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Energy Efficiency 2050 Roadmap for Europe

A cost-effective and energy-efficient strategy for decarbonising

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

Energy Efficiency 2050 Roadmap for Europe: A cost-effective and energy-efficient strategy for decarbonising

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TEP Energy GmbH (TEP), Switzerland
Universiteit Utrecht (UU), Netherlands
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Executive Summary

This report presents the roadmap to meet research based-strategy of a cost-effective and energy-efficient energy system in Europe in 2050. The roadmap is based on the assessment of the energy efficiency first principle within the context of current energy systems as well as a transition towards a cost-effective 100% renewable energy systems for the EU27 and the United Kingdom in 2050, further called the sEE 1.5 scenario. The roadmap also presents a path that enables short-term energy security by phasing out import dependency of Russian natural gas in 2030 (sEE 2030 scenario), while still enabling a path that enables achieving 100% renewable energy in 2050.

The novelty of the roadmap is the investigation and quantification of energy efficiency measures for each of the three sectors transport, industry, and buildings, combining spatial analytics country-specific information and energy grids costs for 27 EU Member states and UK. Towards sEE 2030 we focus on well-known developed technologies, while in the period from 2030 to 2050 sEE 1.5 energy system assumes further developments in cost reductions and efficiency e.g., for wind, hydrogen and PV. This report mainly focuses on 2050 and the back casting of the 2030 step towards that. In the parallel report "REPowerEU and Fitfor55 Science-based Policy Recommendations for achieving the Energy Efficiency First Principle" the focus is on 2030 policy recommendations.

As a part of the roadmap, an investment strategy highlights which investments are necessary to be prioritized to achieve both short-term security of supply in 2030 and long-term decarbonisation goals in 2050.

- sEE 1.5 demonstrates that applying the Energy Efficiency First Principle, focusing on energy conservation, energy efficiency, energy supply changes and resource security can bring Europe to become **fully decarbonised by 2050** using 100% renewable energy.
- In traditional energy systems, fuels represent the highest share of costs. In future renewable smart energy systems, technology investments are prioritised over variable costs. Our analysis shows that there is a need for over **5 trillion € investments in EE measures** in buildings, transport and industry, out of a total of approximately 9 trillion €. More than 2 trillion € should be dedicated to renewable energy and over 1 trillion € spent on system redesign measures. While investments are higher in energy efficiency compared to supply and system redesign measures, it is important to note that all investments should be initiated and implemented simultaneously.
- **40% reduction of final energy demand** can be achieved by saving about 2 PWh in both buildings and transport sectors, and 1.5 PWh within industry, out of a total final demand of 13.6 PWh.
- **Building stock refurbishment costs represent the largest investment** related to energy savings, followed by investments in the electrification of the transport sector and industry as well as in renewable capacities, primarily wind and solar.
- The sEE2030 recommendations demonstrates a **14-22% larger natural gas reduction** compared REPowerEU and Fitfor55 for EU27.
- **Health costs from air pollution can be reduced** to approximately 71 billion EUR/year in sEE 1.5 towards 2050, down from approximately 299 billion EUR/year in 2015 and 154 billion EUR/year in the PRIMES 2050 Baseline.

The building sector

- An investment of **2.2 trillion € is required to reach the final target of 40% heat savings** in the building stock by 2050. Such savings enable synergies with our system redesign as it increases the energy efficiency of the supply system and increases the possibilities to integrate renewable heat and low-temperature heat sources.
- One of the system redesign components is **district heating, which requires an investment of 420 billion €**, and can unlock the potential of using cheaper heat sources. About 1 PWh or half of the energy savings achieved in the buildings sector is a result of end-demand savings due to building stock refurbishments and the other half is a result of system redesign measures and changes in the heat supply.
- **Half of the heat demand (47%) is supplied by district heating in 2050**, the remaining half is covered by individual heat pumps.
- Excess heat and low-temperature heat sources such as industrial waste heat, geothermal, solar thermal, large-scale heat pumps and electrolysis, can **supply 60% of district heating**, while the remaining 40% is supplied by CHP, waste incineration and boilers.
- Individual heat pumps are an important energy efficiency measure, representing the **fourth largest investment of over 1 trillion € to achieve more than 100 million units** installed in Europe. However, as with unlocking excess heat and low temperature heat in district heating systems, where expansions are in the district heating grids, individual heat pumps also require new infrastructure investments in electricity grids.

The transport sector

- The **transport sector** can deliver the same magnitude of energy savings (2 PWh) as the building sector or about **a 50% reduction**. This requires an energy-efficient urban development as well as high levels of electrification and includes energy inefficiency in the use of hydrogen-based fuels (electrofuels) for heavy-duty transport in aviation and navigation. This will reduce the primary energy demand for the transport sector in Europe by around 50% compared to the baseline in 2050.
- Energy-efficient urban development will **reduce the passenger kilometres driven by a car by 16%** compared to traditional urban development. In order to achieve this, new investments need to be made predominantly in more efficient modes of transport, so that higher transport demands are not induced in in-efficient modes of transport. This entails a dedicated investment of 784 billion € in predominantly railroad infrastructure as well as e-roads and cycling infrastructure.
- Electrification of the transport sector is done through direct and indirect electrification, where direct electrification wherever possible should be prioritised. **Majority of passenger cars and vans (95%) are shifted to battery electric vehicles** in 2050. In 2030, the number of electric vehicles is estimated to be 95 million and 254 million in 2050. This requires 1.3 trillion € in additional investments compared to not switching to electric vehicles, and this is the second largest investment after heat savings. Electrification of heavy-duty trucks is prioritised with the implementation of e-road systems.
- The use of hydrogen and electrofuels should be reserved only for the difficult to electrify modes such as aviation and shipping. Major investments in **electrolysis capacities and hydrogen storage of 327 billion €** need to be made to provide hydrogen and e-fuels for transport and industrial demands. An additional 161 billion € is needed for e-fuel production.

Almost 456 GW of electrolyser capacity is needed in 2050 to cater to this demand. By 2030, the electrolyser capacities are low, since the focus is on implementing energy efficiency measures.

The industry sector

- The implementation of innovative energy efficiency measures and electrification in **industry enables reductions in final energy by 36%** from today to 2050, and which requires 209 billion €. This includes and assumption of increasing production in line with the past trends. Emphasis on EE improvements and electrification are of high importance in order to avoid extensive biomass consumption when pursuing 100% renewable energy.
- Careful considerations must be taken in the **implementation levels of electrification and hydrogen-based technologies** paired with energy efficiency to minimize the costs and energy losses.
- By 2050 **electrification increases to 66% of the total final energy demand** up from 25% in 2015. This is largely in the “others” category for lower temperature sub-sectors such as engineering and the food industry. District heat demand in the industry falls from 5% to 1.5% of the energy mix from 2015 to 2050.

Renewable Energy and System Redesign

- It is expected that by 2030 the **electricity demand will increase by around 32%** from 3,051 TWh due to the electrification of transport, industry, and heating in buildings, and 158% by 2050 to 7,860 TWh, as a result of high hydrogen production in Europe.
- Targeted energy efficiency and the smart energy system, with flexible storage options, can enable the primary energy demands to be kept within sustainable biomass levels and **limit the GW wind power and PV to the potentials available in the EU**. With another system design, with no considerations of more energy-efficient infrastructure investments in transport and with lower utilisation of best practise in industry, the renewable energy installations would be higher.
- The smart energy system requires abandoning silo thinking in each sector and **consider energy storage options between energy vectors** to move the storages towards heating, fuel production and transport sectors rather than keeping it in the power sector. The main three energy storage options are electrofuels (>2,000 TWh), storage of electricity in vehicles (~15 TWh) and large-scale thermal storages (~6 TWh). This way, rounds trip losses will be avoided (electricity to hydrogen and back to electricity) and flexible storage should be enabled e.g., 40-60% operation time of electrolysers and large-scale heat pumps.
- System redesign with high electrification levels requires **large investments in establishing renewable energy capacities**. Wind power represents the third-largest investment towards 2050 of 1.3 trillion €, which amounts to 1,135 GW onshore capacity and 265 GW offshore capacity. In addition, 521 billion € are required to be invested in photovoltaics, amounting to a capacity of 1,400 GW. Investments in gasification and biogas production as well as solar thermal and geothermal are also required.
- The bioenergy consumption is in line with the reference scenario from the JRC ENSPRESO project (2019) of 3,200 TWh (EU27+UK). **Both sEE 2030 and sEE 1.5 are within the sustainable bioenergy levels**. Countries with large amounts of bioenergy and renewable electricity could become the main producers of electrofuels for transport due to shortfall in some countries.

Furthermore, due to the inefficiency of biofuels, biofuel quotas should be phased out with increased focus on e-fuels for sectors not suitable for electrification.

- Redesign of the energy system based on Energy Efficiency First Principle allows a **phase-out of nuclear by 2050**. Replacing nuclear at the end of life with renewable electricity gives lower cost. By 2030, nuclear capacities only decrease marginally to support the quick phase out of Russian natural gas.

sEE 1.5 - combining Energy Efficiency First Principle and energy system analysis

sEE 2030 and sEE 1.5 represent robust system redesigns paired with the Energy Efficiency First Principle, which allow for better integration of variable electricity and the cross-sectorial connections unfold flexibility, i.e., electric vehicles, electrofuels. The scenarios combine cost-effective energy efficiency measures in transport, industry, and buildings with a highly interconnected renewable energy system with increased synergies and reduced primary and final energy consumption. This re-design also provides an opportunity to integrate more cost-effective renewable energy such as solar PV and wind, which in turn allows us to balance the overall energy system with energy storage and transfer technologies such as thermal storages, district heating and PtX.

As a result, primary and final energy demand can be reduced significantly compared to a 2015 reference energy system (comparable to the EU Commission's PRIMES scenarios), by 44% and 40% respectively. This is possible by building renovations and supply measures, and extensive electrification of the transport and the industry sectors both via direct and indirect electrification among other measures. This enables a 2050 system to be supplied with 100% renewable energy for all the EU27 and the UK.

sEE 1.5 has lower primary and final energy demand than the 1.5 TECH PRIMES scenario and is more cost-efficient, even though there are fewer energy savings in the building sector. This demonstrates that the impact of energy savings is not always beneficial to the energy system when considering socio-economic costs and bioenergy demand. The performance of the energy system needs to be considered along with the energy savings. Due to the high level of district heating and use of excess heat and low-temperature heat in sEE 1.5, the energy system can utilise excess heat and supply it cost-effectively avoiding the need to further invest in building refurbishments. According to our analyses, building refurbishment in sEE 1.5 should reduce building stock heat demand by 40%. sEE 1.5 has higher energy efficiency than the 1.5 TECH scenario although the final energy is similar. Demand-side energy efficiency improvements allow for the re-design of the overall supply system.

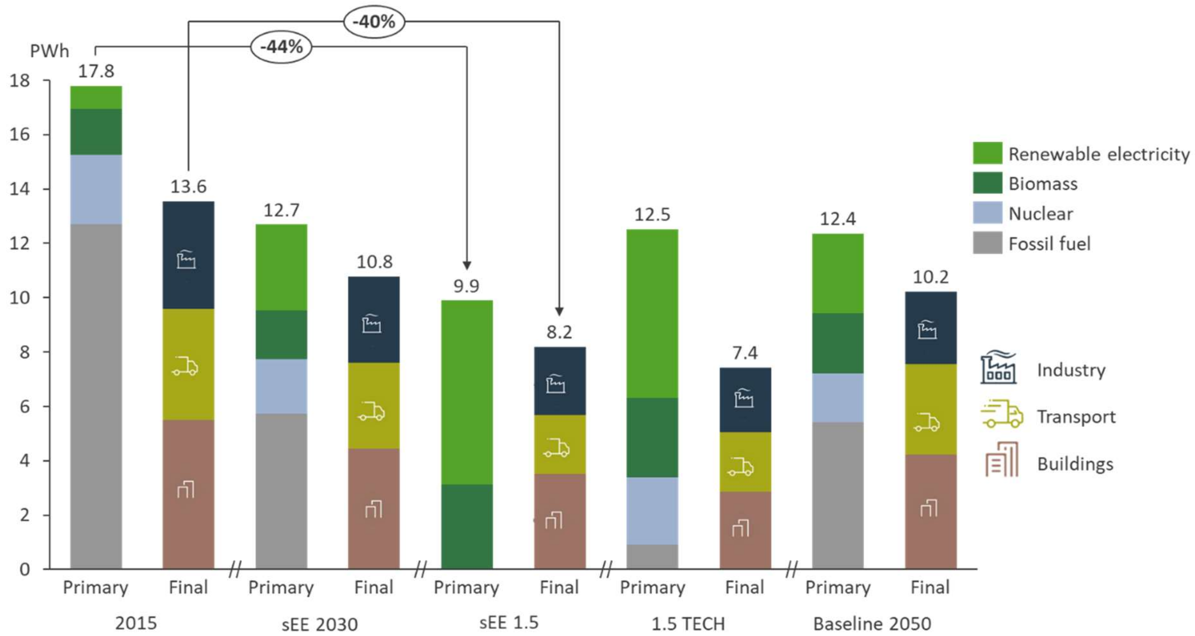

Figure 1. Primary and final energy consumption in 2015 reference, sEE 2030, sEE 1.5 (2050) and 'A clean planet for all scenarios' (1.5 TECH (2050) and Baseline 2050)

Not only that the system redesign has enabled high energy efficiency of sEE 1.5 scenario, it has also resulted in a cost-effective system that has changed its cost structure from fuel intensive to investment intensive. The system redesign into smart energy system that maximizes synergies across different sectors and combines energy efficiency measure with renewable energy paired with energy storages delivers lower costs than a traditional energy system or the 1.5 TECH system proposed by the EU Commission.

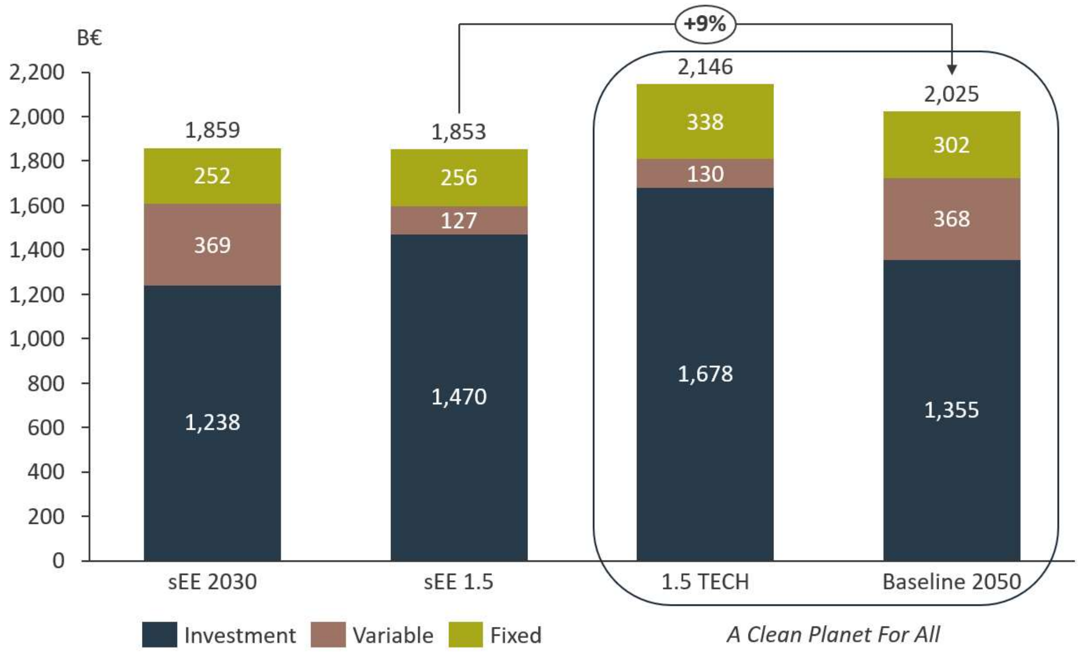

Figure 2. Annualised energy system costs of sEE 2030 and sEE 1.5 (2050) in comparison to 1.5 TECH (2050) and Baseline 2050

The redesign of the energy system in both sEE 2030 and sEE 1.5 implies using large amounts of renewable electricity to support the high electrification rates. In sEE 1.5 the variable renewable electricity doubles compared to sEE 2030 (2700 TWh), relying particularly on onshore wind and photovoltaics due to the generally larger potential of these technologies across all European countries.

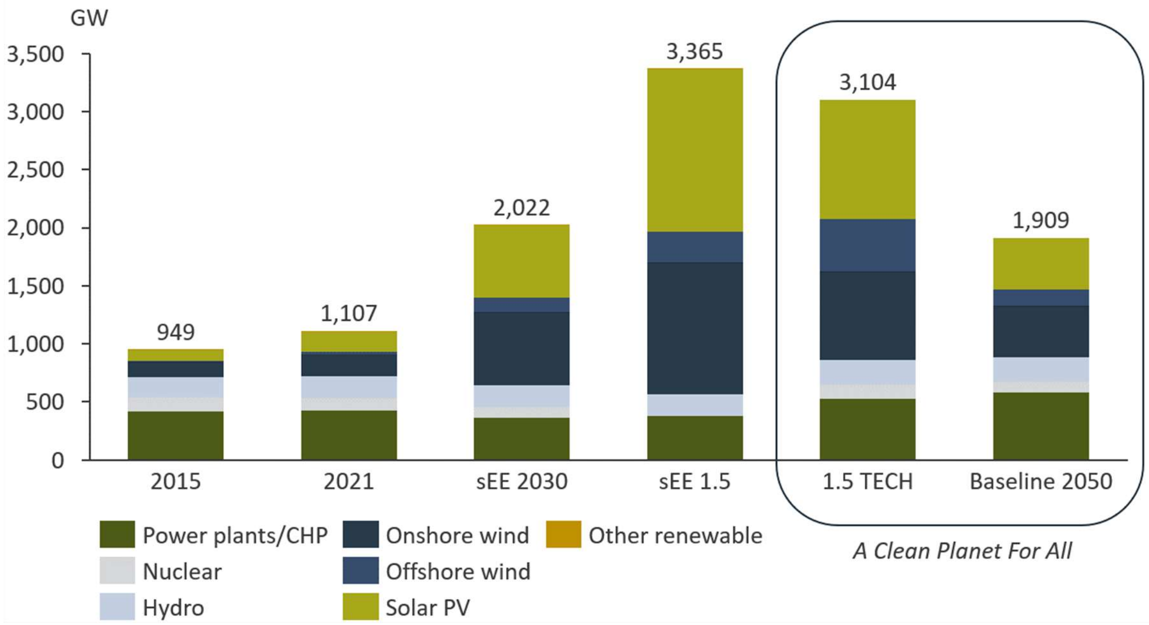

Figure 3. Electricity capacities of 2015 reference, 2021, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

sEE 2030 and acceleration of measures for REPowerEU

The call for action to transform Europe's energy system has been further amplified by the recent geo-political pressures instigated by Russia's invasion of Ukraine. The Commission's REPowerEU Plan thus outlines short-term measures for the twofold goal of ending the EU's dependence on Russian fossil fuels and addressing climate change, via energy savings, diversifying energy supplies and accelerating the deployment of renewable energy to replace fossil fuels in buildings, industry and the power sector.

Regarding natural gas consumption, sEEnergies 2030 shows a 14-22% greater potential gas savings (332 bcm) compared to the total savings set out by Fit-for-55 and REPowerEU measures (271 bcm). The largest gas savings in sEEnergies 2030 are achieved through the system effects of renewable energy and electrification measures as well as the delayed nuclear phase-out until 2030, which are quantified at a total of 83 bcm of natural gas.

The waterfall chart below (Figure 4) shows the full potential for gas savings of the energy efficiency and renewable energy measures achieved by sEEnergies 2030, including the imported hydrogen, behaviour and fuel price changes, as well as the fuel shift with coal and LNG, as set out by REPowerEU. Please note that this 2030 figure only includes EU27 and is further described in the parallel report – Deliverable 6.4 (REPowerEU and Fitfor55 science-based policy recommendations for achieving the Energy Efficiency First Principle).

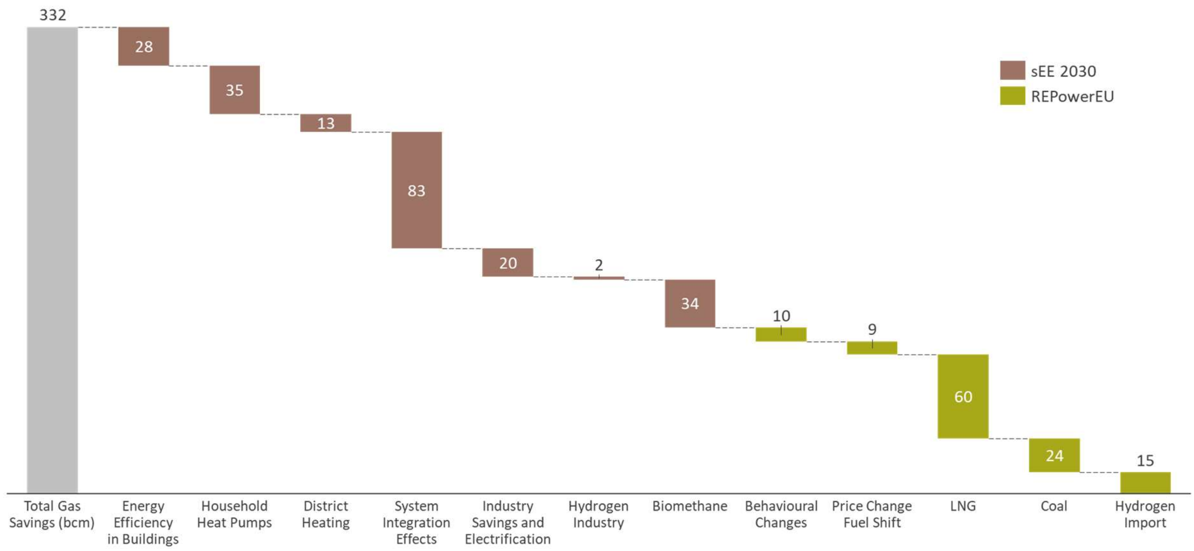

Figure 4. Breakdown of total natural gas savings achieved by sEEnergies 2030, including the imported hydrogen, behaviour and fuel price changes, and fuel shift with coal and LNG, as set out by REPowerEU.

Resource security and health impacts

The biomass energy demand (bioenergy) of the energy system is within range of the sustainable bioenergy limit of the JRC scenarios medium (3.201 TWh) and high (forestry 400 Mm2) (3.389 TWh) quantified in the ENSPRESO project. Although the overall bioenergy demand is within sustainable levels, there is an imbalance between bioenergy potential and demand in numerous countries. This means that bioenergy trade will become more important for the future energy system or countries with abundant bioenergy will develop bioenergy demanding energy sectors. Bioenergy is consumed in three main forms, biogas, solid biomass and waste (municipal).

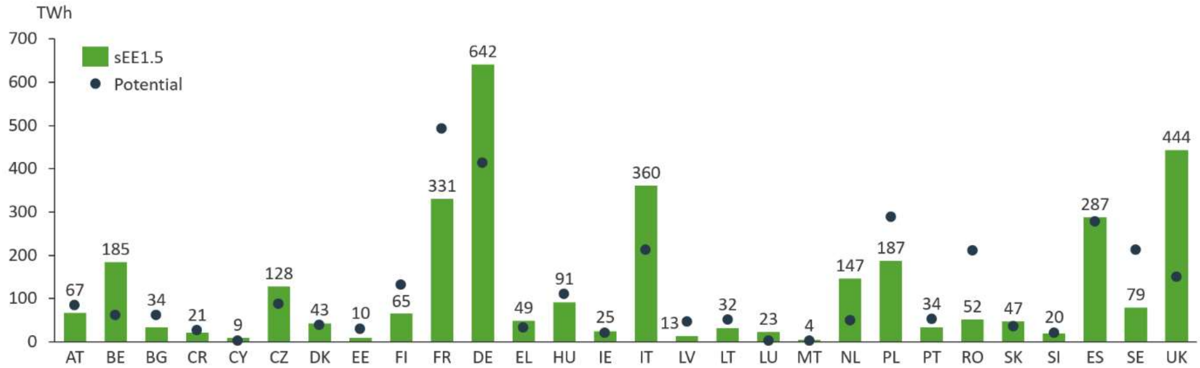

Figure 5. Bioenergy demands and potential per country in sEE 1.5 (2050)

Total health costs from gaseous emissions are significantly lower in sEE 1.5, due to energy efficiency improvements paired with high levels of renewable energy in the electricity system and extensive electrification of the transport sector, which generates significant energy savings and reductions in emissions. Therefore, if the energy efficiency measures of the sEE 1.5 scenario are implemented throughout Europe, there will be savings of approximately 228 billion EUR in 2050 relating to health costs.

