Fraunhofer ISI

Study on Energy Savings Scenarios 2050

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The project is financed by the European Climate Initiative (EUKI). EUKI is a project financing instrument by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). It is the overarching goal of the EUKI to foster climate cooperation within the European Union in order to mitigate greenhouse gas emissions. It does so through strengthening across-border dialogue and cooperation as well as exchange of knowledge and experience. The information and views set out in this report are those of the authors and do not necessarily reflect the official opinion of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

Executive Summary

As part of its internal reflection on the development of a 2050 Energy Efficiency Vision, the Coalition for Energy Savings has commissioned Fraunhofer ISI to assess the potential for energy savings by 2050 under three different scenarios (see below). The tasks included an update of the techno-economic energy savings potentials and to develop and assess scenarios focusing on changes in life-style, the impact of digitalisation, of a shared economy and many more (so called **"New Societal Trends"**). These changes can have an impact on energy efficiency improvements and contribute to decrease or increase energy consumption beyond the linear trends. In particular, an increase in energy consumption might be the result of new societal trends that are not accompanied by policies with a strong implementation of the Energy Efficiency First (EE1) Principle.

Fraunhofer ISI carried out three scenario workshops with Members of the Coalition for Energy Savings (about 20-30 experts on average) in the period between January and September 2018 to explore the 2050 energy perspective in order to inform the selection of trends and literature and the Fraunhofer ISI expert decisions regarding modelling assumptions. The three workshops focused on: the development of micro-worlds in 2050 (Workshop 1), the selection of (energy-relevant) megatrends and trend profiles (Workshop 2), and the development of three scenarios and one variant up to 2050 (Workshop 3). The work focussed on identifying the most energy-relevant trends and combined the trends into four main societal trend clusters, consisting of detailed trends with relevance for energy consumption and which formed the basis for the scenario work in this report (Table 1).

Table 1: Definition of Societal Trend Clusters & Detailed Trends

Cluster	Trend
Digitalisation of Life	Human Machine / Shift towards smart products and services
New Social and Economic Models	Sharing Economy
	Prosumer
	Awareness (of personal footprint)
	Social Disparities / Energy Poverty
	New forms of funding - Public spending towards greener and more efficient options
Industrial Transformation	Reindustrialisation
	Circular Economy - new requirements for material flows for consumer goods
	Decarbonization of the Industry
Quality of Life	Increasing importance of health (e.g. air quality, noise, heat)
	Regionalisation - Urban governance solving global challenges locally in cities
	Urbanisation - Global trend towards larger shares of the population living in cities

Three scenarios are developed and compared to EU's latest energy projections:

(1) **Baseline:** the most recent EU reference projections, the PRIMES projections from 2016, which covers energy policies until 2016, but excludes the new 2030 energy efficiency framework, in particular the new Buildings Performance and Energy Efficiency Directives which concluded in December 2018.

(2) **Removing Market Barriers Scenario** uses a bottom-up method to identify techno-economic savings potentials based on realising all efficiency investments across sectors projected to offer a positive return on investment and leading to growth of the energy services market.

(3) **New Trends Inefficient Scenario** which is characterised by strong non-linear societal trends due to penetration of shared/digital economy and strong rebound effects.

(4) **New Trends Efficient Scenario**, which is also characterised by strong non-linear societal trends but the realisation of the EE1 Principle strongly contributes to maximise energy savings from the New Societal Trends.

The New Trends Inefficient and the New Trends Efficient Scenarios rely on the following working steps:

- Thorough literature research on pre-existing studies – impact of societal trends on energy consumption.

- Assessing the magnitude of numbers given in existing studies and thereby evaluating the impact of the detailed trends on important modelling parameters of the various wedges set up in the techno-economic scenario. Both, energy-increasing and energy-decreasing impacts were considered. Care was taken, when analysing the studies to understand, which part of the trend was already included in the Baseline development and the techno-economic scenarios. It should be recalled that both already include a part of the New Trends which can be considered the continuation of developments of the past.

- Translating the impacts into modelling parameters while estimating open model parameters. Care was taken to use conservative estimates as to the impacts of such trends.

- Finally scaling of the scenarios by sector and by wedge occurred with the estimated parameters.

The work performed on these scenarios is a pioneering work. It has gathered information on the relation of New Societal Trends to the best of present knowledge and closed gaps with estimates. More studies on individual trends are required in the future to gain more certainty on the quantitative impacts. Estimates, both upward and downward, were carried out in a conservative way, in order not to overestimate the impacts of the New Societal Trends. The following points summarise limitations of the present work:

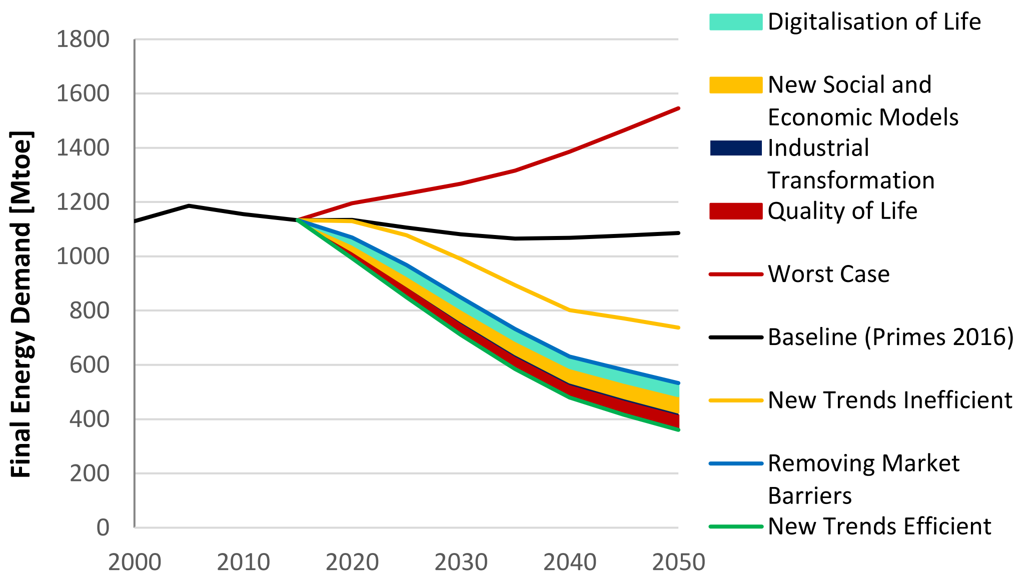
- For many trends no previous studies exist, which determine even the qualitative effects of the trend on the energy consumption (e.g. consumer; financing; urbanization) and, instead, had to be completed by own expert estimates on impacts.
- Specifically, up to this date there is quite often no quantification of these trends
- Existing studies are often not transparent in their baseline assumptions
- Parameters need to be adapted to the EU context.
- The model parameters need to account for double-counting of certain mechanisms. Care was taken here to eliminate such double-counting among the different societal trends but more in-depth analysis could better separate such overlapping impacts.

The main findings from the analysis are the following (Figure 1):

- In the Baseline the decrease in Final Energy Demand FED until 2050 is small (-6% compared to 2010)

- With the realisation of techno-economic potentials (Removing Market Barriers) a quite important decrease of the FED is possible (- 51% compared to the Baseline in 2050)
- New Societal Trends without EE1 (New Trends Inefficient) could diminish the effect of the realized techno-economic potentials for FED to a 32% reduction. If techno-economic potentials for FED are not realised, the New Societal Trends, if not counteracted by a strong EE1 Principle, could even increase energy consumption up to 42% compared to the present baseline (Worst Case, variant of New Trends Inefficient).
- New Societal Trends supported by a strong EE1 Principle (New Trends Efficient) could decrease FED further (- 67% compared to the Baseline in 2050)
- The Gross Inland Consumption and the (energy-related) GHG emissions follow these trends closely.

Figure 1: Final energy demand (EU28) for all sectors in the three scenarios and the variant (Worst Case). The graph shows also the contribution of the four large Trend Clusters in the case of the New Trends Efficient Scenario



1 Background and Objective

As part of its internal reflection on the development of a 2050 Energy Efficiency Vision, the Coalition for Energy Savings has commissioned Fraunhofer ISI to assess the potential for energy savings by 2050 under three different scenarios (see below). The tasks included an update of the techno-economic energy savings potentials and to develop and assess scenarios focusing on changes in life-style, the impact of digitalisation, of a shared economy and many more (so called "New Societal Trends"). These changes can have an impact on energy efficiency improvements and contribute to decrease or increase energy consumption beyond the linear trends. In particular, an increase in energy consumption might be the result of new societal trends that are not accompanied by policies with a strong implementation of the Energy Efficiency First (EE1) Principle.

The central aim of the 2015 Paris Agreement is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. To reach this ambitious goal, concerning the energy system two central strategies are principally pursued by the European Union and its Member States:

- enhancing energy efficiency (EE)
- decarbonising energy supply, in particular by large penetration of renewable energy sources (RES).

The order, in which the two main strategies are cited, reflect the **"Energy Efficiency First" (EE1) Principle**, which was proposed by the European Union as a fundamental principle applied to policymaking, planning and investment in the energy sector. The principal is gaining increasing visibility in European energy and climate policy. Briefly described, the concept of EE1 prioritizes investments in customer-side efficiency resources (including end-use and supply side energy efficiency and demand response) whenever they would cost less, or deliver more value, than investing in energy infrastructure, fuels, and supply alone. Although in the Energy Union Strategy energy efficiency has been recognised as a resource in its own right at the same level as generation capacity and the EE1 as a guiding principle has been brought forward, previous studies suggest that still numerous barriers impede this principle to be streamlined and the benefits of energy efficiency to be adequately taken into account in financial and political planning and decision making (BMU and Fraunhofer ISI 2012; Fraunhofer ISI 2009; Schleich 2009; Schleich and Gruber 2008).

Further, **New Societal Trends** are arising, linked to general Megatrends, which can have potentially large (increasing or decreasing) impacts on energy consumption (see for example Grubler et al. 2018). Such trends include among others:

- the digitalisation of the economy and of private life
- autonomous driving
- the trend towards a Shared Economy
- the move towards low carbon industrial processes
- the circular economy and material efficiency.

In this context the Coalition for Energy Savings has commissioned Fraunhofer ISI to assess the potential for energy savings by 2050 under these different scenarios (see below) to serve as input to its internal reflection process on a "2050 Energy Efficiency Vision". The Coalition for

Background and Objective

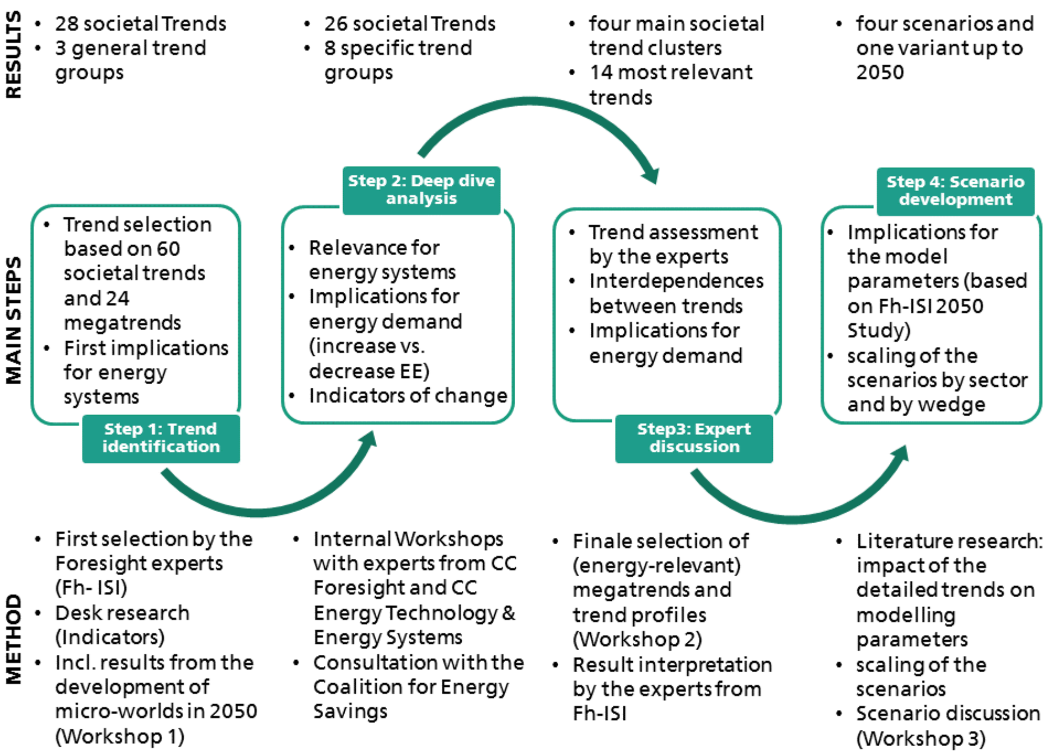
Energy Savings aims for a vision to increase the collective understanding of the sectoral perspectives and potentials of energy efficiency in an ever-changing world with different ways of living, moving and working, where energy demand and supply are integrated and net carbon emissions have to be zero.

2 Methodological Approach

2.1 Trend Selection, Clustering and Scenario Development

The Efficient and Inefficient New Trends Scenarios rely on the following working steps: Trend Identification (Step 1), Deep dive analysis (Step 2), Expert discussion (Step 3) and Scenario development (Step 4). Steps 1 to 4 have focused on the identification of the most relevant societal trends for the energy systems in general, particularly for the increase or decrease of energy efficiency and energy demand. Step 4 focused on the analysis of the impact of societal trends on the modelling parameters and the scenario development.

Figure 2: Scenario development process



Fraunhofer ISI carried out three scenario workshops with members of the Coalition for Energy Savings (about 20-30 experts on average) in the period between January and September 2018, to explore the 2050 energy perspective, supported by analytical work (expert analysis). The aim and results of these workshops are described below.

