT scenarios in the year 2030 and 2050 Kg/cap (Left axis) and ktonne (right axis)

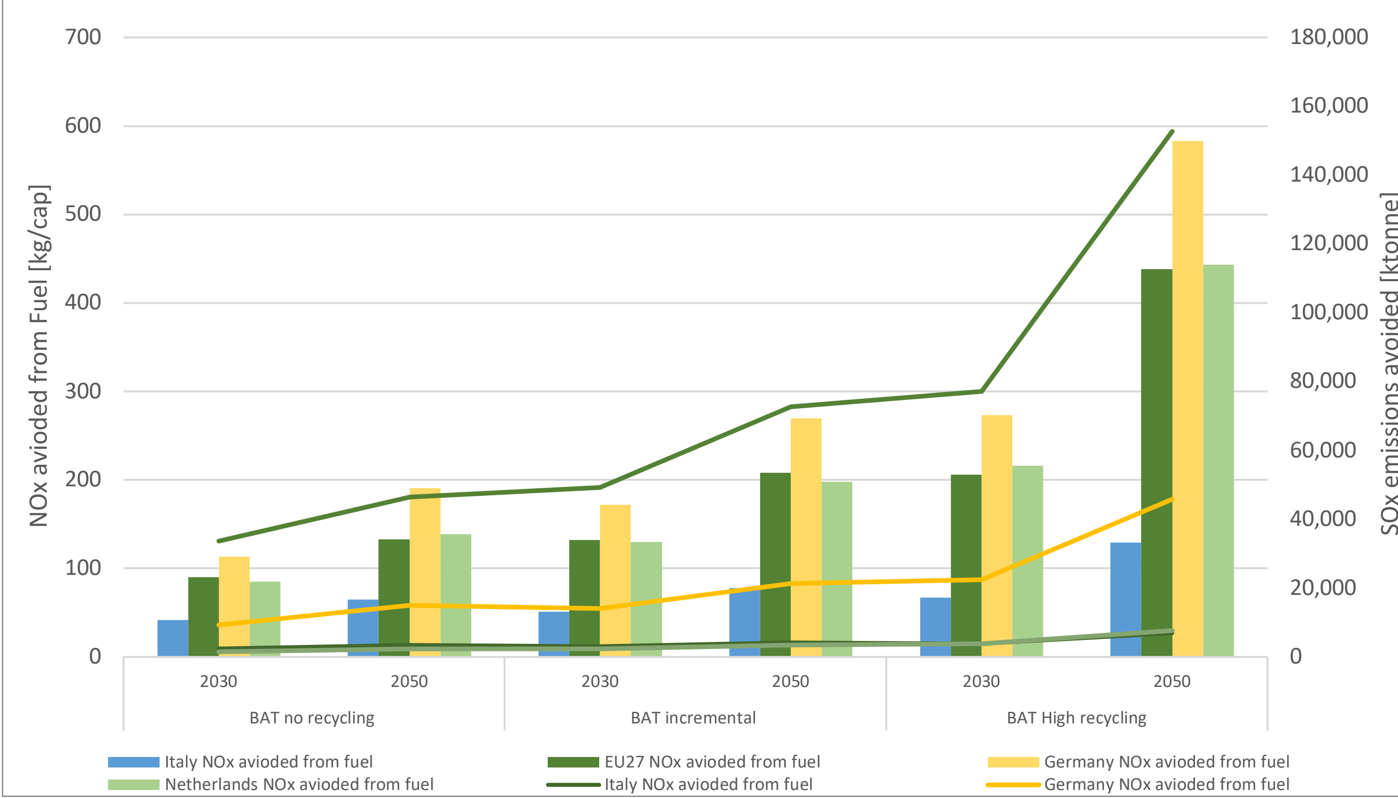

Figure 18: Total NOx emissions avoided from fossil fuel by implementing EEMs in three BAT scenarios in the year 2030 and 2050. Kg/cap (Left axis) and ktonne(right axis)

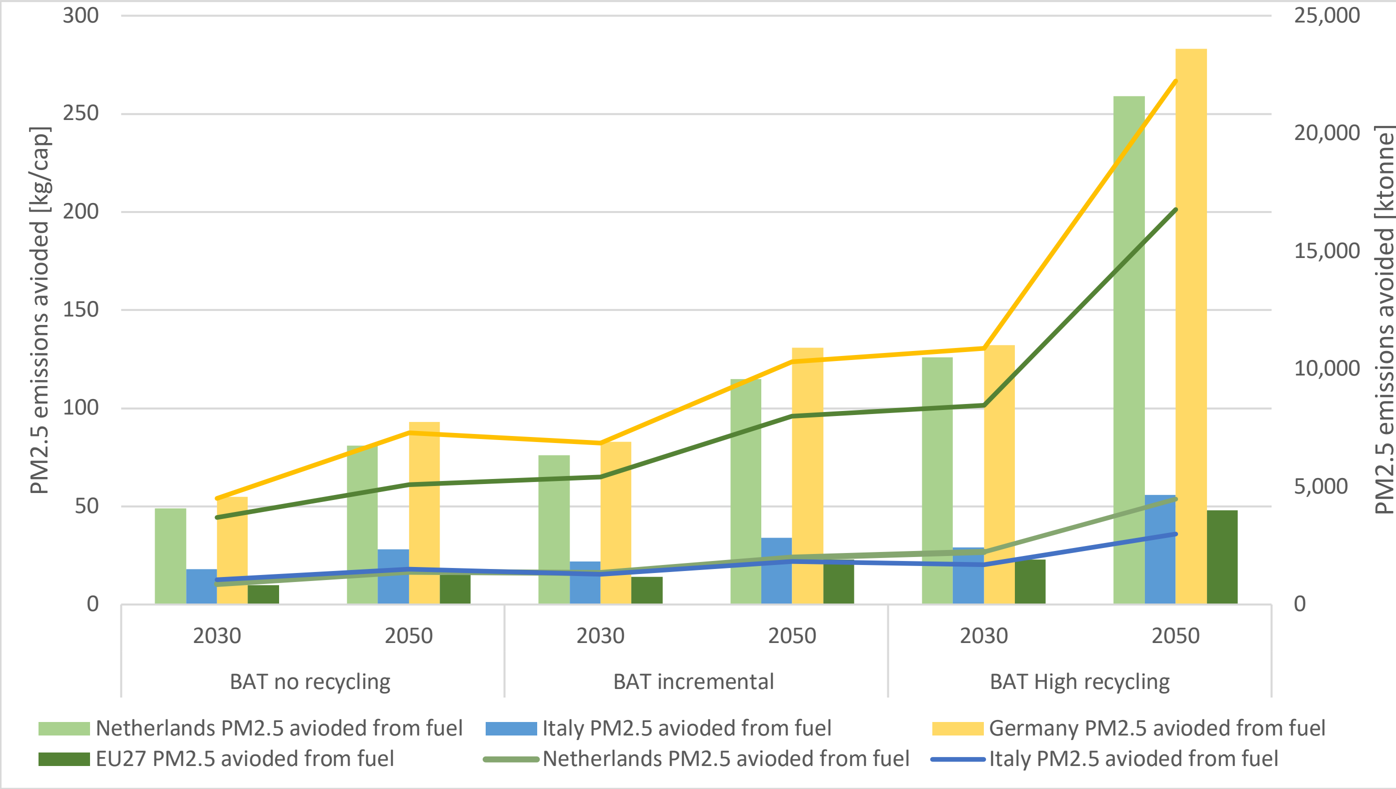

Figure 19: Total PM2.5 emissions avioded from fossil fuel by implementing EEMs in three BAT scenarios in the year 2030 and 2050 Kg/cap (Left axis) and ktonne(right axis)