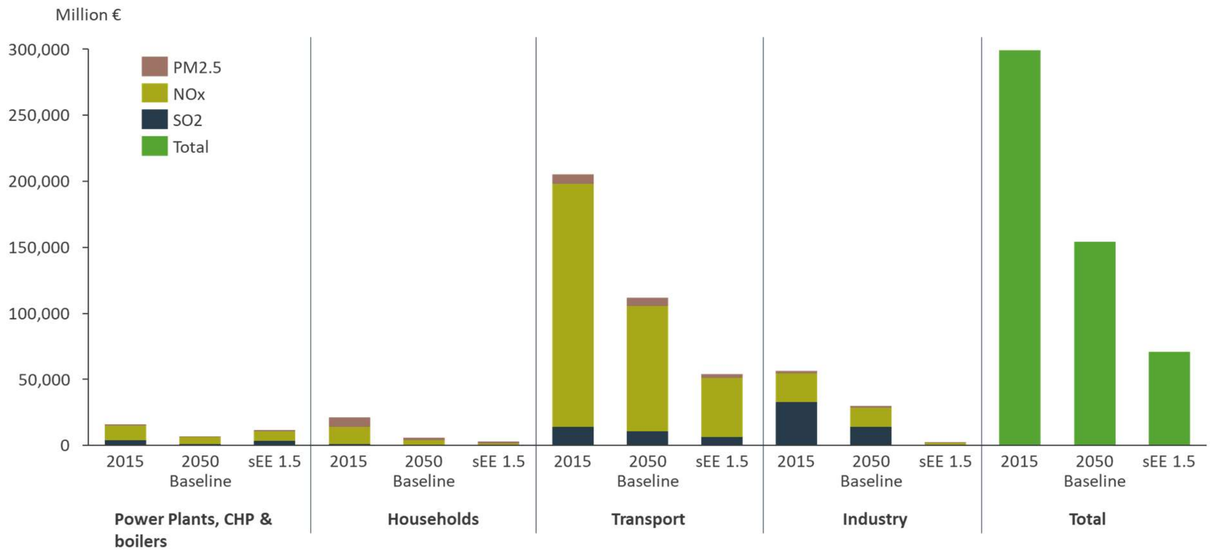

Figure 6. Total health costs by pollutant type and sector in sEE 1.5 (2050) in comparison to 2015 reference scenario and Baseline 2050

Development of the energy system scenarios towards 2050

For each country, numerous sector energy efficiency scenarios were assessed within a 100% renewable energy system analysis using EnergyPLAN. Then, the energy system performance of the system scenarios was assessed based on the socio-economic cost of the energy system, renewable electricity capacity, level of electricity exchange with surrounding countries, balancing district heat production and demand, and biomass consumption. Energy grids and spatial analytics were also considered in the scenarios. Energy efficiency scenarios from the three sectors were then assessed within the system level - considering the impacts on the system. In general, the scenarios showed similar outcomes at sector and system level. As a result, the developed energy system models combine demand and supply-side energy efficiencies and create synergies considering the sustainable biomass levels and renewable energy potentials

The sector energy efficiency scenarios include (Figure 7):

- Four scenarios for transport: 1) biofuels 2) hydrogen 3) battery electric vehicles + e-fuels and 4) electrification+. Electrification+ was the most cost-effective scenario for all countries and was selected for sEE 1.5.
- Four scenarios for industry: 1) Low EE (energy efficiency) 2) High EE 3) High EE and electrification and 4) High EE and electrification with H_2. “High EE and electrification with H_2” scenario was selected for all countries in sEE 1.5 due to it being more cost-effective and less resource demanding, while the inclusion of hydrogen which adds flexibility
- Twenty-four scenarios for the building sector (3 different refurbishment strategies and eight 10% increments (0-70%) of district heat implementation). Each country had a different refurbishment strategy and heat supply mix due to different building age classes and types.

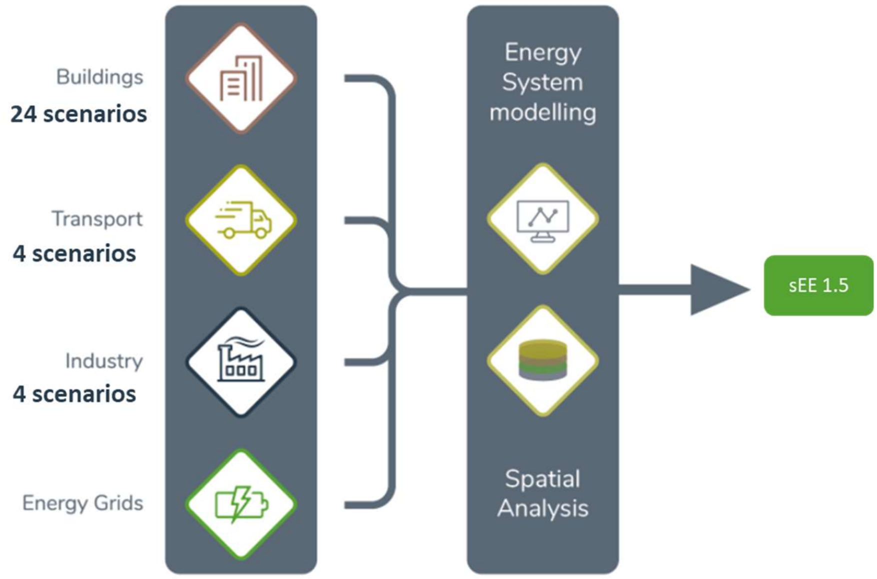

Figure 7. Methodological approach to final sEE 1.5 (2050) scenario. Analysis considers numerous energy efficiency scenarios for transport, industry and buildings as well as energy grid costs and spatial analysis

In order to generate the Energy Efficiency transition roadmap towards sEE 1.5 for 2050, a transition scenario for 2030 was developed by backcasting (Figure 8), resulting in an energy system model for 2030 for EU27+UK. Fifty-two transition curves were developed for each energy system component, e.g., onshore wind development. The sEE 2030 energy system was used to prioritise energy efficiency measures and to create the investment strategy for the sEE 1.5 energy system. Furthermore, based on sEE 1.5, transformative action and policy that influences short-term implications have been developed in Deliverable 6.4.

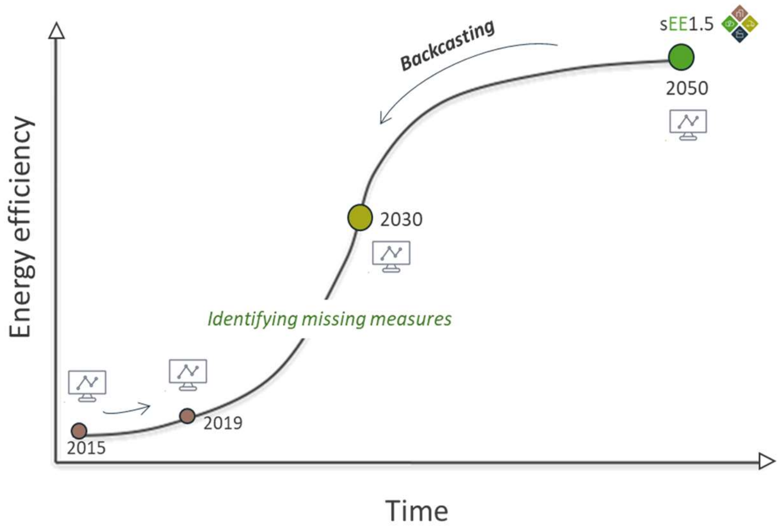

Figure 8. Concept for backcasting transition curve from sEE 1.5 (2050) to identify the energy value for 2030

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Acronyms & Abbreviations

Term	Description
bcm	Billion cubic metres
BEV	Battery electric vehicle
CHP	Combined heat and power
CO_2	Carbon dioxide
EAF	Electric arc furnace
EE	Energy efficiency
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
GJ	Gigajoule
GW	Gigawatt
H_2	Hydrogen
HFO	Heavy fuel oil
JRC	Joint Research Centre
kWh	Kilowatt hour
LNG	Liquid natural gas
Mpkm	Million person kilometres
NOx	Nitrogen oxide
PHEV	Plug in hybrid vehicle
$PM_{2.5}$	Particulate matter 2.5
PtX	Power to X
PV	Photovoltaic
PWh	Petawatt hour
SO_2	Sulphur dioxide
TWh	Terawatt hour
UK	United Kingdom

Introduction

The overall aim of sEEnergies is to assess the Energy Efficiency First Principle within the context of decarbonised and cost-effective energy systems in European countries. The project quantifies and operationalizes the potential for energy efficiency in buildings, transport and industry, by going beyond current state-of-the-art science-based knowledge and methods. The project combines sectorial bottom-up knowledge with hour-by-hour energy system modelling and spatial analytics, for the EU and for the 27 member states including the United Kingdom (Figure 1).

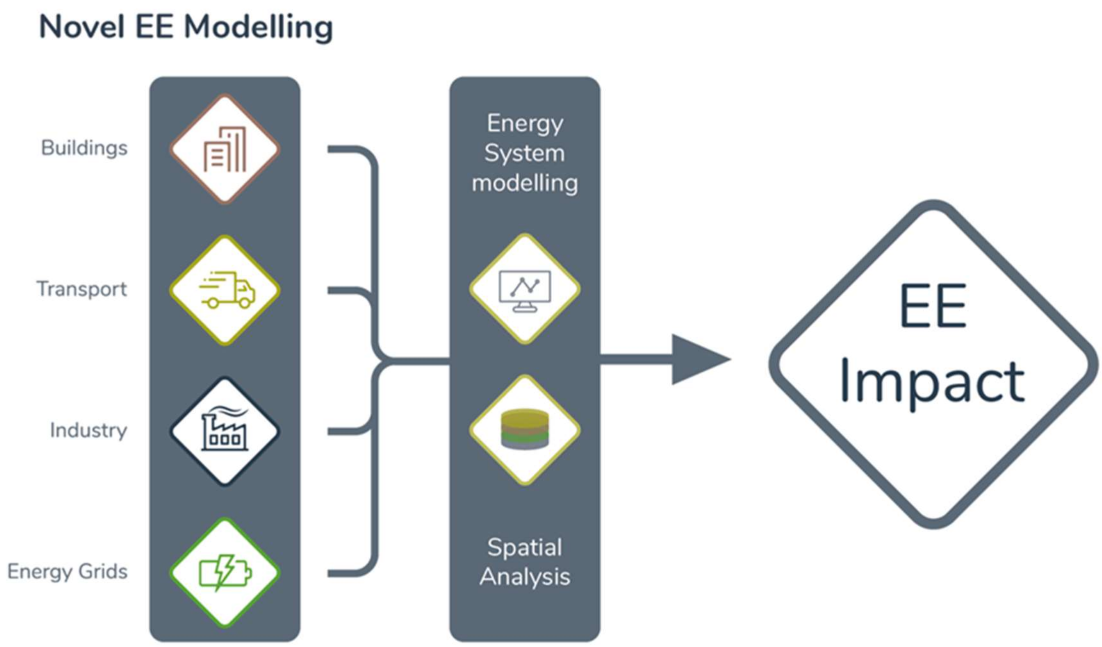

Figure 1. Concept of sEEnergies to quantify potentials for energy efficiency first principle and its impacts

Work Package 6 analysed the energy efficiency measures and scenarios from the Work Packages for the buildings sector (residential and services) (WP1), transport sector (WP2) and the industry sector (WP3). It also considered the grids (WP4) and spatial modelling (WP5) within the energy system context. Work Package 6 develops an Energy Efficiency Roadmap to 2050 for Europe, which is described in this deliverable (Deliverable 6.3).

Inputs for energy efficiency on a sector level i.e., transport, buildings and buildings are taken from their respective work packages. Underpinning different energy efficiency sector level pathways. Several different alternate scenarios are proposed by the three sectors, with the transport and industry sectors outlining four different scenarios, whilst the building sector provides 24 energy efficiency scenarios. The most feasible of these standalone sector scenarios are then taken to form an overall sEEnergies energy systems scenario, which are then assessed in synergies with other possible scenarios to verify the synergetic effects of different combinations. The combinations are compared based on - but not limited to - resource consumption and socio-economic costs.

The final energy efficient European system for 2050 is called **sEE 1.5**. A 2030 energy system was also developed which is called sEE 2030. The results of sEE 1.5 are compared to the PRIMES Baseline 2050 and 1.5 TECH 2050 scenarios.

This document contains two parts which can be seen as individual reports and read independently.

1. **Background report** on the development of the energy efficiency scenarios for each country and EU27+UK. Contains the methodology and background information for the development of the final scenarios, investment roadmap and country reports
2. **Energy Efficiency Roadmap** for EU28. Presents the results for the energy efficiency scenario including investments for different energy efficiency measures and energy supply. It also ranks measures based on energy efficiency impacts in the short (2030) and long term (2050).

Individual country scenario reports are also available and can be downloaded at seenergies.eu.

Introduction to the background report

The background report contains the methodology and background information for the analysis of the energy efficiency scenario development and analysis for the EU27+UK. The results are used to form the final scenarios and the Energy Efficiency Roadmap/investment strategy and country reports.

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sEEnergies guiding principle: Energy Efficiency First Principle

The basic guiding principle for the sEEnergies project is the Energy Efficiency First Principle. The principle aims to ensure that only needed energy is produced (thus increasing energy efficiency) and the energy is produced in a cost-effective way. Energy efficiency is seen as a source of energy, which can compete and be prioritised before more costly energy supply sources. It prioritises demand-side solutions that are more cost effective than energy infrastructure and at the same time meeting policy objectives. The principle limits the investment needed to transition to 100% renewable energy and reduces resources consumption while increasing resilience of the European energy system.

Based on this principle, in sEEnergies, each sector was assessed independently identifying all the energy efficiency potentials before considering the energy system supply. Therefore, the structure of the project is bottom-up from individual measures at sector and country level through to whole energy system (Figure 2). Furthermore, this was done for each country to form the overall EU27+UK energy system (herein called sEE 1.5).

Figure 2. Illustration of bottom-up analysis from transport, industry and building sectors to energy system for each country

Sector scenarios

To capture all possible energy efficiency opportunities, measures in each sector were analysed in detail by creating numerous energy efficiency scenarios. In the transport and industry sectors, all the 100% renewable scenarios in each sector focused on reducing sector activity demand (i.e., person and tonne-kilometres in the transport sector) through energy efficiency measures. Secondly, 100% renewable energy was achieved by replacing fossil fuels with renewable resources such as bioenergy or via electrification. Usually in each scenario, the energy efficiency measures were maximised and the main difference between scenarios was the type of fuel used to replace the non-renewable fuel. However, the industry sector included one non-efficient scenario that used a significant amount of bioenergy.

From a sector perspective, each scenario for transport and industry could be compared based on energy efficiency, resource demands and economic costs. This can be seen as a preliminary assessment of energy efficiency impacts between the scenarios. In Work Package 6, the secondary assessment was carried out by analysing each scenario from a system perspective.

In the building sector, only activity demand was changed in the scenarios, and the supply of energy was not assessed. Therefore, to determine the final building sector scenario a full energy system analysis was needed. Since each country has unique building stocks regarding building types and ages, the energy system analysis was done for each country.

Transport scenarios

The transport sector has four 100% renewable scenarios developed using TransportPLAN which are described in detail in Deliverable 2.3 (Report on energy efficiency potentials in the transport sector and conclusions from the developed scenarios) (Abid et al., 2021). The basic details of these scenarios are presented in Table 1.

Table 1. Overview of modelled 100% renewable energy scenarios developed in TransportPLAN for transport in Work Package 2

Scenario	Baseline 2050	1. Biofuels	2. Hydrogen (H_2)	3. Electrification and e-fuels	4. Electrification +
Passenger transport					
Passenger Cars	35% BEV 19% PHEV 4% FCEV 4% Gaseous 18% Gasoline 20% Diesel	35% BEV 40% Biodiesel 25% Bioethanol	35% BEV 65% FCEV	100 % BEV	100 % BEV
Buses	5% BEV 36% Hybrid 21% Gaseous 38% Diesel	5% BEV 95% Biodiesel	5% BEV 95% FCEV	95 % BEV 5% Electrofuels	95 % BEV 5% Electrofuels
Rail	87 % Electric, 13 % Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric
Aviation	3% bio-jetfuel 97% kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	19% Electric 81% E-kerosene	22% Electric 78% E-kerosene
Shipping	13% Gaseous 87% Diesel and HFO	100% Biofuels	50% Hydrogen 50% E-methanol	50% Electric 50% e-methanol	50% Electric 50% e-methanol
Freight transport					
Trucks	1% BEV 29% Hybrid 18% Gaseous 51% Diesel	50 % Biogas 50 % Biodiesel	1% BEV 99% FCEV	27% BEV 73% E-methanol	27% BEV 73% Electric Roads-BEV
Vans	26% BEV 1% FCEV 19% PHEV 54% Diesel	26% BEV 38% Biodiesel 36% Biogas	26% BEV 74% FCEV	95% BEV 5% Electrofuels	95% BEV 5% Electrofuels
Rail	87 % Electric, 13 % Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric
Aviation	100 % Kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	100% E-kerosene	100% E-kerosene
Shipping	100 % Diesel and HFO	100% Biofuels	50% E-ammonia 50% E-methanol	50% E-ammonia 50% E-methanol	50% E-ammonia 50% E-methanol

The energy demand and annualised cost results for each scenario for EU27+UK combined on a sector level including upstream energy demands are presented in Figure 3. The electricity demand includes charging electric vehicles and upstream electricity required for hydrogen production and other fuel synthesis processes. The bioenergy demand includes bioenergy for biofuels and upstream electrofuel production.

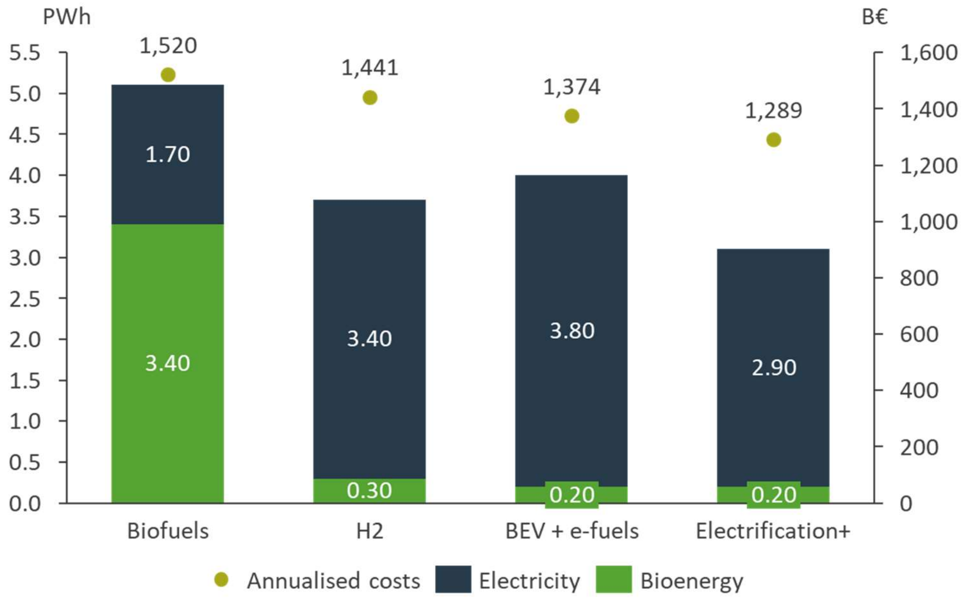

Figure 3. Sector results for 100% renewable scenarios for the transport sector for EU27+UK

The biofuels scenario has the highest bioenergy demand, which is beyond sustainable levels. The annualised transport system costs are also the highest. Based on a sector perspective the Electrification+ scenario has the lowest annualised costs and primary energy demand.

Industry scenarios

The industry sector has four 100% renewable scenarios developed using IndustryPLAN which are described in detail in Deliverable 3.4 (IndustryPLAN tool results) (Johannsen, Vad Mathiesen, & Ridjan Skov, 2020). The basic details of these scenarios are described in Table 2.

Table 2. Overview of modelled 100% renewable energy scenarios developed in IndustryPLAN for industry in Work Package 3

<table>
<tr><th>Scenarios/Sector</th><th>Iron & steel</th><th>Non-metallic minerals</th><th>Non-ferrous metals</th><th>Chemicals</th><th>Paper and pulp</th></tr>
<tr><td>1) Low EE</td><td colspan="5">Limited adoption of energy efficiency measures (BATs);
No increase in material efficiency;
Partial electrification (50% of potential – see electrification measures in 3));
Solid bioenergy fuel shift for remaining fossil fuel demand.</td></tr>
<tr><td rowspan="2">2) High EE</td><td colspan="5">Wide adoption of energy efficiency measures (BATs);
Innovative measures;
Partial electrification (50% of potential – see electrification measures in 3));
Solid bioenergy fuel shift for remaining fossil fuel demand;
Material efficiency improvements:</td></tr>
<tr><td>Share of EAF steel increase from 39% to 67%</td><td>Clinker to cement ratio decreases from 76% to 60%</td><td>Share of secondary aluminium increases from 60% to 70%</td><td>-</td><td>Share of paper from recovered fibres increases slightly</td></tr>
<tr><td rowspan="2">3) High EE and elec.</td><td colspan="5">Wide adoption of BATs;
Material efficiency same as in high EE;
Innovative measures;
Solid bioenergy fuel shift for remaining fossil fuel demand;
Electrification measures:</td></tr>
<tr><td>DR electrolysis (Ulcowin, Siderwin, Ulcolysis), electric furnaces</td><td>Thermal plasma torches (cement); electric melters (glass)</td><td>Induction furnaces (aluminium)</td><td>Hydrogen is used as feedstock (ammonia, ethylene, methanol); Heat pumps and electric boilers for steam generation</td><td>Heat pumps and electric boilers for steam generation</td></tr>
<tr><td rowspan="2">4) High EE and elec./H_2</td><td colspan="5">Wide adoption of BATs;
Material efficiency same as in High EE;
Innovative measures;
Electrification measures;
Solid bioenergy fuel shift for remaining fossil fuel demand;
Hydrogen measures:</td></tr>
<tr><td>Hydrogen based direct reduction (H-DR)</td><td>-</td><td>-</td><td>Hydrogen used as feedstock (ammonia, ethylene, methanol);
Hydrogen boilers for steam generation</td><td>Hydrogen boilers for steam generation</td></tr>
</table>

The results for each scenario for EU27+UK on a sector level including upstream energy demands are presented in Figure 4. In Scenario 4 (High EE and elec./H_2), 551 TWh of hydrogen is used and the upstream electricity demand for this is included in the total electricity demand assuming 65% efficiency to produce hydrogen.

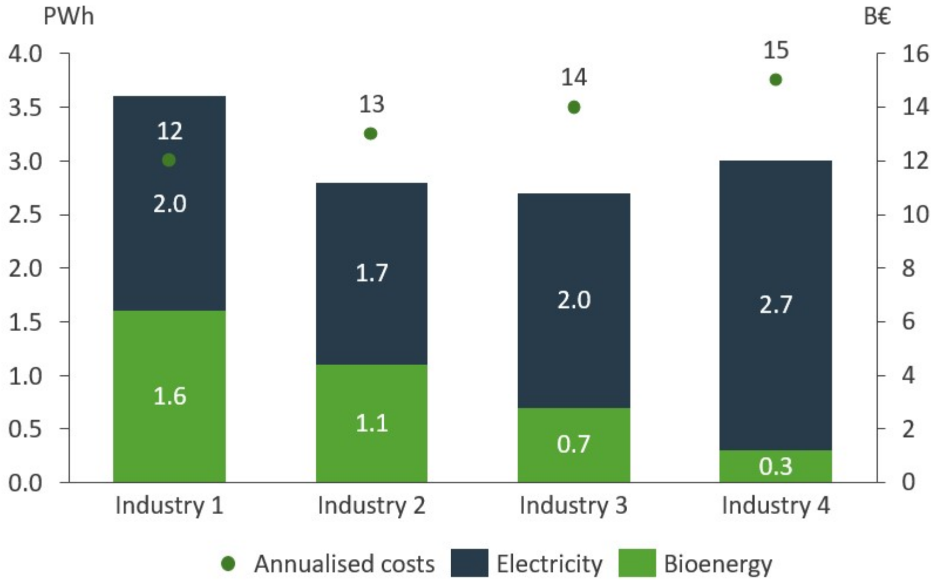

Figure 4. Sector results for 100% renewable scenarios for the industry sector for EU27+UK

Based on a sector perspective Scenario 4 (High EE and elec./H_2) has the lowest bioenergy demand but the highest cost. Scenario 4 (High EE and elec./H_2) includes hydrogen use, which increases flexibility due to its storage possibility. Scenario 1 (low EE) has the lowest cost since it adopts the least ambitious energy efficiency measures, but it has the highest bioenergy demand due to reliance on fuel replacement.

Building scenarios

In the building sector, three building refurbishment strategies (i.e., heat reduction levels) were provided by Work Package 1 including total investment costs for refurbishing existing buildings and new building envelope (this includes replacement and new stock) in each country for each heat activity level[1] (Figure 5). Each heat reduction level includes investment and operation and maintenance costs, and lifetimes for the energy efficiency measures. Deliverable 1.1 (Data set on energy efficiency potentials, describing the aggregated cost curves for building envelope refurbishment measures) (Reiter, Palacios, & Lienhard, 2021) describes the heat reduction measures used in buildings. The heat demands for each country and investment costs are presented in Appendix A in Table A.1.

[1] Electricity demand for non-heating uses such as lighting and appliances was adjusted based on population change. Cooling electricity demand was based on Heat Roadmap Europe 4 (Heat Roadmap Europe 4, 2018).

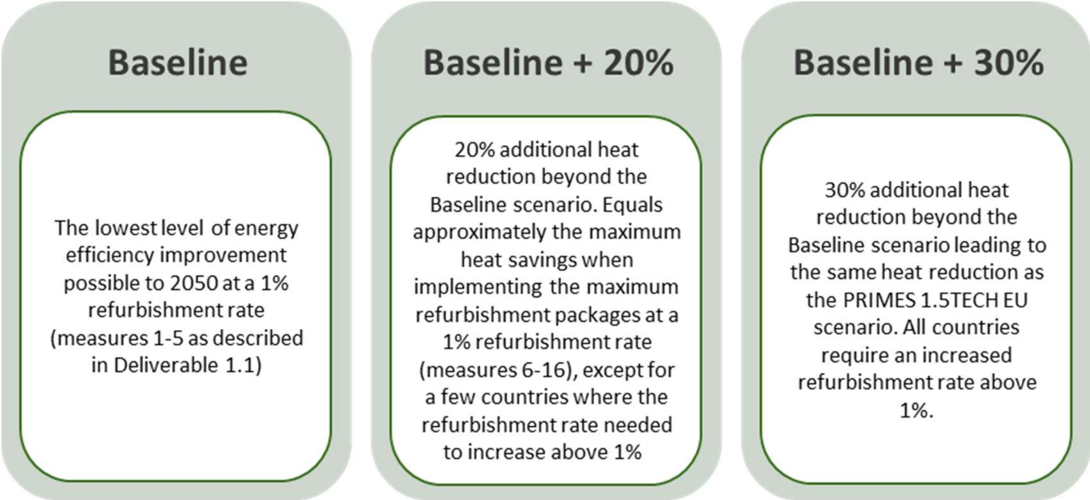

Figure 5. Building refurbishment levels and total heat demand reduction for each country

In Work Package 1, refurbishment packages were analysed for the building stock in each country to achieve the different heat activity levels. At the Baseline heat reduction level, all countries can achieve heat savings at their average refurbishment rate, estimated at 1% per year. When a higher level of heat reduction is assessed then the average annual refurbishment rate would need to increase above the average of 1% for some countries.