Step 1: Trend Identification

The Trend Identification departed from a set of megatrends and detailed trend profiles developed in the context of a Foresight Process Cycle 2 carried out on behalf of BMBF. The search criteria for the identification of societal trends in the BMBF Foresight Process were:

- Social relevance: The importance of a trend is determined by significant social and/or economic and in some cases also disruptive impacts.

- Time dimension: Impacts of the trend are relevant in a period of time extending from now until 2030.
- Relationship to research and innovation (R&I): The trend as a whole or in some aspects should clearly relate to research and innovation.
- Degree of 'newness' of a social trend: The social trend is wholly or partly new for the research and innovation system, or, in the opinion of the authors and experts involved, has received too little attention to date.

The result of the Process were 60 trend profiles in three categories (1) Society / Culture / Quality of Life, (2) Business and (3) Politics and Governance (see VDI-Technologiezentrum 2017). Since the data base for the development of these 60 trend profiles trends comes from the years 2013-2014, current data and facts have been researched to validate timeliness of the trends. Additionally, the trend profiles were connected to the megatrends identified in actual foresight studies.

All identified trends were linked with the results of the Development of Micro-Worlds in 2050 (Workshop 1). The workshop was organised in a way to allow switching perspectives from a policy-maker and expert perspective to the viewpoint of citizens and users. Participants developed a concrete profile, a so-called persona, and then developed answers to the three key questions (How will we - move in 2050? - work in 2050? - live in 2050?) from the point of view of this persona.

As a result, the relevance for the energy system was analysed and 28 trend profiles (societal trends) as well as 24 mega trends were pre-selected by the Foresight experts in Fraunhofer ISI, based on their project experience with industry clients in the energy sector.

Step 2: Deep dive analysis

In Step 2 to underpin the results of Step 1, that is the relevance of the selected 28 societal trends for the energy system, a deep dive analysis was carried out. The implications for the increase vs. decrease of energy efficiency and energy demand were discussed and the specific indicators of change (key parameters) were identified (see example in Table 2).

Table 2: Template for the Reflexion on the Trends

Trend	Describe relevance for the energy system	Describe how this can		Key parameter(s)
		increase EE	decrease EE	
M5 Declining household size [StS]	• quicker uptake of new services • lower rate of ownership • impact on available income and consumption pattern	If it leads to rapid uptake of EE services and solutions. If it leads to urbanisation and less commuting.	If it leads to more appliances and living surface per capita. If it leads to poverty (capital availability).	• number and age/lifetime of appliances • m2 • pkm

As a next step, the Coalition for Energy Savings consulted their members. The main tasks of the consultations were:

- Trend selection: Choosing the most relevant societal trends
- Trend analysis: first reflection on the most relevant trends

Step 3: Expert discussion

The selection of (energy-relevant) megatrends and trend profiles in workshop 2 was focused on:

- The selection of trends, creation of clusters or limitation of the selection;
- Identification the potential impact of the trends on the energy system
- Linking the selected trends with the scenario description; and
- Pre-identification of parameters for the modelling of the scenarios.

After the second workshop the work focused on identifying the most energy-relevant trends and combined the trends into a group of four main Societal Trend Clusters & Detailed Trends, which formed the basis for the scenario work in this report (Table 3). The four identified clusters are: 'Digitalisation of Life', 'New Social and Economic Models', 'Industrial Transformation' and 'Quality of Life'. Though the development of the clusters was an iterative process with plenty of stakeholder involvement, the definition of these clusters is not carved in stone and might be evolving in future work.

Table 3: Definition of Societal Trend Clusters & Detailed Trends

Cluster	Trend
Digitalisation of Life	Human Machine / Shift towards smart products and services
New Social and Economic Models	Sharing Economy
	Prosumer
	Awareness (of personal footprint)
	Social Disparities / Energy Poverty
	New forms of funding - Public spending towards greener and more efficient options
Industrial Transformation	Reindustrialisation
	Circular Economy - new requirements for material flows for consumer goods
	Decarbonization of the Industry
Quality of Life	Increasing importance of health (e.g. air quality, noise, heat)
	Regionalisation - Urban governance solving global challenges locally in cities
	Urbanisation - Global trend towards larger shares of the population living in cities

Step 4: Scenario development

Through a thorough literature research on pre-existing studies in step four the impact of societal trends on energy consumption was identified. The further process included three main steps (quantifying the results):

- Assessing the magnitudes of the numbers given in the various studies and thereby evaluating the impact of the detailed trends on important modelling parameters of the various wedges set up in the techno-economic scenario. Both, energy-increasing and energy-decreasing impacts were considered. Care was taken, when analysing the studies to understand, which part of the trend was already included in the Baseline development and the Removing Market Barriers Scenario. It will be shown shortly, that both scenarios already include a part of the New Societal Trends which can be considered the continuation of developments of the past.

- Translating the impacts into modelling parameters while estimating open model parameters. Care was taken to use conservative estimates as to the impacts of such trends.

- Finally scaling of the scenarios by sector and by wedge occurred with the estimated parameters.

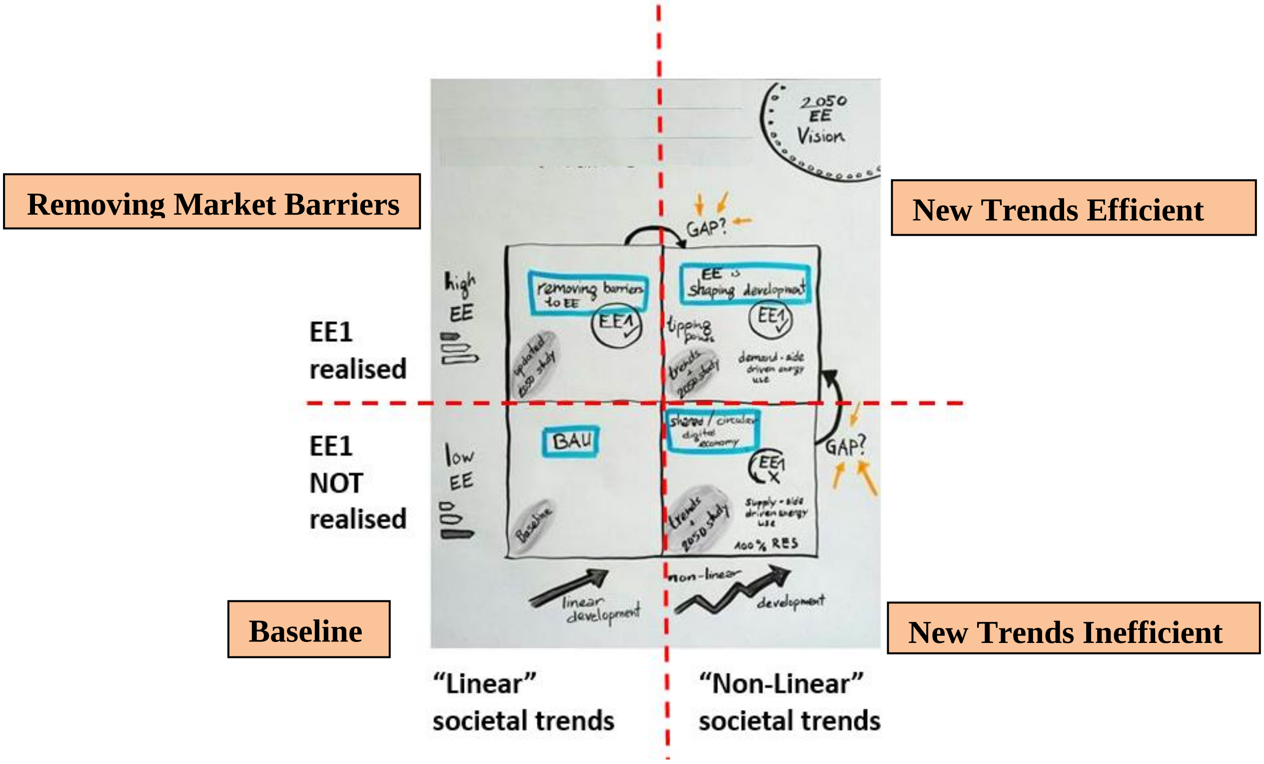
The results of the scenario development in Workshop 3 were three scenarios and one variant up to 2050:

- **Baseline** based on the most recent PRIMES projections from 2016. This scenario provides the reference for the development of drivers of energy consumption. New Societal Trends happen in this scenario but rather as a smooth continuation of previous trends (linear societal trends).
- **Removing Market Barriers**: this scenario focusses on the realization of economic/ near economic potentials for EE, mainly based on technical solutions to EE. New Societal Trends happen in this scenario but rather as a smooth continuation of previous trends (linear societal trends).

The following two scenarios are based on the Removing Market Barriers scenario. In these scenarios, the economic/near economic potentials for EE are realised, and the potentials are either reduced or enhanced due to new trends. A variant – worst case – has been developed where new Societal Trends operate directly on the Baseline,

- **New Trends Inefficient**, which is characterised by strong non-linear societal trends due to penetration of shared/digital economy and strong rebound effects, i.e. energy-increasing impacts of the New Societal Trends.
    - **Variant - Worst Case**: For comparison purposes, in this variant New Societal Trends operate directly on the Baseline.
- **New Trends Efficient**, which is also characterised by strong non-linear societal trends but the realisation of the EE1 Principle strongly contributes to bring forward the energy reducing impacts of the New Societal Trends.

Figure 3: Overview of the three scenarios developed



Three scenarios were developed:	
(1)	Baseline based on the most recent PRIMES projections from 2016
(2)	Removing Market Barriers Scenario: this scenario focusses on the realization of economic/ near economic potentials for EE, mainly based on technical solutions to EE.
(3)	New Trends Inefficient Scenario, which is characterised by strong non-linear societal trends due to penetration of shared/digital economy and strong rebound effects.
(4)	New Trends Efficient Scenario, which is also characterised by strong non-linear societal trends but the realisation of the EE1 Principle strongly contributes to bring forward the energy reducing impacts of the New Societal Trends.

2.2 The Electricity Mix

Although we focus on the demand side of energy use, the potentials have a major effect on primary energy demand. Primary energy saving potentials are the result of conversion efficiency as well as final energy related efficiency measures. The savings in primary energy demand are thus highly influenced by the shift towards a highly efficient electricity generation mix. For the Baseline Scenario the electricity mix of the EC (2016) is implemented (Figure 4). In the other scenarios an electricity mix is applied which follows the EUCO 3030 Scenario (E3MLab & IIASA, 2016) up to 2030 and then a low carbon mix up to 2050 based on an update of Fraunhofer (2012), which reaches over 92% of RES in 2050 (Table 4 and Figure 5).

The conversion from final energy consumption to primary energy consumption is therefore based on a low-carbon electricity generation mix (Table 4). Until 2030, the EUCO 3030 scenario was the basis for the power mix assumptions. Developing a scenario for the energy mix by 2050 was not part of the scope of this study. Therefore, the results related to primary energy demand and greenhouse gas emission reductions are based on existing work and its electricity mix assumptions. In particular, the electricity mix is based on BMU and Fraunhofer ISI (2012). Increased ambition levels since then (Renewables Directive and EC long-term strategy) are not reflected.

Figure 4: Electricity generation mix used in the Baseline Scenario - Primes 2016 (European Commission 2016)

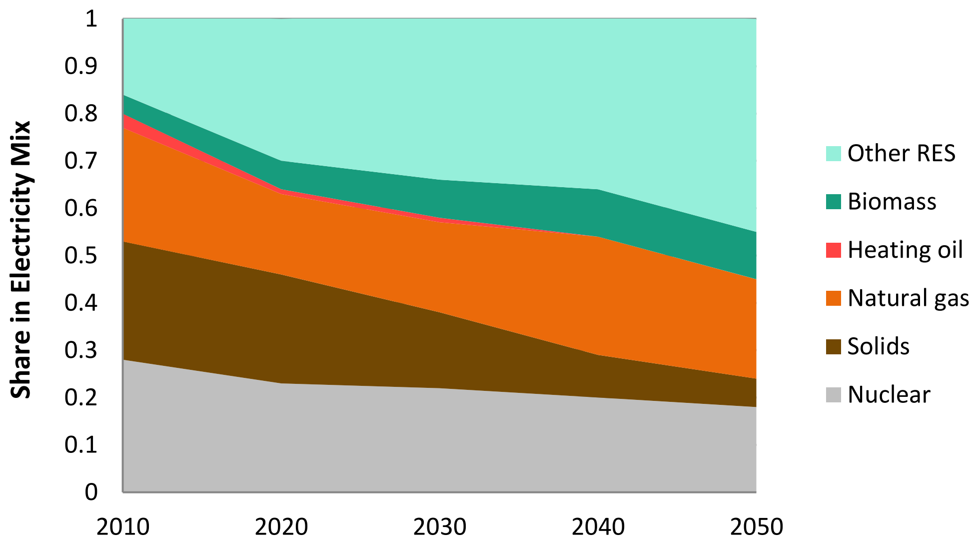
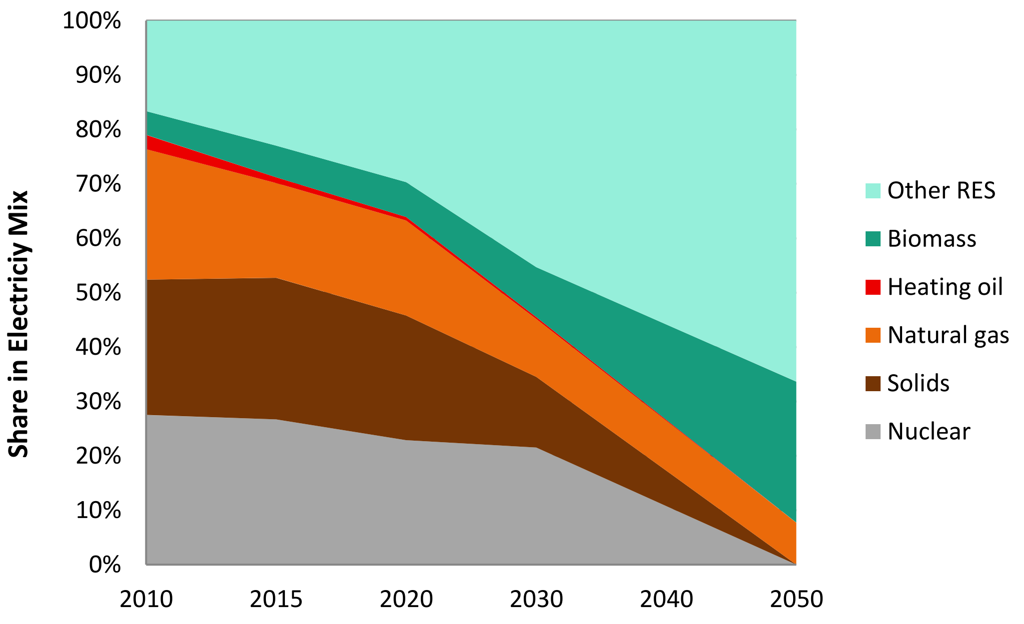


Table 4: Low-carbon electricity generation mix (until 2030 this mix is identical with the electricity mix in the EUCO 3030 scenario, E3MLab & IIASA 2016; afterward extrapolation of BMU & Fraunhofer ISI 2012)

EU long-term	2010	2020	2030	2040	2050
RES (without Biomass)	17%	30%	45%	56%	66%
Biomass	4%	6%	9%	18%	26%
Heating Oil	3%	1%	0%	0%	0%
Natural Gas	24%	17%	11%	9%	8%
Solids	25%	23%	13%	7%	0%
Nuclear	28%	23%	22%	11%	0%

Figure 5: Low carbon electricity generation mix (E3MLab & IIASA, 2016 and Fraunhofer 2012)



2.3 The Baseline

Change in Final Energy Demand (FED):
In the Baseline (based on the most recent PRIMES projections from 2016) the decrease in Final Energy Demand until 2050 is small (-6% compared to 2010).