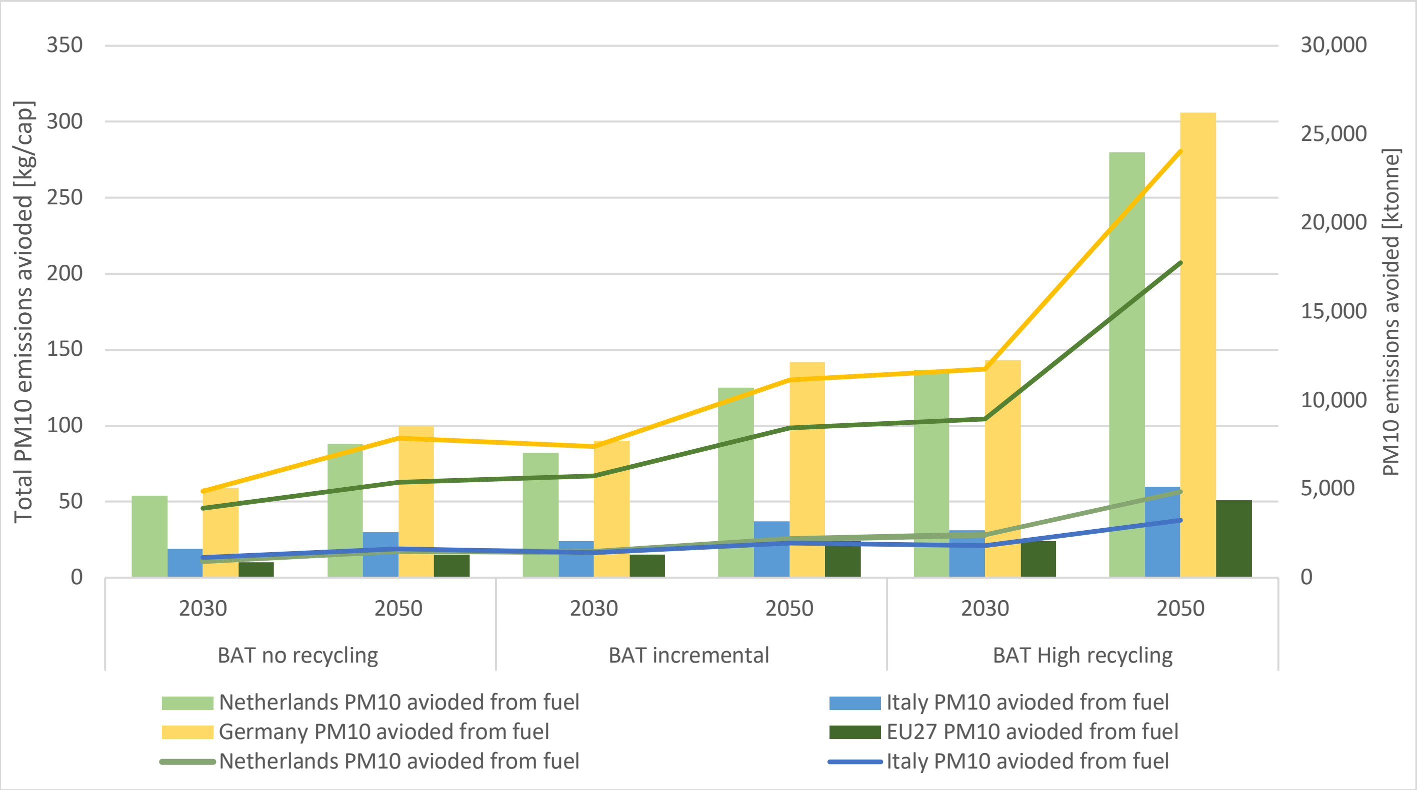

Figure 20: Total PM10 emissions avioded from fossil fuel by implementing EEMs in three BAT scenarios in the year 2030 and 2050 Kg/cap (Left axis) and ktonne (right axis)

5.3. Social Benefit of Energy Efficiency

5.3.1. Health and well-being indicator

The social benefits have the least co-benefits indicator for quantification since many NEBs in this category are unquantifiable or difficult to measure and usually have an indirect impact. However, a measurable is avoidable deaths from air pollutants. This indicator is only calculated for the pollutant's NOx and PM2.5 due to the lack of data on, the air volume and deaths/1 µg/m3 for SOx and PM10. The results are presented in two figures per pollutant; the avoidable deaths compared to the based scenario of the frozen efficiency (figure 21-22) and the number of deaths from the emission concentration and (figure 23-24). Only 80% of steel producers in the EU27 has been measured in this indicator due to a lack of data.

Results show a significant number of deaths avoided for both pollutants in the EU27 in each reference scenario. Most noticeably in 2050 BAT high recycling (681) with Germany making up about 50% of EU27. The PM2.5 levels deaths rate is much higher than NOx on account of its highly harmful health impact. the total amount of deaths avoided from PM2.5 is about 9,000 for BAT no extra recycling and 25,000 for BAT high.

The Netherlands have a higher death rate then Italy from PM2.5 Italy deaths avoided rage from (2300 – 1340) compared to The Netherlands (6750 – 3250), however that's not the case for NOx as it's the other way around's what can explain this is the higher concentration factor, and deaths/(1 µgr/m3).

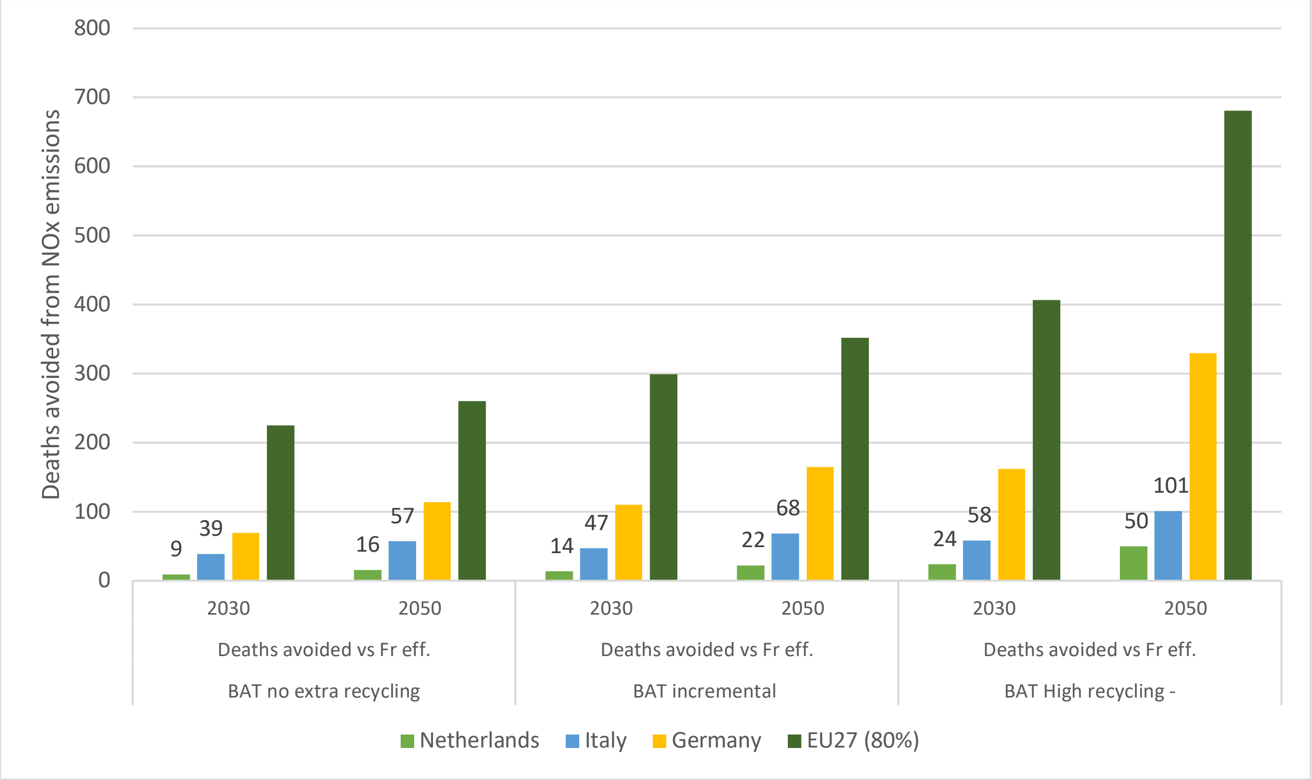

Figure 21: Deaths avoided from NOx compared to the frozen efficiency scenario for three BAT scenarios in 2030 and 2050.

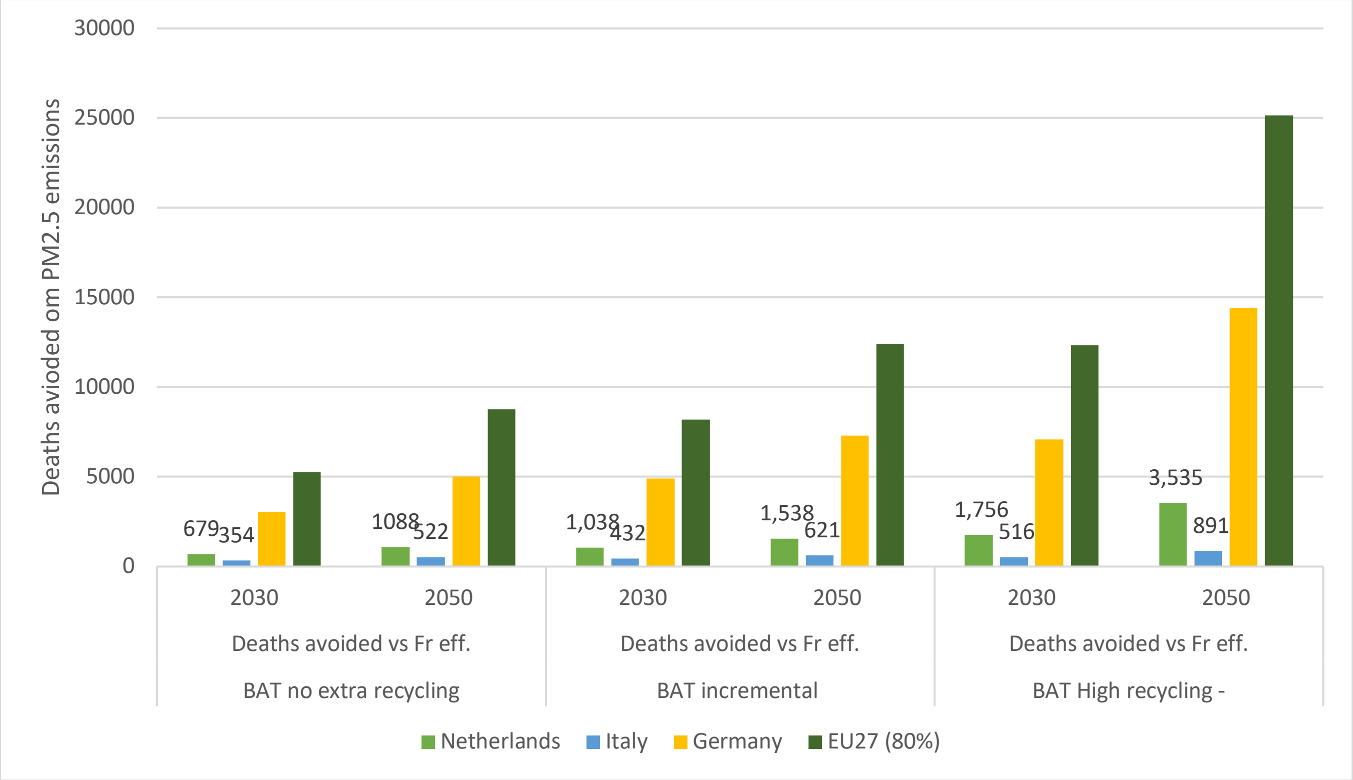

Figure 22: Deaths avoided from PM2.5 compared to the frozen efficiency scenario for three BAT scenarios in 2030 and 2050.

