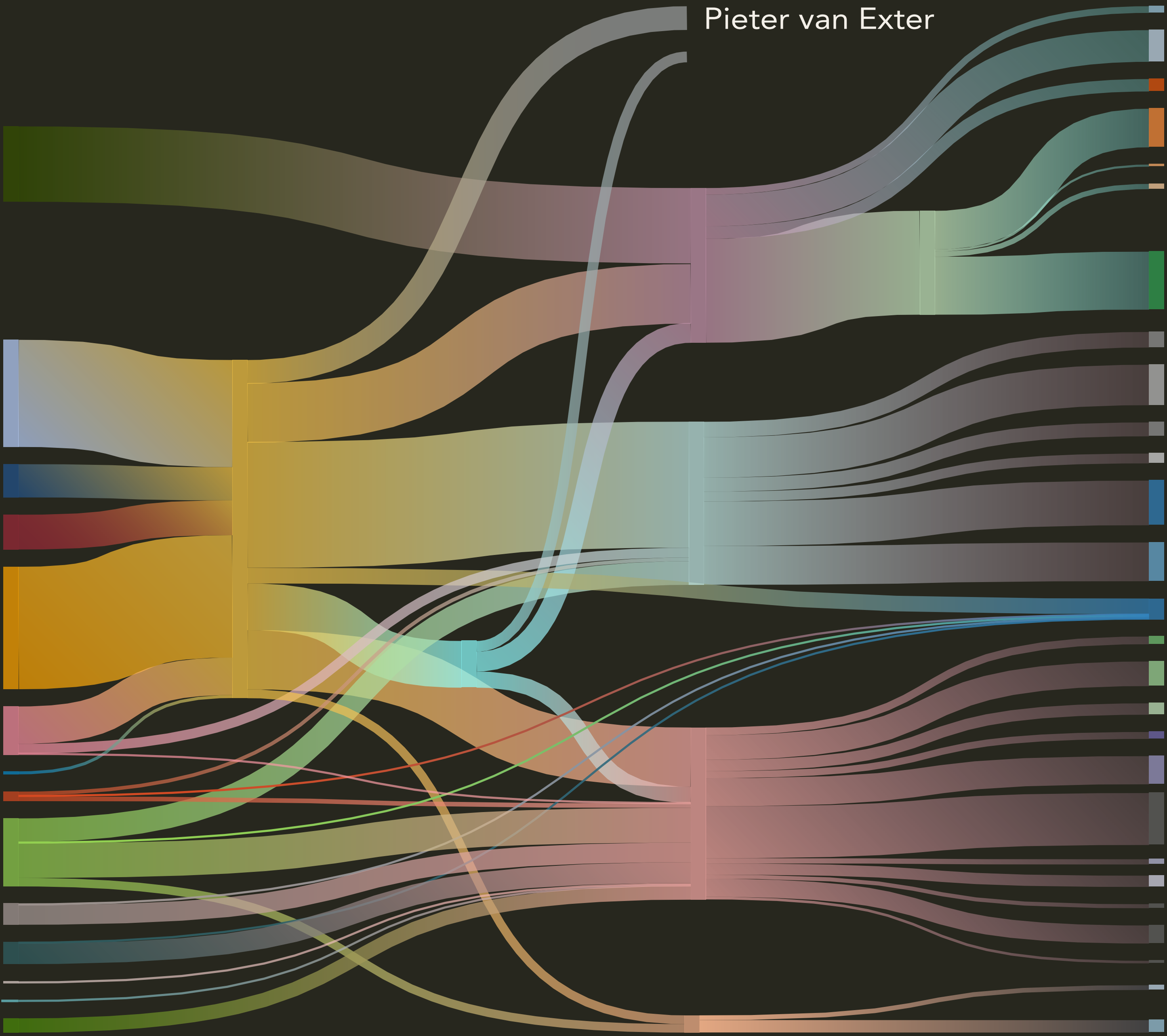
A Hitchhiker's Guide to Energy Transition Within 1.5 °C

Backcasting Scenario for 100% Decarbonization of the Global Energy System by 2050

Pieter van Exter



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A Hitchhiker's Guide to Energy Transition Within 1.5 ℃

An Energy Backcasting Scenario for 100% Decarbonization of the Global Energy System by 2050

By

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In partial fulfilment of the requirements for the degree of

Master of Science
in Industrial Ecology

At the Delft University of Technology and Leiden University,
to be defended publicly on Tuesday October 31, 2017 at 16:00.

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Preface

The 7 months I have been working on this research felt like an intergalactic journey through the energy system. A trip that took me to all corners of the field: from traditional wood fires, via Fischer-Tropsch biodiesels, intermittent solar photovoltaics to advanced direct hydrogen reduction. Electric rickshaws, induction cooking stoves, smart grids, super grids, hybrids, plugin-hybrids, blast furnaces, kilns, heat pumps, they all passed by during this trip. Sometimes, I stopped to further examine their potential and decide to take them on board or not. The path did not seldom led me to heated debates, whether it concerned the sustainable application of biomass, the ethical objections of negative emissions or intermittent renewable integration. And of course, an old-fashioned fight of hydrogen versus electric transport was not missing either.

A considerable risk of such an extensive undertaking is to end up in a black hole. Fortunately this did not happen, due to the guidance by a very knowledgeable mission control centre. For the occasion, it was relocated from Houston to the Kanaalweg 15-G in Utrecht. The regular meetings with Kornelis Blok and Wouter Terlouw at Ecofys helped me to set course to next galaxies. Just as the regular discussions I had with other colleagues at the office. The couple of visits to the biochemistry lab from Wiebren de Jong, shed new light on my results and gave perspective on the relation between the micro and macro world.

The ultimate goal of this expedition was not just to provide outcomes alone, but rather to address the trade-offs, bottlenecks and barriers, and explore the context and decisions that need to be made. Outcomes alone are insufficient as demonstrated in the science fiction comedy of which the title has small similarities with this one. In one episode, the Deep Thought computer calculated the answer to the “ultimate question of life, the universe and everything” and found it be 42. The 7.5 million years of calculation it took to come to this answer were pointless if you don’t know the line of reasoning behind it.

Many argued that staying within 1.5 degrees, requires extra-terrestrial efforts. And they might be right. Yet, the only chance we have to save spaceship earth is to get down and come into action.

Abstract

Limiting global temperature increase by 1.5 ˚C rather than 2 ˚C reduces the impacts of climate change significantly (Knutti et al., 2015; Schleussner et al., 2016). It requires a rigorous transition of the global energy system in a very short time span. Though, the published energy scenarios that focus on 1.5˚C are limited (Peters, 2016). In this thesis, a backcasting study is conducted to develop a global energy transition scenario to stay within 1.5˚C, reaching net zero emissions by 2050. The backcasting framework comprises of six different steps of analysing: 1) goals and constraints, 2) current production and consumption, 3) future demand for energy services, 4) final energy demand, 5) outline the energy supply, 6) describe the implications.

The growing population and economy are expected to come with an increase in demand for energy services in the coming decades. Especially in developing countries, a catch up is foreseen. Efficiency improvements and use of more efficient technologies nevertheless enable a decrease of total primary energy supply between 2014 and 2050 (-21%). Furthermore, the final electricity demand triples in this scenario (up to 241 EJ by 2050) of which 73% is met by photovoltaics and wind. Electricity should be derived from 100% renewable sources by as soon as 2040.

Despite the rapid decarbonization, the carbon budget for 1.5 ˚C is exceeded. In total, 680 Gt CO_2 is emitted from fossil fuel combustion and cement between 2014 and 2050, of which more than 78% is emitted between 2014 and 2030. Total additional negative emissions would still be required of between 370 and 587 Gt CO_2 by the end of this century.