When the refurbishment rate was increased above the average for each country then it was assumed that some people are refurbishing their buildings before their current building elements have reached their end of life. Thus, they start paying for new refurbishments earlier than expected. It was assumed that when the refurbishment rate was increased, the lifetime of current elements would be reduced by 5 years (i.e., new refurbishments are installed 5 years early). On average, the lifetime for energy refurbishments in each country is 40 years so by reducing the lifetime by 5 years the annual costs would increase by 12.5% for the building elements (since the person is paying both for the old elements and new elements for 5 years). Thus, when increasing the refurbishment rate, the total investment costs for the building stock increase due to 1) more people refurbishing and 2) those same people spending more money for their refurbishments.

Energy system analysis of sector scenarios for each country

All sector scenarios were simulated and analysed within an energy system analysis. As mentioned above, the building scenarios could only be assessed from an energy system perspective. Although the transport and industry scenarios could be compared at sector level, they were also analysed within the energy system analysis, along with the building scenarios.

The energy system modelling platform is built on an energy system simulation program (using EnergyPLAN) for each country using different sector scenarios. The modelling platform to carry out this analysis is described in Deliverable 6.2 (Modelling platform development and new scenarios based on EEFP) (Maya-Drysdale, David & Magni Johannsen, 2021). The platform involves two main components, 1. The scenario inputs for transport, industry and buildings and 2. The energy system configuration around the scenarios, i.e., energy supply system. The steps to operationalise the platform and determine country specific results and EU27+UK results are described in Figure 7.

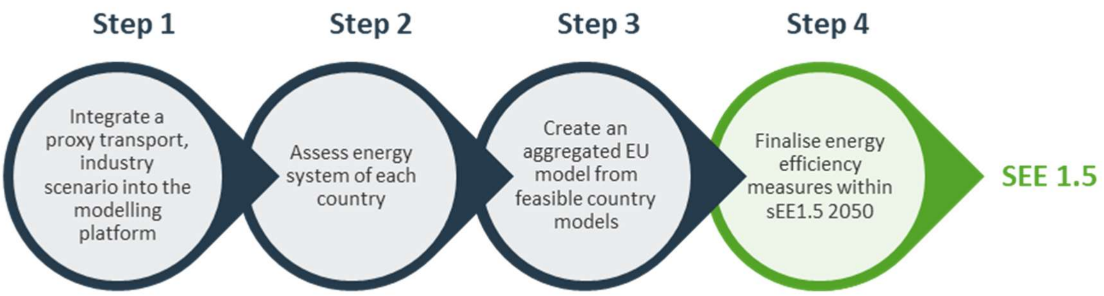

Figure 6. Steps to develop and assess Energy Efficiency First Principle in the sEE 1.5 model

Step 1. Integrate one transport, industry scenario into the modelling platform

To determine the appropriate level of heat savings in buildings the analysis in Step 2 was done for a full energy system, therefore data was required for all energy demands and supplies as well as the building heat demand and supply. For instance, a full energy system required inputs for transport and industry. Therefore, for transport and industry, one scenario from the sector comparison was selected as a preliminary scenario to be able to complete the energy system analysis for the building scenarios. This is Step 1 in the modelling platform presented in Figure 6.

The preliminary scenarios remained the same for each building sector scenario for each country. The results for the building sector scenarios are not affected by the type of scenario selected for transport and industry since they do not affect the building heating supply, however, they allow a full energy system analysis. The full energy system configuration leads to a balanced energy system and it provides a platform for later comparison of the remaining transport and industry scenarios.

Based on the sector comparison of results for transport and industry, Electrification+ and Scenario 4 (High EE and elec./H_2) for the industry sector were deemed reasonable as preliminary scenarios based on the sectorial results thus, they were selected in Step 1.

The remaining transport and industry scenarios were assessed in the system in Step 4 to determine if the preliminary scenarios should be changed (the results showed that the preliminary scenarios were appropriate and should not be changed).

Step 2. Assess energy system of each country

As mentioned above, the supply of energy to buildings was not included as was done for transport and industry. Therefore, to compare the scenarios in the building sector the supply side needed to be added via an energy system analysis to understand the difference between the scenarios. This involves assigning heat supply options for each country. In Step 2 the building scenarios were assessed within an energy system analysis along with the selected transport and industry scenarios.

The two main categories for heat supply for buildings are individual heating and district heating, each involving different heat supply technologies. Therefore, for each of the three heat demand levels, the mix of individual and district heating was adjusted by 10% increments. For instance, in Scenario 1 district heat is set at 0% and individual heat at 100%, Scenario Two is 10% district heat and 90% individual heat and so on. In total there were eight scenarios analysed for each heat level summing to 24 scenarios analysed for each country. Including all the 28 countries there were 672 scenarios analysed. The full set of scenario types is presented in Table 3. An example country of a set of scenarios is presented in Appendix A in Figure A.1.

Table 3. Matrix of 24 scenarios analysed for each country.

DH/Individual heating % share	0/100	10/90	20/80	30/70	40/60	50/50	60/40	70/30
Baseline	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6	Sc. 7	Sc. 8
Baseline+20% additional heat-saving	Sc. 9	Sc. 10	Sc. 11	Sc. 12	Sc. 13	Sc. 14	Sc. 15	Sc. 16
Baseline + additional 30% heat-saving	Sc. 17	Sc. 18	Sc. 19	Sc. 20	Sc. 21	Sc. 22	Sc. 23	Sc. 24

Simulation of the energy system using EnergyPLAN

Each of these scenarios were assessed for each country within the simulation tool EnergyPLAN (Lund et al., 2021) to determine which heat activity level each country should have. EnergyPLAN allows for the assessment and comparison of scenarios based on the total socio-economic costs, resources demands and technical feasibility of the energy system. EnergyPLAN was soft linked with a scenario tool built in Microsoft Excel, which allowed rapidly running and partially optimising numerous energy system scenarios containing different efficiency measures for each country.

The assessment helped determine the level of heat reduction in each country and the heat supply, which led to the most feasible outcome for economic costs, resource demand and technical feasibility. The appropriate heat reduction level was determined by assessing the total socio-economic cost, resource demand and technical feasibility of the full energy system. Bioenergy demand was assessed in relation to the JRC bioenergy potential for each country from the Reference Scenario from the ENSPRESO project (Ruiz et al., 2019).

In each scenario, the individual heating proportion consisted of a mix of heat pumps (90%), supplemented with a bioenergy boiler (5%), and hybrid-solar heating (5%). Thus, if the building stock is supplied with 50% individual heating, the building stock heat supply would consist of 45% heat pumps and 2.5% each for bioenergy boiler and solar thermal.

The district heat is supplied through a diverse mix of sources i.e., combined heat and power (CHP), electric boilers, industrial excess heat, solar thermal and so on. The mix depended on the resources available in each country. Deliverable 5.1 (Documentation on excess heat potentials of industrial sites including open data file with selected potentials) (Fleiter et al., 2020) provided the excess heat potentials of industrial sites in Europe. The other sources were based on energy system design criteria, which are described in Table 4.

For each scenario, a new technically feasible energy system configuration was made for each country according to the new configuration of heat demands and supplies (Figure 7). The results were analysed to determine the most feasible building sector scenario. This process was carried out for each country.

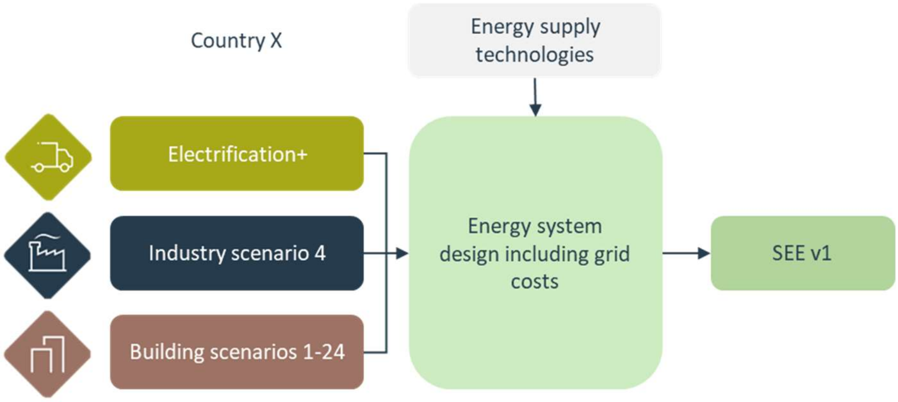

Figure 7. Step 1: Scenario components for each building sector scenario

Energy system design including grid costs

The design process for the energy system for the building sector (energy system) analysis required that it led to a technically feasible energy system. Therefore, there were two steps in the design process. Step 1 was to assign some preliminary energy supply capacities and Step 2 was to assess the performance of the energy system in Step 1 and adjust capacities until the energy system was technically feasible.

To assign some preliminary energy supply capacities scenarios for the energy system in 2050 were informed by the PRIMES EU2050 scenarios (European Commission, 2018a) including 2050 Baseline and decarbonised 2050 scenarios. These scenarios provided technology efficiencies and energy supply capacities. This ensured that the sEE 1.5 decarbonised scenarios were aligned with EU 2050 targets. However, there were two main differences, CO_2 emissions were reduced by 100% instead of 95% compared to 1990 levels, and nuclear power production was excluded. Nuclear capacity was assessed in a sensitivity analysis.

The PRIMES 2050 Baseline scenario was translated into EnergyPLAN translating the annual level PRIMES data into hour-by-hour models for the 28 member states. Country-specific energy system data were split and adjusted for each country according to the specific characteristics of each country. These characteristics included: their current energy system configuration, their renewable energy potential and the technical feasibility and performance of the energy system design (assessed via analysis).

When running and finalising the scenarios in the modelling platform in EnergyPLAN the configuration of the energy system was adjusted for each scenario based on design principles. The energy system design principles were for a 100% renewable energy system. Basic principles were adopted from the Smart Energy System concept (Mathiesen et al., 2015). This concept relies on balancing energy grids (thermal, electric and gas) and storages (thermal, electric and gas/liquid) to achieve lowest resource consumption and socio-economic costs.

Cross border exchange between countries was also assessed to calibrate energy systems of each country, this included interconnections between countries for electricity and gas grids. As a general design principle, the exchange of energy across borders was minimized to simulate self-sufficiency and security of supply within the countries as far as possible, but in reality, there will be more exchange.

Excess electricity and import of electricity were limited to 5% of the total electricity production. These limitations ensure that over- and under- capacity are avoided, security of supply can be achieved, and production capacity is situated near demand.

The principles to adjust energy supply capacities ensuring technical feasibility in each country is presented in Table 4.

Table 4. Energy system design parameters

	Energy type	Capacity/fuel input design principle
Electricity	Power plant	Capacity increased to ensure import of electricity is not higher than 5% of electricity demand
	Combined heat and power	Annual average district heat demand per hour in one year
	Onshore wind	In line with JRC potentials from ENSPRESO (Ruiz et al., 2019)
	Offshore wind	In line with JRC potentials from ENSPRESO (Ruiz et al., 2019)
	Solar PV/CSP	In line with JRC potentials from ENSPRESO (Ruiz et al., 2019)
	Hydropower	PRIMES EU2050 Baseline
Heating	Individual heat pumps	% defined in the scenario
	Individual bioenergy boilers	% defined in the scenario
	Individual solar thermal	% defined in the scenario
	District industrial waste heat	Potential from IndustryPLAN
	District solar thermal	Potential from (Hansen & Mathiesen, 2018)
	District heat geothermal	Heat Roadmap Europe 4 (Heat Roadmap Europe 4, 2018)
	District heat waste incineration	Proportion of 2015 waste production
	District heat large heat pumps	25% of combined heat and power capacity
	District heat boilers	120% of peak district heat demand
Transport	Fuel inputs	TransportPLAN
Industry	Fuel inputs	IndustryPLAN

EnergyPLAN simulates the energy system on an hour-by-hour basis therefore hour by hour energy demand and supply profiles (required for an annual energy system in EnergyPLAN) were sourced from the Multiplan tool from the REINVEST project (reinvestproject.eu) (Petersen, U. R., Korberg, A. D., & Thellufsen, 2021) which included hour by hour country profiles for all demands and supplies. These were kept the same for each country scenario iteration.

Energy system technology costs were sourced for each country from Deliverable 6.1 (Technology data and costs). Energy grid costs for gas, electricity and district heat were sourced from Deliverable 4.4 (Final cost and capacity analysis for the representative energy grids as function of the decarbonisation scenarios version) (Meunier, Simon; Protopapadaki, Christina; Persson et al., 2021).

The most feasible scenario was selected based on a quantitative and qualitative assessment as well the current configuration of heat supply in each country, i.e., some countries have high district heat share today so that would stay the same or increase. The assessment criteria included:

- Total annual socio-economic costs
    - Socio-economic costs were also assessed by doubling bioenergy costs in each scenario to accentuate the risks with higher bioenergy demands
- Bioenergy consumption

- Peak import electricity demand (indicates dependence on other countries for electricity supply)
- Refurbishment rate of buildings from 2015 to 2050
  - This was a qualitative assessment where the lowest refurbishment rate was prioritised

The results of the most feasible/suitable scenario for each country are presented in the Energy Efficiency Roadmap and the individual country reports.

Step 3. Create an aggregated EU model from feasible country scenarios

In Step 3, based on the energy system assessment for all the scenarios for each country, one feasible scenario for each country was chosen to create the aggregated EU27+UK scenario (sEE 1.5). This aggregated energy system was analysed within EnergyPLAN and minor adjustments were made to ensure a balanced energy system.

The final building sector scenarios for each country used in the aggregation are presented in Figure 8. The reduction in heat demand per metre squared of existing buildings in 2015 to 2050 is presented in Appendix A in Table A.2. The required refurbishment rate in each country is also presented.

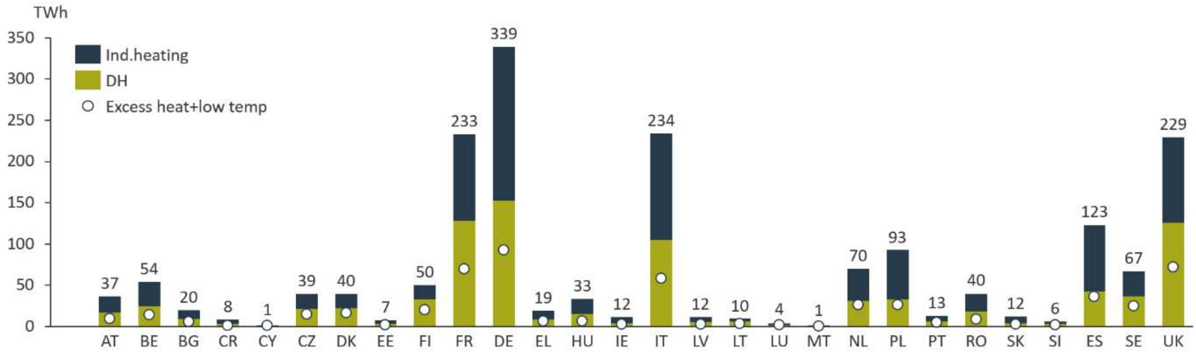

Figure 8. Final building heat demands and supply mixes as well as excess and low temperature heat in district heating

Step 4. Finalise energy efficiency measures within sEE 1.5

Electrification+ and Industry 4 scenario were used as preliminary for the energy system analysis for buildings, meaning that only these scenarios were used when analysing the building sector. Before finalising the sEE 1.5 energy system scenario, the aim in Step 4 was for the remaining three scenarios for transport and industry to be assessed within the aggregated EU27+UK scenario. Each scenario was analysed to understand the system perspective of these scenarios. This also provided further insight into the role of energy efficiency and energy supply in the decarbonisation of the energy system. Based on this insight, the energy efficiency prioritisations and investment strategy roadmap were developed.

After this analysis, the most feasible scenario for transport and industry based on an energy system perspective was selected, with the same scenario selected for each country, i.e., different transport and industry scenarios were not selected for different countries.

The building sector scenarios remained the same as in Step 3.

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Other transport and industry scenarios within sEE 1.5

When a transport scenario is replaced with another one (i.e., Biofuels scenario replaces Electrification+ scenario) the industry scenario remains the same, to understand the impact that the transport scenario has on the energy system. Vice-versa when industry scenarios were interchanged, the transport scenario was kept the same, i.e., Electrification+, since the purpose is to understand the system impacts of the individual sector scenarios. This allowed an understanding of the impact of energy efficiency measures on the energy system and allowed to prioritise energy efficiency measures in the energy system. It also allowed an understanding of the energy supply mix changes when different scenarios were plugged in. This is illustrated in Figure 9.

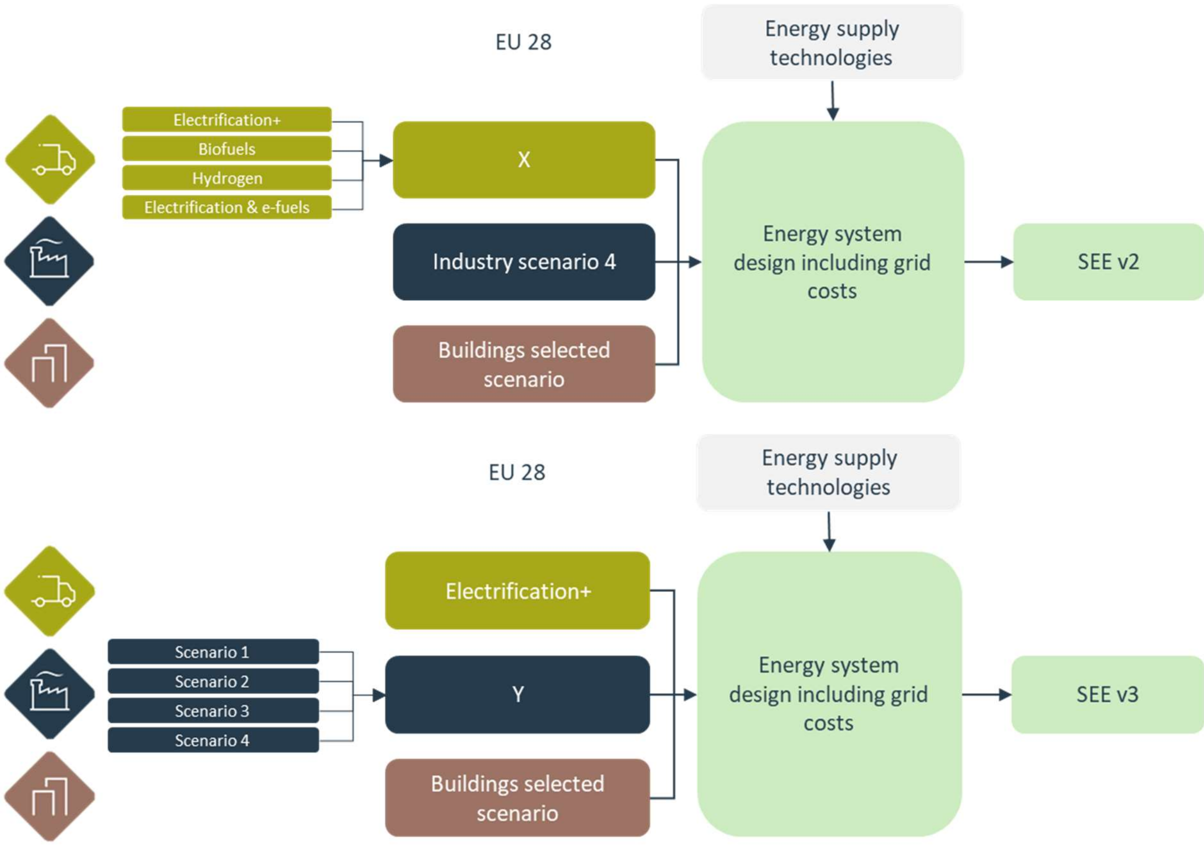


Figure 9. Top: replacement of transport scenario with industry scenario remaining constant. Bottom: replacement of industry scenario with transport scenario remaining constant

Based on the comparison, the final sEE 1.5 scenario kept the preliminary scenarios, electrification+ and industry scenario 4 (high EE and elec./H_2) for all countries (Figure 10). The results are shown in the Energy Efficiency Roadmap. The same transport and industry scenario was selected for each country since the scenario types were more influential than the differences between countries, meaning that electrification+ is the best scenario in every country. Even though the same scenario was selected for all countries, each country had its own specific energy demands within the scenario.

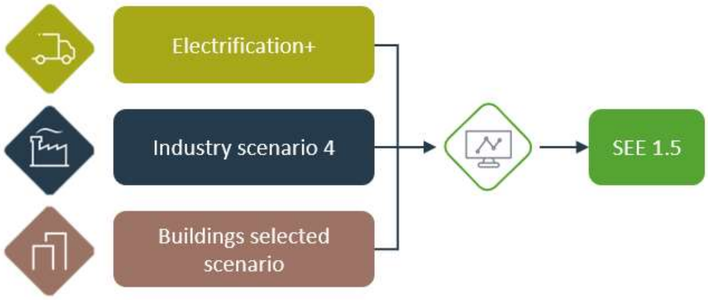


Figure 10. Final scenarios used in sEE 1.5

Additional impacts: Health impacts

The energy efficiency measures will have a significant effect on human health via e.g., their direct impact on pollution. The health cost impact of a fossil-based EU27+UK 2015 energy system, the "business as usual" partly fossil-based 2050 Baseline scenario, and the sEE 1.5 scenario were quantified and compared. The analysis focused on three pollutants, SO_2, NO_x and $PM_{2.5}$, generated from burning fuels in power plants, industries, households and transport.

The first step collected the emissions factors from the different technologies and the respective fuels, including SO_2, NO_x, $PM_{2,5}$. Emissions factors were collected from the socio-economic cost assumptions from the Danish Energy Agency for 2022. These were supplemented with the source data from the Department of Environmental Science (Mikael Skou Andersen, 2019). Emission factors were collected for power plants and boilers of varying sizes and using different types of fuels. Furthermore, emissions factors were collected for transportation modes and their fuels.

The emissions factors were multiplied by the fuel consumption of the different types of plants and transport modes, to find the amount of emissions from each scenario in tons using the EnergyPLAN outputs. These outputs do not have the details about which exact type of plant or transport mode is used, therefore a few assumptions were applied:

- Bioenergy usage in combined heat and power and power plant were assumed to be split between straw and wood pellets, 50% each.
- Bioenergy usage in district heat boilers was also assumed to be split between straw and wood pellets, 50% each.

To calculate the total health impact costs for each scenario, the emissions from each plant type and transport mode for each of the scenarios in tonnes were multiplied by health impact cost factors. The health impact costs were sourced from "Miljøøkonomiske beregningspriser for emissioner 3.0" prepared by the Department of Environmental Science (Mikael Skou Andersen, 2019). It includes a detailed health impact cost for different processes and different emissions. The socio-economic costs considered were based on health impacts related to chronic mortality, acute mortality, hospital admissions, asthma, bronchitis, lung cancer, and sick days.

The results were calculated on an EU level and for three different types of emissions, namely SO_2, NO_x, and $PM_{2.5}$. A comparison is made between the health costs at an overall level and a sectoral level. Total emission reductions were quantified for both the 2050 Baseline and sEEnergies EU2050 scenarios and 2015.

Numerous other additional impacts were quantified at sector level and the results are briefly described in Appendix B. A more detailed overview of these impacts is presented in Deliverable 6.35 (Additional Impacts of Energy-Efficiency Measures: A Systemic Overview of their Implications across Societal, Ecological and Economic Dimensions).

Transitioning to 2050 via a 2030 energy system

The sEE 1.5 energy system scenario provides a balanced, cost effective and energy efficient perspective of how the energy system should develop by 2050, but a shorter-term perspective is also useful to put on track the measures needed to reach the 2050 scenario. For this reason, a 2030 energy system analysis was developed for EU27+UK. Furthermore, transformative action and policy that influences short-term implications needs to be developed to reach the envisioned scenario for 2050 (Figure 11). Thus, the policies described in Deliverable 6.4 (REPowerEU and Fitfor55 science-based policy recommendations for achieving the Energy Efficiency First Principle) are informed by the short-term 2030 analysis.