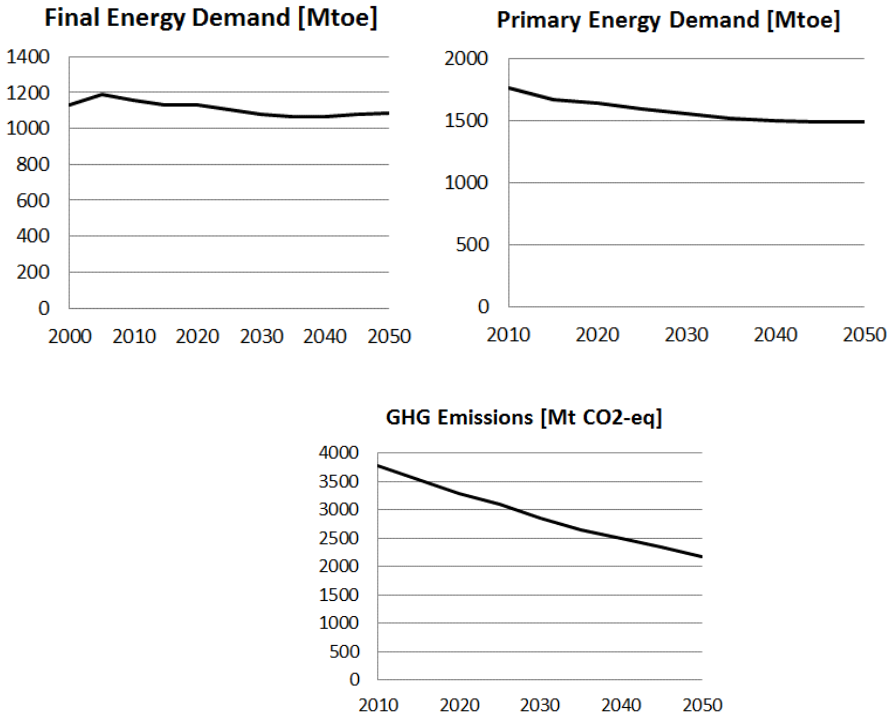
The Baseline is based on the most recent projections of the European Commission with the PRIMES model. Details of these projections can be found in EC (2016).

Figure 6 shows the main features of this scenario:

- Final energy demand stays relatively stable and even slightly increases after 2040
- Primary energy demand decreases somewhat, essentially due to the penetration of renewable energy sources.
- (Energy-related) GHG emissions are lower by about 42% compared to 2010, mainly due to fuel switch towards renewable energy sources.

Though the reduction in GHG emissions is considerable already in the Baseline, overall, these projections are far away from reaching the requirements of the Paris Agreement. Including all GHG emissions and comparing with 1990, in 2050 a reduction of 48% is achieved in GHG emissions (EC, 2016).

Figure 6: Final/primary energy demand and (energy-related) GHG emissions in the Baseline Scenario (EU28) (European Commission 2016)



3 A Techno-Economic Scenario of Energy Efficiency Potentials for the EU until 2050 ("Removing Market Barriers")

The main purpose of this chapter is to give an overview of the (techno-economic) potentials and possible contributions of energy efficiency and energy saving options to meeting the EU's 2030 and 2050 targets for Energy Efficiency and GHG emissions **in a techno-economic scenario ("Removing Market Barriers").** The following issues are addressed in detail:

1. Analysis of the (techno-economic) energy efficiency potentials in the various sectors, considering up to date projections of energy demand and central drivers for energy demand (such as sectoral GDP, population growth and kilometres travelled).

2. Contribution of enhanced energy efficiency in energy conversion and in energy end-use to primary energy savings by 2050.

3. Analysis of the contribution, final energy savings can make to reducing GHG emissions by 2050 through increased energy efficiency and energy savings.

3.1 Methodology for the techno-economic scenario

The energy saving potentials that are identified in this techno-economic scenario have to be understood **as cost-effective or nearly cost-effective technological potentials** for the individual investors or end users. The scenario is based on the key assumption that non-economic barriers for implementing energy efficiency measures are removed in order to realize the existing potential. In this study potentials were determined using a bottom-up approach to identify saving potentials directly linked to the application of a specific technology ("wedges").

Within the project, **ten packages (so-called wedges)** were put together for an in-depth analysis. They include specific energy efficiency options and the underlying technologies which can be addressed by individual policy measures. All saving potentials not covered through these ten wedges are represented in the “estimated wedges”.

Determining the energy saving potentials is mainly based on the work completed for the policy report "Contribution of Energy Efficiency Measures to Climate Protection within the European Union until 2050" [BMU, Fraunhofer ISI, 2012]. In turn, this study draws from the work of the “Study on the Energy Saving Potentials in EU Member States, Candidate Countries and EEA Countries” [Fraunhofer ISI, 2009a], which includes the quantification of energy saving potentials up to 2030 based on a technology specific, bottom up simulation and the ADAM project [Fraunhofer ISI, 2009b] which served as a basis for extrapolating the potentials as well as the baseline development up to 2050.

The original data were determined in comparison to the baseline energy demand projection of the European Commission from the year 2008 [European Commission, 2008]. In order to take into account the current projections of energy demand drivers up to 2050 and the fact that time has moved on (with part of the energy efficiency potentials being realised by policy measures or part being "lost" for energy efficiency, as investments have been taken in less efficient technologies) two adjustments were made:

- the potentials were scaled to the projections of the European Commission (2016 - Primes reference scenario). The saving potentials were adjusted considering the updated final energy demand as well as the changed activities and altered energy intensities per sector.

- Furthermore, potentials that were already realized between 2009 and 2016 are deducted from the previously identified potentials.

Thus, a decrease in potentials in some of the sectors is the result of a combination of decreasing activities and/or already realized potentials, while increasing potentials can be traced back to higher activity projections.

The saving potentials identified should be understood as cost-effective and nearly cost-effective technical potentials, rather than theoretical potentials (see Fraunhofer ISI 2009a for more details). Cost-effective technical energy-saving potentials depend on the future development of drivers such as the economic or social development (e.g. the future GDP, population growth, stock of existing buildings etc.). The drivers underlying the present scenario are the ones underlying the reference scenario of EC (2016).

With regard to the cost-effectiveness of efficiency technologies, only economic technologies are selected (i.e. the financial savings that an investor / end-user can expect through the avoided fuel procurement exceed his or her additional investments required to implement the efficiency technology) or at least near-economic ones, in order to include only technologies that are likely to reach market maturity. The latter ones are chosen in such a manner that the energy system costs are not exceeding the present energy system costs.

3.2 Overall saving potentials

Change in Final Energy Demand (FED):
With the realisation of techno-economic potentials (Removing Market Barriers) a quite important decrease of the FED is possible (-51% compared to the Baseline in 2050)

Since this study is focussed on identifying cost-effective energy efficiency potentials on the demand side, its baseline is the final energy demand projected in Primes 2016, for the sectors above as well as for the overall final energy demand. The techno-economic scenario then models how these demand side potentials can reduce final energy demand. In this section it will be summarized how the bottom-up potentials within the sectors add up to overall potentials, and how final energy demand can be reduced when techno-economic potentials in all sectors are realized.

The overall primary energy saving potential is used as a basis to determine the contribution of energy savings to greenhouse gas emission reductions by applying fuel-specific emission factors under the assumed energy mix. Consequently, primary energy and emission reductions are split into one part related to the shift towards a highly efficient electricity supply system and another part resulting from the actual final energy savings.

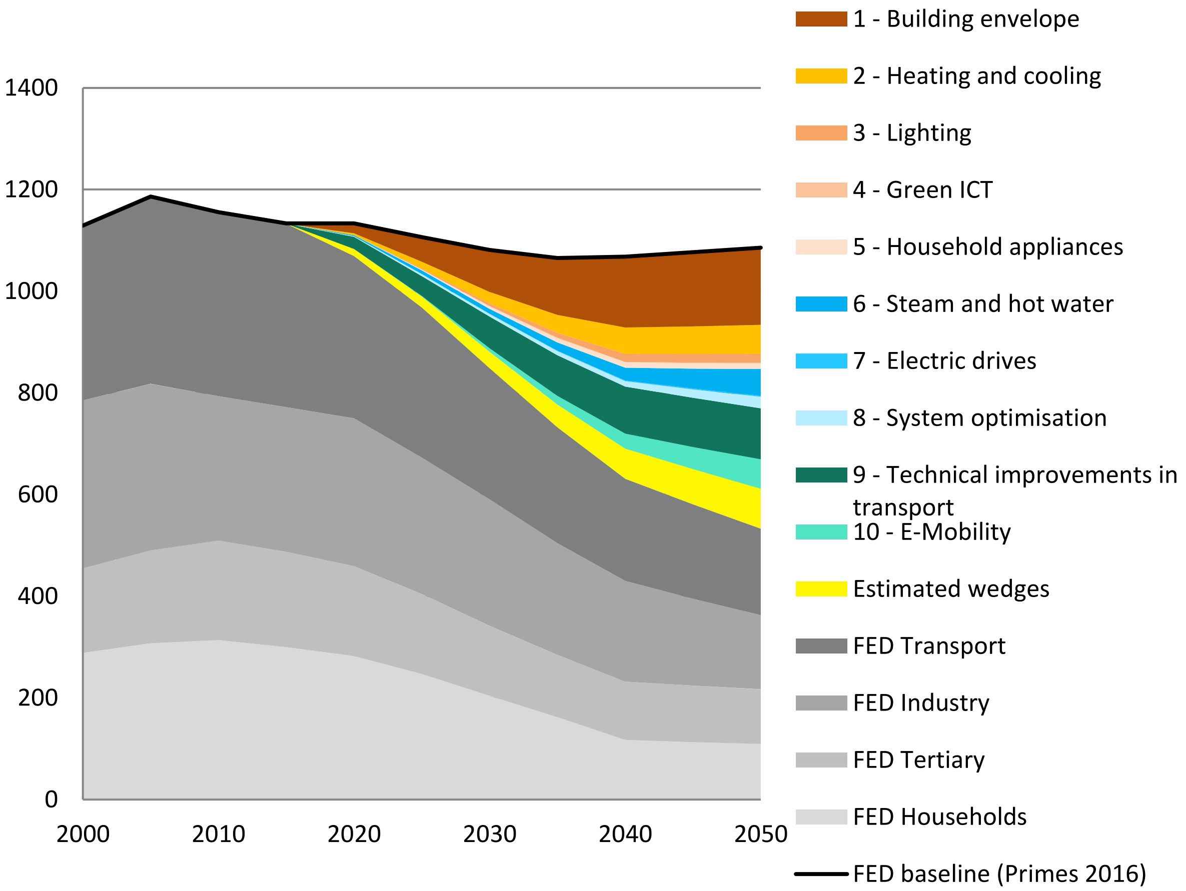
Three limitations of this work have to be kept in mind. First, since European ambitions develop rather rapidly, the latest updates of the primary energy efficiency mix (notably the reviewed Renewables Directive) could not be taken into account. Second, this analysis is based on cost-effective potentials previously identified (BMU & Fraunhofer ISI 2012; Fraunhofer ISI 2009a). Although all potentials were updated considering structural changes, altered activities and updated energy intensities, some haziness cannot fully be excluded. Third, the potentials were updated based on Primes 2016. Thereby, assumptions on structural and lifestyle changes (or the lack of the same), changing activity sizes and energy intensities are adopted from Primes 2016 as well.

Overall final energy demand saving potential

The Primes 2016 baseline of total final energy demand has its peak in 2005 and decreases until 2030. Afterwards it is expected to increase slightly. Overall, a change of minus four percent between 2000 and 2050 is projected.

Compared to this baseline development, final energy demand could potentially be reduced through techno-economic potentials by 51 percent in the year 2050. Figure 7 shows that households and the tertiary sector could deliver 22% (wedges 1-5) the industry sector contributes 7% (wedges 6-8) and the technical improvements in the transport sector together with a notable shift towards electric vehicles (wedge 9 & 10) about 14%. Furthermore, the "estimated wedge" contributes about 7% to the savings and subsumes- among others - low impact industry savings, and certain appliances in the tertiary sector. Overall 14% of final energy demand reduction can be realized solely through building envelope measures. The agriculture sector is hereby included in the remaining final energy demand in the tertiary sector.