A potential pitfall of the proposed transition is that the unilateral focus on mitigating climate change could result in new environmental problems such as intoxication of aquatic and terrestrial ecosystems (UNEP, 2016). Integrated research is required to understand the implications and make trade-offs more explicit.

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1. Introduction

December 12th 2015 is widely considered as a milestone in climate policy history: after a two week conference with all world leaders present, an agreement was reached to keep global temperature rise no more than 2 degrees Celsius in this century. On top of that, the 195 nations agreed to "drive efforts" to stay within 1.5 degrees temperate rise, a "(..) *significantly safer defence line against the worst impacts of a changing climate*" (UNFCCC, 2015). A temperature increase of 1.5 ˚C has substantial advantages over a 2 ˚C scenario (Knutti et al., 2015). The effects of climate change such as sea level rise, coral bleaching, severe droughts, declining crop yields are significantly reduced when limiting climate change to 1.5 degrees compared to 2 degrees (Schleussner et al., 2016). Furthermore, a half degree cooler reduces the loss of permafrost which can evoke dangerous feedback loops (Chadburn et al., 2017).

This half degree difference not only reduces the risks of climate change considerably, it also requires a substantially faster decarbonization pathway. To stay within 1.5 ˚C, around 66% less emissions are allowed between 2011 and 2100 compared to a 2 ˚C scenario (Rogelj et al., 2015). By 2050, emissions from carbon dioxide should reach net zero, which requires a complete transformation of the energy system within a short window of time. Governments should seriously intensify their efforts to reach this target (Rogelj et al., 2016). Phasing out fossil fuels and deploying renewable energy sources on such a large scale within a short time frame, requires all decarbonization options possible (IEA, 2016a). Scenario planning is found to be a useful strategic tool to deal with such complexity and uncertainty in the future (Peterson et al., 2003; Zmud et al., 2014). However, there is an important knowledge gap of scenarios focusing explicitly on 1.5 °C in literature (IPCC, 2014; Peters, 2016; Schleussner et al., 2016).

Integrated Assessment Models (IAM) are todays' dominant framework to assess the interaction between economy and environment. IAM's are regarded as the most advanced tools available to model economic activity, climate change and the effects of policy interventions (van Vuuren et al., 2011). The first integrated climate models were developed in the 1980's and soon formed the basis of the IPCC reporting. Most IAM's are based on an economic optimization rationale to mitigate climate change at minimal costs.

An important limitation of this methodology is that it does not present the possible share of different energy technologies but provide a least-cost pathway under certain constraints (Bruckner, 2016). The focus in the scenarios of the last years has been mostly on *if* a transition is possible and not *how* this can be achieved (Schubert et al., 2015). The underlying economic mechanisms in the least-cost models are unsuitable for long term planning and result in problem shifting to future generations according to Ackerman et al. (2009). An example is the high amounts of negative emissions that are incorporated in most low carbon scenarios in the second half of the century to compensate for the overshoot of emissions in the first half. By relying on these future technologies a risk is taken since the deployment of negative emissions is rather uncertain (Kartha and Dooley, 2016; Vaughan and Gough, 2016).

Another risk of looking at costs only is that under- or overestimations of technology costs can considerably change the outcomes of the scenario. A correction of the experience curve of photovoltaics in an IAM demonstrated that renewable energy technologies can play a much larger role in the energy system by 2050 than was previously assumed (Creutzig et al., 2017).

Furthermore, historical data show that costs alone are not the only parameter in energy transitions (Trutnevyte, 2016). Other aspects such as political feasibility and acceptance by society play an underestimated role (Li et al., 2015; Peters, 2016; Schubert et al., 2015). Schubert et al. (2015) argues that this also requires increased transparency in scenario science, which is often lacking in the reporting from integrated assessment modelling.

Aim and research questions

The aim of this study is to develop an alternative and transparent global energy transition scenario within 1.5 °C in which more aspects than costs are taken into account and thereby avoiding the pitfall of relying on unproven technologies and underestimating the potential of renewable energy technologies as much as possible. This research contributes to the currently limited understanding of the challenges that come with this transition (Peters, 2016). Another addition to the current knowledge is the fact that this study combines quantitative and qualitative data. There is a clear gap between current quantitative and qualitative scenarios and the importance of combining both types of knowledge is addressed in many papers (Fortes et al., 2015; Robertson et al., 2017; Söderholm et al., 2011). A backcasting study is conducted in which the current energy system is transformed into a net carbon neutral system by 2050, while providing the full demand for energy services. This research is based on the energy backcasting framework by Robinson (1982). This framework consists of six steps which are formulated into the research questions of this study:

- What are the goals and constraints of the energy transition?
- What are the characteristics of the current energy system in terms of consumption and production?
- How will the demand for energy services develop towards the future?
- What is the future energy demand in the different sectors?
- How is the future energy supplied?
- What are the implications of this energy transition in terms of cumulative and negative emissions?

A model is built to integrate all steps, calculate the future energy demand and supply and ultimately provide the cumulative atmospheric CO_2 emissions that are released.

The study starts with a literature review in which scenario planning is described in more detail. A review is conducted of the diffusion of innovations theory in general and the diffusion of renewable energy technologies specifically. Also, the debate on negative emissions is elaborated upon. Then, the methodology is explained and all the model components are described. Subsequently, the goals and constraints of the model are formulated. Next are the results of this study which are divided into several sections. At first in the results, a description of the current energy system is presented, including the activity levels and energy intensities. An analysis is then conducted to assess the future demand for energy services. After these steps, the energy transition is described including technology switches and efficiency improvements. The energy supply section describes the energy supply and zooms in on the production of electricity. The last part of the results is the implications of this transition in terms of greenhouse gas emissions. A sensitivity analysis provides more insights in the implications of uncertainties. Finally, the results are reflected upon in the discussion section and then recommendations are presented and conclusions are drawn.

2. Literature review

In this section, the existing literature of several topics and concepts is discussed and explained. Firstly, the *diffusion of innovations* concept is treated and its application on renewable energy technologies. Subsequently, the characteristics of renewable energy technologies in the power sector are discussed. Finally, the link is explained between energy and CO_2 emissions and an overview is provided of the discussion on negative emissions.

2.1 Diffusion of innovations

The energy transition requires the deployment of new low carbon technologies that replace current practice. That is why it is important to understand how these technologies typically developed over time. When looking at the development of new technologies over time, a common similar pattern is found which is described in the diffussion of innovations theory by Rogers (1962). According to this theory, a new technology is first used by the consumer groups who are referred to as the *innovators* and *early adopters*. These types of consumers are generally less receptive of risk and more progressive. The technology is still in a niche phase and growth rates increase exponentially in this stage. As the technology slowly makes it entrance on the market, people get more and more familiar with the product and the costs decrease, the *early* and *late majority* start adopting the technology as well. The exponential growth stabilizes and decreases slowly as the market gets saturated. Finally, a 100% market share is reached when the *laggards* are convinced and stop holding on to the technology they were used to.

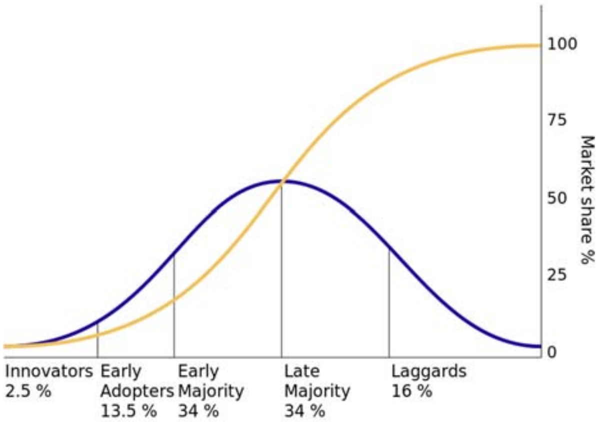


Figure 2.1 Typical diffusion pathway according to Rogers et al. (1962)

Visualizing the growth of market share over time (yellow line in figure 2.1), an S-curve is visible. The growth rate of the market share is depicted by the blue line.