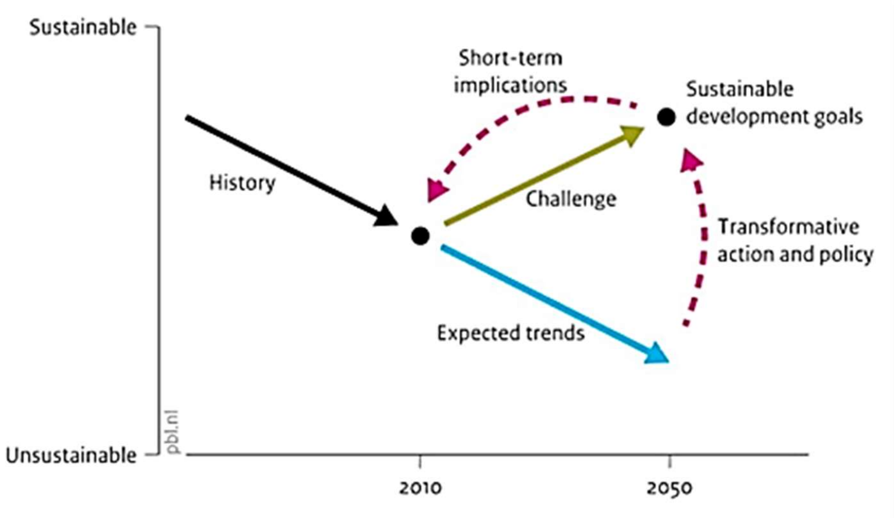


Figure 11. Transitions from historical trajectories towards future goals (van Vuuren et al., 2015)

The 2030 energy system was determined based on three main components:

1. Trend curves from 2015 to 2019 for numerous energy system components (historical data)
2. Transition S-curves to project the timing for the investment and implementation from 2015 to 2050
3. Prioritisation and timing of the energy efficiency actions based on their impacts, current development level and role within the reconfiguration of the energy system design to 2050

Transformative action and policy can follow current and expected trends, however, to determine the 2030 energy system configuration, the current energy policy making was challenged from a transition perspective. Within the sEE 1.5 energy system, there are numerous components that require a transition from unsustainable to sustainable outcomes. Furthermore, they integrate with each other within the new energy system configuration creating synergies. To develop this new energy system configuration, interim transition objectives need to be developed. These can be derived from backcasted long-term objectives for different energy system components (found within the sEE 1.5 energy system) (Figure 12).

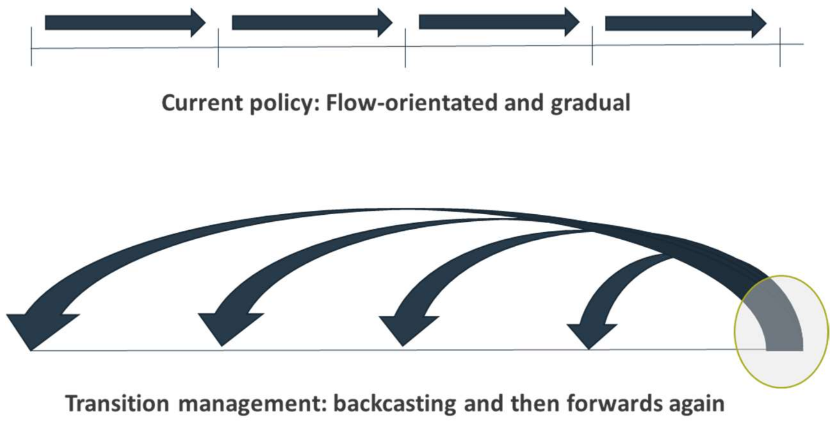


Figure 12. Short-term versus long-term policy (Adapted from Rotmans, Kemp, & Asselt, 2001)

The interim objectives contain quantitative measures but also qualitative. For instance, the interim objectives can appear like current policy objectives (e.g., primary energy demand of X amount by 2030), but the objective has additional components related to the overall energy system configuration in 2050. For instance, primary energy demand is reduced by X amount by 2030 but only because the energy system configuration needed to be configured that way by that point in time to achieve the longer term 2050 goal. Interim objectives need to be accompanied by process and learning objectives to ensure the transition path leads to the 2050 end goal. Process objectives are put in place to assess the quality of the transition, whereas learning objectives are put in place to ensure that objectives are readjusted based on learning.

Thus, to determine the interim objectives for 2030 and beyond, the energy system configuration was not developed based on trends and flows from today but rather backcasting from 2050 (Figure 12). There are four phases of transition as defined in Rotmans, Kemp, & Asselt (2001 (Figure 13). Each component in the energy system was analysed using these transition phases. All external factors or shocks that could influence any of these stages in the transition were excluded in the analysis. The phases include:

1. Predevelopment
2. Take-off
3. Acceleration (breakthrough)
4. Stabilisation

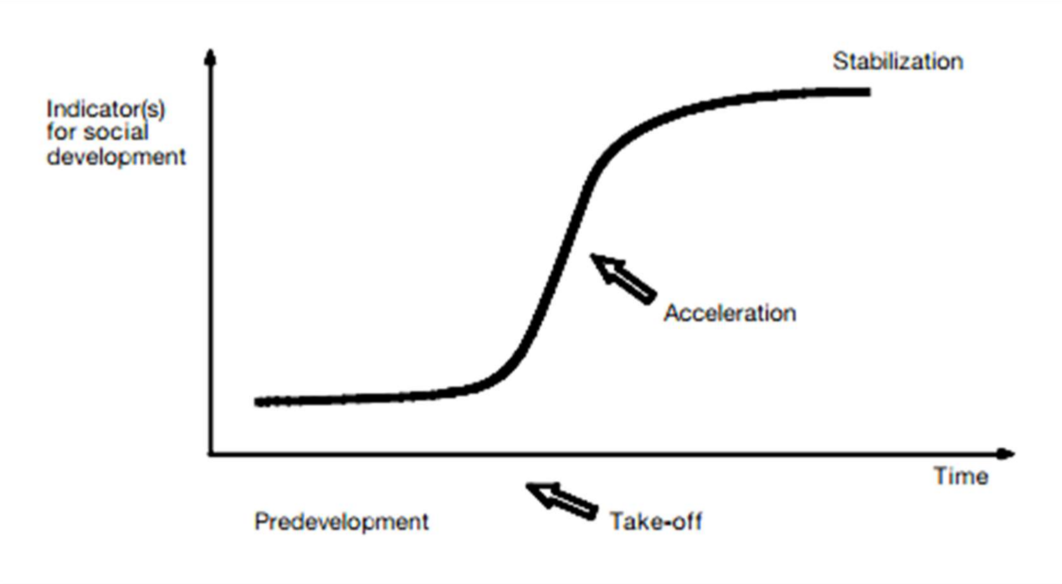


Figure 13. The four phases of transition (Rotmans, Kemp, & Asselt, 2001)

A transition curve was developed for all energy system demands and supplies in 2050. For instance, for onshore wind capacity integration, building heat demand reduction and so on. In total, 52 transition curves were developed for each component in the energy system. To model the transition of different energy system components, the transition curves were developed using three dimensions (Figure 14):

1. Speed of change (slope of the curve)
2. Size of change (for all components this was the 2050 end point from within sEE 1.5 energy system)
3. Time period of change (inflection point from acceleration to deceleration)

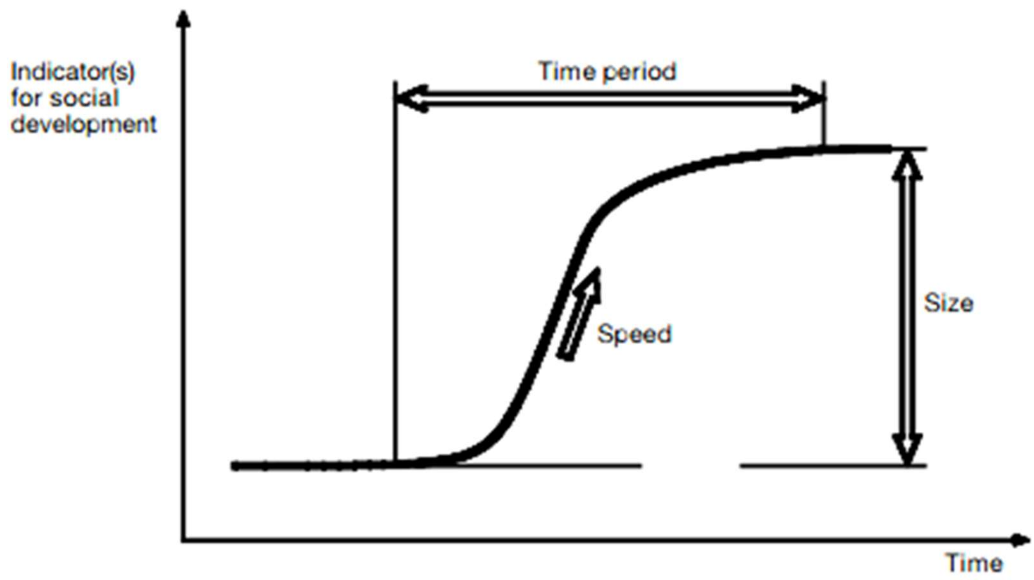


Figure 14. The three system dimensions of transition (Rotmans, Kemp, & Asselt, 2001)

The energy data for each system component was extracted for the 2030 point in the curve (Figure 15).

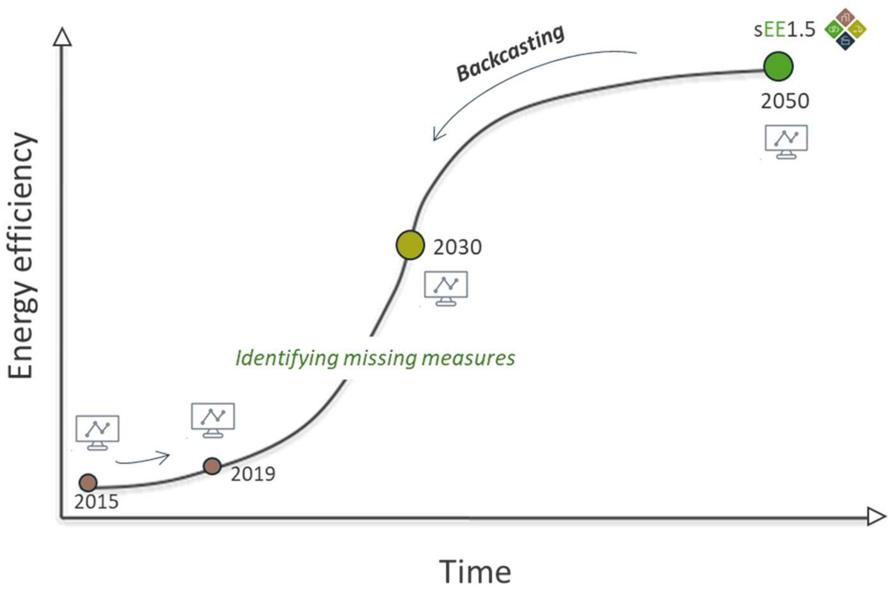


Figure 15. Illustration of the method used for creating the sEE 2030 scenario

To plot the inflection point in the transition curve and determine the values for each year from 2015 to 2050, a logistic regression fit, when not assuming logged X-values, was used following the equation [1].

$$y = min + \frac{max - min}{1 + \left(\frac{X50}{x}\right)m} \quad [1]$$

Where:

- min and max are the lower and upper asymptotes of the curve (these were fitted approximately to the min and max values at 2015 (from the Eurostat database) and sEE 1.5 respectively. The 2030 point was located somewhere on the curve.
- m is the slope of the curve at its midpoint (determining the speed of change) and X50 is the x-coordinate of the inflection point (x, y) (determining the time period of change).

Points were plotted for every year from 2015 to 2050 utilising this formula for each energy system component. All the points for the minimum and maximum values for the different energy components were sourced from the Eurostat database (2015) (European Commission, 2021) and the sEE 1.5 model, respectively.

The curve was adjusted by modifying the inflection point (X50) and the slope at the midpoint (m). Data from 2019 from Eurostat (REF) added an additional point in the curve that enforced a change in the shape of the curve to fit this point. Lastly, for transport, industry and building heating, energy demand data for their respective 2050 scenarios was also supplied for 2030 and this demand data was utilised to help form the curves for these components.

Based on the scenarios from the transport, industry and the buildings Work Packages, the energy demand in 2030 was provided, thus the demand curves needed to fit these values. Numerous energy supply curves are affected by the energy demand curves. For instance, district heat supply curves need to fit the district heat demand, therefore this was also considered when developing the curves. The development of curves for supply of electricity also had to follow the demand growth as well, especially when integrating hydrogen electrolysers.

Once all the curves for each component were determined, a preliminary EU 2030 scenario was developed in EnergyPLAN based on all the 2030 values from the curves. An energy system analysis was done in EnergyPLAN to test for energy system technical feasibility using the data from the curves. If infeasible, then the curves were adjusted for key components until the system was technically feasible, i.e., solar PV and onshore wind capacities could be lowered for 2030 due to an oversupply of electricity.

The sEE 2030 energy system was used to prioritise energy efficiency measures and inform the investment strategy for the sEE 1.5 energy system. Some known technologies were prioritised until 2030 to achieve the Fit for 55 and REPowerEU goals, for instance industrial electrification. This is described further in Deliverable 6.4 (Handbook for science-based interaction with objectives aiming for achieving the Energy Efficiency First Principle) where the 2030 analysis and results are used to assess the EU energy policies.

The results for sEE 2030 and sEE 1.5 is presented in the following Energy Efficiency Roadmap sub-report. All the country reports are provided in the third sub-report of this deliverable.

Introduction to the Energy Efficiency Roadmap

The Energy Efficiency Roadmap for Europe presents the quantitative results, impacts and guidelines for the proposed design of the energy efficient sEE 1.5 scenario as well as the sEE 2030 scenario. It includes a comparison with the PRIMES Baseline 2050 and 1.5 TECH (2050).

Supplementary project deliverables - found at seenergies.eu - provide further results. For instance, the Open Data Hub, the EnergyPLAN models, and sector specific databases and reports.

The Energy Efficiency Roadmap presents:

- The sEE 2030 and sEE 1.5 system efficiency
- The transport, industry and buildings sector energy efficiency
- The sEE 1.5 energy system redesign
- Resource security and health impacts
- Sensitivity analysis, and
- An investment strategy and ranking of energy efficiency measures

sEE 1.5 and sEE 2030 system efficiency overview

The application of the energy efficiency first principle makes it possible to have a highly efficient decarbonized European energy system by 2050 (Figure 16). Primary and final energy demand can be reduced significantly compared to the 2015 energy system (2015 was used as the reference), reducing by 44% and 40%, respectively (Figure 16). Compared to the 1.5 TECH scenario, the final energy is similar in sEE 1.5, however the energy efficiency in sEE 1.5 is greater considering the primary energy supply. By 2030, primary and final energy can be reduced by 28% and 23%, respectively.

In 2030, the primary energy supply mix can be modified where renewables such as solar PV and wind make up 25 % of the share and fossil fuels around 45% (Figure 16). In 2050, the share of solar PV and wind increases to 68%, while fossil fuels are pushed out of the system.

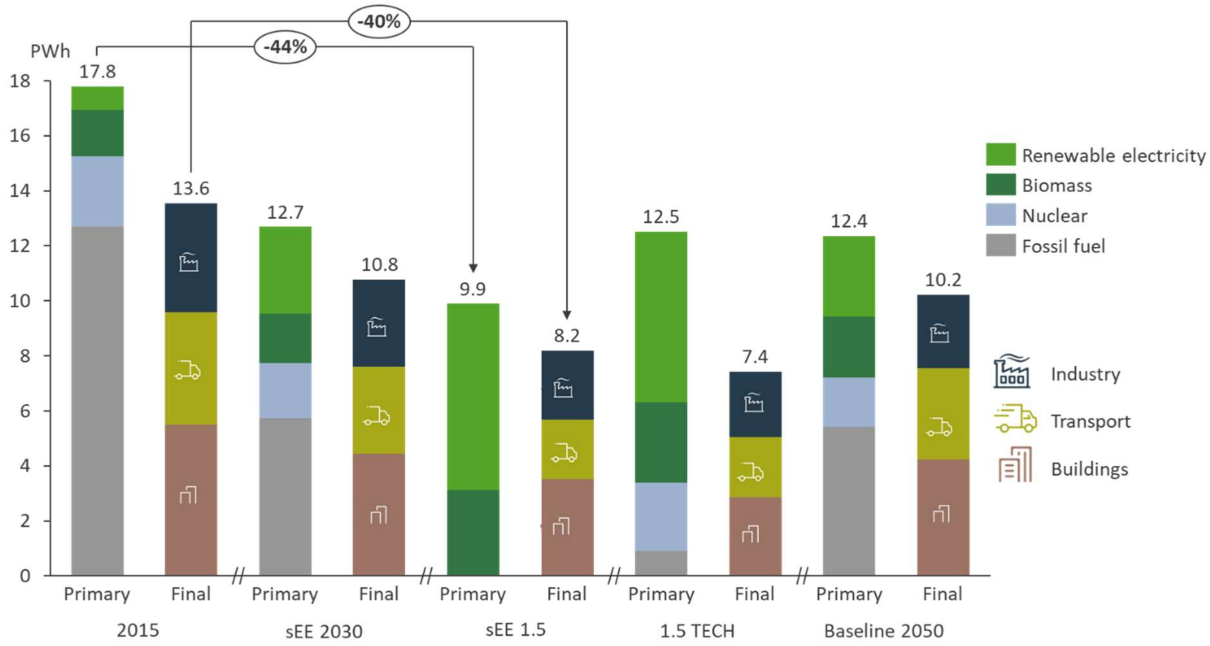


Figure 16. Primary and final energy consumption in 2015 reference, sEE 2030, sEE 1.5 (2050) and 'A clean planet for all scenarios' (1.5 TECH (2050) and Baseline 2050)

Bioenergy is limited to a sustainable level (in line with the reference scenario from JRC ENSPRESO project (Ruiz et al., 2019). Compared to 1.5 TECH, bioenergy demand is marginally higher than in sEE 1.5. However, the 1.5 TECH scenario consumes fossil fuels, which requires carbon capture and storage/utilization. For sEE 2030, the biomass consumption increases marginally compared to 2015 and is in line with the projected consumption for sEE 1.5.

The sEE 1.5 scenario can be achieved without incurring large additional energy system costs (Figure 17). Overall, the total annualized costs are lower than 1.5 TECH due to less intensive energy efficiency measures (especially in the building sector), a more optimised transport system including modal shift and energy efficient urban planning, and the exclusion of nuclear power. In general, most costs in sEE 1.5 arise from investments in infrastructure, with fuel costs decreasing when transitioning from the current fossil fuel and nuclear energy system.

The sEE 2030 scenario sees an increase in the annualised investment costs compared to 2015, primarily due to the new investments in energy efficiency, conversion technologies and new electric vehicles, but manages to stay below the cost in PRIMES Baseline and 1.5 TECH scenarios. In fact, sEE 2030 appears similar to the PRIMES Baseline, at least in terms of cost structure, showing that many of the system changes that would happen by 2050 can be frontloaded by 2030. The investment strategy describes the investment costs in more detail for sEE 1.5 and sEE 2030.

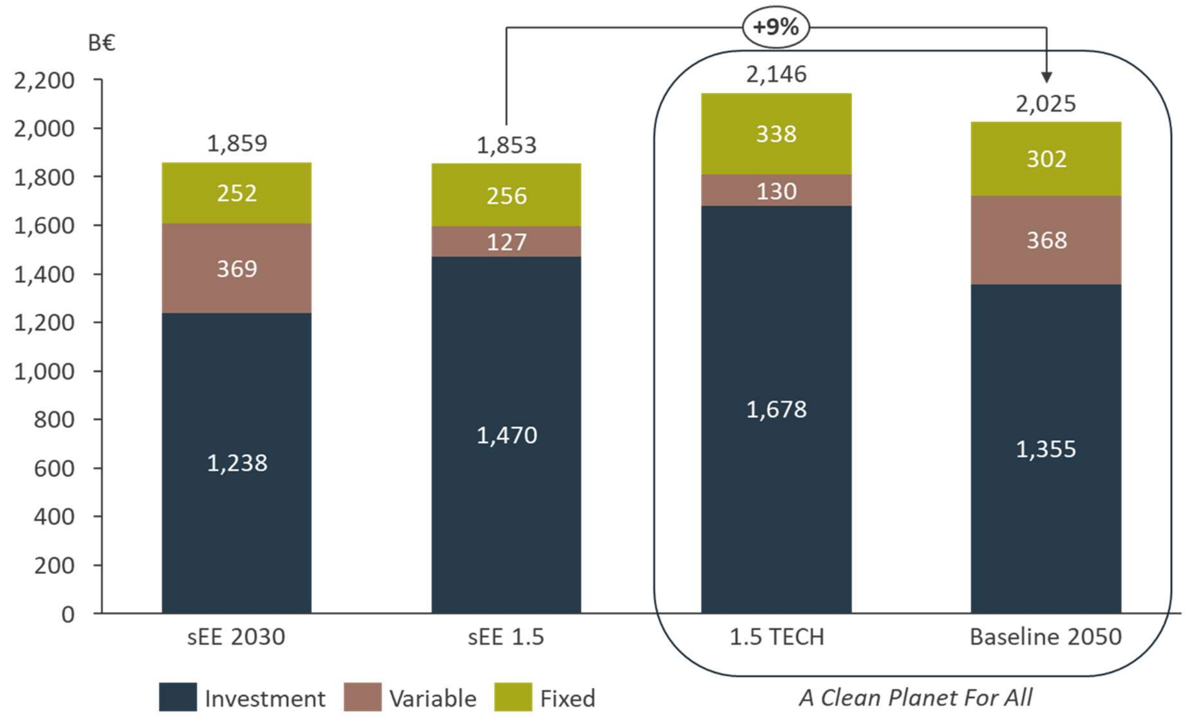


Figure 17: Annualised energy system costs of sEE 2030 and sEE 1.5 (2050) in comparison to 1.5 TECH (2050) and Baseline 2050

Sector energy efficiency overview

The sEE 1.5 energy system scenario is possible due to the energy efficiency improvements within the industry, transport, and building sectors. Final energy demand is reduced for transport, industry and buildings from 2015 to 2050 by 49%, 36%, and 34%, respectively (Figure 16). Buildings include residential and service buildings including data centers. The energy demands include heating, cooling and electricity demand.

A brief recap of the scenario results here shows the results for each sector as applied in the sEE 1.5 and sEE 2030 scenarios. A full detailed overview and description of the energy efficiency scenarios for each sector are presented in Deliverable 1.2 (WP1), Deliverable 2.3 (WP2) and Deliverable 3.6 (WP3) located at seenergies.eu webpage. TransportPLAN and IndustryPLAN are the tools used to develop the scenarios for transport and industry and these can be found at seenergies.eu.

Transport sector

The transport sector can reduce final energy demand by 48% from 2015 to 2050 (Figure 18) due to: 1) technology development (electrification and electrofuels) and 2) sustainable urban planning. Sustainable urban planning involves: 1) urban spatial development 2) economic instruments (road pricing) and 3) infrastructure development (described in detail in Deliverable 2.3). Urban spatial development involves densification of urban areas.

By combining technology development with sustainable urban planning, all fossil fuels can be removed from the energy mix. Electrification accounts for 62% of the energy mix, which is increased due to freight transport converting to e-roads - trucks are electrified via an electric grid. E-roads allow trucks to reduce final energy demand by 13% compared to the battery electric and electrofuels scenario. Electrified rail increases by 217% from 2015 to 2050 from 436 Mpkms to 1381 Mpkms. By 2030, 95 million light vehicles would be electric.

Indirect electrification involves electrofuels, produced in large quantities only after 2030. Electrofuels represent an indirect use of electricity that produces hydrogen as feedstock for chemical synthesis to a variety of fuels involving carbon or nitrogen. In sEE 1.5 they are consumed by the hard-to-abate sectors as aviation and shipping.

Sustainable urban planning can decrease final energy demand by 25% compared with traditional development. Energy efficient urban development has a significant impact on final energy demand due to reduction in light vehicle use decreasing by 1045 Mpkms or 17% from a traditional urban development perspective.

The ownership of light vehicles per capita reduces in the energy efficiency urban development compared to the traditional development by around 16% from 0.62 to 0.52 cars per capita. Total light vehicles are reduced by 52.3 million between the scenarios. In the energy efficiency urban scenario, the light vehicles per capita slightly reduces from 0.53 to 0.52 from 2015 to 2050, meaning people with light vehicles can still drive as much as they do today. The difference is that less people have light vehicles overall due to modal shift.

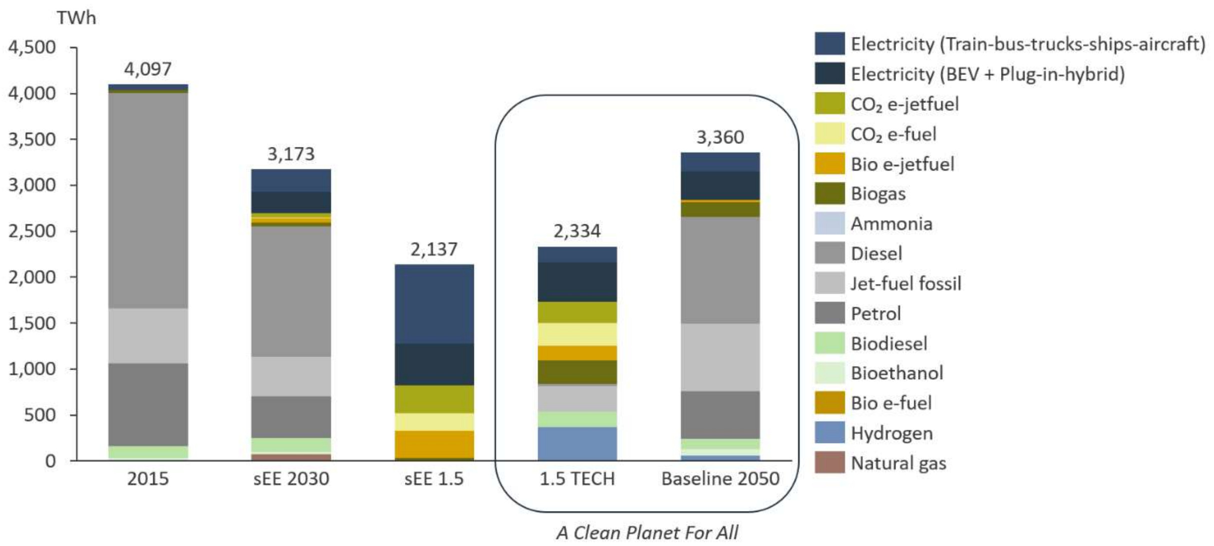


Figure 18. Transport final energy mix for the 2015, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

Industry sector

The industry sector can reduce final energy demand by 36% from 2015 to 2050 (Figure 18). In the industry sector, numerous energy efficiency measures are adopted in various industrial sectors, for example improved hot blast stove control in pig iron production or improving process control in electric arc furnaces in steel production (the energy efficiency measures are described in Deliverable 3.6 and in IndustryPLAN). In total there were 184 energy efficiency measures adopted in seven industrial subsectors, including best available technology and innovative measures, electrification and hydrogen. The measures adopted in each country differ depending on their industrial arrangement.