Figure 7: Overall final energy demand and final energy savings (Mtoe)



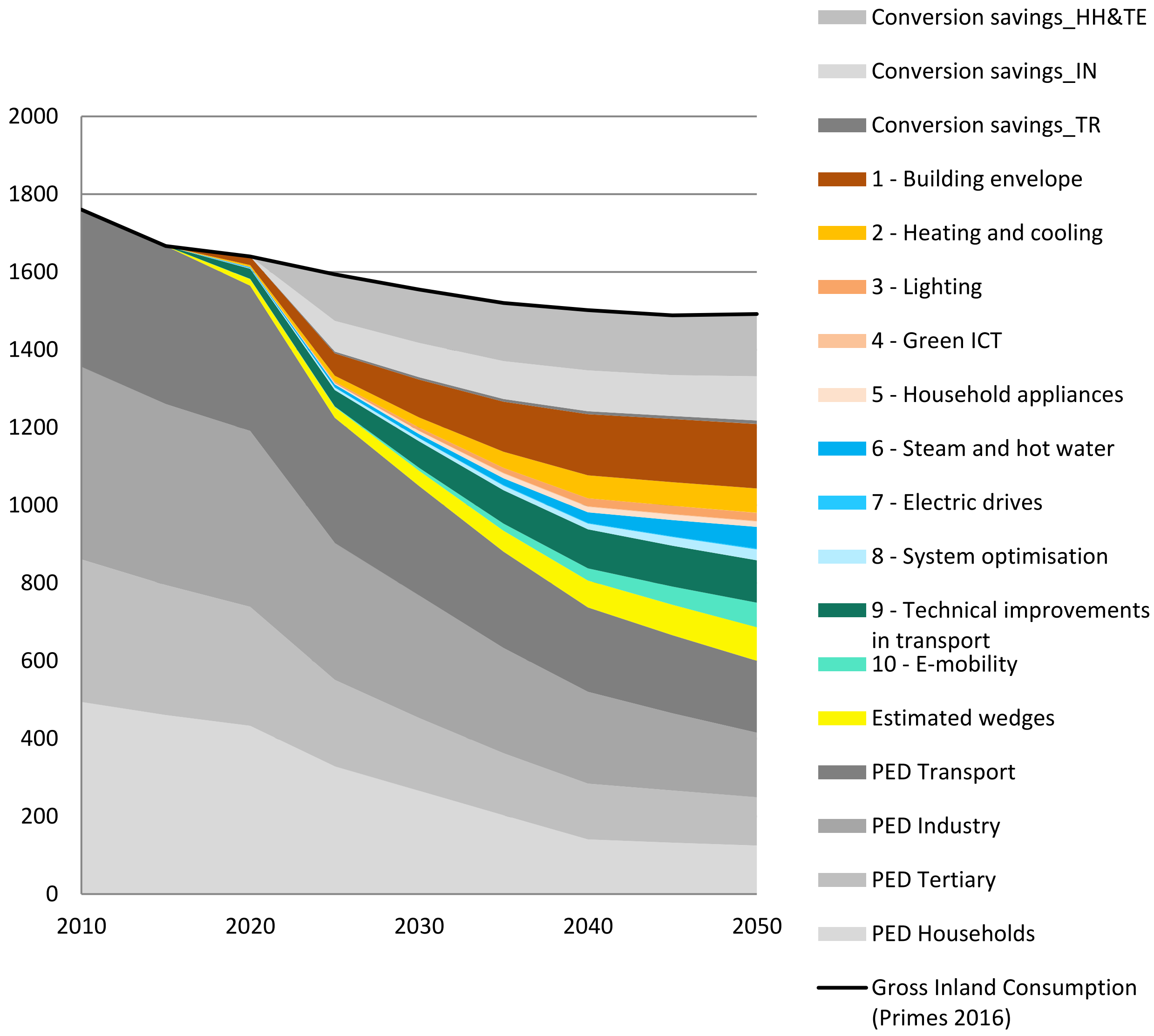
Overall primary energy saving potentials

Based on a decrease of final energy demand in the Primes 2016 baseline, the primary energy demand will also decrease slowly but steadily. The primary energy demand hereby includes non-energy uses. In the baseline scenario, it is expected to be 15% lower in 2050 as compared to 2010.

The primary energy saving potentials, as shown in Figure 8 are divided into "conversion savings" triggered by the shift towards a highly-efficient, mainly renewable energy-based electricity supply system (Table 4) and "final energy savings" due to exploiting the final energy saving potentials described above.

Primary energy demand can be reduced by up to 20% by 2050 due to conversion savings. Final energy related savings imply an additional 40% reduction in primary energy demand making a total of 60% avoidable.

Figure 8: Gross Inland Consumption for all Sectors - Baseline and 'Removing Market Barriers' Scenario (including non-energy use) (Mtoe)



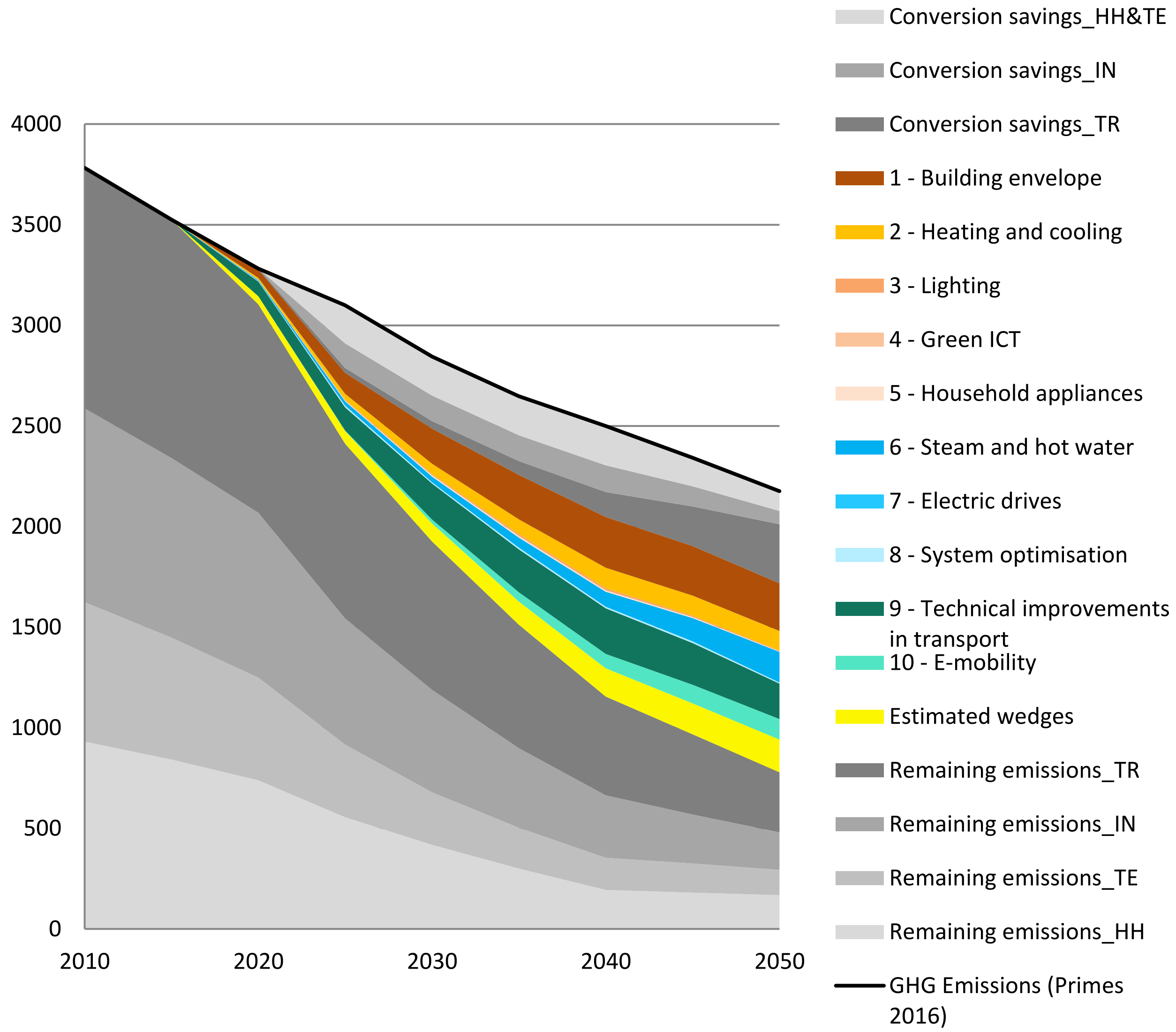
Energy efficiency contribution in GHG emission reductions

In the Primes 2016 baseline, GHG emissions are projected to decrease drastically by 43 percent between 2010 and 2050 (Figure 9). This is based on the fact that electricity is increasingly generated using low-carbon generation technologies. The additional emission reduction potential due to "conversion savings" lies at 21% in 2050 compared to the baseline, 13.5% of which are due to the increase of electric vehicles in passenger transport.

The overall contribution from energy efficiency measures related to final energy lowers GHG emissions by an additional 43% compared to the baseline emissions. This can be translated into a 79% emission reduction compared to the 2010 level and 81% emission reduction compared to the 1990 level (of 4.139 Mt CO2-equivalent). It has to be noted, that these figures represent only energy related GHG emissions reduction potentials and do not reflect measures in other areas with further GHG emission reduction potentials.

As already mentioned, it is worth pointing out once again that the higher the initial share of electricity as a final energy carrier in a sector, the lower the contribution of this sector to additional GHG emission reduction (compared to the baseline) as a result of the autonomous decarbonisation of the power sector under the baseline.

Figure 9: Energy related GHG emissions resulting from final energy savings (in Mt CO2-equivalent)



3.3 Sectoral saving potentials

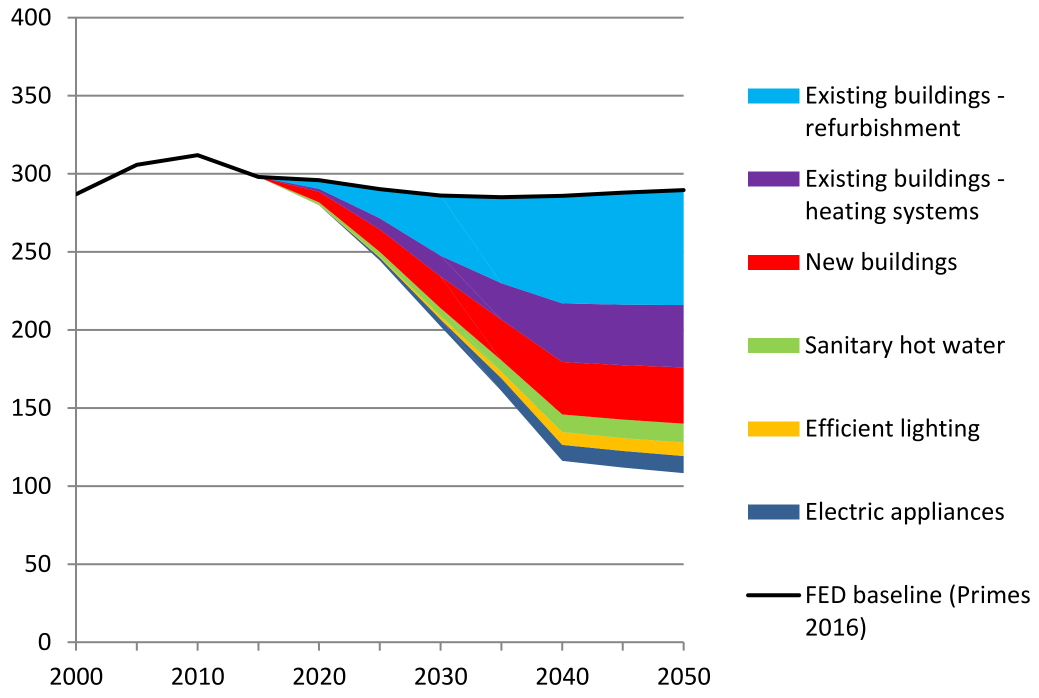
Household Sector

According to Primes 2016, the baseline final energy demand in the household sector is projected to have peaked in 2010 and to decline from 2010 until 2030, with a small increase afterwards. Final energy demand is projected to again reach the level of 2025 in the year 2050 (~290 Mtoe).

By 2050, the final energy saving potentials identified in the household sector can lead to a reduction in final energy demand of 63 percent compared to the baseline development (Figure 10).

More than half of these savings are related to the building shell refurbishment of existing buildings, with the refurbishment of old buildings (25%) and the restoration of heating system in existing buildings (13%). Furthermore, 12 percent of savings can be realized in the construction of new buildings. The savings in sanitary hot water (4%), efficient lighting (3%) and electric appliances (4%) contribute to a significant lesser extent to the overall savings.