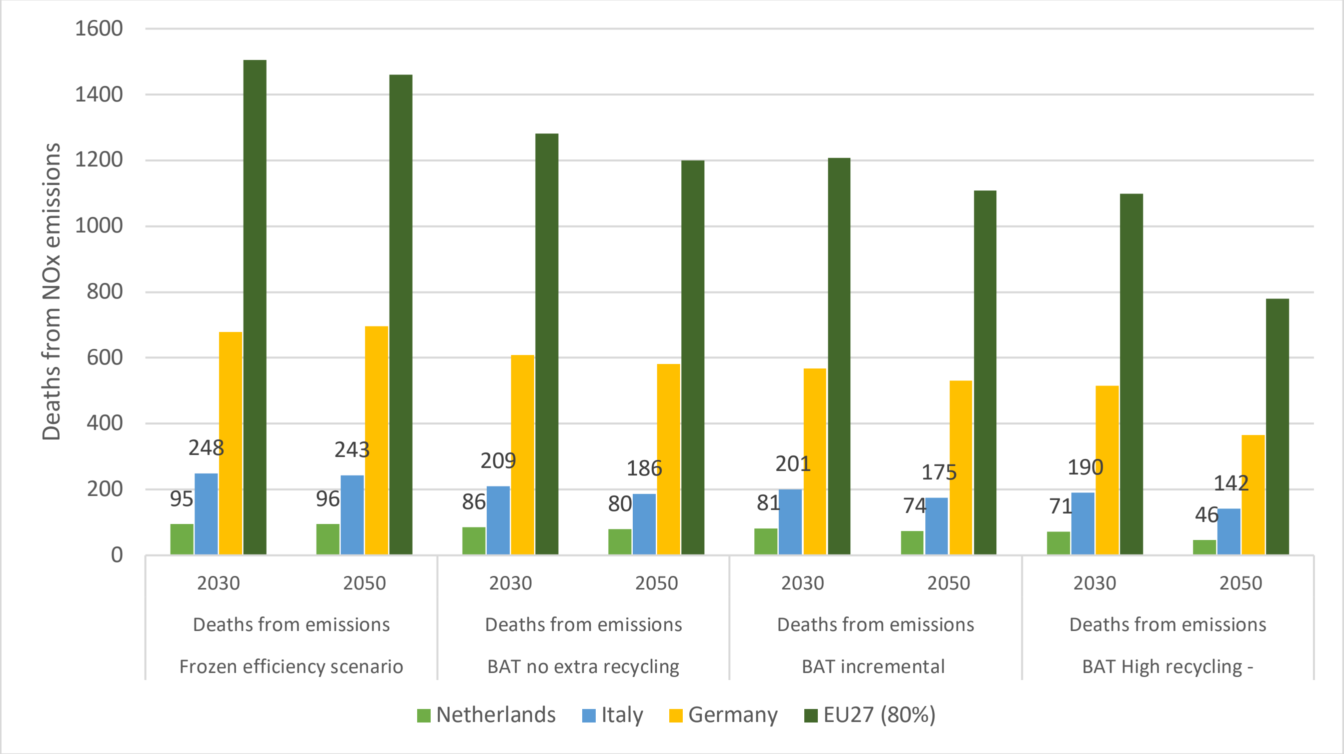

Figure 23: Projected Deaths caused by NOx emissions for three BAT scenarios compared to frozen efficiency scenario in 2030 and 2050.

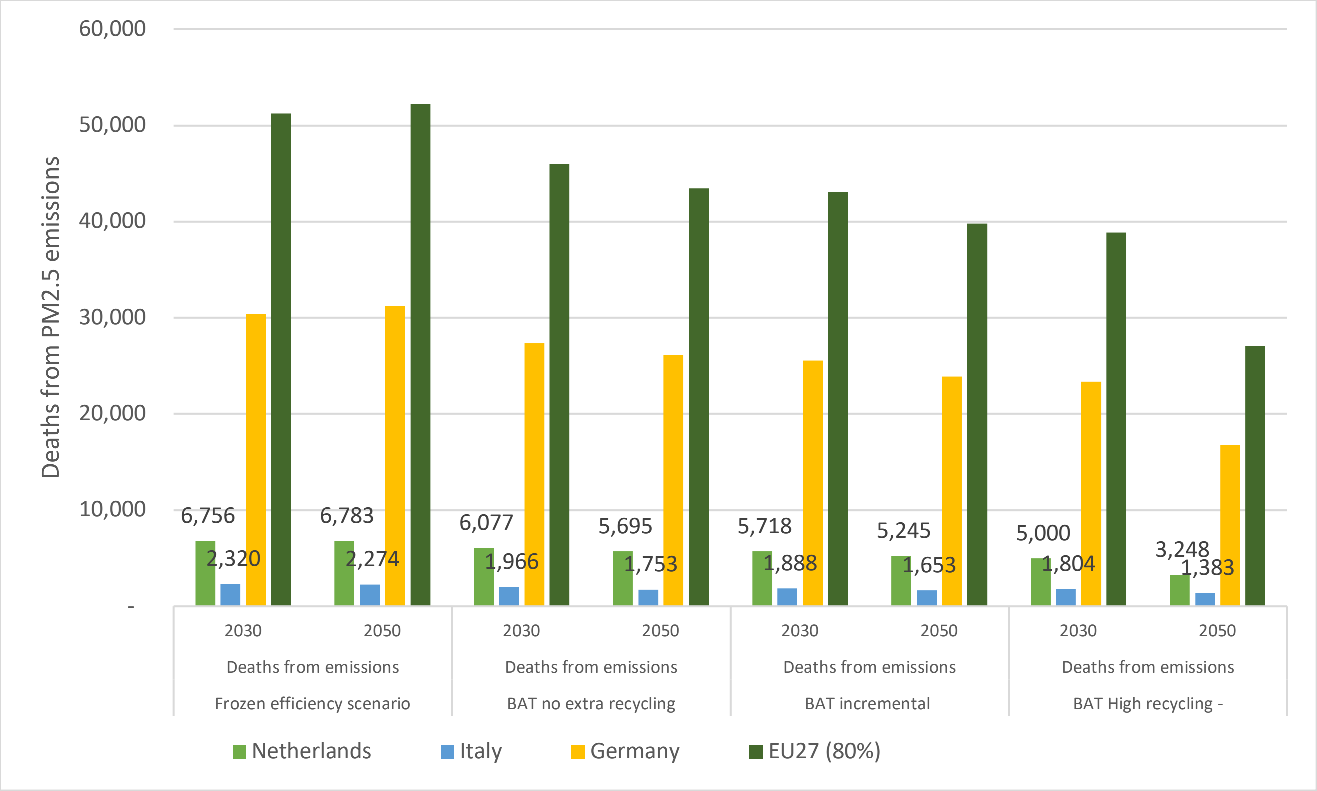

Figure 24: Projected Deaths caused by PM2.5 emissions for three BAT scenarios compared to frozen efficiency scenario in 2030 and 2050.

Overall, the quantified NEBs have shown a large impact on each indicator, the additional recycling scenarios have added a significant amount of saving and reduction, most prominently with high recycling. The EE measures for EAF has decreased its demand, however, only in the higher recycling rates it has seen a spike of uptake in EAF energy demand. As recycling is a driver for more products in the electric arc furnaces route. This subsequently decreases the output demand of BF-BOF as seen with pig iron - the most energy demanding product.

The fuel share and electricity power mix of each country has a noticeable difference in all emissions reduction and deaths from emissions. NEB impacts on the electricity saving is less impactful than fossil fuel, however it has a negative value due to the uptake of recycling it demonstrated potential fuel switch towards electricity generation in the steel industry. Germany and the Netherlands high share of coal in steelmaking have signified the potential of emissions they can be avoided by implementing energy efficiency measures/technology. There is a correlation bet ween the air pollutants (NOx, SOx, PM2.5 and PM10) and amount of fossil fuel saving potential in each country. The avoidable deaths indicator has shown a staggering number of preventable deaths that are caused by NOx and PM2.5, the EU27 can prevent 12000 deaths by 2030 and just over 25000 by 2050 from the steel sector emissions alone. This indicator shows the strength of measuring NEBs alongside EE improvements emphasising the notion of beyond energy saving and paves the way for a sustainable pathway for the steel industry.

6. Discussion

This section covers the interpretations and implications of the main findings of identifying and quantifying the NEBs in different BAT reference scenarios. Secondly, the limitation faced in the study will be discussed and finally, the recommendations for further study will be suggested.

6.1. Contribution to literature

6.1.1. Implementation of EEMs and NEBs in the BAT scenarios

This research has continued upon the findings from the SEEnergies project regarding the impact of implementing 20 new energy efficiency measures and technologies within the energy-intensive process of the iron and steel industry in the scope of the European Union. This has shown the potential of energy saving per tonne of process output the industry can achieve in the short term and long term. The BATs relate primarily to the techniques to recover and transform the excess energy to useful energy throughout the existing steel process. These measures are either add on, process controls or new technologies implemented within the five-production process of steel products (Coke oven, rolled steel, EAT steel, BF-BOF steel and pig iron). While some EE measures directly reduce fuel inputs in the production process with better monitoring and waste recovery, other technologies increase and improve producing steel from lower-emitting processes such as EAF, which contributing to indirect savings of emissions from recycling and fuel switching. Hence, implementing BAT results in many non-energy benefits other than fuel savings.