Many empirical evidence of these typical S-shaped market share rates of new technologies have been found in history. For instance in the diffusion of household appliances in the United States (see figure 2.2).

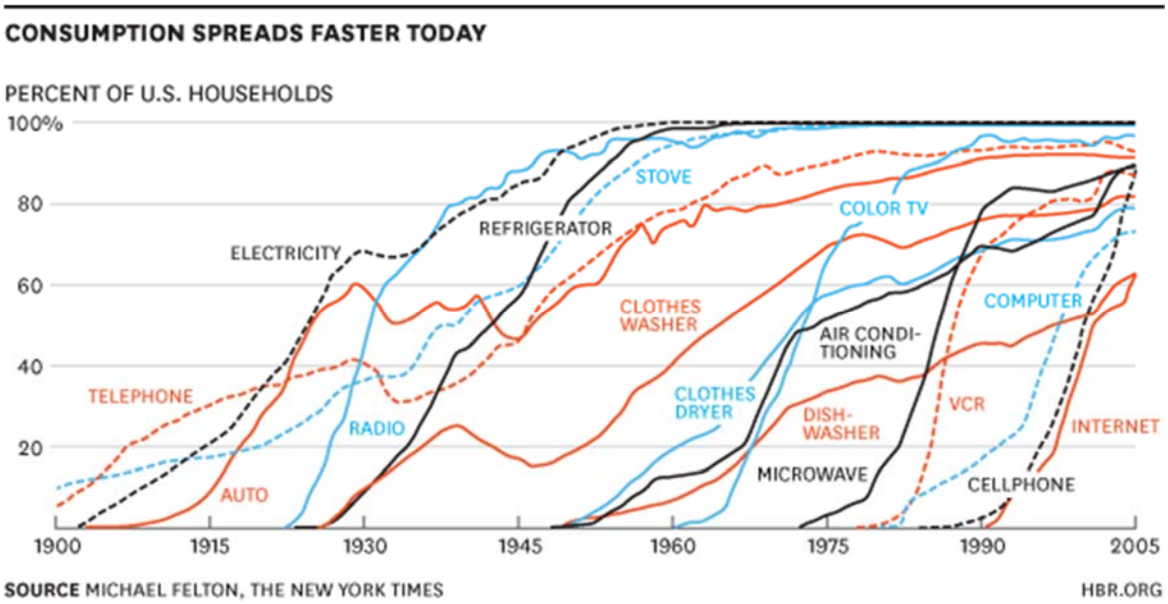


Figure 2.2 Diffusion of electronic appliances in households in the US shows similarities with the typical logistic function described by Rogers (1962) (Source: Harvard Business Review, 2016)

A recent example can be found in the introduction of the internet. The deployment of internet in 30 countries is plotted in figure 2.3. Although, the growth curves are different for each country, the pattern is generally the same. A plot of the percentage of people with internet access shows a clear starting phase between 1990 and 2000. From 200 until 2008 the majority was introduced to the digital world and in the last years of the diffusion, the laggards (think of remote areas or even your parents or grandparents) switched.

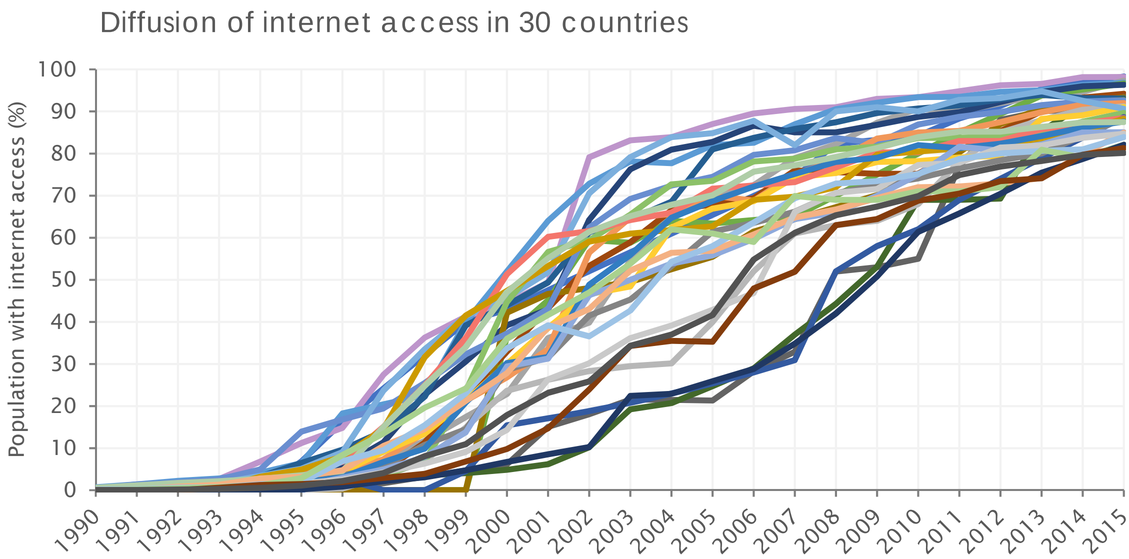


Figure 2.3 Population share in 30 countries with access to internet between 1990 and 2015 (Source: World Bank, 2017)

These S-curves are also found in previous energy transitions, such as the introduction of the steam engine and subsequently the combustion engine (Fouquet, 2010). Furthermore, S-curves are found in the introduction of many different technologies to produce power such as coal and nuclear plants or wind turbines in Denmark (Wilson, 2012). The complete introduction of these technologies take between 10 and 70 years generally, according to Wilson (2012). It is furthermore noticeable that the more contemporary energy transitions (nuclear, or wind turbines in Denmark) are remarkably faster than transitions that took place in the beginning of this century (cars, coal plants).

2.2 Diffusion of renewables in the power sector

Most renewable energy technologies stand at the beginning of this diffusion curve. The deployment of electricity from photovoltaic solar (PV) and wind currently show impressive annual growth rates of 51% and 22% respectively between 2006 and 2016 (BP, 2017). Yet, with a current contribution to the global electricity production of 3.9% for wind and 1.3% for photovoltaics, their share in absolute terms is still rather limited. As these energy sources are expected to play a dominant role in a low carbon energy system, the question of how the growth will further develop is therefore highly important.

Though the current growth rates of wind and PV are very high, these growth rates are expected to decrease as the total share of these technologies increases and enters the *majority* phase. Studies have placed the growth of these variable renewable energy sources (VRE) in a historical context by examining previous diffusions of technologies such as nuclear power, deployment of cars or oil refineries and expect the same S-curve trend for renewable energy technologies (Schilling and Esmundo, 2009; Wilson et al., 2012).

Even at favourable economic conditions (low technology costs), growth can be tempered by social, institutional and behavioural factors as well as uncertainty in climate change policy (Iyer et al., 2015). Also the industrial capacity to build technologies is a stringent factor which is often forgotten (Kramer and Haigh, 2009). According to Davidsson et al. (2014) and Tao et al. (2011) physical constraints as well as the maximum annual supply of natural resources are often neglected. A workshop with energy scientists from the United Kingdom resulted in a list of the most important factors for technology penetration rates (Napp et al., 2017a):

1. Availability of complementary or supporting technologies/infrastructure
2. Degree to which there has been a ramp-up “tail” period before rapid deployment
3. Lead-time to build and deploy the technology
4. Cost reduction potential of the technology

The availability of sufficient infrastructure to support and build the capacity was found to be the most important factor as well as the period in the run up to the large-scale deployment.

According to Kramer and Haigh (2009), growth path of energy technologies typically switch from exponential to linear growth when a technology reaches “materiality” which is defined as providing around 1% of the world energy. Growth rates then typically drop from 26% to around 2-4% (Kramer and Haigh, 2009).