Figure 10: Final energy demand and energy saving potentials by wedge in the household sector (in Mtoe)

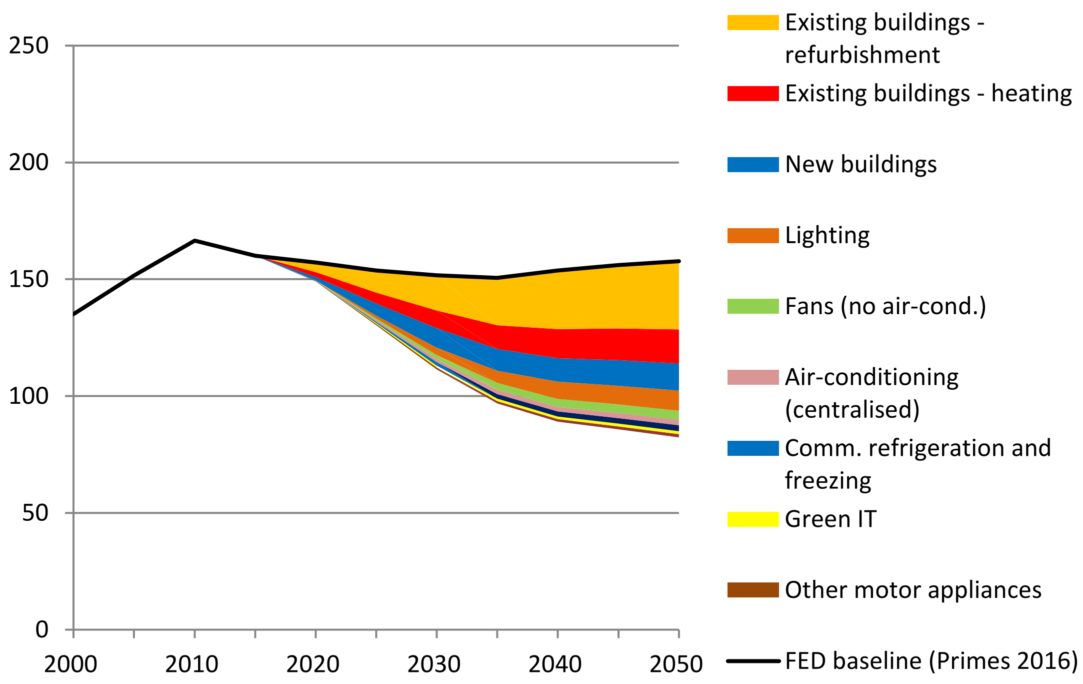


Tertiary Sector

The Primes 2016 baseline for the tertiary sector shows the final energy demand decreasing slightly since 2010, with the lowest projection in 2035 with approx. 150 Mtoe, but in 2050 it is projected to have increased again to the level of 2020 (~157 Mtoe). The final energy demand of the agriculture sector is hereby not considered.

By 2050, 47 percent of the projected final energy demand in the tertiary sector can be saved. While efficient electric appliances represent the most attractive saving option given their particularly high specific energy cost savings, building-related efficiency measures trigger the highest overall benefits due to the size of the potential. Similar to the residential sector, efficient heating and insulation systems in existing and new buildings represent three quarters of these total savings.

Figure 11: Final energy demand and energy saving potentials in the service sector (in Mtoe)



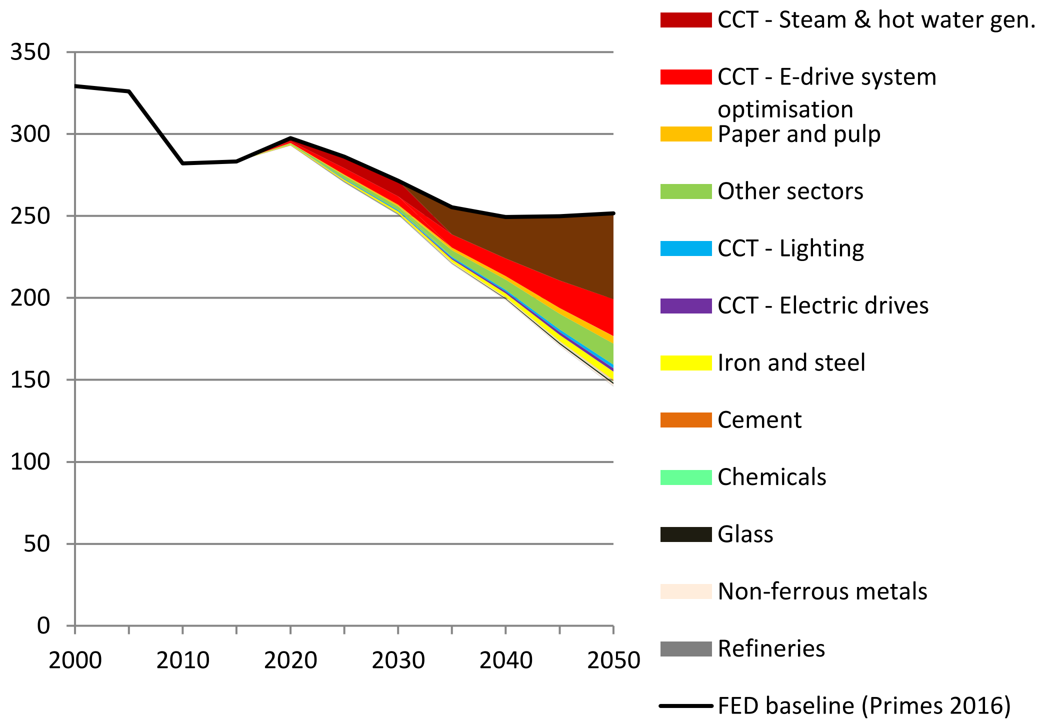
Industry Sector

The baseline final energy demand of the industry sector is, according to Primes 2016, projected to decrease by 30% between the years 2000 and 2050. Despite increasing amounts of value added, the final energy demand is expected to decrease.

Although efficiency effects have been taken into account for the updated projection of the final energy demand, plenty of further potentials are available to further decrease the final energy demand in the industry. The untapped cost-effective potentials could reduce the final energy demand by 42% in the year 2050. 73 percent of these possible savings would have to be realized from cross-cutting technologies (CCT, i.e. efficient steam and hot water generation as well as optimisation electric drives).

Even though efficient steam and hot water generation technologies (i.e. improved efficiency of heat generation units, further diffusion of combined heat and power technology (CHP) and highly efficient industrial space heating) represent half of the final energy saving potential, their contribution in terms of cost savings is much smaller and depends heavily on the assumptions made about the fuel mix of the generation capacities displaced by CHP. Electric drive-based system optimisation, on the other hand, triggers an immediate cost reduction.

Figure 12: Final energy demand and energy saving potentials in the industry sector (in Mtoe)



Transport Sector

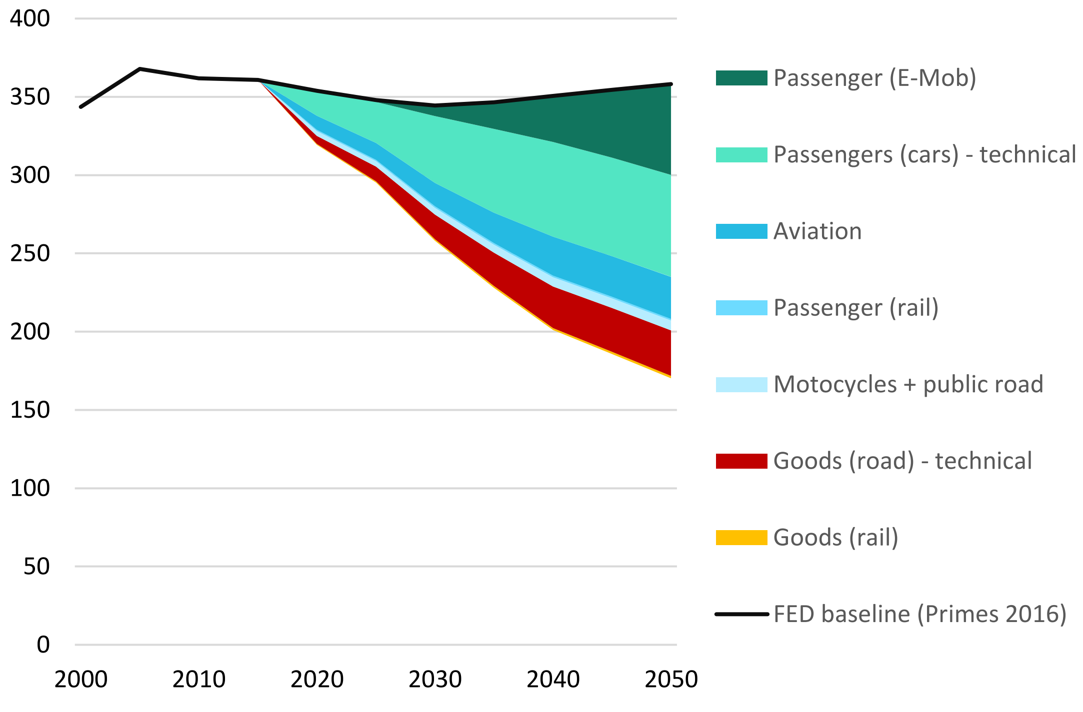
In the Primes 2016 baseline the final energy demand in the transport sector is increasing again from 2030 upwards, following a slight downward trend in the previous years. This upward trend is a combination of a projected drastic increase of km travelled (50% of person km (pkm) and 80% of ton km (tkm) between 2000 and 2050) and of the increasing trend towards energy intensive private cars.

In the techno-economic scenario, final energy demand in the transport sector could be reduced by 52% as compared to the baseline. This reduction needs to counterbalance increasing km travelled through pushing technical improvements in passenger as well as freight road transport, which account for half of the overall saving potential in 2050. Furthermore, a strong shift towards electric vehicles in passenger transport (in this scenario half of the person km travelled in 2050 are travelled with electric vehicles) could reduce final energy demand by another 16%

The technical potentials of other traffic modes (technical measures in the rail, air and public road transport sector) are less significant, given the comparatively small share, at present, of these transport mode (though aviation is increasing considerably at the 2050 time frame).

The modal shift towards more energy efficient means of transport or behavioural changes such as eco-driving, are neither part of the techno-economic scenario, nor considered in the baseline scenario of Primes 2016. The techno-economic scenario is intentionally not focusing on such behavioural issues (while in reality, they may have some impact). Modal shifts and changes in behaviour will, however, play a major role in the Energy Efficiency First scenario of the Energy Efficiency Vision, which aims in identifying potentials that go beyond mere technical advancements.

Figure 13: Final energy demand and energy saving potentials in the transport sector (in Mtoe)



4 Efficient and Inefficient New Trends Scenarios

Within the Energy Savings Scenarios 2050, two scenarios complement the baseline and techno-economic scenarios, which take structural and societal changes and their (increasing or decreasing) impacts on energy consumption more explicitly into account, contrasting the techno-economic scenario. The two scenarios developed here are contrasting scenarios: in particular the "New Trends Inefficient" Scenario is gathering the increasing impacts of these trends while the "New Trends Efficient" Scenario supposes that realisation of the EE1 Principle leads to the enhancement of the decreasing impacts of the trends on energy consumption. De facto, increasing and decreasing impacts may be observed at the same time. This could be established by evaluating the likelihood of one or the other trend, e.g. in further expert workshops. This could not be carried out in the frame of this work.

The main purpose of this chapter is to give an overview over the Efficient and Inefficient New Trends Scenarios. The following issues are addressed in detail:

1. What we know about the impacts of New Societal Trends on energy consumption.

2. Contribution of enhanced energy efficiency in energy conversion and in energy end-use to primary energy savings by 2050.

3. Analysis of the contribution, final energy savings can make to reducing GHG emissions by 2050 through increased energy efficiency and energy savings.

4.1 Methodology for the Efficient and Inefficient New Trends Scenarios

The work performed on these scenarios is a pioneering work. It has gathered information on the relation of New Societal Trends to the best of present knowledge and closed gaps with estimates. More studies on individual trends are required in the future to gain more certainty on the quantitative impacts. Estimates were carried out in a conservative way, in order not to overestimate the impacts of the New Societal Trends.

The Efficient and Inefficient New Trends Scenarios rely on the following working steps:

- Thorough literature research on pre-existing studies – impact of societal trends on energy consumption.

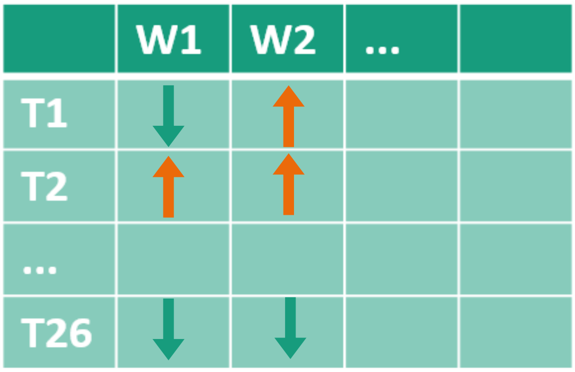
- Assessing the numbers given in the various studies and thereby evaluating the impact of the detailed trends on important modelling parameters of the various wedges set up in the techno-economic scenario (see the scheme in Figure 14; details are provided with the sectoral results). Both, energy-increasing and energy-decreasing impacts were considered (see the examples in Figure 25 and Figure 20). Care was taken, when analysing the studies to understand, which part of the trend was already included in the Baseline development and the techno-economic scenarios. It should be recalled that both already include a part of the New Societal Trends, which can be considered the continuation of developments of the past.

- Translating the impacts into modelling parameters.

- Estimating open model parameters. Care was taken to use conservative estimates as to the impacts of such trends

- Scaling of the scenarios by sector and by wedge with the estimated parameters.

Figure 14: Scheme for linking the trends with important modelling parameters for each wedge



The following points summarise limitations of the present work:

- For many trends no previous studies exist, which determine the even the qualitative effects of the trend on the energy consumption (e.g. consumer; financing; urbanization) and had to be completed by own expert estimates on impacts.

- Specifically, there is quite often yet no quantification of these trends

- Studies often are not transparent in their baseline assumptions

- Parameters need to be adopted to the EU context. Specific EU studies may enhance the validity for the European context.

- The model parameters need to account for double-counting of certain mechanisms. Care was taken here to eliminate such double-counting among the different societal trends but more in-depth analysis could better separate such overlapping impacts.

4.2 Overall results for the Efficient and Inefficient New Trends Scenarios

Change in Final Energy Demand (FED):
- New Trends Inefficient Scenario: -32% compared to the Baseline in 2050. Variant Worst Case: +42% compared to the Baseline in 2050.
- New Trends Efficient Scenario, -67% compared to the Baseline in 2050.

The Final Energy Demand (FED), the Gross Inland Consumption and the (energy-related) GHG emissions are shown in Figure 15, Figure 16 and Figure 17. The Gross Inland Consumption and the GHG emissions are based on the low carbon electricity mix shown in Figure 5.