In sEE 1.5, electrification of industry accounts for 66% of the final energy demand (Figure 19). Hydrogen consumption increases to 22% of the final energy demand. This limits the bioenergy demand in industry to only 10% of the energy mix meaning it can be utilized elsewhere in the energy system, however it increases from its original 6% in 2015. District heat demand in industry falls from 5% to 1.5% of the energy mix from 2015 to 2050. Currently, in some countries such as Portugal district heat is only sent to industry rather than buildings and the heat source is excess heat.

By 2030 electrification increases to 39% of the total final energy demand up from 25% in 2015. This is largely in the “others” category for lower temperature sub-sectors such as engineering and the food industry, consisting of food, drink, tobacco, engineering and textiles among others. This reduces the overall final energy demand due to efficiency gains. By 2030 increased electrification makes the “others” category more energy efficient and best available technology measures are implemented at low assumed implementation rate.

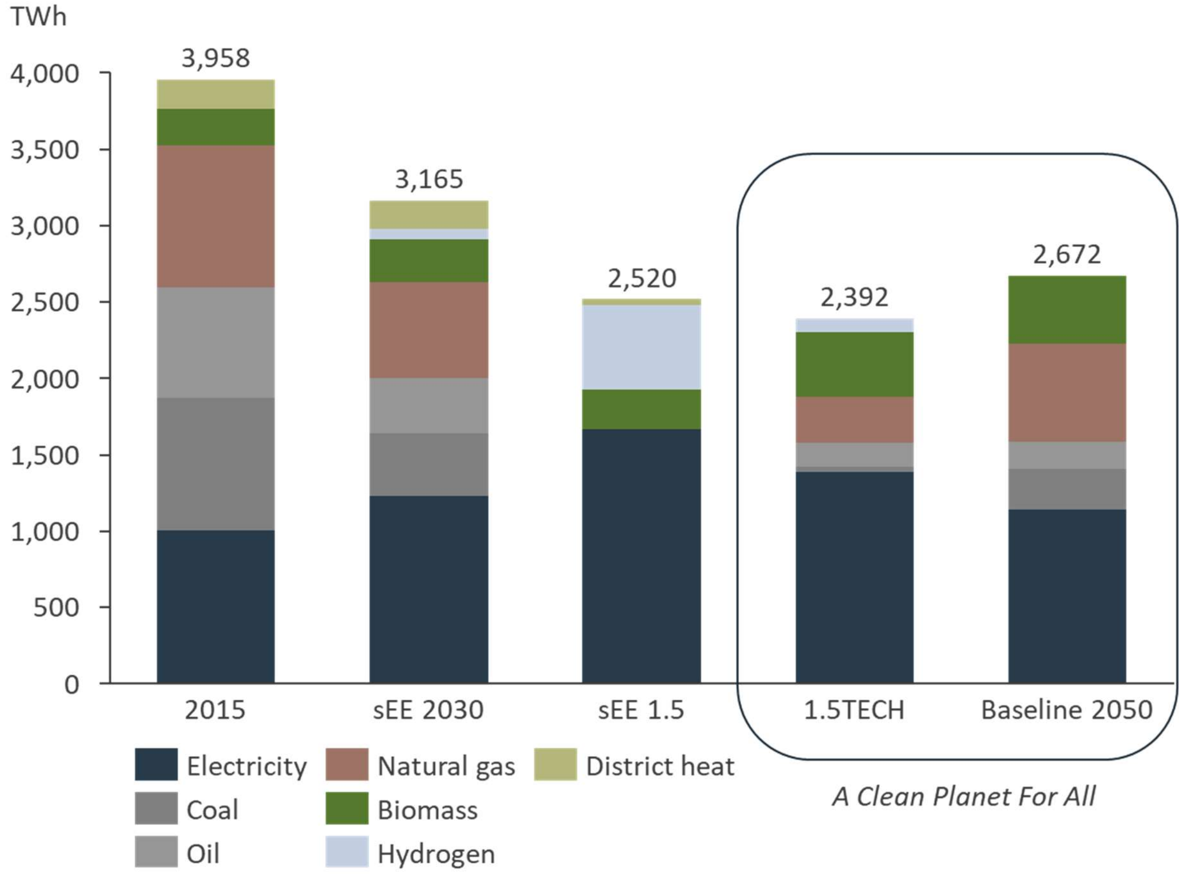
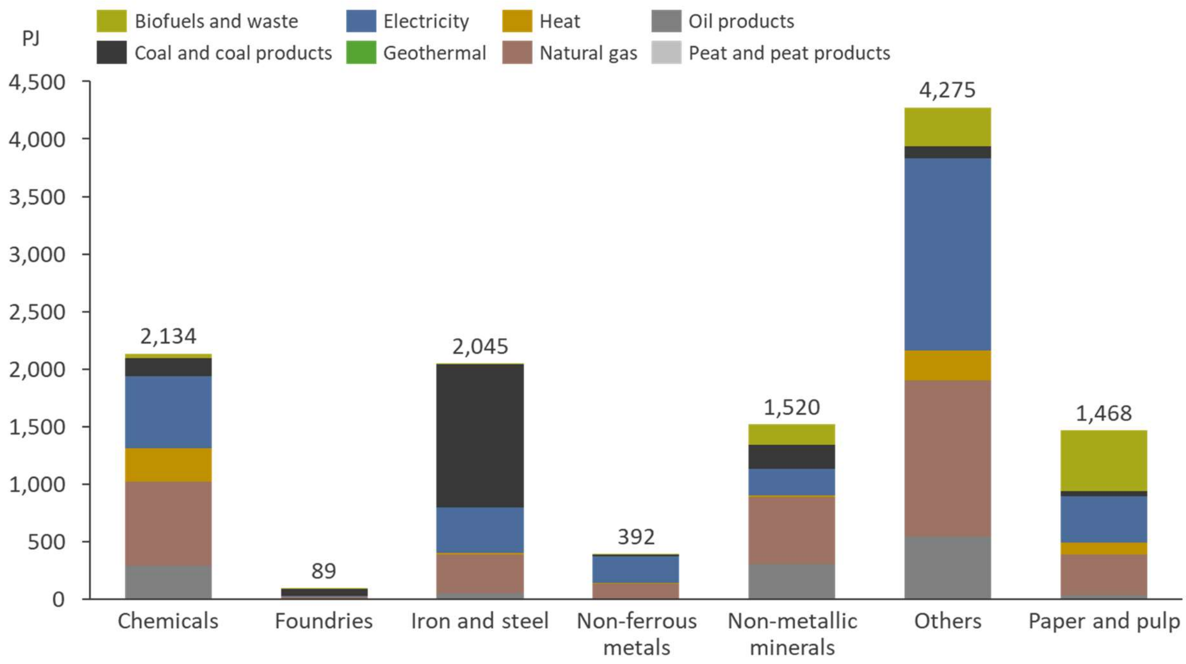


Figure 19: Industrial final energy mix for 2015, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

At sub-sector level, most industrial final energy is consumed in “others” subsector, The “others” subsector can reduce final energy by 25% and be mostly electrified. Chemicals, iron and steel require higher levels of bioenergy. Paper and pulp consume the most hydrogen. (Figure 20). The energy efficiency scenario includes measures for the paper and pulp sector implementing H_2 boilers for chemical pulp, mechanical pulp etc., and by 2050 the possible implementation rate is high. Bioenergy is used as a last resort option for any small amounts of remaining fossil fuels that could not be displaced by other measures available in the scenario.



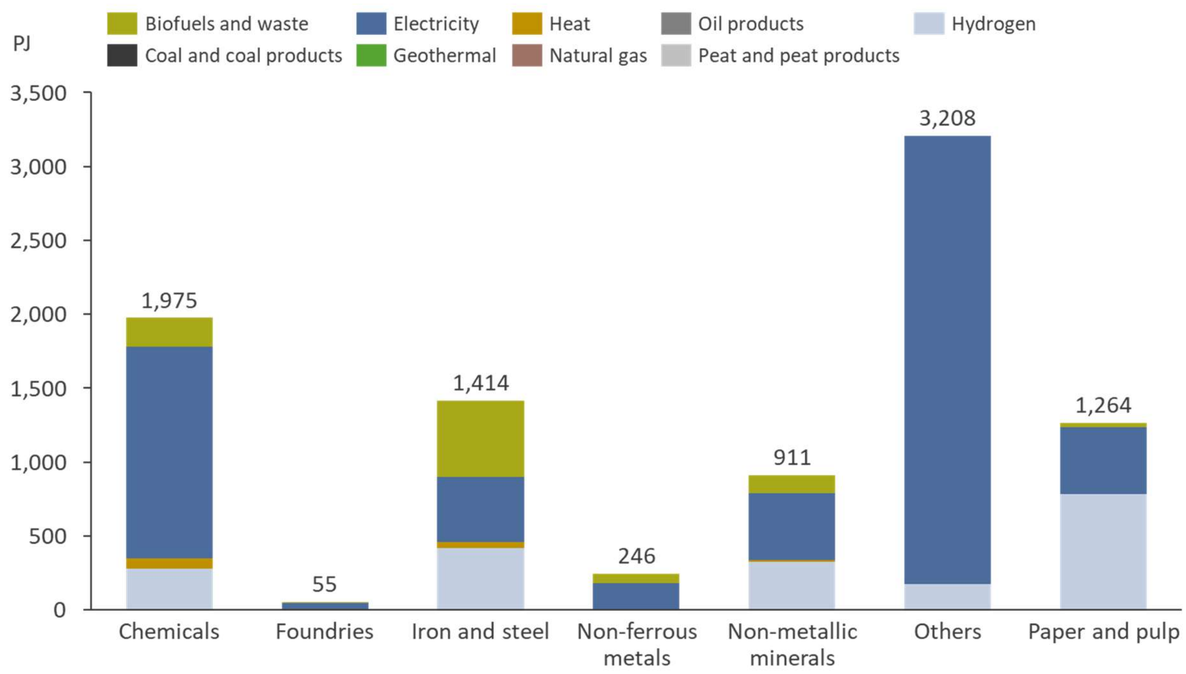


Figure 20. Industry sub-sector energy demand in 2015 (Top) and sEE 1.5 (2050) (Bottom)

Buildings sector

In the building sector, a detailed analysis of building energy refurbishment strategies and heat supply allowed to identify the energy efficiency levels for each country. Existing buildings will account for 90% of the building stock heat demand in 2050. For the EU27+UK aggregated energy system the cost-effective heat reduction for the existing building stock is around 45% from 2015 to 2050. The average heat demand for existing buildings per dwelling would decrease from 234 kWh/m2 to 73 kWh/m^2 from 2015 to 2050. The new heat demand per metre squared is similar to the PRIMES 2030 scenario (European Commission, 2018a). The average refurbishment rate would increase to 1.1.

The heat demand for the total building stock would be 1860 TWh down from 3074 TWh in 2015. (Figure 21). By 2030, 13% of the heat demand could be reduced at a similar refurbishment rate as today. There is also less electrification than 1.5 TECH due to an increase in cost-effective district heating from around 12% to 47% of the heat supply for residential and service buildings in 2050 (Figure 21).

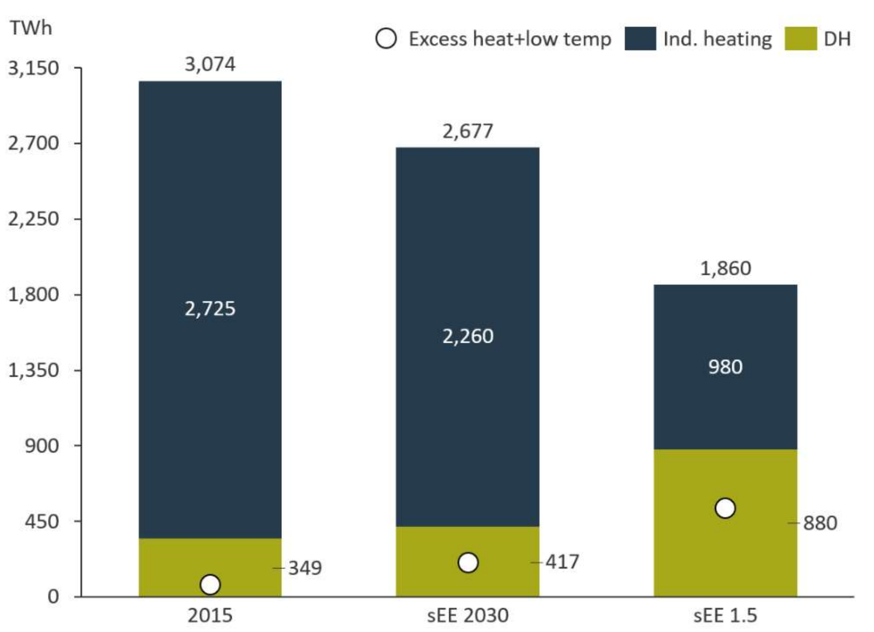


Figure 21. Individual and district heat demand and excess/low temperature heat supply for 2015, sEE 2030 and sEE 1.5 (2050)

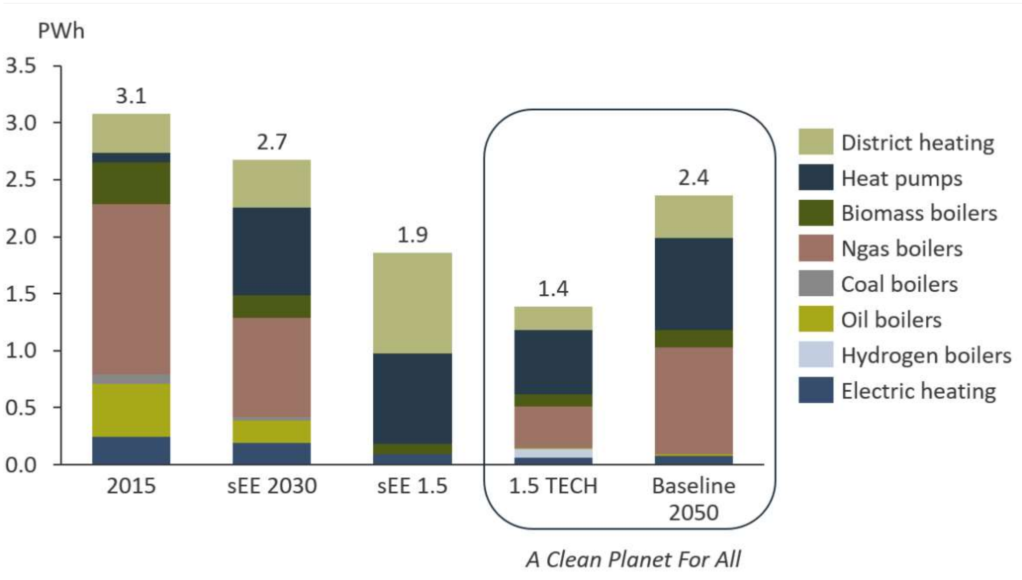
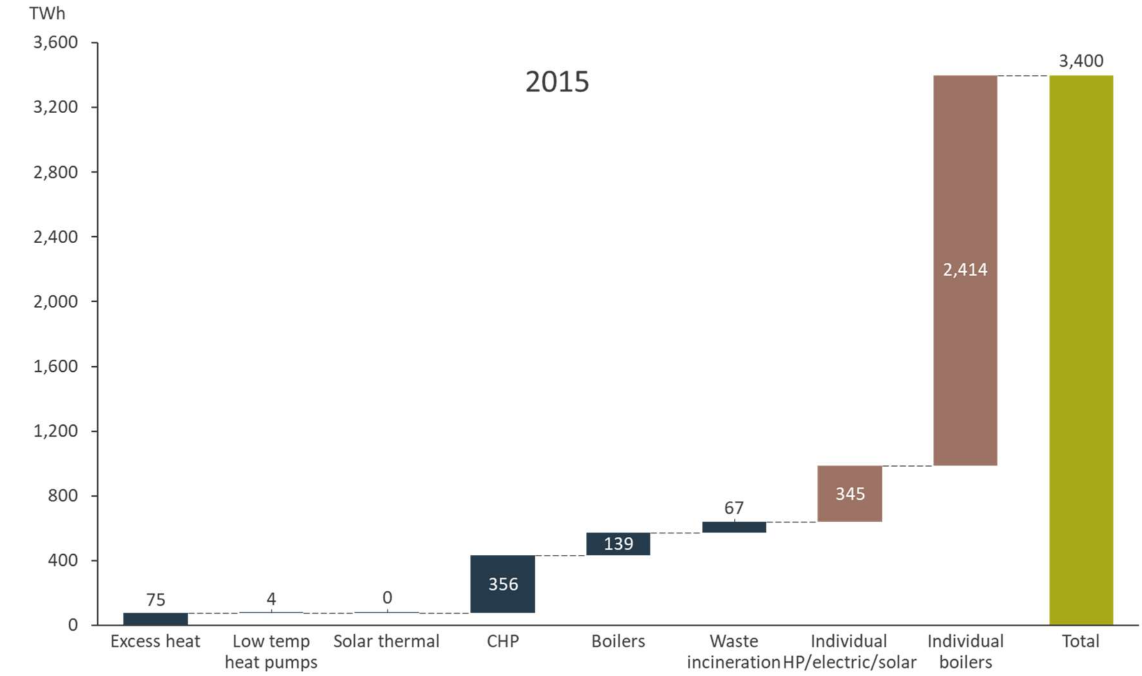


Figure 22. Heat demand sources for buildings in 2015, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

District heating is cost-effective even with lower heat demands due to energy refurbishment in buildings and the decommissioning of large heat producing power plants since the heat supply arises from numerous heat sources (Figure 23). This means the heat supply mix can become more diversified than focusing only on individual heat pumps.

For countries that have district heating already, supply of abundant renewable heat can make the district heating more cost-effective and less resource demanding as the mix of heat sources is expected to grow.



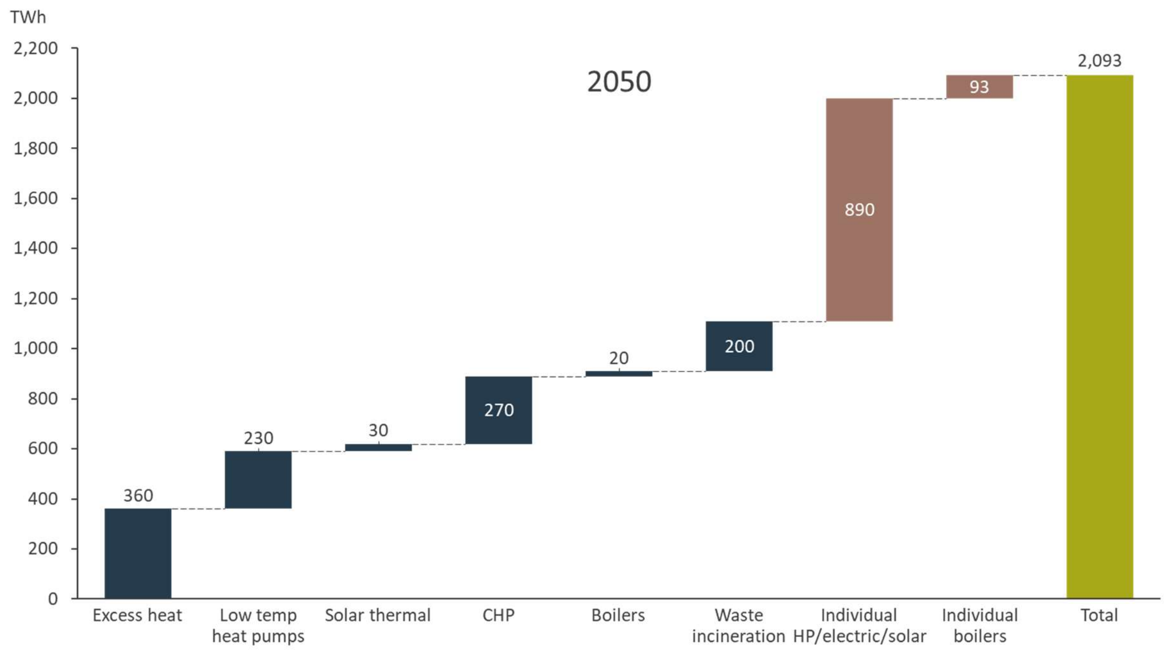


Figure 23. Heat sources for district heating (Dark blue) and individual heating (Light brown) for EU27+UK in 2015 (Top) and sEE 1.5 in 2050 (Bottom)

The heat produced from CHP, boiler and waste incineration is the same between 2015 and 2050 however the mix between the years is different since waste incineration increases and CHP reduces.

District heat can be increased cost-effectively due to the large excess heat and low temperature heat resources and potential for integration in each country (Figure 24). These resources have been quantified in WP4 and WP5. In most countries, the excess and low temperature heat supplies over half of the district heat and over a quarter of the entire heat supply in the country.

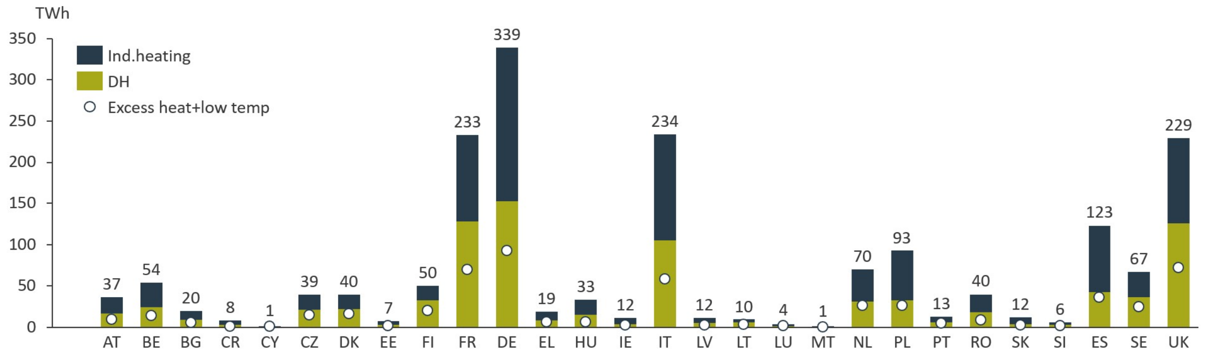


Figure 24. Excess heat from industry, solar thermal and low temperature heat pumps excess heat in DH in each country in sEE 1.5 (2050)

sEE 1.5 and sEE 2030 energy system redesign overview

The energy efficiency measures allowed for a system redesign with some key differences to 1.5 TECH. The electricity demand in sEE 1.5 is higher than 1.5 TECH due to the higher electrification. The differences are primarily given by the higher number of electric vehicles and heat pumps which increase the electricity demand but decrease the demand for fossil fuels and reduce the need for measures such as carbon capture (prevalent in 1.5 TECH). Therefore, primary energy demand is lower than in 1.5 TECH even with higher electricity demand. Higher electricity demand in the flexible and transport demand-type means the energy system is more flexible and capable of integrating fluctuating renewable electricity. Overall, when compared to 2015, sEE 1.5 increases the electricity demand by 150%.

Higher electricity demand can also be identified in sEE 2030. Almost 1000 TWh of new electricity consumption is added to the system, directly reducing even larger demands for oil, gas and coal. Domestic and industrial demand (dark blue in Figure 25) manage to stay unchanged due to more efficient appliances, lighting and other units. Overall, sEE 2030 is again similar to the Baseline 2050, but it frontloads many of the measures that were initially assumed to take place in 2050.

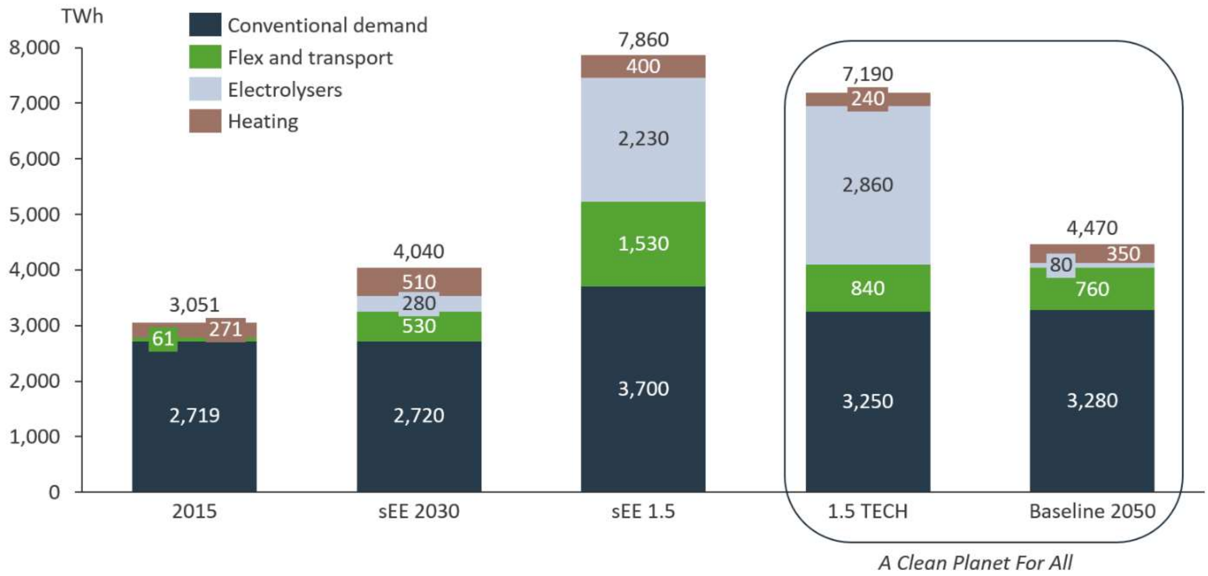


Figure 25. Electricity demand in 2015, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

Hydrogen electricity demand for fuel production is expected to be as high as the total domestic electricity demands, even when considering the very high shares of electrification in transport and heating used in this model and that hydrogen is limited only where electrification is not possible (Figure 26). This is another reminder of how much hydrogen Europe will need in the future even in the energy efficient scenario presented here.