The non-energy benefits have grown in the past two decades with the increase of energy efficiency awareness, the literature review in this research has identified and categorised numerous NEBs from past studies, such as Pye and McKane, (2000) and Worrell et al., (2002). Which were further investigated by Thema et al., (2017) Nehler et al., (2018) presenting NEB quantification methods in the industry. Reuter et al, (2020) study further examined the NEBs and created measurable and monetizable indicators and methods for each NEB. Which has led to this research selecting quantifiable environmental, social and economic indicators to seen the additional impact caused by the selected EEMs. the findings have shown significant benefits on fossil fuel savings, avoidable air pollutants (CO2, SOx, NOx, PM2.5, PM10) and the indirect avoidable deaths caused by the pollutants (NOx, PM2.5). hence applying the NEBs increase the assurances of enforcing the energy efficiency measures within the steel industry.

6.1.2. Steel Recycling Fuel Switch

The EEMs were applied in three references scenarios that have a different rate of recycling. Implementing the recycling rates determines the difference in NEB outcomes when the recycling of scrap increases with the addition of EEMs, such as ‘Improving process control in EAF reduces 0.24 GJ/tonne product. The impact of recycling is very significant comping to the incremental and no extra recycling. for instance, Germany’s GHG avoidance increases by 42% in incremental recycling compared to no extra recycling, but it drastic increases by 209% in the high recycling compared to no extra recycling. The increase shows a significant reduction of emissions and energy saving in each indicator, most notable difference in the selected countries is the decrease of BF-BOF intensity and the increase of EAF production. This is because EAF is the process of remelting steel scrap from recycled steel, hence in increases in activity. An assumed shift from BF-BOF steel production to EAF production would see a reduction in EU27 energy demand of 45% and increases by 27% for EAF comparing frozen efficiency to high recycling in 2050, which acounts for 140 PJ in reduction in energy demand. This is about one-third of the BOF process since EAF use of natural gas substantial emission reductions relative to coal.

The NEB indicator increases the significance of the benefit of recycling, showing a drastic impact on emission and fossil fuel reduction, as well as the indirect impact of deaths from emissions. the health and well-being indicator highlights the major effect of quantifying NEBs when considering an investment in EEMs, emphasising that EEMs go beyond energy savings and can save lives. The indicator estimated 25,000 avoidable deaths for BAT high for the EU27 and12,000 for BAT incremental compared to the frozen efficiency scenario between now and 2050.

The findings from comparing the selected counties from implementing the EEMs establishes the importance of fuel share and power share of the country's energy consumption. Fuel switching which refers to the substitution of fossil energy inputs with less carbon-intensive alternatives or renewable energy sources or electrification refers to shifting to electricity using commercial technologies, would increase the direct and indirect non-energy benefits outcomes. the steel industry is the largest consumer of coal, the shift from coal furnaces, innovative smelting reduction, gas-based direct reduced iron (DRI) and various innovative blast furnace concepts would decline the use of coal and increase natural gas use and other electrification processes. Direct electrification of the essential fossil-based process with the current technologies available would be costly and impractical, however, it can become an option in the long-term with innovations.

6.2. Limitations and Assumptions

The first restraint of this study was the limited time frame, which only allowed to focus on specific non-energy benefit indicators. As several direct and indirect economic co-benefits result in enforcing the best available technologies in the steel sector. Additionally, calculating the selected NEB indicators for each EU27 country would require a lot of time. This would have given more comprehensive results when comparing the performance of each county to one and the other. Other NEB indicators such as RES targets, impact on GDP would have given more insight to the macro and microeconomic impact of energy efficiency measures/technologies to additional reassure the necessity of quantifying NEBs within the steel sector and other industries. Moreover, there are a wide arrange of EEMs and technologies that are applicable in the iron and steel process that have not been reviewed or elaborated on. The complex and energy-intensive process of steelmaking has much greater margins of energy-saving potential, this includes, technologies for fuel switching demand to hydrogen and electrification of furnaces.

The steel sector data currently available has many gaps and limitations, that could be decreased through improving data collection initiatives led by industry associations, governments and private companies. Specific areas of enhancements include the greater premotion in data collection among steel, and to assist in the development data collection system that complies with competition requirements, which can include mandatory emission reporting.

Two main barriers are identified in this study. First is the limited methods of quantifying NEBs found in the literature review. After reviewing 39 papers, Reuter et al., (2020) was the only research paper that had simple indicators to quantify the NEB categories. Even though the paper has had a major impact on the topic of NEBs, the study is relevantly new and comparing other quantifiable methods could have strengthened the results.

The second barrier in the study is the need to making assumptions due to the limitation of available data. the NEB analysis did not include the indicators, industrial productivity and asset value even though they were one of the most cited NEBs in literature. industrial Productivity, for example, would have expressed the added value per unit of energy used, this would have shown how the recycling and BAT scenarios have a significant impact on the indicator. Since the gross value added is required and it was left out of the study.

Finally, the assumptions made in this study were due to the lack of data and the need to generalize the finding when comparing countries saving potential. The energy efficiency measures, implementation rate, energy-saving potential for fuel and electricity in 2030 and 2050 were all equal in each EU27 country. these measures are presumed in the scenario study since each country does not have a projected EEMs to implement in the steel sector yet. Additionally, the projected production of steel products and final energy consumption used in the scenarios are developed from the frozen efficiency scenario. Since the timeframe is 2030 and 2050, we cannot predict growth trajectory changes, such as the economic crisis in the wake of the covid-19 pandemic, which lead to an estimated 5% decline in global iron and steel output in 2020 relative to 2019 (IEA, 2020).

6.3. Recommendations for Further research

Studying the impact of non-energy benefits in the industry is relatively new in literature and industry, and only recently has seen a surge in research and development of quantifying tools. Quantifying other NEBs would shed light on environmental, social and economic impacts caused by EEMs other than energy saving, it would also result in increased the attractiveness of investments for decision-makers. In addition, further research is needed quantifying the NEBs for the electrification and hydrogen scenarios for the steel in the study from the SEEnergies project, since more benefits would be seen in these scenarios. Finally, identifying and measuring non-energy benefits can be applied in any industrial sector therefore should be applied in cost-benefit analysis and investment risk assessment across all sectors to better understand the positive and negative impact a project conveys.

7. Conclusion

The present study aimed to identify and quantify the additional non-energy benefits that are neglected from implementing energy efficiency measures and technologies in the iron and steel sector. The research follows the European commission directive (2016) to promote the principle of 'energy efficiency first' introducing's a binding set of energy efficiency measures to achieve the set targets for end-users and energy suppliers. The research develops upon the findings from the SEEnergies project as part of the horizon 2020 Research and Innovation Program.

Hence, this research aims to answer the research question; "To what extent can including NEBs increase the attractiveness of energy efficiency measures in the Iron and steel sector in the EU and to what degree can they be quantified?"

industry impact the socio-environmental non-energy benefits in the European Union and influence investment decision-makers?". The study followed three main steps to answer the research question; identification, quantification, and measuring the impact of implementing NEBs within a selected industry. The Iron and steel sector was chosen due to its high energy-intensive process and large output of production in the European Union.

For the first step, an analysis of literature from the period of 1999 – 2020 was done to understand the findings in the field and to identify the most reoccurring NEBs in the industrial sector. Findings from studies such as Pye and McKane, (2000), Worrell et al., (2003) and Hall & Roth, (2004) have paved the way for the identification and categorization of the NEBs. The second step of quantifying the benefits was found from recent literature building up from earlier findings, studies such as Rasmussen, (2015), Nehler et al., (2018) and Reuter et al, (2020) have provided insight and accurate methodology approaches for quantification. A selection of NEB indicators was chosen based on the data available to be applied to the steel sector based on the energy efficiency measures promoted by the SEEnergies Project. In the third step, the NEBs were applied to three mitigating Best Available Technology's (BATs) reference scenarios developed by the SEEnergies project, which applies varying degrees of recycling and production rates to the EEM innovations to construct different energy demand pathways for the EU industry for the year 2030 and 2050.

Finally, the quantified NEBs in this study were fossil fuel-saving, avoided air pollutants (CO2, SOx, NOx, PM2.5, PM10) and avoided deaths caused by pollution, and turnover of EE goods. these indicators have shown significant benefits in each BAT scenario, with BAT incremental and high recycling having larger benefits due to the respected recycling rate.

Limitations faced were the lack of available data to quantify other NEBs in the duration of the research and the time constraint due to the extensive data analysis required. Additional data should be collected by institutions to improve and streamline researchers' studies. Further research and awareness of the importance's of NEBs are required, including the benefits in investments schemes increase the attractiveness of financial institutions and investors to support EEM adoption and look beyond just energy saving and moving away from emission-intensive technologies. policymakers can apply NEBs in the design process of energy efficiency policies, thus allowing the consideration of several aspects at an earlier stage and potentially accelerating the promotion of EE policies. Further work may also analyse if the NEB indicators can be combined into composite indicators and aggregate them into single ones for further simplification. Ultimately, the findings of this study highlighted the fraction of unnoticeable benefits and saving potential for the industrial sector as a whole, demonstrating the wide prospect for future research in the field of non-energy benefits.

8. References

Cagno, E., Moschetta, D., & Trianni, A. (2019). Only non-energy benefits from the adoption of energy efficiency measures? A novel framework. Journal of cleaner production, 212, 1319-1333.