The main findings from the analysis are the following:

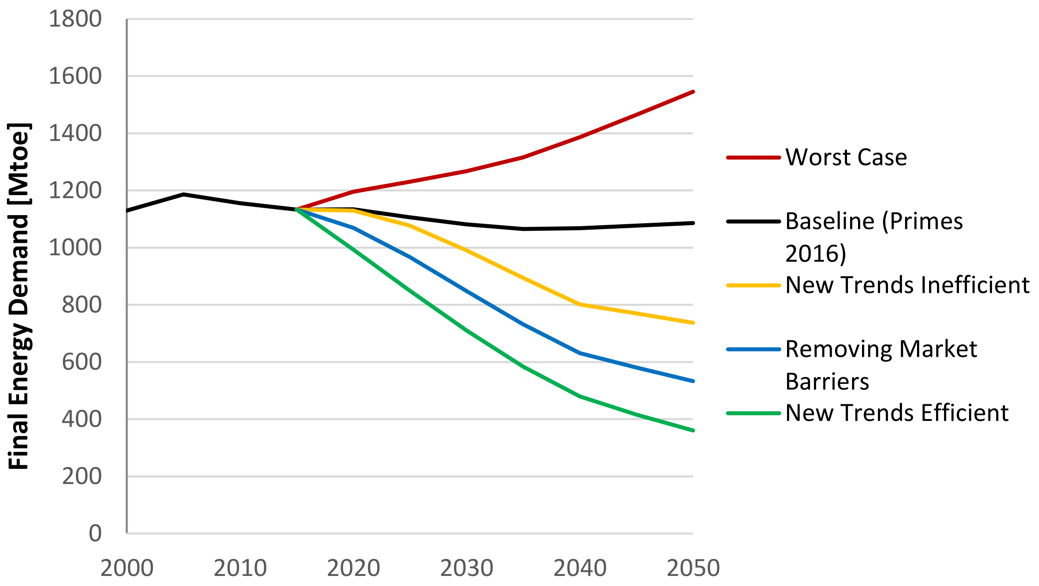
- New Societal Trends without EE1 (New Trend Inefficient Scenario) could diminish the effect of the realized techno-economic potentials for FED to a 32% reduction.

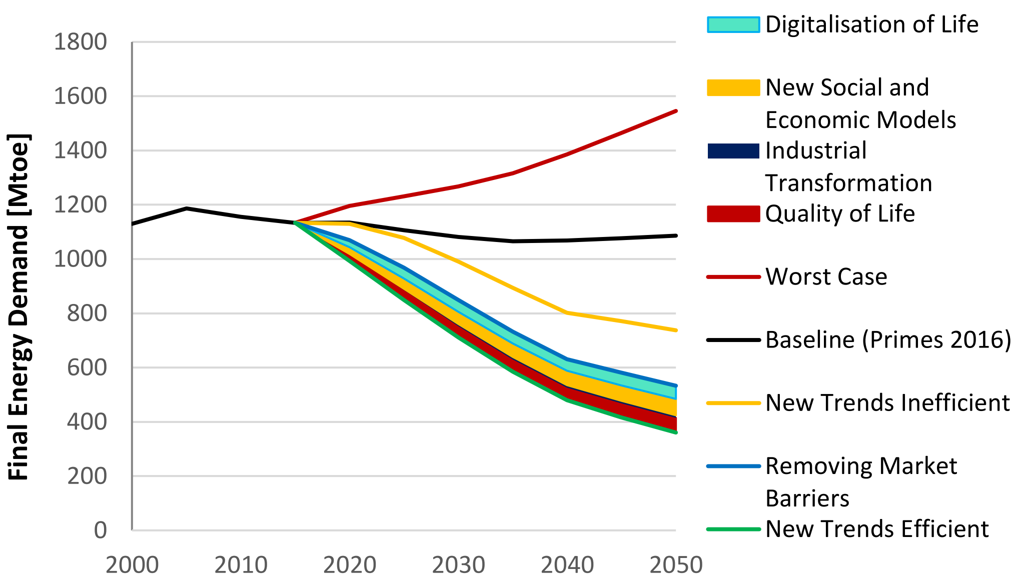
- If the New Societal Trends would unfold the energy increasing trends, without the realisation of the techno-economic potentials (Worst Case variant to the New Trends Inefficient Scenario), the FED could be strongly increased by up to 42% above the Baseline

- New Societal Trends supported by a strong EE1 Principle (New Trends Efficient Scenario) could decrease FED further (-67% compared to the Baseline in 2050)

The Gross Inland Consumption and the (energy-related) GHG emissions follow closely these trends based on the energy mix described in section 2.2.

Figure 15: Final energy demand (EU28) in the three scenarios and the variant Worst Case. The lower graph shows the contribution of the four large Trend Clusters in the case of the New Trends Efficient Scenario





Efficient and Inefficient New Trends Scenarios

Based on the final energy demand of the three scenarios and the Worst Case Variant the Gross Inland Consumption and the energy-related GHG emissions were calculated, given the low-carbon electricity mix in Figure 5 as well as the electricity shares in Table 5.

Table 5: Electricity Shares per Sector

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Household	21%	22%	23%	24%	24%	26%	27%	28%	29%	30%	32%
Tertiary	35%	37%	39%	41%	43%	46%	49%	52%	53%	55%	55%
Industry	28%	30%	31%	30%	30%	32%	33%	35%	37%	38%	39%
Transport	1%	1%	1%	1%	2%	2%	2%	5%	11%	20%	32%

Figure 16: Gross Inland Consumption [Mtoe] in the three scenarios (EU28) and the Variant Worst Case

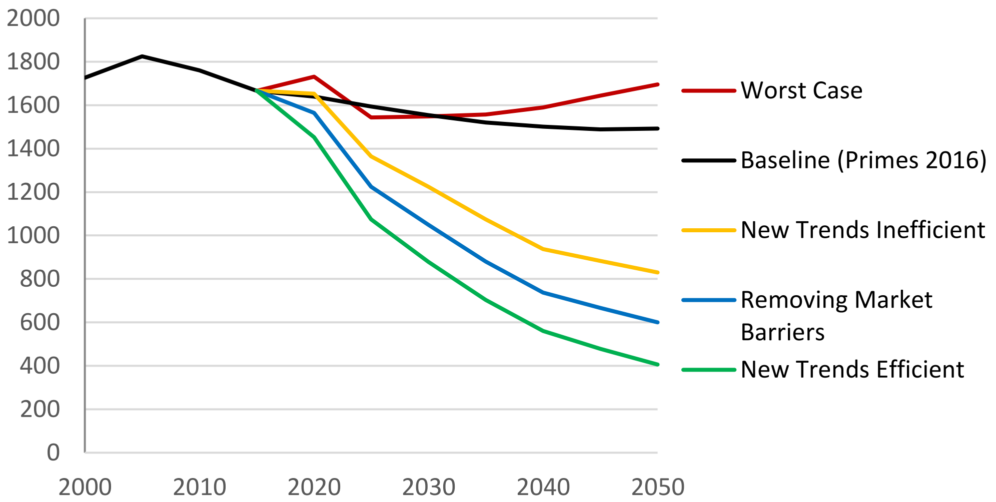
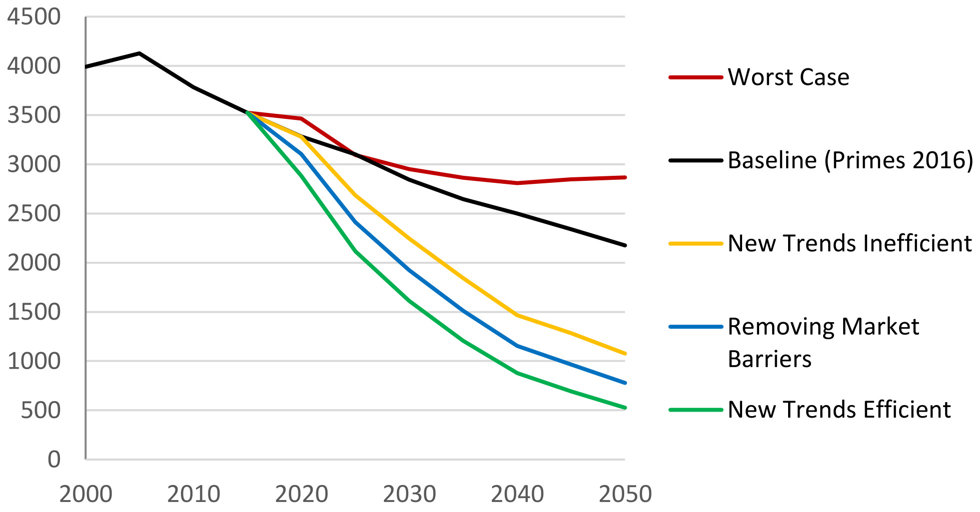


Figure 17: Energy-related GHG emissions [Mt CO2-equivalent] in the three scenarios (EU28) and the Variant Worst Case



4.3 A sectoral view to the Efficient and Inefficient New Trends Scenarios

Household and Tertiary Sector

For the household and tertiary sectors the following main impacts of the New Societal Trends on energy consumption and scenario parameters are relevant:

In the New Trends Inefficient Scenario (increasing impacts on energy consumption):

- Building automation and interconnection of appliances increases the energy demand of the buildings
- Despite a widespread awareness consumers have increasing energy demands (e.g. due to changes in comfort levels)

In the New Trends Efficient Scenario (decreasing impacts on energy consumption):

- Building automation raises consumer awareness
- Decentral generation of electricity raises the awareness of the value of energy
- Urbanization contributes to reducing living areas and adapting them to the living context.
- Consciousness about the personal (carbon) footprint impacts consumer choices on buildings and appliances.

Behavioural choices such as the adaptation of space to the living context, consciousness about the personal footprints and decentral generation of electricity, supported by policy settings, contribute to New Trends Efficient Scenario.

The major impacts by New Societal Trends in the Efficient and Inefficient New Trends Scenarios for the different wedges in the household/tertiary sector are given below (Table 6). The speech bubbles show exemplary how the parameters were derived. Results for final energy demand (EU28) in the three scenarios and the variant is provided in Figure 18. Both, energy-increasing and energy-decreasing impacts were considered (see the examples in Figure 19 and Figure 20).

Efficient and Inefficient New Trends Scenarios

Table 6: Major parameter settings derived from studies and estimates for the main trend clusters and main wedges in the household and tertiary sectors

	Energy demand	
	Heating and Cooling	Appliances and Lighting
New Trends Efficient Scenario		
Digitalisation of Life	0.95	0.79
New Social and Economic Models		
Consumer / Citizens	0.8	0.9
Sustainable Finance	0.95	1
Industrial Transformation	1	1
Quality of Life		
Health & Comfort	1	1
Regionalization / Urbanization	0.9	1
Total Scenario Changes	0.65	0.71
New Trends Inefficient Scenario		
Digitalisation of Life	1.1	1.5
New Social and Economic Models		
Consumer / Citizens	1.1	1.1
Sustainable Finance	1	1
Industrial Transformation	1	1
Quality of Life		
Health & Comfort	1.1	1.1
Regionalization / Urbanization	1	1
Total Scenario Changes	1.33	1.82

Own estimate based on projections by *IEA 2017 - Digitalization & Energy*

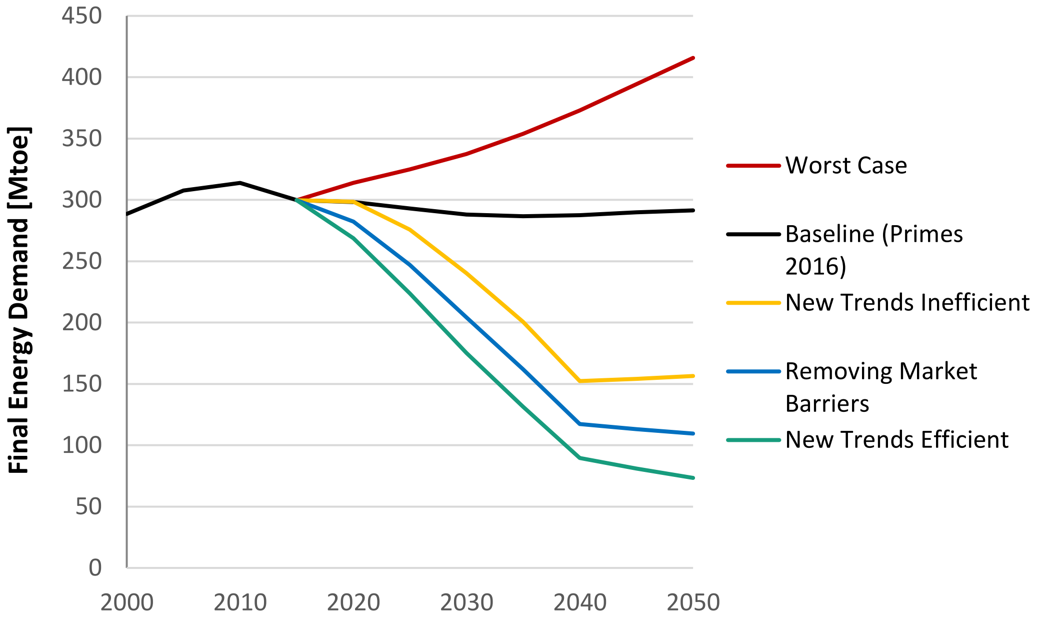
Own estimate based on *UKERC - Energy 2050 - Energy Demand Lifestyle and Energy Consumption*

Gains through increased public spending in renovation

Increasing demand based on longer heating and cooling hours due to remote control

Changes in comfort levels, e.g. room temperatures

Figure 18: Final energy demand household sector (EU28) in the three scenarios and the variant Worst Case. The lower graph shows the contribution of the four large Trend Clusters in the case of the New Trends Efficient Scenario