However, Kramer and Haigh's (2009) theory may be contradicted by the historic diffusion of wind energy in nine different regions between 1990 and 2016, growth rates indeed tend to decrease as its share of total electricity production increases (figure 2.4). However, growth rates are still considerable (20%) even at penetration rates above 5% which are found in OECD-Europe. The same patterns are found for photovoltaics, although its share of total electricity production is smaller than wind.

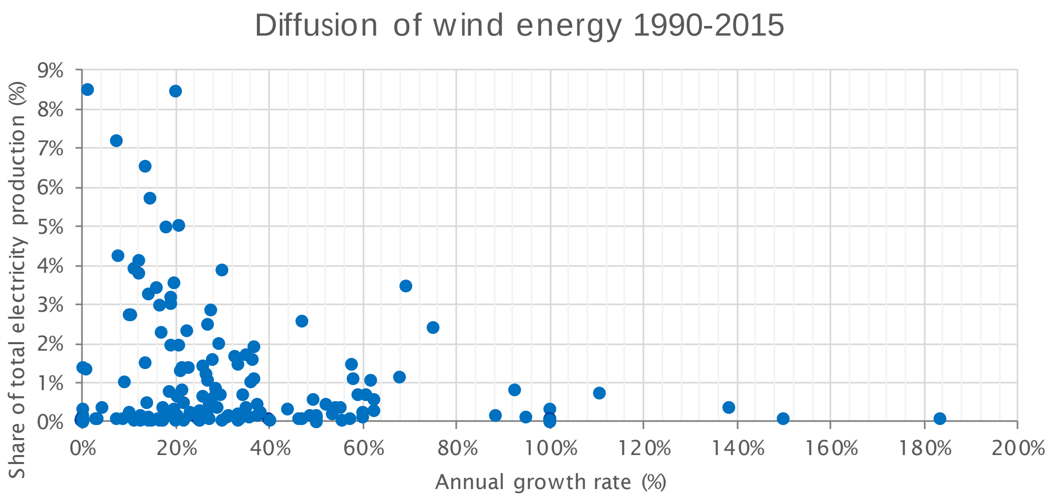


Figure 2.4 Share of wind energy in total electricity production and annual growth rates between 1990 and 2015 (Source: BP, 2017).

These smoothing growth rates are also found in other low carbon scenarios such as the IEA Below 2 Degrees Scenario (2017) and the Greenpeace Advanced Revolution scenario (2015) where average annual growth rates at the final stage decrease to 1-4%. In the scenario by Deng at al. (2012), offshore-wind and photovoltaics still grows by 5-7% annually between 2040 and 2050.

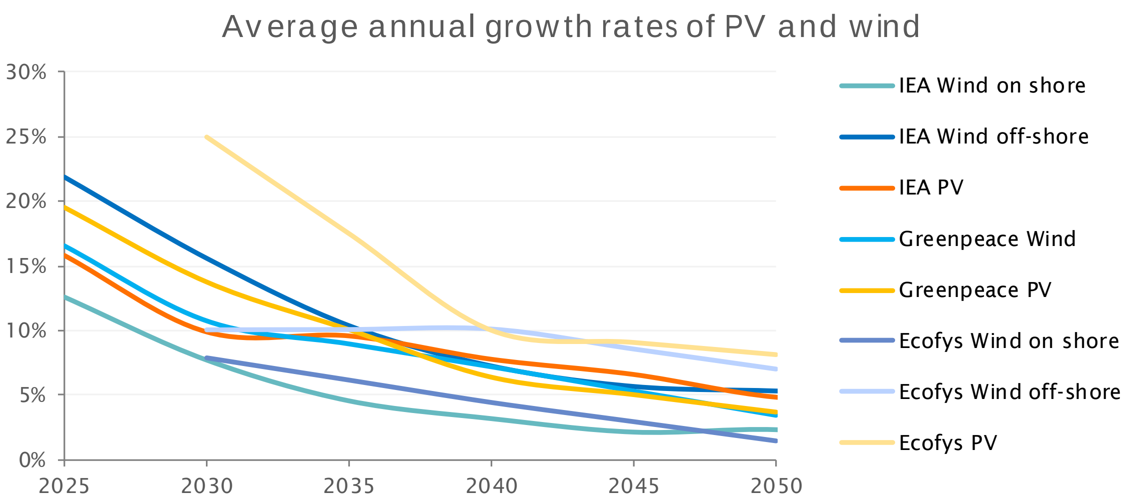


Figure 2.5 Average annual growth rates of wind and photovoltaics in different scenarios.

The assumed future growth rates in the scenarios might be underestimating the actual potential. According to Napp et al. (2017), growth rates of photovoltaics post materialization are likely to be higher than Kramer and Haigh (2009) suggest. Furthermore, Wilson et al. (2012) placed the diffusion of renewable energy technologies in a historic context and found that most scenarios are too conservative. According to this study, full deployment is likely to be reached well before the projections in most scenarios.

A recent study by Creutzig et al. (2017) addressed that scenarios have underestimated the deployment of photovoltaics and growth of PV "(..) consistently exceeded expectations" (pp 1). Therefore, photovoltaics are likely to play a much larger role in the global electricity system than was previously assumed.

2.3 Drivers of CO_2 emissions

From the 1950's, the global annual CO_2 emissions from fossil fuels and industry more than tripled up to 35.5 Gt in 2014 (Boden et al., 2017). This exponential growth is explained by an increase of the global population and an increase in their welfare. The drivers of energy related CO_2 emissions are presented in an equation by Japanese Scientist Kaya in 1990 which is now known as the Kaya identity and adopted by the IPCC.

$$CO_2 = Cap. \times \frac{GDP}{Cap.} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy}$$

In this equation, population is multiplied with three factors: income, (GDP / Cap.) energy intensity (Energy / GDP) and carbon intensity (CO_2 / Energy) (Girod et al., 2009).

Looking at the developments between 1990 and 2015, energy and CO_2 emissions appear strongly linked. In this period, energy related CO_2 emissions increased by 55%, while the total primary energy supply (TPES) increased with 62%. Thus, the carbon intensity (CO_2 per energy) decreased with only 4% in 25 years. In the same period of time, population and GDP increased with 39% and 329% respectively. This means that, the income level (GDP per capita) increased with 237%. The energy intensity per GDP did decrease significantly between 1990 and 2015 with 51%. Also note that the financial crisis in 2009 had a significant effect on CO_2 emissions.

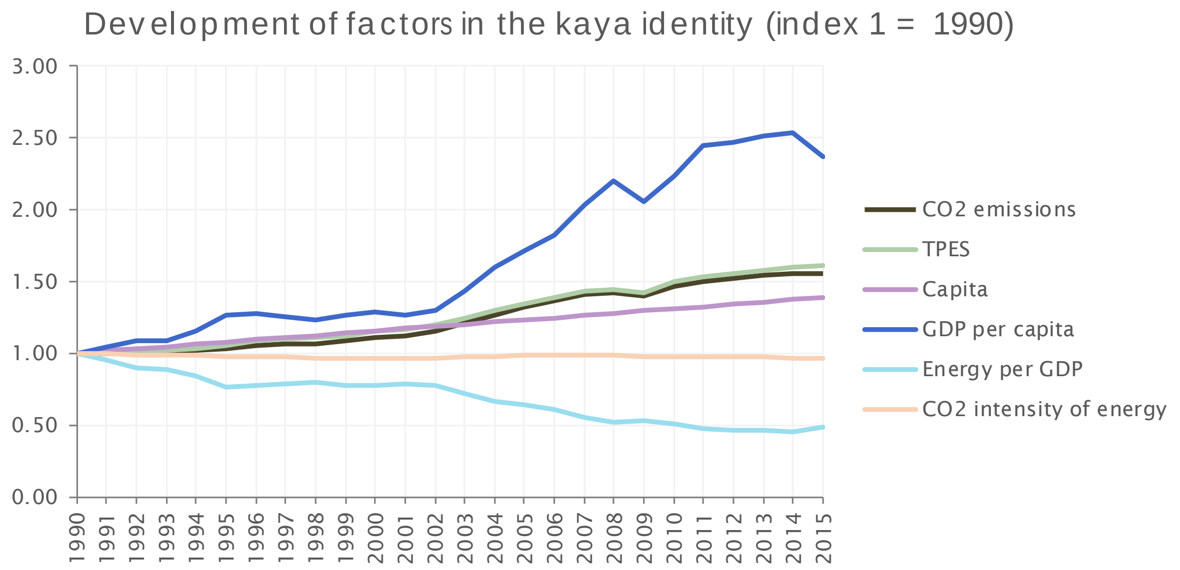


Figure 2.6 Indexed developments of global GDP, population, energy and growth of CO_2 emissions (Source: BP 2016; World bank 2017)