Further, the transport sector retains a small share of the electricity demand despite the high direct electrification rate. In the industry sector the rate of electrification increases, particularly for those types of industry where low heat demands are needed. Here, heat pumps and direct electricity replace large amounts of fossil fuels. Overall, industry energy demands increase towards 2050, but the increase is not reflected to the same level in the energy used by this sector.

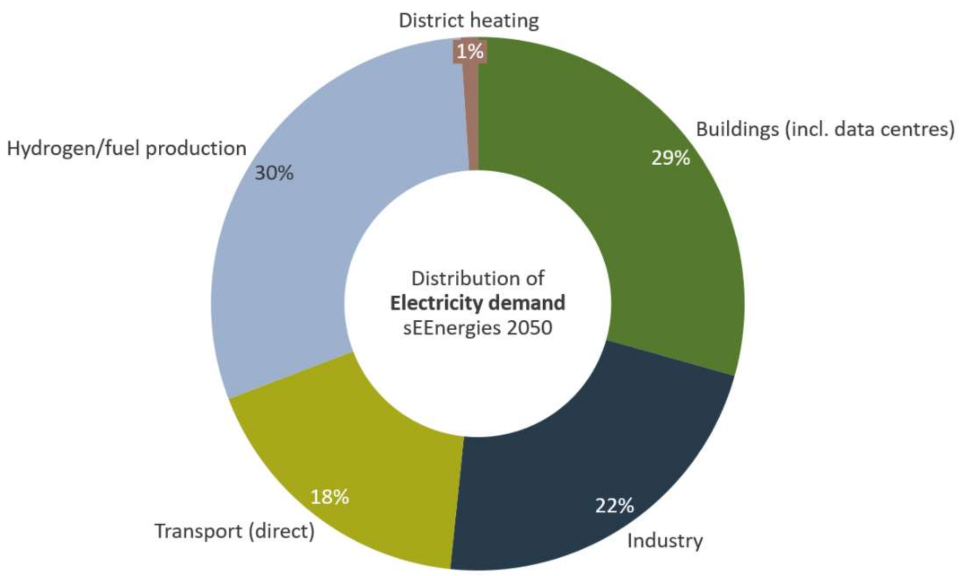


Figure 26. Electricity demand split per energy sector in sEE 1.5 (2050)

The redesign of the energy system in both sEE 2030 and sEE 1.5 implies using large amounts of renewable electricity to support the high electrification rates (Figure 27 and Figure 28). The sEE 2030 scenario implements over 2700 TWh of renewable electricity originating from wind and solar in different proportions. Onshore wind and photovoltaics bring the largest contributions due to the generally larger potential of these technologies across the European countries. In sEE 1.5 the variable renewable electricity further doubles compared to sEE 2030, relying again in particular on onshore wind and photovoltaics.

The sEE 2030 scenario sees similar nuclear production as today, which contributes approximately 15% of the total electricity generation. This also reduces the need for thermal power generation, making sEE 2030 the scenario with the lowest generation of this type. sEE 1.5 sees a complete phase out of nuclear, where it is assumed that all installed capacity today will be phased out by 2050 and no new reactors will be built. From an energy system perspective, this is mainly due to the high cost of nuclear energy in comparison to cheap wind and solar. There are also no indications that nuclear energy will go down in cost, and it still presents safety and security concerns.

The necessity of thermal power plant generation increases to similar levels as in 2015 as a measure to balance and stabilize the energy system with fluctuating renewables. Unlike the 2015 model, this electricity is produced from green gases in efficient gas turbines and engines. On the other hand, 1.5 TECH requires less thermal power plant generation because it assumes the construction of new nuclear reactors. Overall, the redesign of the energy system allows to increase the intermittent renewable share (solar PV and wind) in the primary energy supply up to 80%, while the rest is supplied by bioenergy, mostly for peaking power plants and combined heat and power (CHP) units.

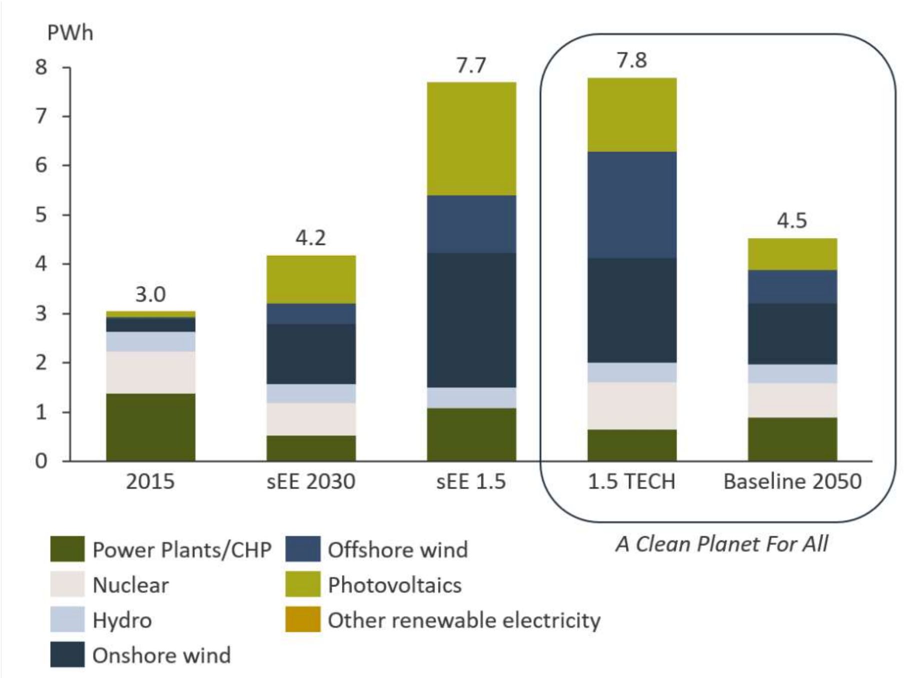


Figure 27. Electricity production supply mix in 2015, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

In terms of overall installed capacities, Figure 28 shows that flexible thermal power plants remain in place despite operating for fewer hours, as a security-of-supply measure.

All types of renewables increase in capacity in sEE 2030 i.e., 520 GW onshore wind, 115 GW offshore wind and 670 GW of photovoltaics. There is significantly higher onshore capacity in sEE 1.5 compared to 1.5 TECH, since the emphasis of 1.5 TECH is towards the offshore wind (450 GW) compared to 265 GW in sEE 1.5. Due to the country-based renewable potential data sEE 1.5 has a higher onshore capacity. Based on the bottom-up approach, each country maximized its own potential rather than relying on a few countries. While this is one modelling approach, more emphasis could be put on offshore wind, but in terms of investments, onshore wind will always be a lower-cost solution. Table 5 illustrates both the potential for variable renewable electricity and the capacities used in each EU member state in the 100% renewable energy systems´ for each country.

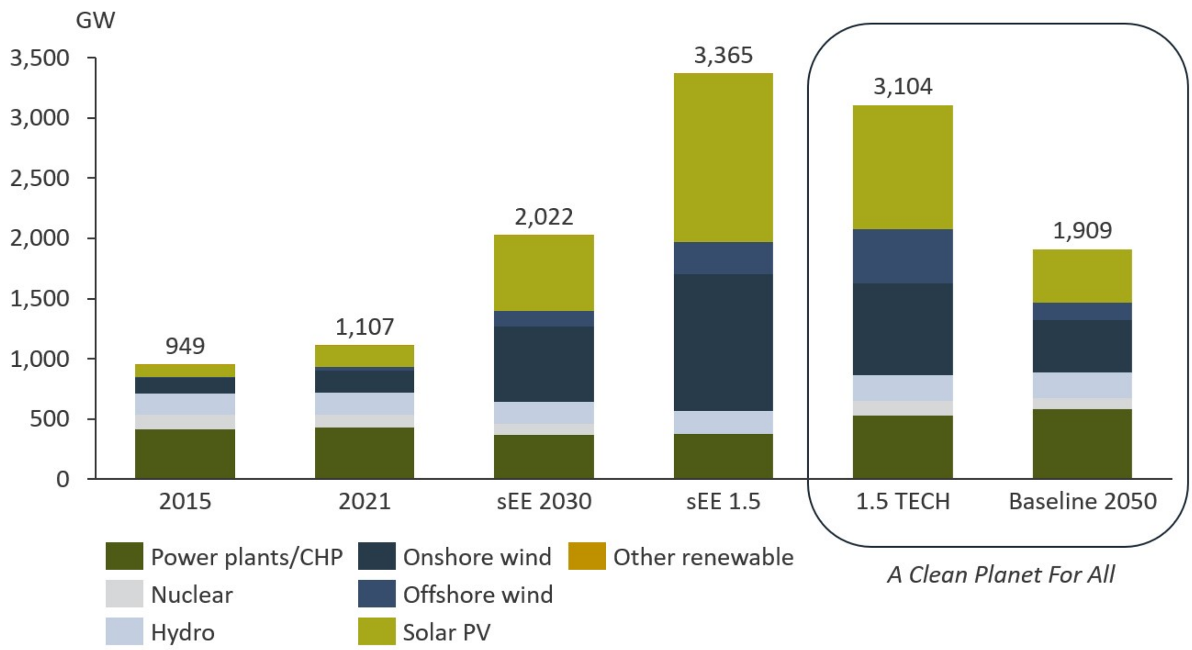


Figure 28. Electricity generation capacities in 2015, 2021, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050

Table 5. Variable renewable electricity potential in each country versus actual capacity in the country models

2050	Offshore (GW)				Onshore (GW)				Solar PV+CSP (GW)	
	sEE 1.5	JRC (Ruiz et al., 2019)			sEE 1.5	JRC			sEE 1.5	JRC
		Low	Med	High		Low	Med	High		85W/m² 3%
AT	-	-	-	-	18.0	30	15	73	38.9	73
BE	5.0	-	2	2	24.0	1	18	24	52	52
BG	-	-	-	62	15.5	88	155	167	13.4	149
CR	2.5	1	5	179	6.4	22	54	61	4	50
CY	0.6	-	-	48	1.5	4	6	11	1.9	12
CZ	-	-	-	-	26.5	13	93	117	17.5	112
DK	13.0	-	27	235	9.6	13	55	83	8.5	76
EE	1.0	-	1	62	2.2	23	27	46	1.7	28
FI	14.0	14	21	293	20.5	27	31	59	12.0	36
FR	11.5	3	16	736	200.0	296	906	1051	217.0	822
DE	85.0	1	28	106	86.0	86	144	463	440.0	494
EL	-	-	-	301	25.0	225	264	270	19.5	157
HU	-	-	-	-	18.0	111	133	220	7.5	161
IE	-	1	1	828	13.5	71	147	164	6.0	113
IT	6.0	1	6	590	156.0	212	292	376	152.0	443
LV	-	5	15	134	2.6	57	128	142	0.5	48
LT	-	-	3	21	7.5	50	111	123	4.5	93
LU	-	-	-	-	5.9	-	2	2	6.0	3
MT	0.95	-	-	129	-	-	-	-	0.85	1
NL	49.0	-	48	97	13.0	4	49	49	67.0	67
PL	12.0	-	12	119	57.0	121	105	523	78.0	447
PT	-	-	-	115	27.0	64	102	110	23.0	92
RO	5.0	-	9	109	21.0	227	387	418	19.0	381
SK	-	-	-	-	13.0	14	45	52	10.1	60
SI	-	-	-	-	3.0	3	7	8	7.2	18
ES	5.0	-	1	434	152.0	838	1098	1140	102.0	658
SE	11.0	11	31	555	57.0	125	138	198	18.0	71
UK	44.0	44	104	2,008	152.5	166	230	436	70.0	347
EU28	266	81	330	5,157	1,134	2,891	4,742	6,386	1,398	5,064

Energy storages are important components in the sEE 1.5 and sEE 2030 scenarios and supplement the extensive electrification and cross-sectorial integration (Figure 29). The renewable energy system is balanced with new types of energy storage and bridging technologies such as district heating, electric vehicles, electrolysis or fuel syntheses. Conventional gas and liquid storages already exist today in all countries and are used to store natural gas and oil products in large quantities, with capacities of 1,100 TWh for natural gas and 1,300 TWh for oil product storage. Due to the significant reduction in both gas and liquid fuels by 2050 these storages are already sufficient to meet the future demands. Many of these storages can be adapted to work with new gases (like hydrogen or green gases) and liquid fuels (like electrofuels). Electrofuels add electricity flexibility and storage to the electricity sector and short-term storage (3 months) of electrofuels is a significant component of the energy storage arrangement in the energy system in the renewable energy systems (Figure 29).

1.5 TECH does not have thermal storage, since district heating is a small and marginalised energy system component. However, thermal storage for district heating systems is required and should be expanded in every country at a larger scale since it can offer system flexibility that few other storages can offer at this cost level.

Direct electricity storage is also part of the system redesign, and all scenarios utilise it in individual and vehicle batteries. Small individual electricity capacities are used in stationary storage for load balancing, intra-day market and as energy reserves, and this is also reflected in all country scenarios. However, the overall storage capacity of individual batteries is insignificant compared to other electricity storing capacities. Pumped hydro would not increase to 2050, since direct electricity storage in electric vehicle batteries and individual batteries would supplement pumped hydro.

Hydrogen storage develops significantly in the sEE scenarios and 1.5 TECH, however sEE1.5 has higher capacity to increase system flexibility. In the sEE scenarios hydrogen has the role of bridging the electrolysis and fuel syntheses and does not operate as a long-term storage, while this appears to have another role in 1.5 TECH, where hydrogen is used directly in boilers or industry.

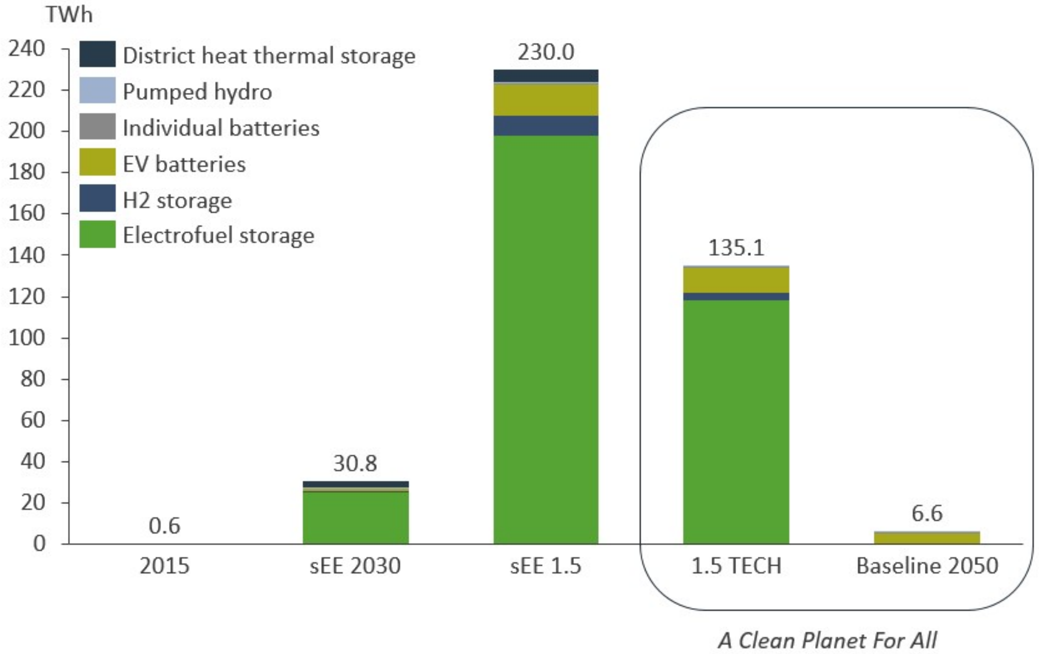


Figure 29: Energy storage in 2015, sEE 2030, sEE 1.5 (2050), 1.5 TECH (2050) and Baseline 2050. The gaseous and liquid fuel energy storages that exist today are excluded from the graph (>2.000 TWh).

Resource security and health impacts

Resource security especially regarding bioenergy becomes critical in sEE

1.5. In this scenario, biomass consumption is restricted to 3,130 TWh per year, which is in line with the reference scenario from the JRC ENSPRESO project (2019) of 3,200 TWh (EU27+UK) (Ruiz et al., 2019) or 21.8 GJ/capita (based on 2050 population forecast (European Commission, 2018b).

Although the overall bioenergy demand is within sustainable levels, there is a substantial imbalance between bioenergy potential and demand in five major countries – Belgium, Germany, Italy, Netherlands, and United Kingdom (Figure 30). This means that bioenergy trade will become more important for the future energy system sourcing bioenergy from bioenergy rich countries such as Romania, Sweden, France and Finland. Alternatively, countries with abundant bioenergy would develop bioenergy demanding energy sectors.

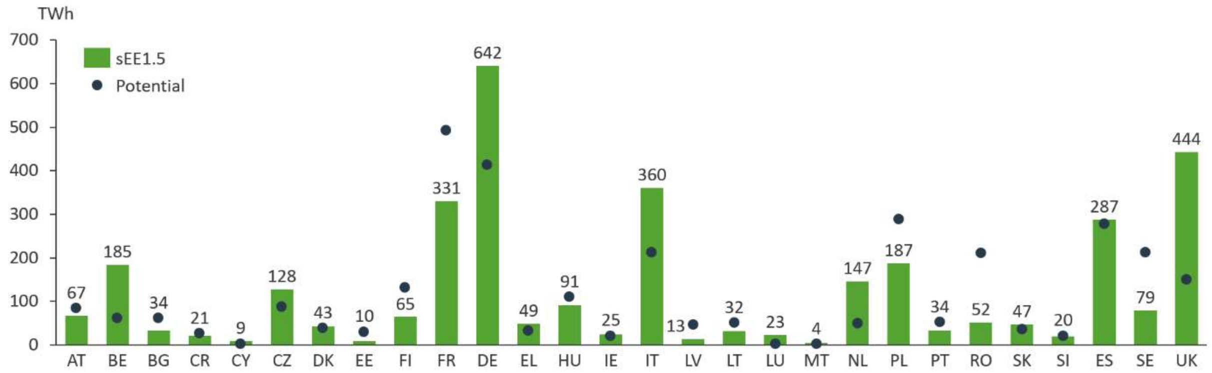


Figure 30: Bioenergy demand and potential supply per country in sEE 1.5 (2050)

Bioenergy is consumed in three main forms, biogas, solid biomass and waste (municipal). Both CHP and power plants consume 60% of bioenergy which is mostly biogas (75%) supplemented with solid biomass (Figure 31). As mentioned above, less than 20% of the electricity would be produced with bioenergy.

Electrofuel production directly consumes 15% of the bioenergy however, there is also indirect consumption from the electricity generated and used for electrolysis and direct transport electrification. Industry consumes 8% of the bioenergy directly and indirectly consumes bioenergy via electrification. As mentioned above the bioenergy per country depends on the energy system configuration and the bioenergy resource demand needs to be considered when reconfiguring the energy system placing high bioenergy demand near where bioenergy is more available. For more details about the bioenergy consumption per country, the EnergyPLAN models can be downloaded at energyplan.eu/seenergies.

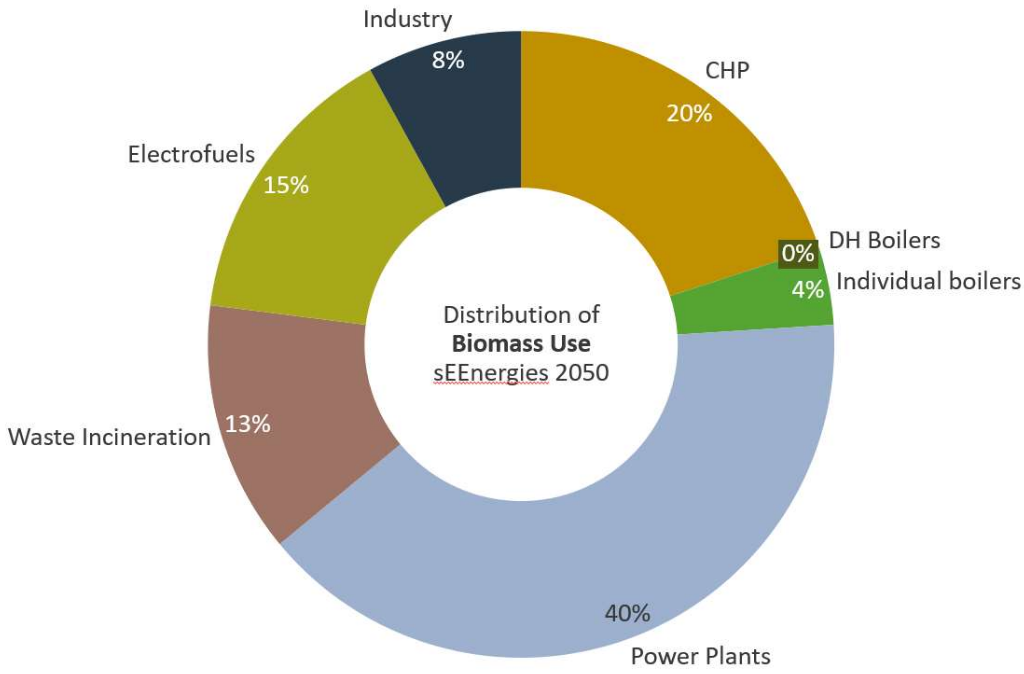


Figure 31: Bioenergy consumption per energy sector in sEE 1.5 (2050)

Health impacts

Across all sectors and scenarios, human health costs are primarily linked to NO_x emissions due to the significant emissions (Table 6). Total SO_2, NO_x and PM2.5 emissions with the greatest costs originating from the transport sector (Figure 32). Total health costs are significantly lower in sEE 1.5, due to the conversions to bioenergy and more renewable energy in the electricity system and extensive electrification of the transport sector which generates significant energy savings and reductions in emissions.

Table 6. Total SO_2, NOx and $PM_{2.5}$ Emissions

Tons/year	SO_2	NO_x	$PM_{2.5}$	Total
2015	1,852,420	8,250,134	239,641	**10,342,196**
2050 Baseline	784,335	4,241,963	131,814	**5,158,112**
2050 sEEnergies	260,565	1,921,135	83,038	**2,264,738**

These costs are reduced to approximately 71 billion EUR/year, from approximately 299 billion EUR/year in 2015 and 154 billion EUR/year in the PRIMES 2050 Baseline. Therefore, if the energy efficiency measures of the sEE 1.5 scenario are implemented throughout Europe, there will be savings of approximately 228 billion EUR in 2050.

In EU 2015, the largest share of health costs is linked to the emissions of petrol, diesel and jet fossil fuel in the transport sector (Figure 32).

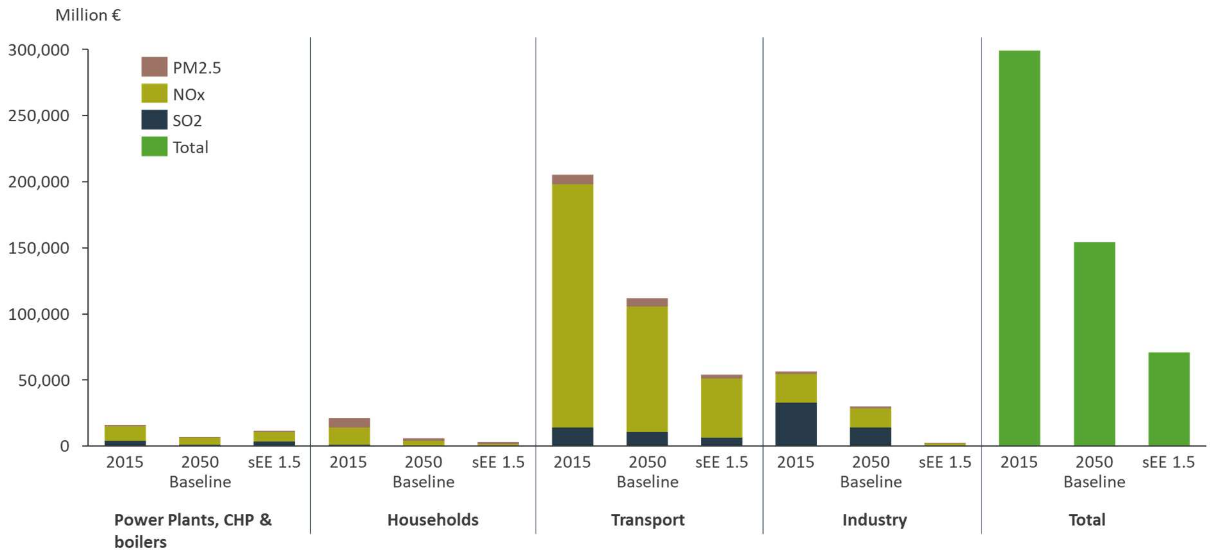


Figure 32. Total health costs by pollutant type and sector in sEE 1.5 (2050) in comparison to 2015 reference scenario and Baseline 2050

Sensitivity analyses for expanded insights

Several sensitivity analyses were performed in this study to determine their effect on the sEE 2030 and 2050 models. The sensitivity analyses can go in many directions and cover many technologies and assumptions, both technical and economic. In this section five scenario have been chosen, which may be considered extreme, but nonetheless probable. The role of this analysis is therefore to illustrate that some configurations and measures are more important than others, but also to explain why some of these measures have not been included in main models. All EnergyPLAN models are available at energyplan.eu allowing users to carry out more sensitivity analyses.

sEE 2030

The results for the sEE 2030 analyses have been split in three main sensitivity analyses. Figure 33 shows the fuel consumption and system cost differences compared to the sEE 2030 scenario, while a more detailed explanation of the results can be found below the figure. Each scenario is overlaid on the main scenario to understand the system changes in case parts of the system do not change.