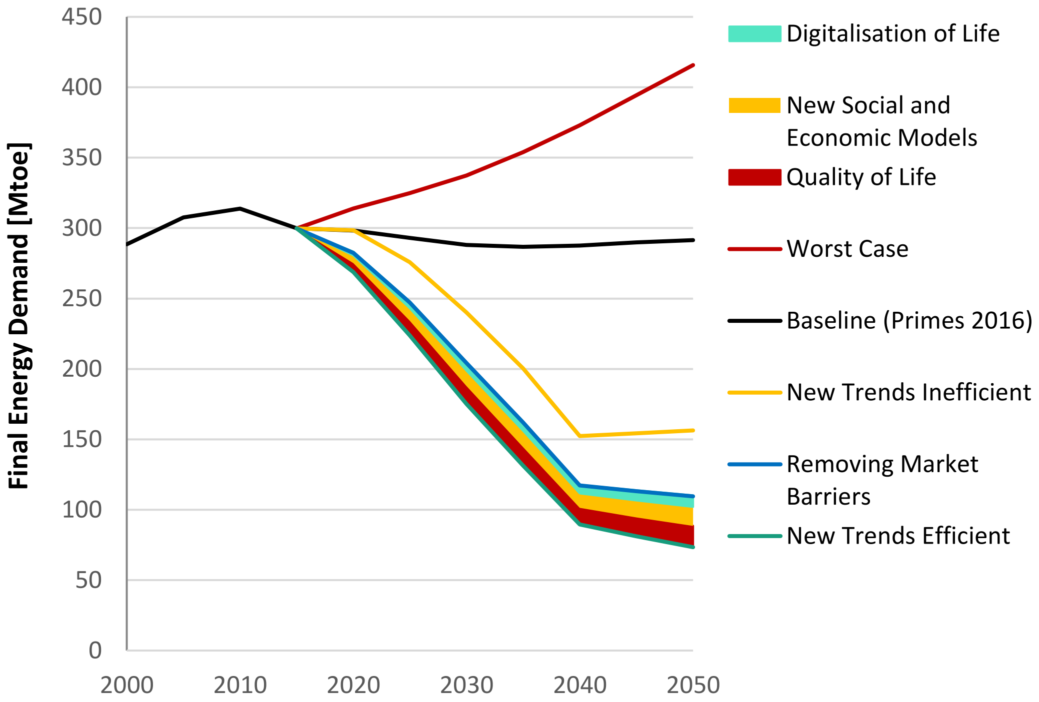
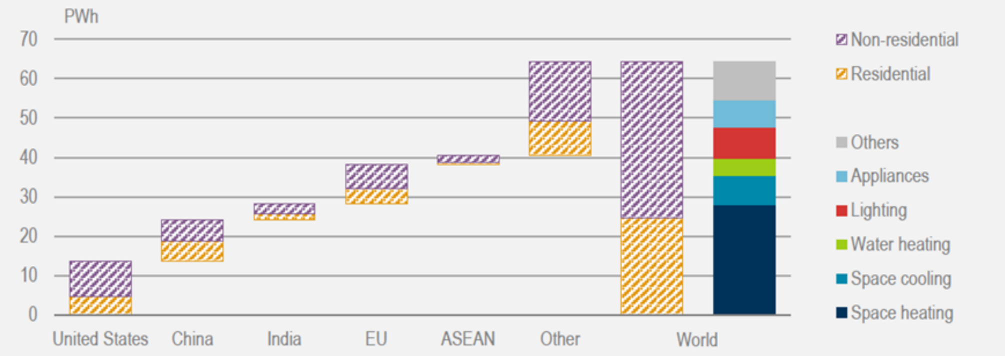


Figure 19: Example for increasing or decreasing impacts on energy consumption from buildings automation (IEA, 2017)

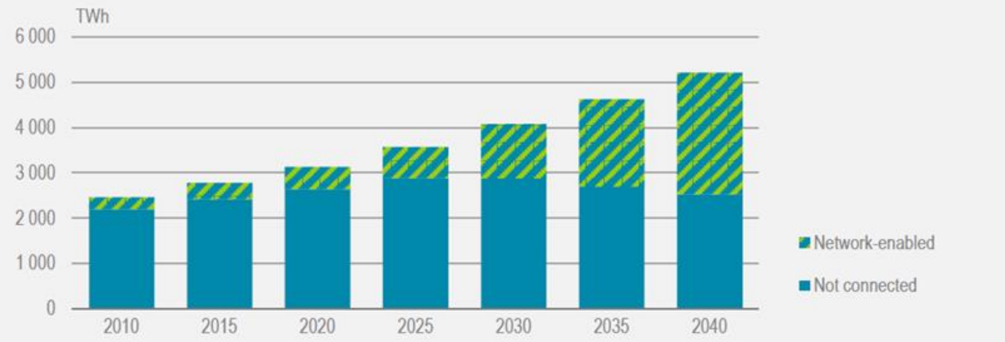
Figure 2.4 Cumulative energy savings in buildings from widespread digitalization



Key message: The widespread deployment of active controls, assuming limited rebound effects, would save up to 65 PWh cumulatively to 2040, or twice the energy consumed by the entire buildings sector in 2017.

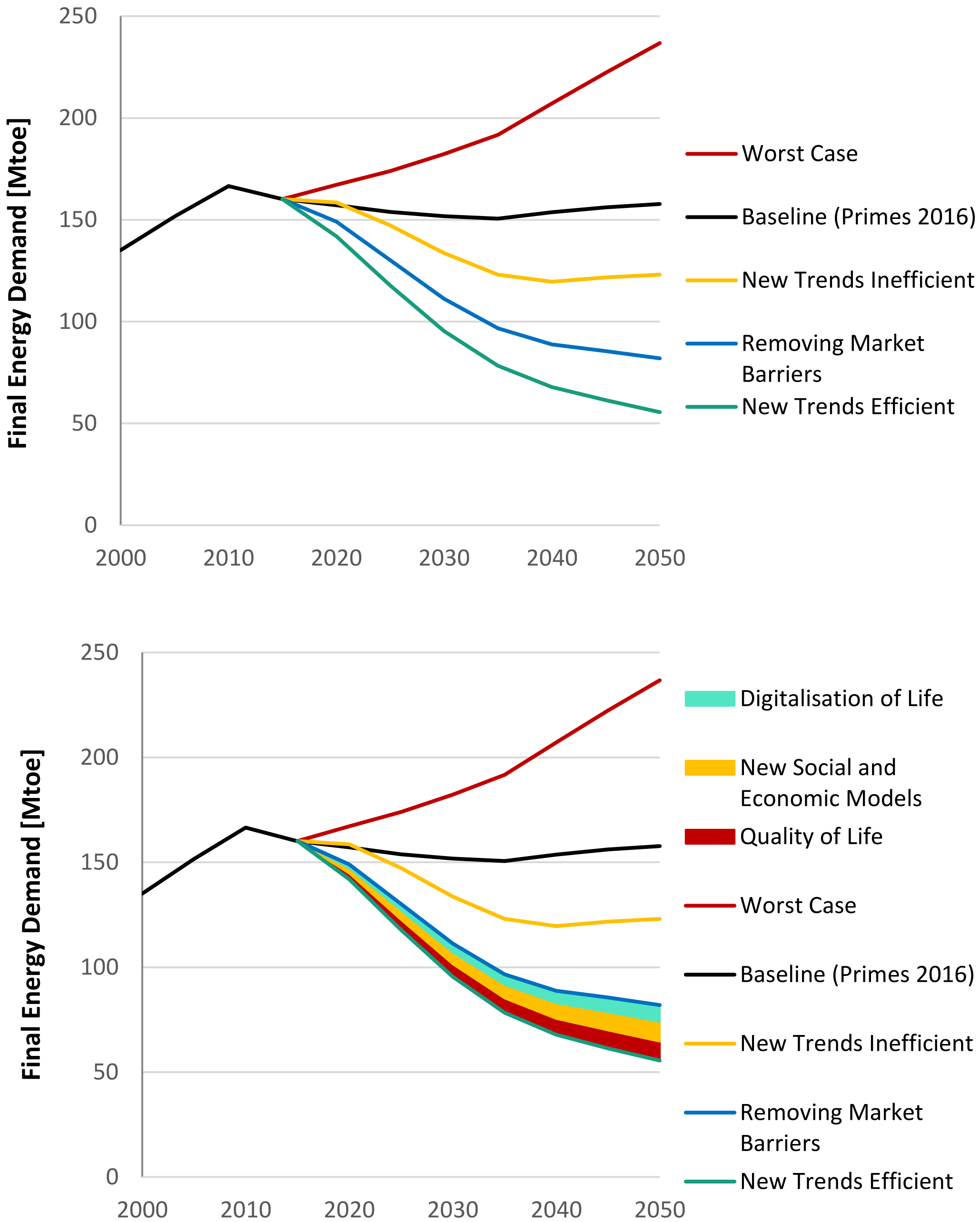
Figure 20: Example for an energy increasing impact from digitalisation of household appliances (IEA, 2017)

Figure 2.5 Household electricity consumption of appliances and other small plug loads



Key message: The share of connected "network-enabled" appliances in total household electricity consumption is set to grow rapidly, presenting opportunities for smart demand response but also increasing the need for standby power consumption.

Figure 21: Final energy demand tertiary sector (EU28) in the three scenarios and the variant Worst Case. The lower graph shows the contribution of the four large Trend Clusters in the case of the New Trends Efficient Scenario



Industry Sector

For the industry sector the following main impacts of the New Societal Trends on energy consumption and scenario parameters are relevant:

In the New Trends Inefficient Scenario (increasing impacts on energy consumption):

- Decarbonisation efforts increase the energy demand and notably the electricity demand from low-carbon processes
- Energy requirements of recycling processes increase energy demand (recycling of more heterogeneous scraps)
- Advanced and composite materials, complex types of batteries increase energy demand for production and recycling of such components

In the New Trends Efficient Scenario (decreasing impacts on energy consumption):

- Circular economy and the trend towards a shared economy reduce demand for energy intensive materials but also for products (e.g. cars)
- Digitalisation enhances the modularity of industrial processes

The circular economy and digitalisation enhancing the modularity of processes play a major role in the New Trends Efficient Scenario for the industry. However, it needs to be noted that the majority of the potentials that arise through a circular economy and through digitalisation are cost-effective and thus already included in the techno-economic potentials (Removing Market Barriers Scenario). So while the sectoral savings from the Baseline to the Removing Market Barriers Scenario sum up to 42% by 2050, the additional potential savings arising through the trends - which are not cost-effective - are relatively low. This should not be understood as if the overall impact of digitalisation and a circular economy would be insignificant.

The major impacts by New Societal Trends in the Efficient and Inefficient New Trends Scenarios for the different wedges in the industry sector are given below (Table 7). Results for final energy (EU28) demand in the three scenarios and the variant is provided in Figure 22. Both, energy-increasing and energy-decreasing impacts were considered (see the examples in Figure 23).

Table 7: Major parameter settings derived from studies and estimates for the main trend clusters and main wedges in the industry sector

Material Economics 2018 – The circular economy

IEA 2017 – Digitalisation and Energy

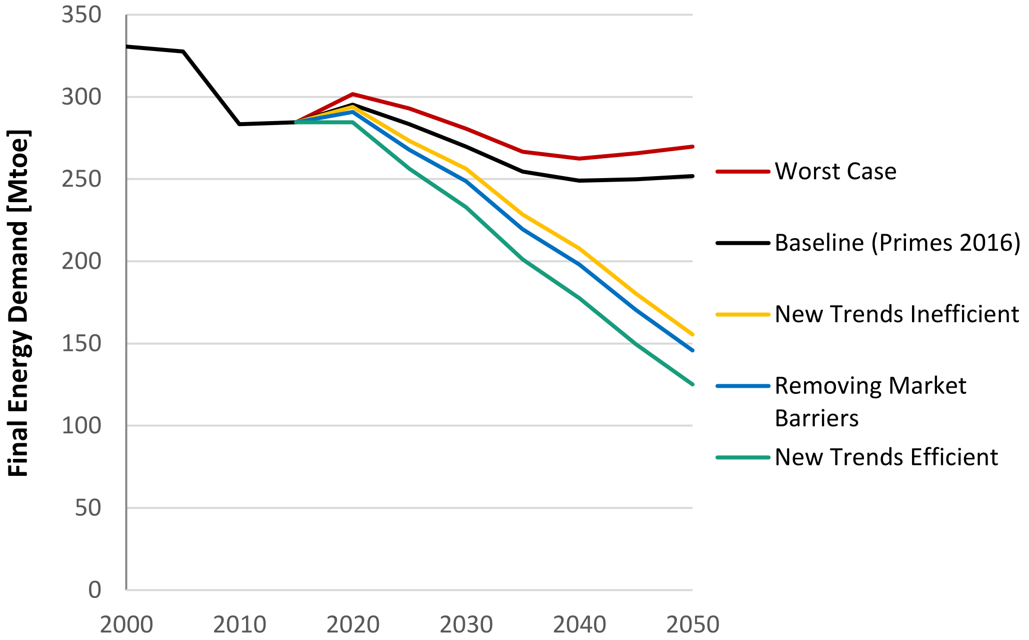
Birat 2011 - Pathways for Carbon Transitions D3. 2011. Qualitative description of links between social services and technologies in post-carbon society

	Final Energy Demand								
	Iron and steel	Non ferrous metals	Chemicals	Non metallic minerals	Paper and pulp	Food, drink and tobacco	Engineering	Textiles	Other industries
New Trends Efficient Scenario									
Digitalisation of Life	1	1	0.96	1	0.98	0.96	1	1	0.91
New Social and Economic Models									
Consumer / Citizens	0.8	0.76	1	1	1	1	1	1	1
Sustainable Finance	1	1	1	1	1	1	1	1	1
Industrial Transformation	0.84	0.82	1	0.83	1	1	1	1	1
Quality of Life									
Health & Comfort	1	1	1	1	1	1	1	1	1
Regionalization / Urbanization	1	1	1	1	1	1	1	1	1
Total Scenario Changes	0.672	0.6232	0.96	0.83	0.98	0.96	1	1	0.91
New Trends Inefficient Scenario									
Digitalisation of Life	1	1	1	1	1	1	1	1	1
New Social and Economic Models									
Consumer / Citizens	1	1	1	1	1	1	1	1	1
Sustainable Finance	1	1	1	1	1	1	1	1	1
Industrial Transformation	1.32	1.35	1	1	1	1	1	1	1
Quality of Life									
Health & Comfort	1	1	1	1	1	1	1	1	1
Regionalization / Urbanization	1	1	1	1	1	1	1	1	1
Total Scenario Changes	1.32	1.35	1	1	1	1	1	1	1