Campbell, N., Ryan, L., Rozite, V., Lees, E., & Heffner, G. (2014). Capturing the multiple benefits of energy efficiency. IEA: Paris, France.

Carpenter, A. (2012). CO2 abatement in the iron and steel industry. IEA Clean Coal Centre, 25.

Christiansen, I. S., Gudbjerg, E., & Dyhr-Mikkelsen, K. (2016). New robes for NEB research—Open and expanding data. Proceedings of the ECEEE Industrial Summer Study, Berlin, Germany, 12-14.

COMBI Project. (2021). Retrieved 12 July 2021, from https://combi-project.eu/benefits/air-pollution/

Cooremans, C. (2011). Make it strategic! Financial investment logic is not enough. Energy Efficiency, 4(4), 473-492. doi: 10.1007/s12053-011-9125-7

EU climate action and the European Green Deal - Climate Action - European Commission. (2019). Retrieved 23 August 2020, from https://ec.europa.eu/clima/policies/eu-climate-action_en

EU Environmental Economic & Social multi benefits efficiency tool | ODYSSEE-MURE. (2021). Retrieved 12 July 2021, from https://www.odyssee-mure.eu/data-tools/multiple-benefits-energy-efficiency.html

Eurofer Statistics. (2021). Retrieved 12 July 2021, from https://www.eurofer.eu/statistics/

EUROFER: EU steel exports. (2020). Retrieved 29 September 2020, from https://www.steelorbis.com/steel-news/latest-news/eurofer-eu-steel-exports-fall-in-january_april-1158677.htm

European Commission (2014). assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by Article. Brussels, Office for Official Publications of the European Communities.

European Commission (EC). (2019). Clean energy for all Europeans. European Commission, Brussels, Belgium. https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

European Environment Agency (EEA). (2016). 1.A.2. Manufacturing industries and construction (combustion). EMEP/EEA air pollutant emission inventory guidebook 2016.

Eurostat (2021). Employment by occupation and economic activity (from 2008 onwards, NACE Rev. 2)

Finman, H. and J.A. Laitner. (2004) Industry, energy efficiency and productivity improvements. Proceedings of the 2001 ACEEE Summer Study on Energy Efficiency in Industry. P.561-570.

Fleiter, T., Schleich, J., & Ravivanpong, P. (2012). Adoption of energy-efficiency measures in SMEs—An empirical analysis based on energy audit data from Germany. Energy Policy, 51, 863-875.

Gudbjerg, E., Dyhr-Mikkelsen, K., & Andersen, C. M. (2016). Spreading the word—An online non-energy benefit tool. Proceedings of the ECEEE Industrial Summer Study, Berlin, Germany, 12-14

Hasanbeigi, A., Lobscheid, A., Lu, H., Price, L., & Dai, Y. (2013). Quantifying the co-benefits of energy-efficiency policies: A case study of the cement industry in Shandong Province, China. Science Of The Total Environment, 458-460, 624-636. doi: 10.1016/j.scitotenv.2013.04.031

IEA (2016), Technology Roadmap – Low-Carbon Transition in the Cement Industry, https://webstore.iea.org/technology-roadmap-low-carbon-transition-in-the-cement- industry.

IEA (2019), World Energy Outlook, IEA, Paris, https://www.iea.org/reports/world-energy- outlook-2019.

IEA (2020b), CO2 Emissions from Fuel Combustion 2020 Edition: Database Documentation, IEA, Paris, https://iea.blob.core.windows.net/assets/474cf91a-636b-4fde-b416-56064e0c7042/WorldCO2_Documentation.pdf.

IEA (International Energy Agency) (2013a), World Energy Outlook 2013,

IEA (International Energy Agency) (2020a), World Energy Balances, https://www.iea.org/reports/world-energy-balances-overview.

International Energy Agency (IEA). (2012). Spreading the net - The Multiple Benefits of Energy Efficiency Improvements. New Electronics, 40(2), 39–40. https://doi.org/10.2307/1478864

International Energy Agency (IEA). (2014). Capturing the Multiple Benefits of Energy Efficiency (2nd ed.).

International Energy Agency (IEA). 2016. Energy balances 2016 edition. OECD/IEA, Paris, France

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, RK Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

ISO (International Organization for Standardization) (2020), ISO/FDIS 14404-4 Calculation Method of CO2 Emission Intensity from Iron and Steel Production — Part 4: Guidance for Using ISO 14404 Family, https://www.iso.org/standard/77622.html.

Jakob, M. (2006). Marginal costs and co-benefits of energy efficiency investments. Energy Policy, 34(2), 172-187. doi: 10.1016/j.enpol.2004.08.039

Johansson, M., & Söderström, M. (2011). Options for the Swedish steel industry – Energy efficiency measures and fuel conversion. Energy, 36(1), 191-198. doi: 10.1016/j.energy.2010.10.053

Kermeli, K. and Crijns-Graus, W. (2020). Energy efficiency potentials on top of the reference scenario. sEEnergies Deliverable 3.6.

Killip, G., Fawcett, T., Cooremans, C., Crijns-Graus, W., Krishnan, S., & Voswinkel, F. (2019). Multiple benefits of energy efficiency at the firm level: a literature review. European Council for an Energy Efficient Economy: Stockholm, Sweden.

Lilly P, Pearson D. Determining the full value of industrial efficiency programs. In: Proceedings 1999 Summer Study on Energy Efficiency in Industry. Washington DC: American Council for an Energy-Efficient Economy; 1999, p. 349–62.

López-Peña, Á., Pérez-Arriaga, I., & Linares, P. (2012). Renewables vs. energy efficiency: The cost of carbon emissions reduction in Spain. Energy Policy, 50, 659-668. doi: 10.1016/j.enpol.2012.08.006

M-Benefits. (2021). Retrieved 12 July 2021, from https://www.mbenefits.eu/

McKinsey & company. China's green revolution prioritising technologies to achieve energy and environmental sustainability. McKinsey & Company; 2009.

Meier A, Wright J, Rosenfeld AH. Supplying Energy through Greater Efficiency: The Potential for Conservation in California’s Residential Sector. Berkeley, CA: University of California Press, 1983.

Mzavanadze, N. (2018). WP3 Air pollution Quantifying air pollution impacts of energy efficiency D3. 4 Final report.

Næss-Schmidt, H. S., & Hansen, P. M. B. W. WP6 Macro-economy Macro-economic impacts of energy efficiency D6. 4 Final report.

Nehler, T. (2018). Linking energy efficiency measures in industrial compressed air systems with non-energy benefits – A review. Renewable And Sustainable Energy Reviews, 89, 72-87. doi: 10.1016/j.rser.2018.02.018

Nehler, T. Non-Energy Benefits of Industrial Energy Efficiency Improvements.

Nehler, T., & Rasmussen, J. (2016). How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry. Journal of Cleaner Production, 113, 472-482.

OECD Steel Committee. (2015). Energy efficiency in the steel sector: why it works well, but not always. 38 p.

OECD/IEA, Paris, www.iea.org/W/ bookshop/add.aspx?id=455 (accessed 28 June 2014)

Pye, M., Mckane, A., 2000. Making a stronger case for industrial energy efficiency by quantifying non-energy benefits. Resources, Conservation and Recycling 28, 171e183.

Rasmussen, J. (2014). Energy-efficiency investments and the concepts of non-energy benefits and investment behaviour. In ECEEE 2014, Industrial Summer Study: Retool for a competitive and sustainable industry, June 2-5, 2014, Arnhem, The Netherlands (Vol. 2, pp. 733-744). European Council for an Energy Efficient Economy (ECEEE).

Rasmussen, J. (2017). The additional benefits of energy efficiency investments—a systematic literature review and a framework for categorisation. Energy Efficiency, 10(6), 1401-1418. doi: 10.1007/s12053-017-9528-1

Ren, H., Wu, Q., Zhu, Q., & Gao, W. (2019). Cost–benefit analysis of distributed energy systems considering multi-benefits and multi-stakeholders. Energy, 189, 116382. doi: 10.1016/j.energy.2019.116382

Ren, H., Wu, Q., Zhu, Q., & Gao, W. (2019). Cost–benefit analysis of distributed energy systems considering multi-benefits and multi-stakeholders. *Energy*, *189*, 116382. doi: 10.1016/j.energy.2019.116382

Reuter, M., Patel, M., Eichhammer, W., Lapillonne, B., & Pollier, K. (2020). A comprehensive indicator set for measuring multiple benefits of energy efficiency. Energy Policy, 139, 111284. doi: 10.1016/j.enpol.2020.111284

Schweitzer, M., & Tonn, B. (2003). Non-energy benefits of the US Weatherization Assistance Program: a summary of their scope and magnitude. Applied Energy, 76(4), 321-335. doi: 10.1016/s0306-2619(03)00003-5

sEEnergies |. (2020). Retrieved 29 September 2020, from https://www.seenergies.eu/

Shaoxiang, H. Sangao, C. Jinming, Unification of emission performance standards for evaluating environmental impacts of energy utilisations. J. Eng. Thermophys. 27(1), 5–8 (2006)

Skumatz, L. (2006), Measuring "Hard to Measure" Non-energy Benefits (NEBs) from Energy Programs: Methods and Results, American Evaluation Association, Portland.

Skumatz, L. (2015). Efficiency Programs' Non-Energy Benefits: How States Are Finally Making Progress in Reducing Bias in Cost-Effectiveness Tests. The Electricity Journal, 28(8), 96-109. doi: 10.1016/j.tej.2015.09.008

Skumatz, L., Khawaja, M. S., & Krop, R. (2010). Non-Energy Benefits: Status, Findings, Next Steps, and Implications for Low Income Program Analyses in Californi. In Prepared for Sempra Utilities.