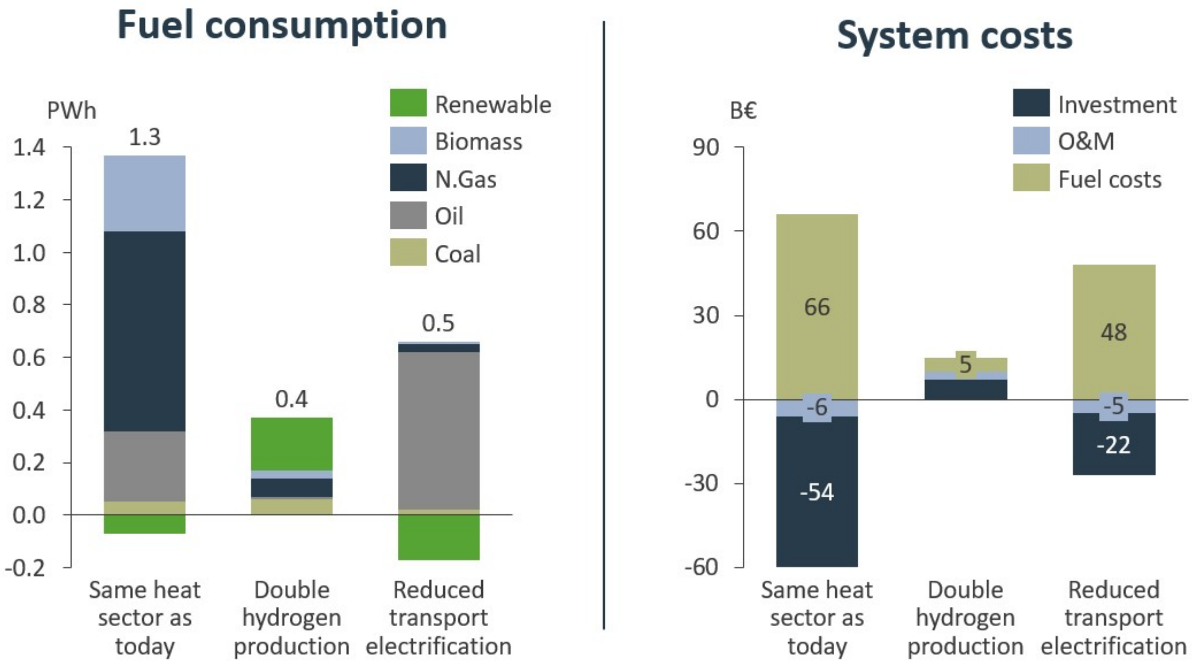


Figure 33. Variations in fuel consumption and system costs between the main sEE2020 scenario and three sensitivity analyses

Same heat sector as today

The first analysis illustrates the system effects of not changing the heating sector compared to the one in place today. This means that there are no heat savings, no replacement of gas boilers with heat pumps, no expansion of district or use of waste heat. This way the differences in the energy system are stark. Gas demand is 700 TWh higher while biomass and oil demands are also increased due to their higher use in heating. This is also reflected in the costs, which show that 66 B€ more would have to be spent annually on fuels, although a similar amount would be "saved" on investments and O&M. Therefore, not taking action on the heating sector is the worst alternative on the heating sector, with higher impact than not investing in electrification of cars and vans.

Doubling the hydrogen production

An alternative scenario to the energy system would be the production of additional amounts of green hydrogen. Hydrogen production in sEE 2030 is already high but is in line with the EU28 demands for decarbonisation and upscaling of hydrogen. Producing more hydrogen will then require more renewables, along with other fuels in power plants, because renewables alone cannot take over all additional production because of system balancing needs, which also reflects in additional costs.

Reduced transport electrification

The last sensitivity analysis retracts the proposed developments on electrified transport and illustrates a sEE 2030 model without sufficient level of electrification, where EVs (cars and vans) represent only a 5% market share (compared to the 30% share proposed in sEE 2030). The results less renewable electricity integration and large increases in oil consumption, that represent around 600 TWh compated to the “saved” renewable electricity of 170 TWh. This again illustrates the efficiency of electric cars in reducing fossil fuel consumption despite their higher cost. Overall, such a system without sufficient electric vehicles is more expensive than a system with electric vehicles.

sEE 1.5

Figure 34 illustrates to which extent these scenarios deviate from sEE 1.5 in terms of investment costs, O&M and fuel expenditures. Furthermore, the results and implications of this scenario are explained below.

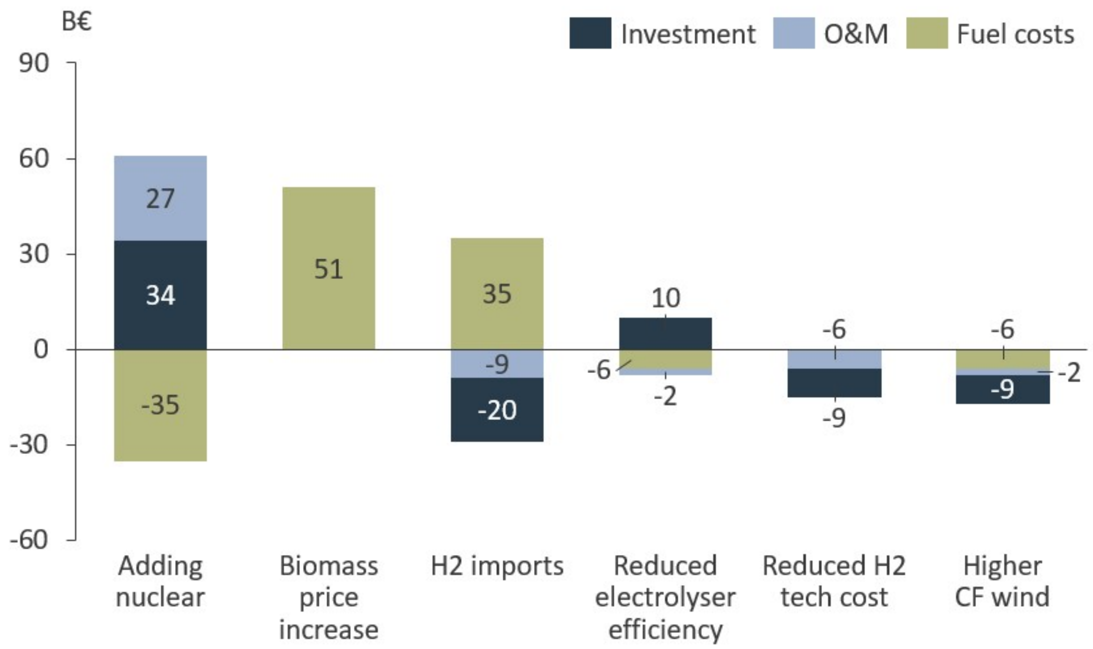


Figure 34: Side analyses with deviations from the main sEE 1.5 scenario in terms of annual investment costs, O&M and fuel expenditures.

Adding nuclear

The addition of nuclear energy to sEE 1.5 has major effects on the energy system. One of these effects is on the primary energy supply, which increases by 1500 TWh, due to the low energy efficiency of nuclear. Two-thirds of this energy is heat, which would have to be wasted, as the system already has sufficient excess heat to supply district heating. Another system effect refers to wind and solar capacities. These decrease marginally, ~35 and ~177 GW respectively, meaning that increasing nuclear production does not absolve the system on deploying large capacities of renewables. The total "saved" capacity is higher than the installed nuclear (120 GW), but while nuclear sees a total investment of 1000 B€, the "saved" wind and solar amounts to ~120 B€.

In effect, the results of this analysis show that nuclear has the potential to reduce biomass consumption in the system, since power plants operate fewer hours. This measure comes however at a high cost, even without including the "difficult-to-account" externalities of nuclear power production. Despite the added nuclear capacity, power plant capacity is still needed in full to deal with the remaining peak demands.

Increasing biomass price

In this analysis the biomass price is doubled, from 6.6 to 13.2 €/GJ. sEE 1.5 uses 3130 TWh of biomass, which is about a third of all fuel consumption in the system, thus doubling the price of biomass significantly increase the energy system costs. In fact, this measure has the largest impact on the system costs among all tested, increasing the system costs by over 50 B€ annually.

Importing hydrogen

In this analysis half of the hydrogen demands are assumed to be imported at a price of 25 €/GJ (3 €/kg hydrogen). This amounts to importing 775 TWh of hydrogen from outside the European energy system, making the system costs particularly dependent on the import price of hydrogen. At the price level used in this sensitivity analysis, the energy system costs are marginally higher than in the main sEE 1.5 scenario. This can mean that if hydrogen import costs are below 2.5 €/kg, then the system may benefit from importing it, assuming that no cost reduction can be achieved within the European system. Another result is that the energy system with hydrogen imports does not loose flexibility with this measure, as sEE 1.5 is already very flexible, but imposing large hydrogen imports on other system designs may produce other results. Another question one should answer in case of such large hydrogen imports is on how the exporting energy system(s) may be affected by such decisions. In all cases, further research should investigate if importing hydrogen is a suitable measure and at what cost this should be done.

Reduced electrolyser efficiency

In this analysis the electrolysis efficiency is decreased from 70% to 60%. The results show that such a measure has limited effects on the energy system. On the one had it requires more investments in electrolysis capacity and renewables to deal with supplying the same hydrogen demand at lower efficiency. The other effect is a reduction in power plant utilisation and effectively in biomass demands, as the energy system uses more renewable electricity, measure that partly offsets the additional investments in wind and electrolysis. However, the energy system with lower efficiency in electrolysis has a higher overall cost of +10 B€. This cost also depends on which type of renewables one chooses to deploy further. The additional 10 B€ in this analysis are identified when increasing offshore wind capacity, but other costs and system effects can be observed if increasing onshore wind and photovoltaics, which are both deployed already at high capacities.

Lower cost for hydrogen technologies

Investment in electrolysis and hydrogen storage is halved from 0.4 M€/MW and respectively 15 M€/TWh. The results of this analysis show a moderate cost reduction in investments and O&M of 15

B€ (considering that the total installed capacity is over 400 GW, with 5000-6000 full load hours), demonstrating that the investment in H_2 technologies can only be limited to marginally reducing the system costs, compared to other measures that involve fuels (H_2 imports, biomass price increase). This measure may make it more attractive producing hydrogen within Europe compared to importing hydrogen.

Higher capacity factor wind

In this analysis, the capacity factor for onshore and offshore wind is increased by 4-5% to 32% and respectively 54%. The reason behind this side analysis was to understand how much the installed capacities would decrease if capacity factors were higher and how robust the renewable capacities proposed in this analysis are. The capacity factor for photovoltaics has not been altered, as that is already considered to be high at 19% (and is a result of the country-based models).

Wind was particularly interesting as the capacities used in sEE 1.5 (1135 GW onshore and 265 GW offshore) are significantly different than the ones presented in the 1.5 TECH scenario (758 GW onshore and 451 GW offshore), or at least, more focus is put on offshore wind than onshore. The reason behind the higher onshore capacity in sEE 1.5 stems from the country-based models, rather than an optimisation on a European system level. However, the results of this analysis still show that large capacities of wind of both types are necessary, around 1000 GW onshore and 250 GW of offshore wind when using the higher capacity factors. This also shows that the total wind capacity is now closer to the one proposed in 1.5 TECH, but that high renewable capacities are still needed irrespective on the assumptions on capacity factors.

Investment strategy and ranking of energy efficient measures

Considering the current international energy crisis, the high focus on natural gas, the economic situation, high inflation rates and global logistical challenges, it is important to identify the most critical investments and prioritizations. In sEEnergies investments are prioritized between what can happen faster, with known technology, towards sEE 2030, and what should happen in the longer term towards sEE 1.5. In this report we accelerate those elements we believe are possible to accelerate.

This section provides an overview of the major investments for different energy system components for two periods namely, 2020-2030 and 2030-2050. These components are categorized into '*System redesign*', '*Energy supply*' and '*Energy Efficiency*' (mostly demand-side) measures. There are a total of 15 system components or technology collections with a total investment cost of around 9 trillion euros until 2050. Figure 35 summarizes the major investments (> 20 billion €) for the two periods.

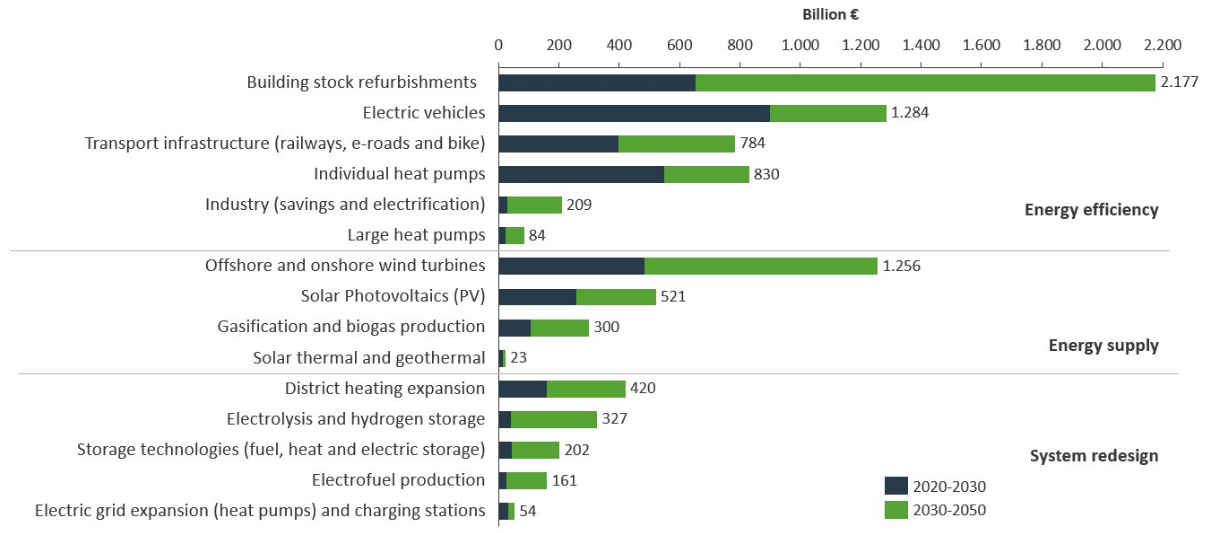


Figure 35. Investment strategy for sEE 2030 and sEE 1.5 in 2050

A system redesign based on the energy efficiency first principle and renewable energy entail that the energy system changes from a system with high fuel cost to a system with very high investments. In energy-efficient 100% renewable energy systems the increase in investments is compensated by the decrease in the variable costs such as fuel costs for the system. The annualized costs in a smart energy system using synergies across sectors, combining energy efficiency and energy storages with renewable energy are lower than the costs of more traditional energy systems such as the EU Baseline for 2050 or the 2050 1.5 TECH system proposed by the EU Commission (see Figure 36). In sEE 1.5 for 2050 we can keep the overall system cost at a level of about 10% lower than of the Commission's scenarios.

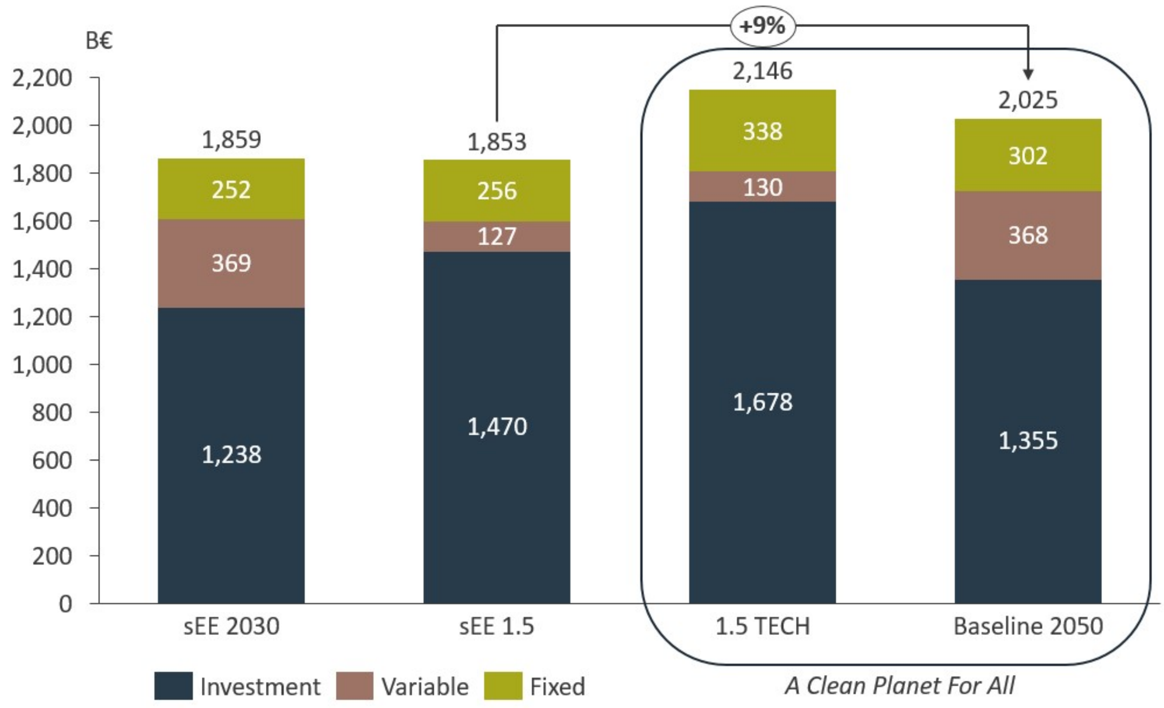


Figure 36. Socio-economic costs for sEE 2030 and the three scenarios for 2050

Both energy efficiency (demand side) measures and energy supply measures are critical in redesigning the system to cross-sectorial based smart energy systems. The former includes investments in measures that directly reduce the final energy consumption such as heat demand savings, changes towards an energy-efficient urban development, electrification of the transport and industry sectors, etc., whereas the latter includes energy supply measures such as replacing more power plants with existing renewable energy supply technologies such as wind and solar. The supply system and end-demand systems are combined with conversion technologies, energy grids and energy storages to form a smart energy system. This avoids the so-called *'silo thinking'*, where optimization is done in each sector or energy vector instead of the energy system.

Table 7 outlines the capacity development for components we suggest investments in from 2020 to 2050 for EU27 and the UK.

Table 7. Selected key energy system component development until 2050

Energy System Component	2020	2030	2050	Δ (2020-2030)	Δ (2030-2050)
Buildings - heat demand (TWh)	3.2	2.86	1.9	-11%	-34%
Electric Vehicles (Million units)	2.7	95	299	3419%	215%
Individual heat pumps (Million units)	14	70	113	400%	61%
Large heat pumps (GW)	0.5	8.2	31	1540%	278%
Offshore wind turbines (GW)	22	115	266	423%	131%
Onshore wind turbines (GW)	169	520	1135	208%	118%
Solar Photovoltaics - PV (GW)	131	670	1398	411%	109%
Gasification plant capacity (GW)	0	3	118	-	3833%
District heat production (TWh)	0.6	0.71	1.08	18%	52%
Electrolyser capacity (GW)	0	50	456	-	812%

Investment strategy 2020 – 2030

Towards 2030, it is important to front-load some key investments. Energy efficiency in buildings is one of the largest investments, and a measure that takes time to implement. By 2030, the effects are 10% end demand savings on natural gas and other fuels. The other main measure for buildings is household heat pumps, which can be implemented to a significant level by 2030. District heating is another essential infrastructure for buildings. By 2030, district heating should cover 20% of the demand with 8.500-9.000 new district heating systems that can ensure further developments of district heating towards 2050 as these are expanded. This also requires planning regarding where to plan and invest in district heating and where to invest in individual heat pumps, as heat pumps can undermine the cost-effectiveness of district heating. i.e., heat pumps must be implemented first outside larger cities and e.g., only partly in natural gas-heated buildings.

Electrification of transport and industry, as well as heating, serves as a low-hanging fruit in redesigning the energy system in the short term. In industry, heat pumps and electricity can cover large amounts of demands currently met by natural gas and other fossil fuels. In transport, large energy efficiency gains are present with electric vehicles in passenger cars, short-haul ferries, vans etc. For instance, the number of electric vehicles increase from 2.7 million units in 2020 to 95 million units in 2030. Replacing inefficient demand-side technologies such as combustion engines with electric motors and technologies increases the overall electricity demand of the system, but at a much lower rate than the fuels replaced.

Similarly, for the heating sector replacing old fossil-based individual boilers with more efficient individual heat pumps also increases the energy efficiency of the system, while also increasing the overall electricity demand. By 2030 a ramp up of electrolysers is projected to cover hydrogen demands in industry and to start the transition of heavy-duty transport, primarily marine and aviation, using electrofuels. While it is important to ramp-up and start before 2030, the electrolysers also have a large electricity consumption which must be covered by renewable energy. In the current situation, a balance must be met with the renewable energy dedicated to displacing natural gas and fossil fuels through other more energy efficient measures and renewables dedicated to hydrogen, which should receive lower priority. With these measures in place, the electricity demand increases from 3,051 TWh in 2015 to 4,040 TWh in 2030 (32%).

This increase in electricity demand requires a ramp-up in investments for renewables, particularly in the short term. Hence, in Figure 35 majority of the investments for the period 2020-2030 are for increasing the electrification of the system i.e., increasing EV stock, and individual heat pumps and dramatically increasing the renewable electricity production capacities. From Table 7 it can also be seen that onshore wind capacity needs to be increased by 200% until 2030 while offshore requires a ramp up by 400%.

Investment strategy 2030 – 2050

For the long-term strategy until 2050, it is critical to continue investing in the end demand measures such as heat savings in buildings along with the system re-design measures, such as district heating expansion. Building renovations and refurbishments rank the highest in the investment strategy from 2030 – 2050. The heat demand for buildings needs to be reduced from 2.700 TWh in 2030 to around 1,900 TWh in 2050. The reduction in heat demand allows the further expansion of waste heat use within district heating networks, as well as having higher efficiencies in heat pumps in 2050. This is also when most benefits of a system re-design can be gained, based on the concept of smart energy systems and energy efficiency first principle.

An increased expansion of renewable energy capacity with heat demand savings and an increase in district heating allows us to integrate large-scale heat pumps in the overall energy mix. Thus, reducing the need for CHP (combined heat and power plants) and oil boilers. To create synergies and enable deeper decarbonisation and system integration, it is also important to invest in enabling smart energy system components such as electrolysers, hydrogen, and thermal storage units. These become increasingly important after 2030, as the demand for hydrogen for direct use in industry and the production of electrofuels for aviation and shipping increases. A heavy expansion of renewable energy production is needed especially due to further electrification of transport, industry and the use of electrofuels, where there are significant losses. The system proposed in sEE 1.5 considers a bottom-up approach to the energy efficiency first principle, and even with this deep understanding of the possibilities, large amounts of renewable energy are required.

In conclusion, to achieve a 100 % renewable energy system, the key recommendations include:

- In traditional energy systems, fuels represent the highest share of costs. In future renewable smart energy systems, technology investments are prioritised over variable costs. Our analysis shows that there is a need for over 5 trillion € investments in EE measures in buildings, transport and industry, out of a total of approximately 9 trillion €. More than 2 trillion € should be dedicated to renewable energy and over 1 trillion € spent on system redesign measures. While investments are higher in energy efficiency compared to supply and system redesign measures, it is important to note that all investments should be initiated and implemented simultaneously.
- Building stock refurbishment costs represent the largest investment related to energy savings, followed by investments in the electrification of the transport sector and industry as well as in renewable capacities, primarily wind and solar.
- An investment of 2.2 trillion € is required to reach the final target of 40% heat savings in the building stock by 2050. Such savings enable synergies with our system redesign as it increases

the energy efficiency of the supply system and increases the possibilities to integrate renewable heat and low-temperature heat sources.

- One of the system redesign components is district heating, which requires an investment of 420 billion €, and can unlock the potential of using cheaper heat sources. About 1 PWh or half of the energy savings achieved in the buildings sector is a result of end demand savings due to building stock refurbishments and the other half is a result of system redesign measures and changes in the heat supply.
- Individual heat pumps are an important energy efficiency measure, representing the fourth largest investment of 830 billion € to install more the 100 million units. However, as with unlocking excess heat and low temperature heat in district heating systems, where expansions are in the district heating grids, individual heat pumps also require new infrastructure investments in electricity grids.
- Electrification of the transport sector is done through direct and indirect electrification, where direct electrification wherever possible should be prioritised. 95% of passenger cars and vans are shifted to battery electric vehicles in 2050. In 2030, the number of electric vehicles is estimated to be 95 million and 254 million in 2050. This requires a total of 1.3 trillion €, representing the additional cost to switch to electric vehicles compared to not changing this sector. 900 billion € should be frontloaded, which also makes this the largest investment by 2030 (Figure 35). Furthermore, electrification of heavy-duty trucks is prioritised with the implementation of e-road systems.
- Energy-efficient urban development will reduce the passenger kilometres driven by a car by 16% compared to traditional urban development. In order to achieve this, new investments need to be made predominantly in more efficient modes of transport and such that higher transport demands are not induced in in-efficient modes of transport. This entails a dedicated investment of 784 billion € in predominantly railroad infrastructure as well as e-roads and cycling infrastructure.
- The use of hydrogen and electrofuels should be reserved only for the difficult to electrify modes such as aviation and shipping. Major investments in electrolysis capacities and hydrogen storage of 327 billion € need to be made to provide hydrogen and e-fuels for transport and industrial demands. An additional 161 billion € are needed for e-fuel production. Almost 456 GW of electrolyser capacity is needed in 2050 to cater to this demand. By 2030, the electrolyser investments should remain limited to building limited capacities, since focus is on energy efficient measures.
- The implementation of innovative energy efficiency measures and electrification in industry enables reductions in final energy by 33% from today to 2050, which requires 209 billion €, which includes the increase in production in line with the past trends. Emphasis on energy efficiency improvements and electrification must be high on the agenda in order to avoid extensive biomass consumption when pursuing 100% renewable energy.
- System redesign in high electrification levels requires large investments in establishing renewable energy capacities. Wind power investments are of similar magnitude with the ones for electric vehicles at 1.3 trillion €, which amounts to 1,135 GW onshore capacity and 265 GW offshore capacity. In addition, 521 billion € are required for photovoltaics, amounting to a capacity of 1,400 GW. Investments in gasification and biogas production as well as solar thermal and geothermal are also required.