2.4 Carbon budgets and negative emissions

The CO_2 emissions from fossil fuels and industry (E_{FF}) and land use change (E_{LUC}) are transferred in the form of atmospheric growth (G_{ATM}) and ocean (S_{OCEAN}) and land sinks (S_{LAND}) (Le Quéré et al., 2016).

$$E_{FF} + E_{LUC} = G_{ATM} + S_{OCEAN} + S_{LAND}$$

Fossil fuels and industry was responsible for around 90% of the emissions between 2006 and 2015 (Le Quéré et al., 2016). Land use change plays a smaller role and there appears to be uncertainty regarding the actual emissions from this source (Arneth et al., 2017).

On the other side of the equation, Le Quéré et al. (2016) found that between 2006 and 2015, approximately 30% and 25% of the carbon emissions were added to land sinks and ocean sinks respectively. The remaining 45% of the emissions ended up as atmospheric growth.

The accumulation of CO_2 emissions in the atmosphere is the main factor responsible for the global temperature increase. The total amount of emissions that can be emitted to have a good chance of staying below a global temperature increase is referred to as the carbon budget.

Rogelj et al. (2015) estimated the carbon budget, to stay within 1.5 degrees, at 190-450 Gt $CO_{2\text{-}eq}$ between 2011 and 2100 with a median of 350 Gt $CO_{2\text{-}rq}$. Considering the current annual CO_2 emissions, this require an incredibly steep decarbonization path: from 2020, CO_2 emissions should linearly drop to zero before the year 2040 (IEA, 2016). Remaining under 1.5 °C temperature rise is therefore practically impossible without extracting CO_2 emissions from the air on a large scale, which is referred to as negative emissions (IEA, 2016a; Rogelj et al., 2015; van Vuuren et al., 2013). In the analysis by Rogelj et al. (2015), all scenarios from integrated assessment models exceed the carbon budget in the first half of the century and compensate this with high amounts of negative emissions in the second half. There are multiple negative emission technologies (NET) developed that can remove carbon dioxide from the atmosphere (Ecofys, 2016):

- Agricultural soil carbon
- Building with biomass
- Wetland habitat restoration
- BECCS (ethanol fermentation and BLG)
- Biochar
- Afforestation and reforestation
- Enhanced weathering
- BECCS (solid biomass)
- Ocean liming
- Direct air capture
- Magnesium cement

A study by Ecofys on the status and potential of these technologies demonstrates that bioenergy with carbon captures storage (BECCS), direct air capture and afforestation have the highest maximum potential. The amount of negative emissions that are required is dependent on the CO_2 reduction pathway towards net zero emissions (IEA, 2016a).

BECCS is the most applied NET in many low carbon IAM scenarios (Fuss et al., 2014). A benefit of this technique is that it produces electricity or fuels opposed to for example direct air capture which is a highly energy intensive process. However, there are serious concerns regarding the feasibility of these technologies. Vaughan & Gough (2016) point out that carbon capture storage (CCS) has not been executed on a large and commercial scale and the same goes for large scale combustion of bioenergy.

Kartha and Dooley (2016) identified three types of risk associated to negative emissions in scenarios:

1. Negative emission technologies turn out to be unfeasible
2. The deployment on large scale could have intolerable negative impacts on ecology and society
3. The performance of negative emissions could turn out significantly lower than expected

Anderson and Peters (2016) also warn for the great uncertainty of the technological development and the potentially enormous consequences for the society if the techniques appear not to meetup the expectations. They argued that utilization of these technologies should therefore be avoided.

Lackner (2016) and 45 other scientists respond to Anderson and Peters by qualifying their argument as too short-sighted. According to them, there are indeed challenges to overcome but this does not mean that the technologies are useless. Furthermore, they argue that the use of negatives emissions is indispensable according to meet the goals.

Another more ethical objection against BECCS or NET's in general is the fact that it shifts the burden to the future generations (Williamson, 2016). At the same time Williamson (2016) agrees with Lackner (2016) that NET's are inevitable in order to limit the global temperature increase.

3. Methodology

This section describe the methodology of the research and an outline of the conceptual framework. First, the concept of scenario planning is explained in more detail. Afterwards, the energy backcasting framework by Robinson (1982) is elaborated upon as the conceptual framework of this research. Then, the temporal and geographical scope of this research is defined. Finally, the data collection is explained in which there is mostly focused on the adjustments of the energy balances.

3.1 Scenario planning

Scenario planning has long been considered as strategic tool for businesses purposes rather than a scientific discipline. That is why Ogilvy (2002) raised the following question regarding scenario planning:

"*(..) Is it an art or a science or, as many suspect, nothing more than hopes and fears dressed up as science?*" (Ogilvy, 2002, pp. 26)

To answer the self-asked question, Ogilvy (2005) argues scenario planning is both art as well as a science. Looking at the history of scenario planning, it started out as an unstructured practice in the 1980's lacking a methodology. Scenarios were developed based on the intuition and experience of the practitioner. Scenarios were not used in science but mostly developed by large multinationals as a strategic tool. As time proceeded, a methodology or, as Ogilvy (2005) refers to it, a scenariology has been developed. This led to formalization of the process and lifted the black box that covered the topic.

This methodology makes scenario planning replicable which is an important condition for science. However, this does not make that scenario planning can be marked as one of the traditional positivistic sciences. A simple and logical explanation is that the future cannot be predicted, due to the complex interplay of processes and the fact that the future can be influenced by ourselves. Therefore, Ogilvy (2005) argues that scenario planning should be regarded as a new science originating from new insights of complexity theory.

The intention of scenarios is not to predict but rather to present a desirable future and the pathway towards it, given the current opportunities and constraints (Durance and Godet, 2010). This makes scenario analysis an important tool to integrate knowledge and explore the future systematically (Swart et al., 2004)

Börjenson et al. (2006) distinguishes three different types of scenarios:

- Predictive *What will happen?*
- Explorative *What can happen?*
- Normative *How can a specific target be reached?*

Predictive scenarios try to foresee what is going to happen or what the chances are of an occurrence. These scenarios are based on a set of parameters and often include historical data to anticipate on expected situations. Examples of predictive scenarios are weather forecasts or population growth projections. Börjenson et al. (2006) mentions that these models can be self-fulfilling, and therefore not very suitable to assess disruptive events.

In explorative scenarios, not the likelihood but the possibility of an event is of importance to develop a scenario. These events can be both external as well as internal and are commonly used in strategic contexts. Usually, multiple scenarios are developed with a variety of different inputs and explore the long term generally. The scenarios by Royal Dutch Shell are a well-known example of explorative scenarios (Van Notten, 2006)

A third category of scenarios are normative scenarios. With these scenarios there is a clear objective on forehand and scenarios are developed to reach this final goal. Within normative scenario's two different types are distinguished by Börjenson et al. (2006):

- Preserving scenarios
- Transforming scenarios

In preserving scenarios, the aim is to reach a target as efficiently as possible. This can be either quantitative (costs) as well as qualitative (socio-cultural aspects). Integrated Assessment Models are based on this type of scenario: a desirable outcome (e.g. 1.5 degrees) is formulated and then a cost-optimal pathway is developed meeting the target under certain constraints.