Sobhani, N., 2018. The Role of Co-Benefits: Rethinking The Costs and Benefits of Climate Change Mitigation - Niskanen Center [WWW Document]. URL https://www.niskanencenter.org/the-role-of- co-benefits-rethinking-the-costs-and-benefits-of-climate-change-mitigation/ (accessed 11.29.19).

Steel Institute (2018), Steel Institute VDEh PLANTFACTS database (purchased), Stahl-Online, https://en.stahl-online.de/index.php/about-us/vdeh/.

Thema, J., Suerkemper, F., Couder, J., Mzavanadze, N., Chatterjee, S., & Teubler, J. et al. (2019). The Multiple Benefits of the 2030 EU Energy Efficiency Potential. Energies, 12(14), 2798. doi: 10.3390/en12142798

Thema, J., Suerkemper, F., Thomas, S., Teubler, J., Couder, J., Mzavanadze, N., ... & Below, D. V. (2016). Widening the Perspective: An Approach to Evaluating the Multiple Benefits of the 2030 EU energy efficiency potential.

Trianni, A., Cagno, E., Thollander, P., & Backlund, S. (2020). Barriers to industrial energy efficiency in foundries: a European comparison. Retrieved 29 September 2020

Ürge-Vorsatz, D., Kelemen, A., Tirado-Herrero, S., Thomas, S., Thema, J., & Mzavanadze, N. et al. (2016). Measuring multiple impacts of low-carbon energy options in a green economy context. Applied Energy, 179, 1409-1426. doi: 10.1016/j.apenergy.2016.07.027

Vijaykar, N. (2019). Non-Energy Benefits of Energy Efficiency. The Midwest Energy Efficiency Alliance (MEEA). Retrieved from: https://www.mwalliance.org/

Vivian Loftness, F. A. I. A., Hartkopf, V., & Gurtekin, B. (2003). Linking energy to health and productivity in the built environment.

Wang, K., Wang, S., Liu, L., Yue, H., Zhang, R., & Tang, X. (2016). Environmental co-benefits of energy efficiency improvement in coal-fired power sector: A case study of Henan Province, China. Applied Energy, 184, 810-819. doi: 10.1016/j.apenergy.2016.06.059

Woodroof, E., Turner, W., Heffington, W., & Capehart, B. (2012). Energy Conservation Also Yields: Capital, Operations, Recognition, and Environmental Benefits. Energy Engineering, 109(5), 7-26. doi: 10.1080/01998595.2012.10531820

Woodroof, E.A. et al. (2012), "Energy conservation also yields: capital, operations, recognition and environmental benefits", Energy Engineering, Vol. 109, No. 5, Taylor & Francis, pp. 7-26, www.tandfonline. com/doi/abs/10.1080/01998595.2012.10531820?tab=permissions#tabModule (accessed 28 June 2014).

World Bank Group - International Development, Poverty, & Sustainability. (2020). Retrieved 29 September 2020, from https://www.worldbank.org/

World Steel Association (2020a), Crude Steel Production Monthly, https://www.worldsteel.org/steel-by-topic/statistics/steel-data- viewer/MCSP_crude_steel_monthly/CHN/IND.

Worrell, E., Laitner, J., Ruth, M., & Finman, H. (2003). Productivity benefits of industrial energy efficiency measures. Energy, 28(11), 1081-1098. doi: 10.1016/s0360-5442(03)00091-4

Worrell, E., Price, L., & Martin, N. (2001). Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. Energy, 26(5), 513-536. doi: 10.1016/s0360-5442(01)00017-2

Zhang, S., Worrell, E., Crijns-Graus, W., Wagner, F., & Cofala, J. (2020). Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Retrieved 29 September 2020, Zhou, S., Hu, S., & Cheng, J. (2006). Unification of Emmission Performance Standards for Evaluating Environmental Impacts of Energy Utilizations. Journal of Engineering Thermophysics, 27(1), 5

9. Appendix

9.1. Appendix - A

Table 17 frequent used NEBs in industry and their categorisation (Pye and McKane, 2000), Finman and Laitner, 2001), (Worrell et al. 2003),(Skumatz et al. 2000), IEA, 2012), (Rasmussen , 2015).

	Mentioned non-energy benefits	Categorization
Lilly and Pearson (1999)	Extended life of equipment, reduced air emissions and related fines, reduced wear and tear, reduced operations and maintenance expenses	
Pye and McKane (2000)	Increased productivity, improved capacity utilization, reduced production costs (labour, O&M, raw materials), reduced waste costs, improved product quality (reduced scrap costs, customer satisfaction), reduced costs of environmental compliance, improved capacity utilisation, reduced maintenance requirements, improved reliability, worker safety, improved efficiency, reduced emissions, extend equipment life, reduced operating time, reduced ancillary operations, , increased capacity.	
Skumatz et al. (2000)	Improved lighting, improved work environment, lower maintenance, reduced glare, reduced water losses, improved productivity, better control, longer equipment lifetimes, greater comfort, improved air quality, tenant satisfaction, improved temperature control, environmental benefits, , improved efficiency, efficient water use, labour savings, reduced noise,	By type of measure: 1. Lighting measures 2. HVAC measures 3. Water measures 4. Refrigeration
Finman and Laitner (2001) & Worrell et al. (2003)	Use of waste fuels, reduced product waste, reduced waste water, reduced hazardous waste, materials reduction, reduced dust emissions, reduced CO, CO2, NOx, SOx emissions, reduced need for engineering controls, lowered cooling requirements, increased facility reliability, reduced wear and tear on equipment/machinery, reductions in labour requirements, increased product output/yields, improved equipment performance, shorter process cycle times, improved product quality/purity, increased reliability in production, reduced need for personal protective equipment, improved lighting, reduced noise levels, improved temperature control, improved air quality, decreased liability, improved public image, delaying or reducing capital expenditures, additional space, improved worker morale	1. Waste 2. Emissions 3. Operations & maintenance 4. Production 5. Working environment 6. Other
Ürge -Vorsatz et al. (2009)	Waste reduction benefits, Reduction of air pollution, Reduced morbidity and mortality, Improved productivity, Avoided costs to support the human health, working environment, Improved energy security, Lower bad debt, Rate subsidies avoided, Employment creation, Lower energy prices, Decreased energy bill payments, Improved productivity, Transmission and distribution loss reduction, Fewer emergency (gas) service calls Utilities' insurance savings, improved social welfare and fuel poverty alleviation, Benefits to disadvantaged social groups Increased political popularity, Increased awareness, Increased comfort.	1. health effect 2. economic effect 3. ecological effect 4. service provision benefits 5. social effect.
Cooremans (2011)	Follows Worrell et al. (2003) categorisation however adds reduced legal risks, carbon and energy price risks, disruption of energy supply and commercial risk.	Relates to competitive advantage: 1. Cost 2. Value 3. Risk
IEA (2012)	Health, increased asset values, industrial productivity, improved quality, safer working conditions, reduced capital and operating costs, improved competitiveness, reduced scrap and energy use.	By economic level: 1. Individual 2. Sectoral 3. National 4. International
COMBI (2018)	Effects on health, ecosystems, crops, biotic/abiotic, metals and non-metals, disposable income, health, labour market, public finance, GDP, grid, supply-side, energy security	1. Air pollution 2.Resources 3. social welfare/commercial productivity 4. Macroeconomics 5. Energy systems & security

ODYSSEE MB-EE	impact on RES target, energy savings, saving on fossil fuel, GHG savings, local air pollution, industrial productivity, assets value, employment effect, impact on GDP, impact on energy price, public budget, innovation impact, Impact on integration of renewables, Supplier diversity, Import dependency, Turnover of energy efficiency goods, Competitiveness, Health and well-being, disposable household income, Alleviation of energy poverty.	1. Environment 2. Economics 3. Social
Rueter et al., 2020	Savings of fossil fuels, Impacts on RES targets, GHG savings, Local air pollution, Alleviation of energy poverty, Health and well-being, Disposable household income, Innovation impacts, Competitiveness, Turnover of EE goods, Impact on GDP, Employment effects, Potential impact on energy prices 15 Impact on public budgets, (Industrial) productivity, Asset value, Energy security, Impact on integration of RES	1. Environment 2. Economics 3. Social

Table18: Number of times non-energy benefits and energy efficiency measures occur in the reviewed literature and whether NEBs are quantified (Y= Yes, N= No, P= Partially).

	Author	Production	O&M	Work Envi.	Waste	Emission	Other	total	Quantification	No. EEMs
1	Lilly & Pearson, 1999	2	2	0	0	1	0	**5**	N	5
2	Pye and McKane, 2000	3	3	1	1	1	1	**10**	p	3
3	Skumatz et al. 2000	1	3	4	2	2	2	**14**	N	6
4	Finman & Laitner, 2001	1	2	2	2	1	0	**8**	N	1
5	Worrell et al., 2002	3	2	0	1	1	0	**7**	N	54
6	Worrell et al., 2003	5	5	5	5	2	5	**27**	N	13
7	Loftnes, 2003	1	1	1	0	1	0	**4**	N	8
8	Hall & Roth, 2004	2	4	1	3	0	2	**12**	N	18
9	Skumatz & Gardner, 2005	1	0	0	0	0	0	**1**	N	1
10	Lung et al., 2005	5	4	1	2	1	1	**14**	P	54
11	Bement and Skumatz, 2007	1	2	1	0	0	1	**5**	N	12
12	Mills et al, 2008	1	1	1	0	0	0	**3**	N	5
13	Ürge-Vorsatz et al., 2009	3	0	7	1	4	4	**19**	N	15
14	Bunse et al. 2010	0	0	0	0	0	0	**0**	N	13
15	Naess-Schmidt et al. 2012	3	2	1	0	1	0	**7**	Y	2
16	Fleiter et al., 2012	1	0	0	0	1	0	**2**	N	17
17	Willoughby et al., 2012	3	2	2	1	1	0	**9**	P	4
18	Woodroof et al, 2012	0	3	1	0	0	2	**6**	Y	8
19	Larsen et al., 2012	1	1	1	0	1	0	**4**	N	4

Table 118 (continued): Number of times non-energy benefits and energy efficiency measures occur in the reviewed literature and whether NEBs are quantified (Y= Yes, N= No, P= Partially).