BCG 2013 - Steel's Contribution to a low-carbon Europe 2050

Efficient and Inefficient New Trends Scenarios

Figure 22: Final energy demand industry sector (EU28) in the three scenarios and the variant Worst Case. The lower graph shows the contribution of the four large Trend Clusters in the case of the New Trends Efficient Scenario



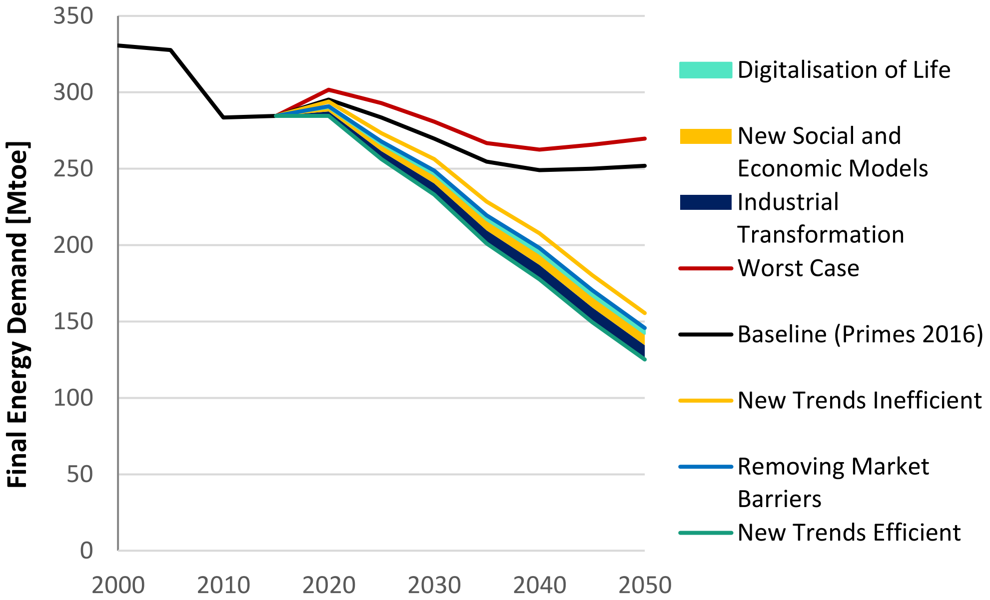
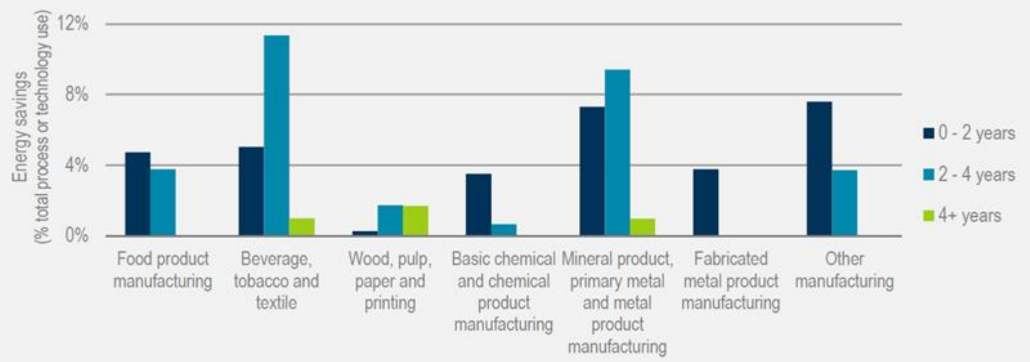


Figure 23: Example for decreasing impacts on energy consumption in industry by digitalisation (IEA, 2017)

Figure 2.11 Potential energy savings from improvements in process control enabled by digitalization by subsector in Australia, 2010-11



Key message: All industrial sectors analysed present opportunities with payback periods of less than two years for energy savings from improved process controls enabled by digitalization.

Source: ClimateWorks Australia (2013), *Industrial Energy Efficiency Data Analysis Project.*

Transport Sector

For the transport sector the following main impacts of the New Societal Trends on energy consumption and scenario parameters are relevant:

In the New Trends Inefficient Scenario (increasing impacts on energy consumption):

- more person & freight km
- technical advancements in traffic automation hinder modal shift away from private transport
- consumer do not develop a sense of personal awareness and further increase their travel demand as well as their consumption behaviour
- Urbanization leads to people wanting to travel more (out of the city; between large cities; to their hometown, etc.

In the New Trends Efficient Scenario (decreasing impacts on energy consumption):

- more person & freight km
- but automation beneficiary for EE
- large modal shift towards public transport
- less consumption of goods due to New Societal Trends leads to less freight transport
- urbanization leads to shorter commutes and thus a shift towards biking and walking
- sustainable investments lead to efficiency increases in public transport

Since both of these scenarios are based on the Removing Market Barriers scenario, they are based on the same assumption of electric vehicles in passenger transport, which assumes that in 2050 half of the car passenger km travelled will be travelled with electric vehicles. In contrast, in the Worst Case scenario no significant increase in electric vehicles is expected.

Modal shifts and changes in behaviour play a major role in the New Trends Efficient Scenario, which aims in identifying potentials that go beyond mere technical advancements.

The major impacts by New Societal Trends in the Efficient and Inefficient New Trends Scenarios for the different wedges in the transport sector are given below (Table 8). Results for final energy demand (EU28) in the three scenarios and the variant is provided in Figure 24. It needs to be noted, that international aviation as well as international shipping are not part of the scenarios, as they are not yet included in the Baseline deducted from Primes 2016. Both, energy-increasing and energy-decreasing impacts were considered (see the examples in Figure 25).

Table 8: Major parameter settings derived from studies and estimates for the main trend clusters and main wedges in the transport sector

	Transport activity		Vehicles efficiency	
Key indicators	Passenger transport activity (Gpkm)	Freight transport activity (Gtkm)	Passenger transport activity (toe/Mpkm)	Freight transport activity (toe/Mtkm)
New Trends Efficient Scenario				
Digitalisation of Life	1.1	1.04	0.78	0.96
New Social and Economic Models				
Consumer / Citizens	1	0.95	1	1
Sustainable Finance	1	1	0.95	1
Industrial Transformation	1	1	1	1
Quality of Life				
Health & Comfort	1	1	1	1
Regionalization / Urbanization	0.95	0.95	1	1
Total Scenario Changes	1.05	0.94	0.74	0.96
New Trends Inefficient Scenario				
Digitalisation of Life	1.18	1.04	1.3	1
New Social and Economic Models				
Consumer / Citizens	1.1	1.1	1	1
Sustainable Finance	1	1	1	1
Industrial Transformation	1	1	1	1
Quality of Life				
Health & Comfort	1	1	1	1
Regionalization / Urbanization	1.1	1.1	1	1
Total Scenario Changes	1.43	1.26	1.3	1

Own estimate based on projections by *IEA 2017 - Digitalization & Energy*

Additional investments in public transport – increasing modal shift

Shorter commutes – increasing shares of biking and walking

Behavioral changes and modal shifts reintegrated from original study *(Fraunhofer ISI 2009a)*

Efficient and Inefficient New Trends Scenarios

Figure 24: Final energy demand transport sector (EU28) in the three scenarios and the variant Worst Case. The lower graph shows the contribution of the four large Trend Clusters in the case of the New Trends Efficient Scenario

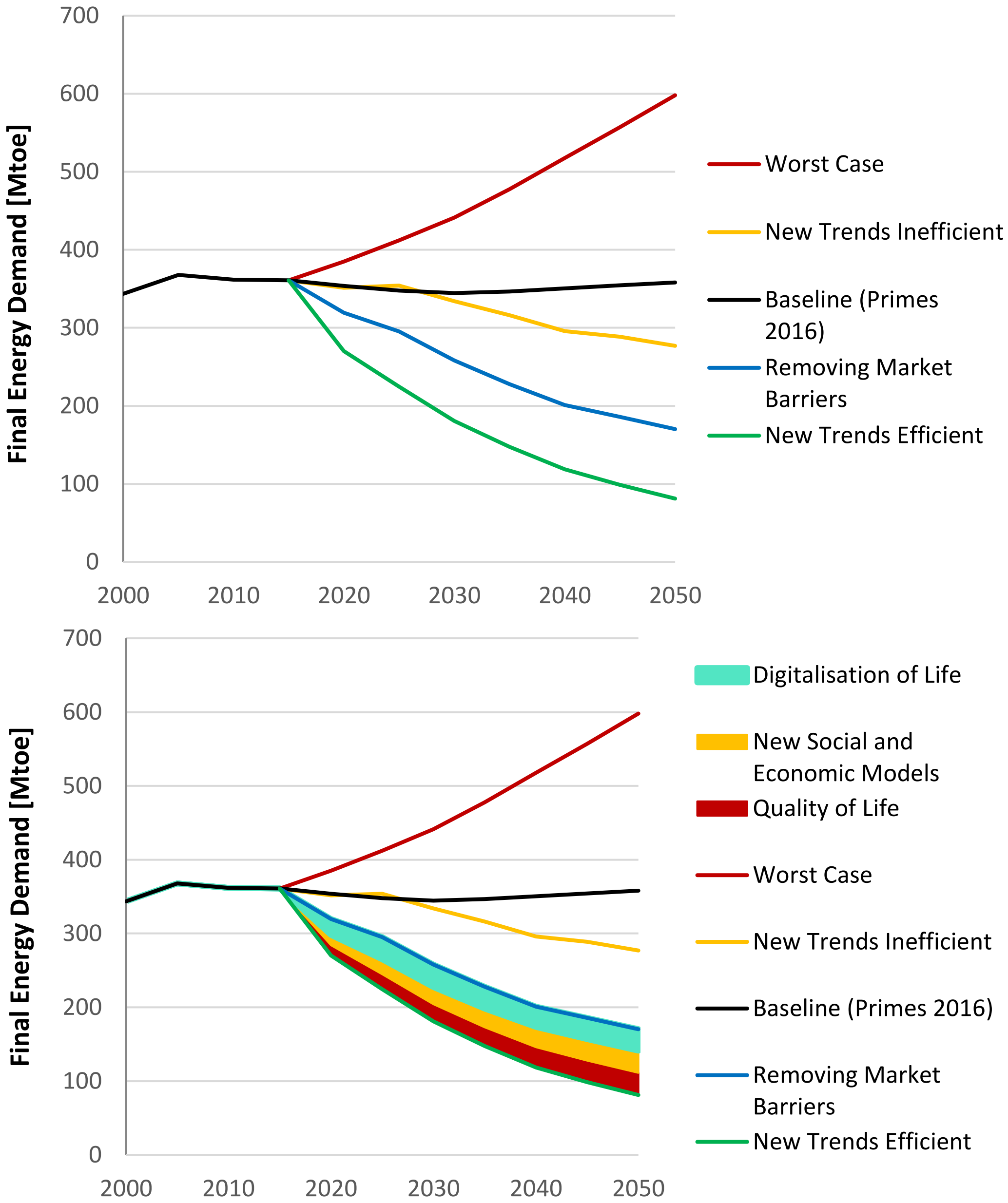
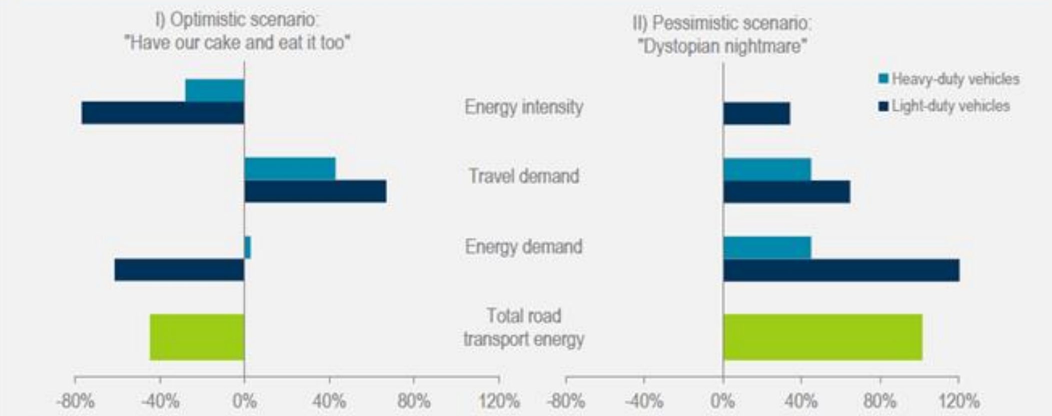


Figure 25: Example for increasing or decreasing impacts on energy consumption in transport from vehicle automation (IEA, 2017)

Figure 2.2 Range of possible energy impacts from vehicle automation in the United States



Key message: US road transport energy demand is reduced by almost half under an optimistic scenario, but more than doubles in a pessimistic scenario.

I) In this scenario, virtually all of the potential benefits of automation are realised, including smoother traffic flow, fewer accidents (vehicles become smaller/lighter) and the widespread adoption of eco-driving and platooning.

II) In this scenario, broad adoption of higher levels of automation is coupled with strong increases in demand for travel, and no efficiency benefits materialise (e.g. no platooning or eco-driving).

Note: This figure only shows two of the four scenarios from the study. One of the other scenarios describes a world with limited automation and minimal impact on energy use, while the other assumes large improvement in fuel efficiency as well as increased travel demand, resulting in a moderate net reduction in energy use.

Source: Wadud, MacKenzie and Leiby (2016), "Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles".

5 Main References

The list provides the main references. A number of further sources were investigated but did not provide enough details to be used in the analysis.

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