An example of a transforming scenario technique is backcasting. This approach is often used when there is a target with high priority which is however unreachable considering the current trends. Dreborg (1996) and Holmberg and Robèrt (2000) state that backcasting is particularly helpful to address complex problems which requires a break with the current trends. An energy transition within 1.5 ˚C degrees temperature rise meets these criteria generously. Therefore, backcasting is used for this research. By dealing with problems both in quantitative and qualitative sense, justice is done to complexity of problems (Vergragt and Quist, 2011). For instance, a quantitative backcasting for low-carbon societies in Kyoto was conducted by Gomi et al (2011).

According to Börjenson et al. (2006) the differences between preserving and transforming scenarios is that the first looks at optimal and efficient solutions whereas *transforming scenarios* rather consider the final goal. This does not mean that costs and efficiency are neglected in transforming scenarios, but it is not a first and absolute condition.

3.2 Conceptual framework

The conceptual framework is based on the proposed method by Robinson (1982). Its framework is the only method specifically designed to conduct energy backcasting analysis and consists of six consecutive steps.

1. Specify goals and constraints
The starting point of the scenario is the formulation of goals and constraints. This will be the foundation of the backcasting study. Whereas in optimisation models, such as least-cost optimisation the outcome is driven by cost curves, energy backcasting is much more based on argumentation and reasoning. These goals and constraints form the guiding principles for the motivation of choices. The explicit desirable final state is a clearly normative aspect of this scenario type. The primary goal of the scenario is to remain within a global carbon budget in line with 1.5 °C temperature increase. Besides, additional goals are formulated.

2. Current energy and activity consumption and production
Now that the desirable end-point has been set, the starting point is explored more in depth in this second step. The current energy demand and production is analysed as detailed as possible. The current most important production processes and energy consumers are described including the current energy intensities and activity levels.

3. Outline of the future demand for energy services
In the third step, the expected developments of the economy are described and analyses are conducted to assess correlation between GDP and demand for energy services (activity level). The link between economy and activity is constructed by analysing present and historic activity levels and present and historic GDP levels per capita. Furthermore, a function is formulated to relate the future economic growth to expected activity levels. Another important step is to validate the relation between activity level and economic growth by comparing the outcomes with results found in literature wherever possible.

4. Energy demand analysis
Now that the future activity levels have been determined, activity is linked to technologies and energy intensities to come to an energy demand profile. The total final consumption of the energy system is described in detail per sector.

5. Production analysis
Now that the amount and the types of energy demand is known, the energy production is analysed. This step will mainly focus on the energy transition in the power sector. Ultimately, a total primary energy supply is depicted.

6. Determine the implications
In the final step, the context and consequences of the energy transition are looked at. These implications can be viewed from an environmental, social, economic, political and technological perspective. Due to constraints of time, the scope of this study and the available data, this step will only focus on environmental implications.

The environmental implications are described in terms of (cumulative) CO_2 emissions.

3.3 Scope

3.3.1 Spatial resolution

This study comprises the global energy system. To add more detail to the scenario and improve accuracy, the world is divided into nine different regions (figure 3.1). This division is derived from the energy balances by the International Energy Agency (IEA) and is based on geographic proximity as well as the economic situation. The IEA does produce energy statistics on a country level, however for most Non-OECD countries a significant part of the data is unspecified and therefore less suitable.

Figure 3.1 Distribution of the nine regions that are assessed in this scenario

Besides, these nine regions two virtual regions are included which cover the global energy consumption of international shipping and aviation.

These regions are used to calculate energy demand and supply in all sectors, except in industry. For the transition in industry sector, the nine regions are combined into three different regions of equal size in terms of energy use in 2014.

Table 3.1 Total final consumption in industry per region (2014)

Name	TFC 2014 (EJ)
OECD	47
Non-OECD (excl. China)	53
China	51

This is aggregation is done for two reasons. First of all the share of non-specified energy use in the industry is very high in some regions (see figure 3.2). Secondly, the available data regarding activity levels and energy intensity was limited.

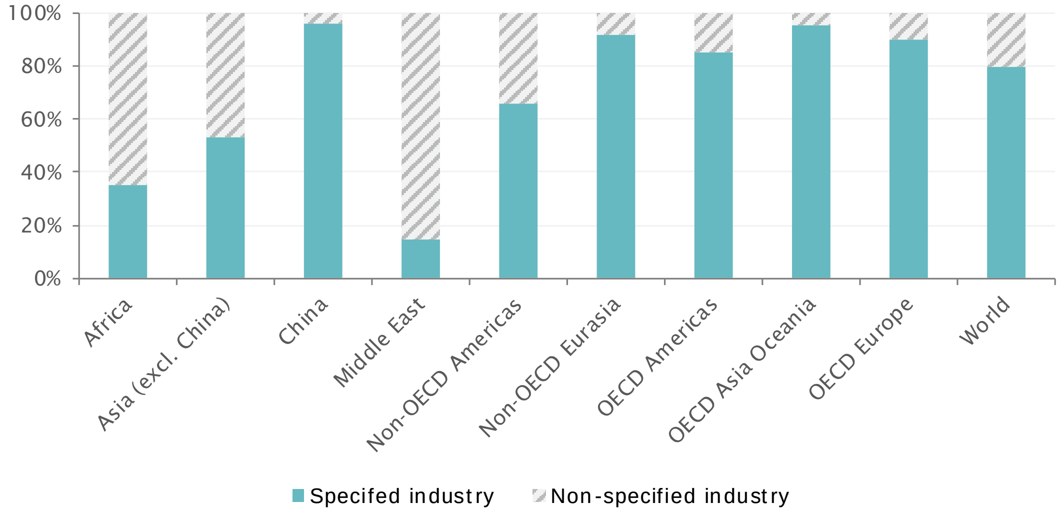


Figure 3.2 Share of non-specified industry across the nine different regions in 2014

3.3.2 Temporal resolution

The scenario covers the period between 2014 and 2050. The starting point was chosen since this was the latest year for which there was full statistics available by the IEA at the start of this research. The end point of the scenario was determined based on the notion that in order to stay within 1.5˚C temperature rise, the energy system should be net zero by 2050 (Rogelj et al., 2015). Intermediate steps are provided every five years between 2020 and 2050. This time interval is commonly used in published scenarios. For instance by the IEA (2017), Deng et al. (2012) or Greenpeace (2015).

3.4 Data collection

The input for the scenario is derived from an extensive amount of literature. The sources and argumentations are described in the next chapter (model explanation) and throughout the research. Here, the focus lies on the energy balances and the establishment of the starting points.

The basis for the starting point of this scenario is the energy balances compiled by the IEA. The IEA publishes the most detailed energy statistics available every year on a country level. An energy balance provides insight into how much and what type of energy is consumed by whom within a specific country or region and year. The energy balance from the IEA consists of 95 rows with different consumers and 66 columns with different energy carriers. The energy consumers are shared under different sections:

- Transformation processes
- Energy industry own use
- Losses

- Total final consumption

The global transformation processes accounts for 135 EJ and comprises of the conversion of energy from one carrier to another. The most important processes in terms of energy consumption in this section are electricity production and production of coke for iron and steel production and subsequently the combustion of the coke in blast furnaces where it is turned into blast furnace gas. The energy industry own use accounts for a total of 35 EJ that was consumed in the industries which produce energy carriers itself. The oil refineries and the extraction of oil and gas are the largest categories and responsible for 61% of the energy consumption in this section. The accounted losses in the energy system are relatively small (9 EJ) and consist for 75% of electricity which can be assigned to transportation losses. The total final consumption is the largest section in the energy balance (395 EJ) and the driver for energy consumption in the previous sectors. Total final energy consumption consists of four categories: Industry, Transport, Other and Non-energy use. These categories consist of multiple subcategories. The total energy consumption per subcategory varies significantly as can be seen in figure 3.3.