	Author	Production	O&M	Work Envi.	Waste	Emission	Other	total	Quantification	No. EEMs
20	Hasanbeigi et al., 2013	0	0	2	0	2	0	**4**	Y	1
21	Yang et al., 2013	0	0	0	0	1	0	**1**	Y	20
22	Gudbjerg et a 2014	2	0	1	0	0	0	**3**	N	2
23	Roser et al., 2014	0	0	0	0	2	0	**2**	N	6
24	Russell et al., 2015	0	1	2	0	1	2	**6**	N	9
25	Naess-Schmidt et al., 2015	0	0	0	0	0	1	**1**	N	2
26	Rasmussen, 2015	1	1	1	1	1	1	6	N	1
27	Cagno et al., 2016	2	3	3	4	3	0	**15**	N	3
28	Ürge-Vorsatz et al, 2016	1	0	1	0	1	0	3	N	3
29	Wang et al., 2016	0	0	1	0	1	0	**2**	P	10
30	Thema et al., 2016	1	0	1	0	1	1	**4**	N	7
31	Rasmussen & Nehler, 2016	2	2	1	0	1	1	**7**	N	1
32	Thema et al., 2017	1	0	0	0	1	1	**3**	N	27
33	Doyle & Cosgrove 2017	1	0	0	0	1	0	**2**	P	1
34	Nehler et al., 2018	2	3	1	1	0	0	**7**	N	45
35	Zhou et al., 2018	0	0	0	0	2	0	**2**	Y	1
36	Mzavanadze et al., 2018	0	0	1	0	2	1	**4**	Y	21
37	Chatterjee & Ürge-Vorsatz, 2018	2	0	2	0	2	1	**7**	Y	4
38	Trianni et al, 2020	8	9	6	5	3	6	**37**	N	16
39	Reuter et al, 2020	7	0	0	2	2	5	**16**	Y	20
	total	**67**	**56**	**52**	**31**	**45**	**38**	**236**	**-**	**444**

Table 19: Level of observed NEBs and level of energy efficiency improvement the reviewed literature in industry.

Authors	level of observed NEB	Level of Energy Efficiency Improvement
Lilly & Pearson, 1999	Specific	Specific
Pye and McKane, 2000	Specific	Specific
Finman & Laitner, 2001	Specific	Technology/Process
Skumatz et al. 2000	Technology/process	Technology/process
Worrell et al., 2002	Technology/Process	Specific, Technology/Process
Worrell et al., 2003	Specific	Specific, Technology/Process
Loftnes, 2003	Technology/Process	Technology/Process
Hall & Roth, 2003	Technology/Process	Technology/Process
Skumatz & Gardner, 2005	Specific	Specific
Lung et al., 2005	technology/Process	technology/Process
Bement and Skumatz, 2007	general	general
Mills et al, 2008	technology/Process	technology/Process
Ürge-Vorsatz et al., 2009	Specific, Technology/Process	Specific, Technology/Process
Bunse et al. 2010	Specific	Specific
Larsen et al., 2010	Specific	Specific
Naess-Schmidt et al. 2012	Specific	Specific
Fleiter et al., 2012	Specific, Technology/Process	Specific, Technology/Process, General
Willoughby et al., 2012	Technology/Process	Technology/Process
Woodroof et al, 2012	Specific	Specific, general
Hasanbeigi et al., 2013	technology/Process	Technology/Process, General
yang et al., 2013	Specific	Specific, general
Gudbjerg et a 2014	technology/Process	Technology/Process
Roser et al., 2014	Specific	Specific, general
Russell et al., 2015	Specific	Specific, general
Naess-Schmidt et al., 2015	Specific	general
Rasmussen, 2015	General	General

Cagno et al., 2016	Specific	Specific
Ürge-Vorsatz et al, 2016	Specific	Specific, general
Wang et al., 2016	Specific	Specific
Thema et al., 2016	technology/Process	Technology/Process
Rasmussen & Nehler, 2016	Specific, Technology/Process	Specific, Technology/Process
Thema et al., 2017	technology/Process	Technology/Process, General
Doyle & Cosgrove	technology/Process	Technology/Process
Nehler et al., 2018	Specific, Technology/Process	Specific, Technology/Process
Zhou et al., 2018	technology/Process	Technology/Process
Mzavanadze et al., 2018	Specific	Specific, general
Chatterjee & Ürge-Vorsatz, 2018	Specific	Specific
Trianni et al, 2020	Specific, Technology/Process	Specific, Technology/Process, General
Reuter et al, 2020	Specific, Technology/Process	Specific, Technology/Process

Table 17: Methods applied in the quantification and monetization of non-energy benefits and evaluation potential in the reviewed literature in in industry. n/a- not available, NVP- Net Present Value, PBP – Payback period, CBR – Cost Benefit Ration, LCOE – Levelized Cost of Energy, IRR – Initial rate of return, CSC – Conservation supply curve, CCE –Cost of conserved energy, CBA – Cost benefit analysis, WTP – willingness to pay, WTA – willingness to act, GE general equilibrium

Authors	Methods for Quantification or Monetization	Methods Applied to Evaluate the Potential
Lilly & Pearson, 1999	n/a	NPV, PBP, CBR, LCOE
Pye and McKane, 2000	n/a	NPV, PBP, IRR
Finman & Laitner, 2001	n/a	CSC, PBP
Skumatz et al. 2000	Relative to the energy savings, Multiplier	n/a
Worrell et al., 2002	Classification of the NEBs based on their importance to the firm	Identification of the NEBs which can act as drivers
Worrell et al., 2003	n/a	CSC, CCE, BPB
Loftnes, 2003	CBA of high-performance building components and systems	CBA
Hall & Roth, 2003	Analysis of interview questions	NEB ranking based on importance
Skumatz & Gardner, 2005	n/a	Valuations of WTP / WTA
Lung et al., 2005	Assessment based on NEBs as reduced costs and increased revenues	CSC, PBP
Bement and Skumatz, 2007	Assessment of willingness to pay/willingness to accept through interviews	CBA, Questionnaire
Mills et al, 2008	n/a	Consumption Index
Ürge-Vorsatz et al., 2009	Review finding from literature	Cost-benefit assessment-based decision-making frameworks
Bunse et al. 2010	n/a	KPI's, benchmarks of EEM
Larsen et al., 2010	evaluates the issue of NEBs in industry through the use of performance-based contracting	lifecycle cost assessment, PBP
Naess-Schmidt et al. 2012	Quantifiable benefits from investing in energy efficient renovation of buildings and the impact on public finances	Aggregating the benefits compared to baseline
Fleiter et al., 2012	bottom-up techno-economic assessment mode of energy demand and saving potentials	CSC, CO_2 abatement cost curve,
Willoughby et al., 2012	analysis of energy consumption and energy efficiency comparing natural gas furnace with coal furnace, Bottom-up model	Cost reduction analysis from rate of available of materials & improvement of quality rate,
Woodroof et al, 2012	Calculating Benefits Related to a Specific Energy Conservation Measure	Surveying energy mangers, energy conservation measure

Yang et al., 2013	MACCs with and without considering the NEBs from avoided environmental impacts; Estimated NEBs as monetised valuation in terms of $/ton of CO2 avoided.	MACC is used to rank mitigation options along with the marginal costs to identify the least costly approach
Hasanbeigi et al., 2013	Analysis of six fuel-saving measures estimating health benefits through CCE by comparing CO2/kWh	modified form of the cost of conserved energy (CCE) equation to incorporate the value of these co-benefit
Gudbjerg et a 2014	Index based on calculation or estimations relating to the energy savings, web-based tool	Online tool/database for energy efficiency measures in which NEBs are included
Roser et al., 2014	n/a	potential of organisational measures for energy saving and their cost effectiveness
Russell et al., 2015	Reduced system costs for electric utilities through evaluating NEBs	Survey, values from literature
Naess-Schmidt et al., 2015	Macroeconomic modelling as a tool for policy evaluation	CBA, GE
Rasmussen, 2015	Framework illustrates a matrix of time frame and the level of quantifiability	Quantifiability of the categorised NEB (long term, short term)
Cagno et al., 2016	Classification of non-energy benefits and losses to reveal their impact on the investment process	n/a
Ürge-Vorsatz et al, 2016	Analytical framework systematically addressing interactions among co-impacts.	CBA of energy options
Wang et al., 2016	Quantification of health benefits under different scenarios for the coal-fired power sector	Intake Fraction method is incorporated into Energy CSC
Thema et al., 2016	Assessment of NEB of EEI actions with methods of evaluation	GM modelling for long-run macro-economic effects, LEAP model for energy system modelling.
Rasmussen & Nehler, 2016	Classification of non-energy benefits as costs and revenues	Framework based on time frame and quantifiability to enable the inclusion of non-energy benefits in the investment process
Thema et al., 2017	Impact indicators of Energy system, Power reliability and Energy security related impacts in macroeconomics	Assessment of macroeconomic impacts using gross capacity margin, value of lost load
Doyle & Cosgrove	Non-intrusive method of quantifying the energy consumed by CAS and lost through system leaks, with various means of minimising energy consumption	Multi-site energy analysis by monitoring sites to quantify energy losses due to system leaks
Nehler et al., 2018	n/a	Ranking based on non-energy benefits' importance as drivers
Zhou et al., 2018	Assesses the environmental and water saving co-benefit of long-run EEI	Scenario analysis and rebound conditions of EEI, CGE model
Mzavanadze et al., 2018	impact pathway for avoiding air pollution using Drivers-Pressures-State-Impact-Response	Modelling of air pollution impacts via impact pathway approach using GAINS model
Chatterjee & Ürge-Vorsatz, 2018	n/a	Education increases productivity/earning ability per unit time worked.