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Appendices

Appendix A: Technical data

Table A.1. Heat demand in 2015 and for each building refurbishment including investment costs level for each country

	2015	Baseline	Baseline + 20%	Baseline + 30%	Baseline	Baseline + 20%	Baseline + 30%
	Total heat demand (TWh)				Investment costs (Billion euros)		
AT	63	49	39	34	51.1	64.9	92.5
BE	92	72	58	50	43.0	50.4	69.1
BG	30	26	21	18	10.5	15.6	26.4
CR	27	11	9	8	2.0	3.0	3.7
CY	2	1	1	1	1.3	1.7	2.5
CZ	65	53	42	37	9.7	16.4	24.0
DK	63	53	42	37	51.0	62.3	95.2
EE	14	10	8	7	1.5	2.8	3.7
FI	60	50	40	35	35.5	51.2	72.7
FR	416	310	248	217	297.6	341.9	453.9
DE	682	452	362	317	342.6	429.3	565.3
EL	27	25	20	18	13.6	16.2	24.3
HU	56	44	35	31	12.0	18.3	27.8
IE	23	16	12	11	30.0	33.7	44.3
IT	356	312	249	218	150.4	223.8	331.9
LV	22	16	12	11	1.8	3.2	4.3
LT	28	13	10	9	4.7	7.4	8.6
LU	10	5	4	4	3.0	3.6	4.4
MT	1	1	1	1	0.8	969	1.5
NL	116	93	75	65	74.3	88.2	119.7
PL	178	123	99	86	31.0	56.7	85.2
PT	20	17	14	12	13.0	16.4	25.5
RO	50	40	32	28	5.6	12.8	18.5
SK	48	16	13	11	7.0	11.2	13.4
SI	20	8	7	6	2.2	3.4	3.8
ES	244	116	93	81	61.2	163.5	131.5
SE	78	67	54	47	82.6	117.2	174.2
UK	382	305	244	214	289.2	363.8	500.9
EU	**3,073**	**2306**	**1.845**	**1.614**	**1,628**	**2,180**	**2,929**

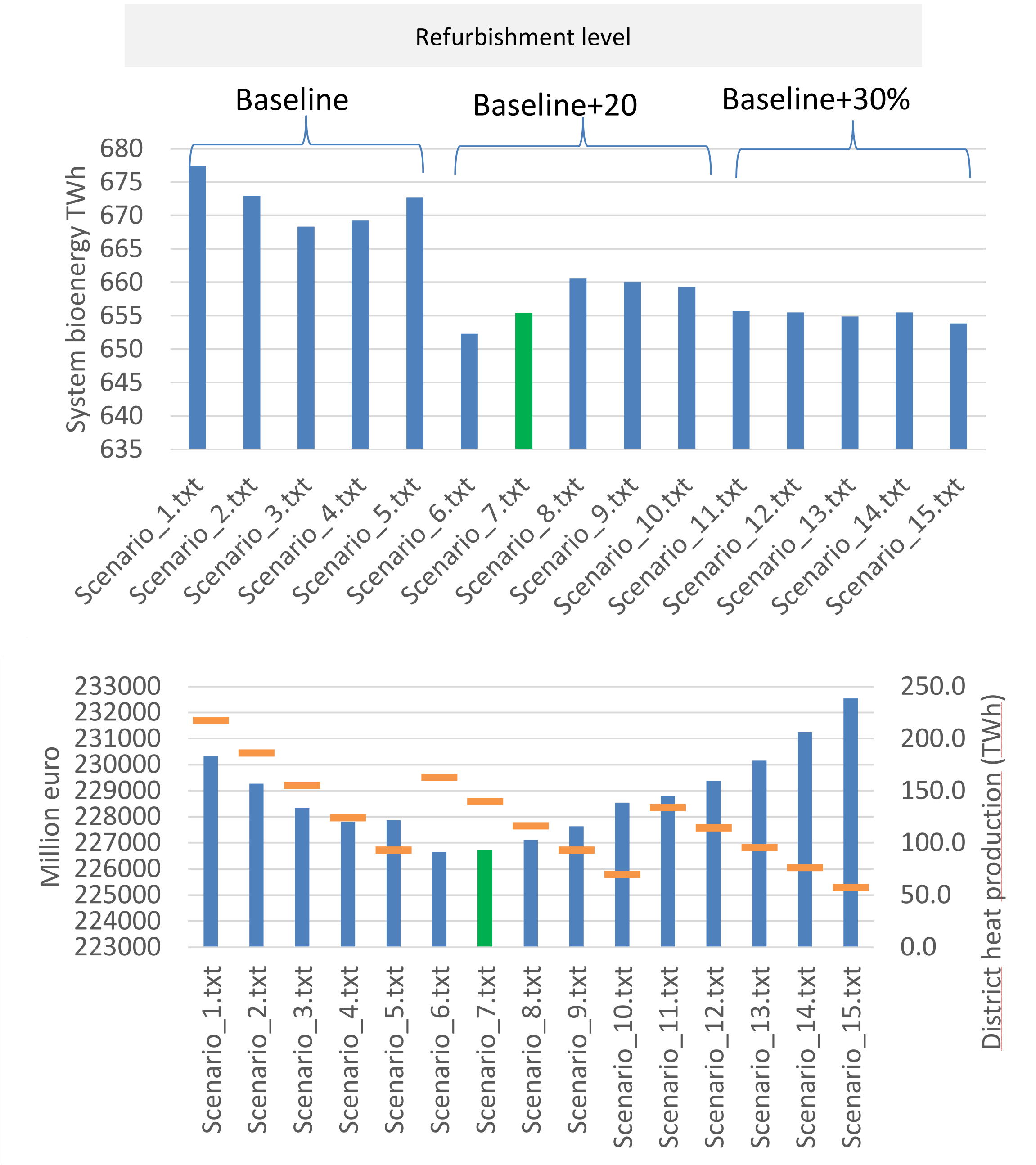

Figure A.1. Sample country results for 15 scenarios showing system bioenergy demand and annualised costs for different building refurbishment strategies and district heat production (orange line) and individual heat shares. The level of refurbishment depends on the system impacts. System analyses were done for each country due to their differing building stocks, heat supply options and the impacts that these combinations have on the rest of the energy system. The scenario results for bioenergy and system socio-economic cost for an example country are presented here. The district heat level starts at 30% for this country since it already has above 20% district heat in its heating system. In this example, Scenario 7 with 60% district heat and 40% individual heat would be selected due to low bioenergy and socio-costs compared with the other scenarios.

Table A.2. Most feasible scenario heating data for each country for the building sector

	2015 kWh/m² stock average	2015 stock kWh/m² in 2050	kWh/m² heat reduction of 2015 stock to 2050	Refurbishment rate
AT	122	68	48%	1.1%
BE	159	85	49%	1%
BG	104	67	42%	1.3%
CR	234	73	72%	1%
CY	36	19	50%	1.1%
CZ	143	82	46%	1%
DK	155	97	42%	1.1%
EE	215	120	50%	1.1%
FI	202	171	22%	1%
FR	112	61	50%	1%
DE	131	67	54%	1%
EL	60	43	35%	1%
HU	133	74	49%	1.1%
IE	79	34	58%	1%
IT	143	90	41%	1%
LV	225	127	49%	1.1%
LT	219	73	70%	1%
LU	248	77	68%	1%
MT	38	25	34%	1.1%
NL	142	79	49%	1%
PL	136	68	53%	1.1%
PT	40	26	41%	1%
RO	109	63	47%	1.1%
SK	195	50	77%	1.1%
SI	206	66	70%	1%
ES	64	50	18%	1.3%
SE	121	99	23%	1.1%
UK	134	75	47%	1.1%
EU	**123**	**70**	**46%**	**1.1%**

Appendix B: Additional Impacts of Energy-Efficiency Measures: A Systemic Overview of their Implications across Societal, Ecological and Economic Dimensions (Deliverable 6.35 provides a fully detailed overview of additional impacts for the transport, industry and building sectors).

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

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

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

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

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

In the following section, we will provide an overview of the additional impacts considered in Reiter et al. (2021), Næss et al. (2021), and Kermeli & Crijns-Graus (2021), which are discussed in further detail in D6.35. Although there are numerous ways to categorise additional impacts (see Cagno et al., 2019), we have chosen to discuss them here in terms of their effects within and across socio-economic, geo-political and ecological dimensions, as well as their relevance and magnitude within and across the building, transport, and industry sectors. In this way, we maintain a systemic perspective on the non-energy related role energy efficiency can play in Europe's energy transition and sustainability agenda.

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

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

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

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

The following Table X provides a detailed overview of the additional impacts of energy efficiency across the three sectors. For some of the impacts, quantitative assessments of the impacts compared to a business-as-usual trajectory were conducted and are included in the table below. However, for the majority of impacts, only qualitative descriptions are provided. As in Næss et al. (2021), a qualitative metric is applied to indicate the degree to which an additional impact is positive or negative, judged against relevant environmental and social criteria.

Table 1. Comprehensive overview of additional impacts.

Qualitative assessment of impact: Substantially positive (+++), Considerably positive (++), Moderately positive (+), Ambiguous (+/-), Moderately negative (-), Considerably negative (--), Substantially negative (---)

Sector	Energy Efficiency Measures	Impact on GHG Emissions	Impact on Air Pollution	Impact on Noise Pollution	Impact on Pollution of Soil, Watercourses, and Groundwater	Impact on Material Consumption	Impact on Land Use	Impact on Employment	Impact on Working Environment	Impact on Quality of Human Life	Overall Impact / EE Measure
Building	**Envelope refurbishment measures incl. windows, walls, roof, floor, and façade painting**	++ Embodied emissions of refurbishment materials, however reductions in heat demand via improved insulation of building envelope (especially roof and windows) induce reductions in GHG emissions.	+ Improvements in building ventilation and heating systems induce reductions in indoor and outdoor air pollution.	++ Reductions in indoor noise pollution via envelope improvements, (especially better insulated windows and walls) since the capacity of insulation materials to reduce thermal transmission correlates with their ability to absorb outdoor noise.		+/- Building refurbishments likely to induce an increase in material consumption, such as windows and insulation materials, however, result data did not provide sufficient insights into the correlation between material needs and efficiency improvements of building envelope.		+ Net job creation due to building refurbishment measures.	+++ Improvements in indoor building conditions, such as air and noise pollution translate to improvements in working environment and employee performance, when taken in the context of office buildings.	++ Reduced levels of air and noise pollution, increased thermal comfort, reduced moisture issues (especially related to insulation measures); increases in disposable income through energy savings; energy affordability and energy access; however, several factors reduce the likelihood of such positive impacts, e.g., tenant-landlord dilemma.	Building refurbishment measures have direct impacts especially related to social and socio-economic factors, since the measures induce explicit changes in the indoor conditions for (human) living and working spaces. Socio-ecological impacts are mostly linked to reductions in heat demand and the related emissions, as well as the various life cycle stages of the refurbishment materials.
Transport	**energy-efficient spatial urban development**	+++ Reduced motorised transport due to concentrated urban development.	+/- Reduced traffic volume, but increased concentration of emissions as a result of inner-	+/- Reduced traffic volume, but more people exposed to noise as a result of inner-city densification.		++ Reduced material needs for dense building types, and shorter networks of pipes, roads,	++ Reduced land conversion of natural areas, but increased pressure on intra-green spaces.		+ Dense cities can lead to higher levels of productivity and innovation.	+/- Dense cities can incur lower levels of safety, but higher levels of urban vibrancy and accessibility.	EE spatial urban development induces positive socio-ecological impacts, especially in terms of GHG emissions, material

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		370 million tons of CO_2	city densification.			cables, sewers, etc.					consumption and land-use, however its impact along socio-economic lines varies.
	halt in new motorway construction	+++ Reduced induced traffic and related emissions. *1400 million tons of CO_2*	+++ Reduced induced traffic and related emissions of airborne pollutants.	+++ Reduced induced traffic and related noise; avoided construction noise.	+++ Avoided release of pollutants during construction; reduced induced traffic and related road runoff.	+++ Reduced need for construction materials.	+++ Avoided deforestation, loss of farmland and natural areas for motorways. *4400 km^2*	- Reduced number of construction and maintenance jobs.	+ Reduced air and noise pollution translate to moderate improvements in working conditions.	+++ Reduced GHG, air, noise pollution and land encroachment induce positive health impacts; avoided construction-related nuisances; reduced traffic accidents.	Halt in motorway construction induces reductions in car traffic, which generate substantially positive impacts, particularly along socio-ecological terms.

	intensified urban rail and metro construction	+ Construction and operating phase emissions counteracted by reduced intra-metropolitan car traffic and related emissions.	+ Construction phase emissions counteracted by reduced car travel and related emissions.	+ Construction-related noise counteracted by reduced car travel and related noise.		- Increased material consumption for railroad and metro construction, but restricted to metropolitan areas.	+/- Land conversion for railroad and metro lines, but reduced land area needed for car parking due to modal shift from car to transit.	++ Increased number of construction, maintenance and operation jobs.	++ Reduced air and noise pollution and travel time translate to considerable improvements in working conditions.	+++ Improved accessibility for residents unable to drive; easier daily life schedule; reduced GHG, air, noise pollution and land encroachment induce positive health impacts; reduced traffic accidents.	Intensified urban rail and metro construction induces reductions in car traffic, which generate positive impacts that counteract the negative socio-ecological impacts linked to the construction phase. Further, modal shift from car to transit generate substantially positive impacts in socio-economic terms, particularly, quality of human life.
	halt in new airport construction/airport expansion	+++ Reduced induced air traffic and related emissions. *1300 million tons of* CO_2	++ Reduced induced air traffic and related emissions.	++ Reduced induced air traffic and related noise; avoided construction noise.	++ Avoided release of pollutants during construction and maintenance phases and de-icing of aircrafts.	++ Avoided material consumption for airfield expansion and terminal buildings; reduced aircraft construction due to reduced air traffic.	+ Avoided deforestation, loss of farmland and natural areas for airport expansion.	- Reduced number of construction, operation and maintenance jobs.	+ Reduced air and noise pollution translate to moderate improvements in working conditions.	+++ Reduced GHG, air, noise pollution and land encroachment induce positive health impacts; avoided construction-related nuisances.	Halt in new airport construction induces reductions in air traffic, which generate substantially positive impacts, particularly along socio-ecological terms.
	improved infrastructure for walking and cycling	+ Modal shifts from car to cycling can reduce car traffic and related emissions, but infrastructure improvements only might not generate substantial modal shifts.	+ Modal shifts from car to cycling can reduce car traffic and related emissions, but infrastructure improvements only might not generate substantial modal shifts.	+ Modal shifts from car to cycling can reduce car traffic and related noise, but infrastructure improvements only might not generate substantial modal shifts.		+/- Material consumption	+ Reduced land area needed for car parking due to modal shift from car to transit.	+ Increase in cycling-related jobs in retail, wholesale, design and jobs related to tourism and administration.	++ Reduced air and noise pollution; active commuting can increase concentration, improve memory, and enhance higher order thinking.	++ Health impacts from reduced GHG, air and noise pollution, as well as direct health impacts from cycling and walking; bicycle friendly cities can contribute to diversity and equality.	Modal shifts induced by improvements in walking and cycling infrastructure generate moderately positive impacts along socio-economic and ecological lines. Direct impacts on human health via active commuting and indirect impacts via reductions in GHG, air and noise pollution.

	economic instruments for transportation demand management	+++ Flight taxes and urban road and parking pricing generate substantial reductions in air and car traffic and related emissions. *2000 million tons of CO_2 [related to air traffic]*	+++ Flight taxes and urban road and parking pricing generate substantial reductions in air and car traffic and related emissions.	+++ Flight taxes and urban road and parking pricing generate substantial reductions in air and car traffic and related noise.	+ Reduced road runoff from reduced car traffic.		++ Reduced land area needed for car parking due to induced reduction in car traffic.		++ Positive impacts on employee performance due to induced reductions in air and car traffic.	++ Health impacts from reduced air and car traffic; better competitive power for transit can lead to improved transit provision, thereby improving accessibility and daily life schedule, reducing traffic accidents.	Economic instruments play a key role in supporting modal shifts and thereby induce reductions in car and air traffic, which generate considerably positive impacts across societal, economic and ecological dimensions.
	other demand management measures	++ Reduced car traffic and related emissions.	++ Reduced car traffic and related emissions.	++ Reduced car traffic and related noise.	+ Reduced road runoff from reduced car traffic.		+ Reduced land area needed for car parking due to induced reduction in car traffic.	+ Car-sharing systems can create jobs related to app development, maintenance, administration, etc.	+ Positive impacts on employee performance due to induced reductions in car traffic.	+ Health impacts from reduced car traffic; improved transit provision, accessibility and daily life schedule, reduced traffic accidents.	Other demand management measures play a similar role as economic instruments, inducing relatively moderate positive non-energy impacts.
	energy-efficient vehicle technology	++ Depends on extent of electrification and source of electricity; positive impacts moderately counteracted by rebound effect that induces an increase in driving distances.	++ Positive impacts moderately counteracted by rebound effect that induces an increase in driving distances.	+ Positive impacts considerably counteracted by rebound effect that induces an increase in driving distances.	- Rebound effect that induces an increase in driving distances increases pollution from road run off.			++ Increased job creation in electromobility value chain, offsetting lost jobs in automotive manufacturing.	+ Positive impacts on employee performance due to reduced levels of air and noise pollution.	+ Positive health impacts from reduced levels of GHG, air and noise pollution.	Positive impacts generated by EE vehicle technology primarily linked to reduced levels of GHG, air and noise pollution; however rebound effect induces an increase in driving distances.
Steel and Iron Industry	**Coke dry quenching**		Reduces dust emissions.						Improves indoor air quality for employees.		Positive impacts primarily linked to air pollution and the related effect on indoor air quality for workers.

	Non-recovery coke ovens		+/- Eliminates air pollution, but likely increases NO_x emissions.		Eliminates wastewater.						Ambiguous impacts linked to air pollution and wastewater.
	Coke Stabilization Quenching (CSQ) (IIP)		Reduces dust emissions. *6g/tonne coke*						Improves indoor air quality for employees.		Positive impacts primarily linked to air pollution and the related effect on indoor air quality for workers.
	Next generation coke making technology		++ Reduces NO_x emissions. *~30% reduction*								Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Emission Optimized Sintering	Minimises CO_2 emissions.	++ Minimises NO_x, SO_x, and CO. Reduces emission of off-gases. *40-65% reduction*						++ Improves indoor air quality for employees.		Positive impacts primarily linked to emissions of GHG and air pollutants and the related effect on indoor air quality for workers and on human and ecological health.
	Injection of Pulverized Coal (PCI)	Reduced coke demand induces reductions in CO_2 emissions.	Reduced coke demand induces reductions in emissions			Reduces coke demand. *3.3 tonnes of coke saved per tonne hot metal*					Positive impacts primarily linked to the reduced coke demand, and the related emissions.
	Injection of Natural Gas	Reduced coke demand induces reductions in CO_2 emissions.	Reduced coke demand induces reductions in emissions			Reduces coke demand. *1 tonne of coke can be replaced with 0.78 tonnes of natural gas.*					Positive impacts primarily linked to the reduced coke demand, and the related emissions.
	Injection of Pulverized Oil	Reduced coke demand induces	Reduced coke demand induces			Reduces coke demand.					Positive impacts primarily linked to the reduced coke

		reductions in CO_2 emissions.	reductions in emissions			*1 tonne of coke can be replaced with 0.8 tonnes of oil.*					demand, and the related emissions.
	Injection of Plastic Waste		+/- Reduced coke demand induces reductions in emissions but increased dioxin emissions.	++ Induces reductions in raw material extraction and the related noise pollution.	+/- Promotes plastic recycling, which would otherwise pollute soils and watercourses. Counteracted by emission of dioxins, which are highly toxic	Reduces coke demand. *1 tonne of coke can be replaced with 1.3 tonnes of plastic*					Impact on air pollution varies. Promotes resource recycling, contributing to CE.
	Charging Carbon Composite Agglomerates (CCB)	Reductions in coke input can reduce CO_2 emissions.	Induces reductions in raw material extraction and the related release of air-borne pollutants.	Induces reductions in raw material extraction and the related noise pollution.	Resource recycling can induce reductions in raw material extraction and the related release of pollutants into soils and watercourses.	Promotes resource recycling; allows for wider range of raw materials.	Resource recycling can induce reductions in raw material extraction and the related landscape fragmentation and destruction.				Positive impacts primarily relate to induced reductions in raw material demand via improved resource recycling.
	Scrap Preheater		-- Increases dust and mercury emissions, which induce threats to human, wildlife and ecosystem health.		-- Increases dioxin and mercury emissions, which induce threats to human, wildlife and ecosystem health.				-- Deteriorates the air quality.	-- Increased dust, dioxin and mercury emissions can induce threats to human health.	Negative impacts on human and ecological health via increased emissions of dust, mercury and dioxin.
	Waste Injection in EAFs		Induces reductions in raw material extraction and the related release of air-borne pollutants.	Induces reductions in raw material extraction and the related noise pollution.	Induces reductions in raw material extraction and the related release of pollutants into soils and watercourses.	Promotes resource recycling; decreases need for coal and coke. *~30% reduction*	Induces reductions in raw material extraction and the related landscape fragmentation and destruction.				Positive impacts primarily relate to induced reductions in raw material demand via improved resource recycling.
	Contiarc® Furnace										

			Reduces waste gas and dust volumes.						Improves the air quality.		Positive impact primarily linked to reductions in air-borne pollutants and related effect on indoor air quality for workers.
	Comelt Furnace		Reduces off-gases.	Reduces noise level. *15 dB(A)*					Improves the air quality and the noise level of the working environment.		Positive impacts directly relate to reductions in off-gases and noise levels, and the subsequent effects on the working environment.
	Near Net Shape Casting					Decreases the need for consumables (e.g. moulds, rolling cylinders).					Positive impact directly related to decreases in material consumption and to the avoided negative impacts linked to material life cycle.
Cement Industry	**Process Control Clinker Cooler**		+ Reduces NO_x emissions. *20% reduction*							Positive impact on human health from reduced NO_x emissions.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.

	Kiln Combustion System Improvements		+++ Reduces NO_x emissions. *30-70% reduction*							Positive impact on human health from reduced NO_x emissions.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Mineralized Clinker		++ Reduces NO_x emissions and kiln dust. *10-50% reduction of NO_x emissions.*							Positive impact on human health from reduced NO_x emissions and kiln dust.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Indirect Firing		Reduces NO_x emissions.							Positive impact on human health from reduced NO_x emissions.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Oxygen Enrichment		-- Increases NO_x emissions.							-- Negative impact on human health from increased NO_x emissions.	Negative impact on air pollution, thereby generating considerably negative impacts on human and ecological health.
	Mixing Air Technology		++ Reduces SO_2 and NO_x emissions.							Positive impact on human health from reduced SO_2 and NO_x emissions.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Cement Suspension Preheater Calcining Technology with High Solid-Gas Ratio		++ Reduces SO_2 and NO_x contents in exhaust. *Reduced to less than 50ppm NO_x and to 200ppm SO_2.*							Positive impact on human health from reduced SO_2 and NO_x contents in exhaust.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Add Precalciner		++								

			Reduces NO_x emissions. *45% reduction*							Positive impact on human health from reduced NO_x emissions.	Positive impacts primarily linked to air pollution and the related effects on human and ecological health.
	Blended Cements	Reduces CO_2 emissions.	Reduces NO_x, SO_2 and PM emissions; can induce reductions in polluting by-products of other industries, such as fly ash.		Induces reductions in polluting by-products of other industries, such as fly ash.	Contributes to effective utilisation of by-products from other industries (e.g. fly ash and furnace slag).				Positive impact on human health from reduced NO_x, SO_2 and PM emissions.	Positive impacts primarily linked to GHG emissions and air pollution and the related effects on human and ecological health. Promotes industrial resource recycling.
	Limestone Portland Cement	Reduces CO_2 emissions.	Reduces NO_x, SO_2 and PM emissions.							Positive impact on human health from reduced NO_x, SO_2 and PM emissions.	Positive impacts primarily linked to GHG emissions and air pollution and the related effects on human and ecological health.

	Use of Steel Slag	Reduces process CO_2 emissions.	++ Reduces NO_x emissions. *9-60% reduction*							Positive impact on human health from reduced NO_x and CO_2 emissions.	Positive impacts primarily linked to GHG emissions and air pollution and the related effects on human and ecological health.
	Use of Cement Kiln Dust	Reduces process CO_2 emissions.								Positive impact on human health from reduced CO_2 emissions.	Positive impacts primarily linked to GHG emissions and the related effects on human and ecological health.
	Reduce Lime Saturation Factor	Reduces process CO_2 emissions.	Induces reductions in limestone extraction and the related release of air-borne pollutants.	Induces reductions in limestone extraction and the related noise pollution.	Induces reductions in limestone extraction and the related release of pollutants into soils and watercourses.	Reduces use of limestone.	Induces reduction in limestone extraction and the related landscape fragmentation and destruction.			Positive impact on human health from reduced CO_2 emissions.	Positive impacts primarily linked to the induced reduction in limestone demand and the related impacts from extraction process.

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