Figure 3.3 Global total final consumption distribution in the IEA energy balance of 2014.

Road, residential, commercial and public services are the largest energy consumers and comprise 52 percent of the total final consumption. Therefore it was decided to disaggregate these rows to allow for more precise analysis and to describe the energy transition with more detail. Energy use in road transport was divided over different modes of transport. The energy consumption in residential and commercial and public services was split according to different functions. These two subcategories were then shared under a new category: Buildings. Furthermore, data was available to split rail transport into passenger and freight rail.

Table 3.2 Overview of disaggregated categories

Road	Rail	Residential	Commercial and public services
Light Duty Vehicles	Passenger rail	Space heating	Space heating
Light road	Freight rail	Space cooling	Space cooling
Bus		Water heating	Water heating
Freight road		Appliances	Appliances
		Lighting	Lighting
		Cooking	

To disaggregate the transport categories, detailed data from the International Council on Clean Transportation (ICCT) for 2012 was used. The ICCT roadmap provides detailed data of the specific fuel consumption of the different road users in different regions. The regions from the ICCT database were matched with the regions from the IEA database and ratios were derived to allocate a weighted percentage of the total diesel consumption in road to one of the four categories (e.g. 80% of the total diesel consumption in road transport in Asia (excl. China) can be assigned to the freight road subcategory). The exact regions that were matched can be found in appendix A. By using percentages rather than exact numbers, minor discrepancies between ICCT statistics and IEA energy balances were removed. The differences found between the databases were generally small.

For the allocation of the energy use in the residential and commercial and public services categories, data from the Energy Technology Perspective published in 2014 by the IEA was used. The same procedure as for road transport was followed. First, the regions (see appendix A) were matched and then, ratios were derived to allocate specific energy carriers to the functions (e.g. 60% of the residential electricity in OECD Europe is assigned to lighting).

These adaptations led to a more extensive energy balance for each region (see figure 3.4).

Figure 3.4 Global total final consumption distribution in 2014 that was used in the 1.5 model

4. Model explanation

An energy model is developed for the quantitative part of the backcasting in Microsoft Excel. This section describes all components of the model, the assumptions and the calculations that are made. First, an overview of the model is presented after which the components are described in more detail.

4.1 Model overview

Components

The model consists of five different type of components. First of all there are *Input variables* which are data that can be easily changed at the front-end of the model. By adjusting these values, the effect of different scenario choices can be analysed. Most input variables in this model concern the required values in 2050, since a backcasting study moves towards a certain point. An example of an *Input variable* is the realized efficiency improvements of electric passenger cars by 2050. A second type of input are *Fixed inputs*. Finding data for these inputs are an important part of the study. Yet, these data are regarded as a given and can in principle not be adjusted to meet the scenario targets. Two examples of a *Fixed inputs* are the current energy intensity of iron and steel production in China or the current passenger kilometres for bus transport in Non-OECD Americas. *External data* considers data from literature which has not been adjusted in this study. Population, *GDP* and emission factors are three important examples of *External data* sources. The fourth type of components covers the *Processes*. In processes, calculations are made based on the inputs and passed through to a next process. Example of a *Process* is Buildings, where all sorts of inputs regarding activity levels and intensities are used to calculate the energy demand of the buildings sector. This energy demand is then passed through to total final consumption. The final *Output* is a process in which all intermediate steps come together and no data is passed through to other components. In this model, the carbon budget with the cumulative carbon emissions is considered to be the *Output*.

Overview of the model

The core of the model is the energy demand which consists of four main sectors:

- Transport
- Buildings
- Industry
- Other

Furthermore, each of these sectors is subdivided into categories (e.g. iron and steel production in industry). Energy demand in each category is modelled by multiplying the *Activity* with the specific *Intensity*. The *Intensity* level itself is dependent on the current *Energy intensities* of specific technologies, the *Efficiency improvements* realized of a technology and finally, the assumed distribution of *Technology shares*. Activity at a certain time is derived by combining the *GDP Growth* projections with *Activity correlations* and the *Current activity levels*. Subsequently, *Population* data is used to define total activity.

The sum of the energy demand in all sectors results in the *Total Final Consumption*. Subsequently, the *Total Primary Energy Supply* is the sum of the *Total Final Consumption* (excluding electricity demand), the primary demand in the *Power Sector* and the energy consumption in energy industry own use and losses (*EIOUL).* Finally, this primary supply is converted into *Annual emissions* by multiplying the energy carriers with the corresponding *Emission Factors.* Process emissions from *Cement production* are also added to the emissions. Finally, the cumulative emissions over the timeframe of the model (in this case 2014-2050) are accounted for in the *Carbon budget*.

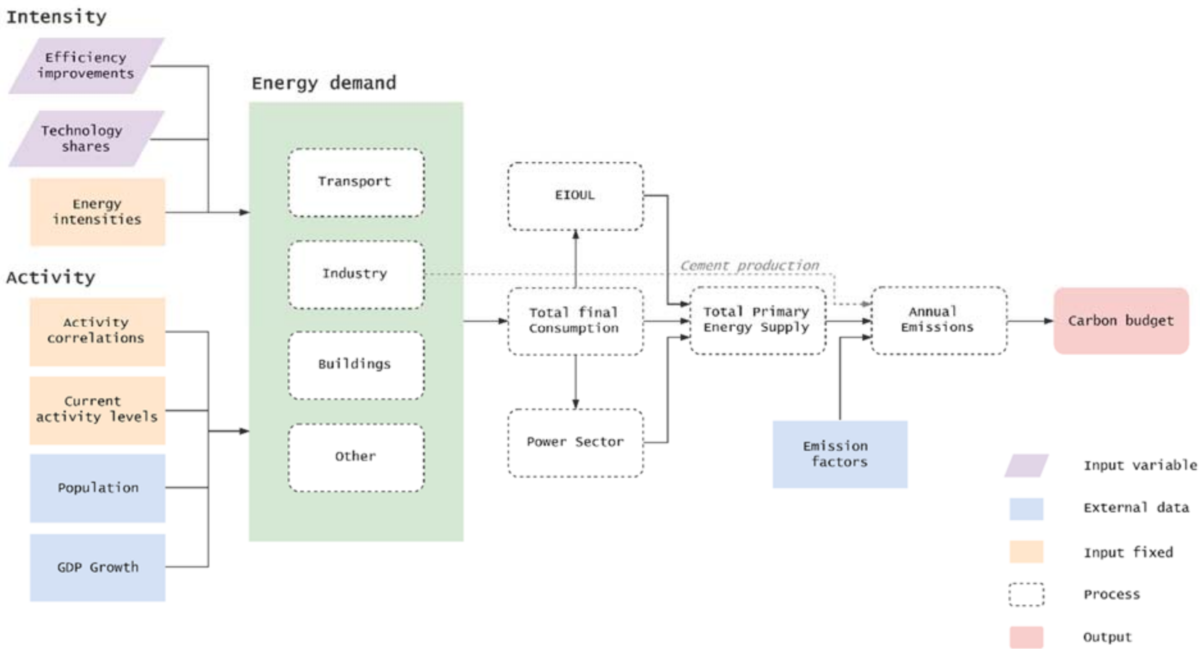


Figure 4.1 General schematic overview of the energy model

4.2 Intensities

4.2.1 Energy intensities

Energy intensities and specific energy carriers for all the included technologies are expressed in terms of energy per unit of activity (e.g. GJ / tonnes or MJ / passenger kilometre). These intensities are derived from literature and described in *Current consumption and production* chapter. These energy intensities are fixed inputs.