Trianni et al, 2020	n/a	n/a
Reuter et al, 2020	Calculation approaches for evaluated indicators for NEBs	Setting indicators to evaluate NEBs

Table 21: Overview of economic NEBs indicators (macro-economic)

NEB Impact	Definition of the Indicator	Calculation Approach
Impact on GDP	The impacts of EE measures on GDP are determined by using I/O analysis (Miller and Blair, 2009).	To calculate the GDP from I/O tables, the total gross value added (GVA) plus taxes on products minus subsidies on products in final and intermediate consumption are summed up (income approach) and given as a percentage of total GDP [%]. The input data are the same as for the analysis of employment effects.
Employment effect	Direct effects of EE on employment are based on two main drivers: investments in EE measures and related energy savings. The former triggers demand impulses in industries producing relevant technology, the latter reduces demand related to energy supply in the long run. In both cases, these impacts indirectly affect other sectors	Input-Output (I/O) analysis is applied to calculate how demand changes affect gross value added (GVA) in selected sectors (Tanaka, 2011), from which employment effects (in fulltime equivalents FTE) can be calculated by using sector specific productivity coefficients. The nature of the EE measure implemented determines which sectors invest and for how long they remain in operation.
Potential impact on energy price	EE measures reduce energy purchase or production. EE measures may impact the consumption of one type of energy carrier more than the others, depending on the sector affected or on price differences across fuels energy savings are likely to induce downward pressure on energy prices	$\frac{(P_2 - P_1)}{P_1} = \eta_i \cdot \frac{(Q_2 - Q_1)}{Q_1}$ to represent potential changes in energy prices due to changes in consumption we use price elasticities ηi for the European Union as a whole for the world market prices for different energy carriers i.Q1 and Q2 represent the quantities of energy consumed in the starting/end year considered while P1 and P2 represent the price of energy in both years and thus showing the change in price.

Impact on public budget	Changes in public budgets triggered by new jobs generated by EE. The impact on public budgets we calculate additional income tax revenue for an average job in the related sectors using country income tax rates, and, this indicator directly builds on "employment effects". Losses of income tax in the energy sector are also considered here	$\Delta IT_i = \Delta FTE \cdot \overline{In} \cdot Ir_i$ additional income tax IT of the country i is calculated by multiplying additional jobs in FTE with the average income in of the branch considered and the income tax rate Ir of the country. We assume a uniform distribution of employment effects over all occupational groups of the branches considered.

Table 22 Overview of economic NEBs indicators (Innovation/Competitiveness)

NEB Impact	Definition of the Indicator	Calculation Approach
Innovation impact	Suitable indicators are in particular patent shares for a given EE technology as well as the Revealed Patent Advantage (RPA), normalised to the size of a country and calculated by dividing the patent share of the country for energy efficiency technology by the sum of the patent shares of the country in all fields (Eichhammer and Walz, 2009).	$RPA_{ij} = 100 \cdot tanln \left[\frac{—p_{ij}/\sum_i P_{ij}}{\sum_j P_{ij}/\sum_i P_{ij}} \right]$ where pij represents the number of patents for a certain technology j from a country i. Thevalue of RPA is positive if the patent share of a given technology is over-proportionally large compared to other technologies there is more national innovation activity.
Competitiveness	Developing innovative EE technologies can contribute to the competitiveness. The Revealed Comparative Advantage (RCA) used for calculating the relative competitive advantage or disadvantage of goods or services as evidenced by trade flows.	$RCA = 100 * \left(\frac{X_i/IM_i}{X/IM} \right)$ Where Xi and IMi describe the exports and imports of a branch i, while X and IM describe the total exports and imports of a country. The formula gives normalised results for the RCA between - 100 and + 100.
Turnover of EE goods	A high turnover with EE goods may contribute to the economic benefits of a country and might trigger innovation in this field. To estimate the total turnover related to EE goods, the total energy saved is multiplied by the weighted average of these investments per unit of energy savings.	$TO = ES \cdot SH_i \cdot f_{in} \cdot IN_{tech}$ TO turnover is calculated based on the energy savings ES and the share of space heating SH in final energy consumption of country i, as well as the share of savings fin due to insulation and efficient heating systems and the typical investments IN per unit of energy saved. The turnover of energy efficiency goods is given in billion Euro [G€].

Table23: Overview of economic NEBs indicators (micro-economics)

NEB Impact	Definition of the Indicator	Calculation Approach
Industrial productivity	Energy efficiency enhances productivity. Saving energy reduces the energy costs. This will have an effect on energy productivity expressed as added value per unit of energy used. Based on the savings calculated and a typical mix of energy carrier of the sectors the energy cost saved can be estimated and related to additional industrial value added.	$\Delta P = P^0 - P^1 = \frac{GVA^0}{FEC^0} - \frac{GVA^0 - \sum_i (ES_i * p_i)}{FEC^1}$ P represents the productivity with (P0) and without (P1) energy savings. The product of the energy savings ES for energy carrier i and the price for the energy carrier i and the corresponding price gives the energy cost saved. These are subtracted from the GVA without energy savings (GVA0) to calculate the difference between the productivities. The change in productivity is given in million euro per Peta joule [M€/PJ].
Asset value	To estimate the changes in asset value through increased EE we calculate the average savings in services, i.e. heating and cooling. Using average costs per energy for heating and cooling, we assess the additional average net income due to avoided energy costs.	$\Delta AV = \frac{\sum_i ES_i * p_i}{cr}$ To estimate the changes in asset value through increased EE we calculate the average savings in services, i.e. heating and cooling. Using average costs per energy for heating and cooling, we assess the additional average net income due to avoided energy costs.

Table 24 : Overview of environmental NEBs indicators Global and Local Pollutants and energy/ resource management

NEB Impact	Definition of the Indicator	Calculation Approach
Final energy saving	Annual energy savings (top-down/bottom-up)	Derived from the ODEX developed in the ODYSSEE-MURE project (top-down) and/or detailed policy evaluations (bottom-up; both types of savings are included when available for a country).
Savings of fossil fuels	Annual fossil fuels saved due to EE	$ES_{foissil,j} = \sum_i ES_{final,i} \times \frac{FEC_{ij}}{FEC}$ ES represents energy savings from fossil energy carrier j and FECij/FEC is the final energy consumption share of energy carrier j in sector i, relative to total final energy consumption FEC.

Local air pollution	Avoided emissions of air pollutants are calculated by multiplying energy savings expressed in primary terms (using country specific factors to calculate the primary energy from final energy savings) by the average emission factor emf of the country, for each type of pollutant, per unit of final energy consumed.	$E_k = \frac{\sum_j ES_j \times emf_{jk}}{pop}$ Ek emissions per capita of pollutant k; ESj = energy saving per energy carrier j; emfjk the emission factor for energy carrier j and pollutant k;pop refers to the population. Local emissions are given in kilotons [kt] and as a relative value in kilogram per capita [kg/cap] and they are calculated for the sum of all sector and on a national level.

Table 25: Overview of social NEBs indicators (Social impacts

NEB Impact	Definition of the Indicator	Calculation Approach
Health and well-being	Health benefits represent a more indirect effect of EE. Impacts on health are strongly related to (local) emissions, by reducing the energy consumption, a part of this air pollution can be avoided. Health and well-being benefits can be estimated by combining avoided local air pollution with premature mortality rates (Lelieveld et al., 2015).	$\boxed{AD_i = EM_i \cdot cf \cdot \Delta conc_i \cdot pop}$ Where the AD =avoided deaths related to the pollutant i is calculated from the emission EM of the pollutant multiplied with the concentration factor cf and the corresponding change in pollutant concentration and population of the country (derived from EEA data (EEA, 2019)

9.2. Appendix - B

Table 18: shows the fuel share and for each selected county.

fuel share	EU27	Germany	Italy	Netherlands
Coal	15%	77%	54%	89%
natural gas	23%	18%	38%	11%
oil	32%	5%	3%	0.17%

Table 19: power mix for each selected county.

Power mix	EU27	Germany	Italy	Netherlands
Coal	23%	30%	6%	16%
Wind	16%	20%	7%	9%
Natural gas	27%	15%	49%	59%
Nuclear	0%	12%	0%	0%
Solar PV	6%	8%	8%	4%
Biofuels	6%	7%	6%	3%
Hydro	26%	4%	16%	0.10%
Waste	0%	2%	2%	3%
Oil	2%	1%	4%	1%

Table 20: air volume and deaths deaths/(1 μgr/m3) for NOx and PM2.5 for each country.

	NOX		PM2.5	
Country	air volume (10^9 m3)	deaths/(1 μgr/m3)	air volume (10^9 m3)	deaths/(1 μgr/m3)
Germany	67.4	481.7	8.0	5130.1
Italy	33.4	517.4	10.4	3374.2
Netherlands	12.4	78.4	1.1	825.0
EU27 (80%)	171.06	947.84	38.0	9,051