4.2.2 Efficiency improvements

Energy intensity of technologies can be reduced by improving the efficiency. An achieved efficiency improvement by 2050 is the input variable of the model which is turned into an average annual improvement rate. Intensity of a technology at a certain year (*t*) is calculated with a constant percentual decrease which is calculated with the following formula:

$$TechInt_t = TechInt_{2014} \times (1-EffImpr)^{(t-2014)}$$

With

t = *in years*

$TechInt_{2014}$ = *Energy intensity in 2014*

EffImpr = *annual efficiency improvement rate*

4.2.3 Technology shares

Technology shares for 2014 are either derived from literature or by looking at the specific energy consumption and the energy intensity and dividing this by the total useful energy in that sector:

$Tech_{share2014} = (ETech_{t2014} / EffTech_{2014}) / \sum (E_{2014} / Eff_{2014})$

With

$ETech_{2014}$ = *Specific energy used for that technology in 2104*

$EffTech_{2014}$ = *Specific energy efficiency of that technology in 2014*

4.3 Activity

4.3.1 Population and GDP growth

The population and GDP growth projections are derived from the shared socio-economic pathways (SSP) by Riahi et al. (2017). These pathways are developed by the scientific climate modelling community to make the results of the scenarios more comparable with each other. Furthermore, five distinct future pathways were formulated to explore the bandwidths more systematically. Each SSP is based on a consistent storyline and assumptions resulting in different socio-economic projections. As can be seen in figure 4.2, the population size in the highest and lowest scenarios varies with 1.5 billion by 2050. Furthermore, the global GDP in SSP3 is 51% smaller than in SSP 5.

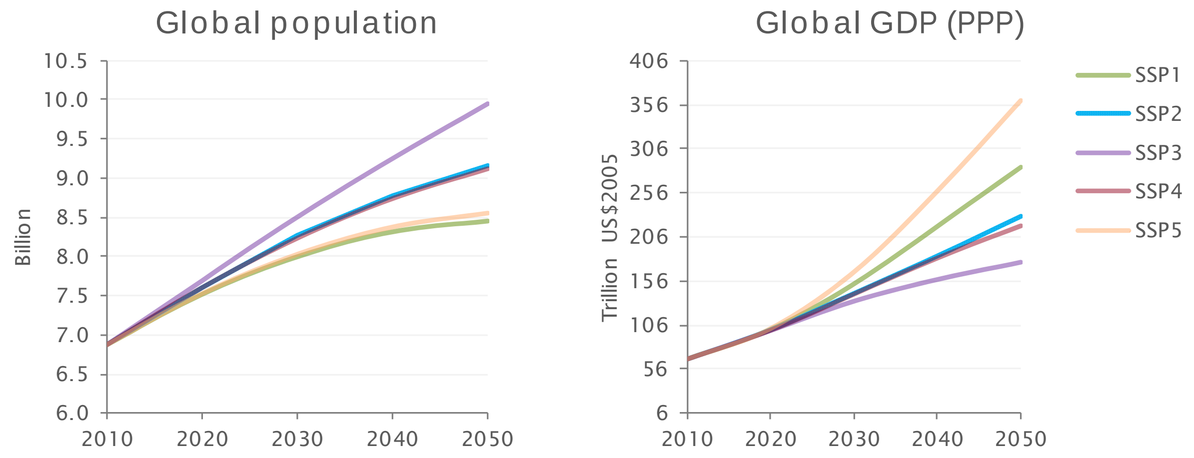


Figure 4.2 Population and GDP size projections in different SSP pathways (Source: Riahi et al. 2017)

For this scenario, the growth projections of the SSP2 narrative is used which is described as a medium scenario (Riahi et al., 2017). GDP and population rates are provided on country level for every 10 years. Average values are taken for the intermediate five years. At the end of the study, a sensitivity analysis is conducted to estimate the impact of different socio-economic pathways.

4.3.2 Activity correlations

Activity levels between 2014 and 2050 are expressed with formulas relating activity to GDP per capita levels. These formulas were derived by analysing the current or historic activity levels and the GDP. Several studies in the past have demonstrated a relation between activity and GDP, for instance in transport (Garcia et al., 2008) or the consumption of aluminium (Menzie et al., 2010).

One typical pattern in the relation between activity level and GDP per capita corresponds to the shape of a natural logarithm: relatively high additional increase of demand at low incomes and a reduced additional activity demand as GDP increases (Chontanawat et al., 2006). An example of this trend is the use of passenger cars. As average income increases in regions, more people can obtain and maintain a car and use it to transport themselves. At a certain GDP per capita level at which every household purchased one or multiple vehicles, the passenger kilometres per capita is not expected to grow much further.

Another type of relation is a Kuznets curve. This curve is described as an inverted U-shape, where activity first increases and then decreases as income grows (Dinda, 2005). These curves are for instance found for material demand in developing regions with high economic growth rates. Large amounts of construction materials are required to build infrastructure (e.g. roads, houses) to meet the growing demand. Once the basic infrastructure is in place, the demand per capita for materials decreases again.

A third type of relation between GDP and activity is linear or even exponential. In these cases, no decrease in growth rates is (yet) found at high levels of GDP per capita.

The activity developments for buildings and transport, move parallel to the trendline instead of converge to the trendline. This is done to account for regional differences other than income levels. For example: passenger rail transport activity in OECD-Americas is significantly lower than in other OECD regions, while the use of car transport is much higher due to the low population density and cultural aspects. With the parallel growth principle, passenger rail transport increases in this region as GDP increases, but not too a level that would correspond with its GDP per capita level (see figure 4.3).

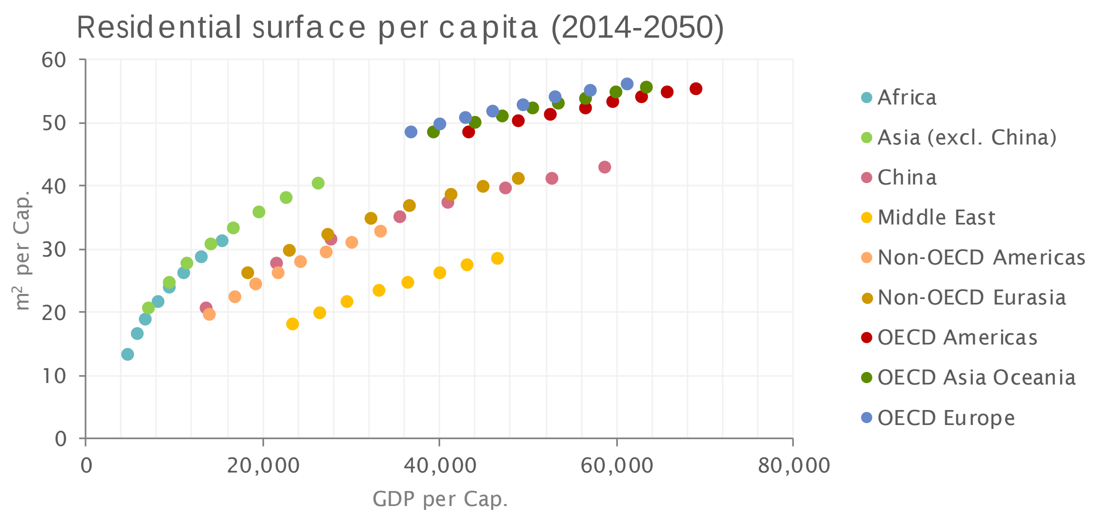


Figure 4.3 Example of relation between activity developments and GDP levels for buildings and transport

The activity developments in industry do converge to the trendline by the end of the scenario. This is done to account for the demand peaks for materials that are currently found in China and are expected to decrease. Examples are cement and iron and steel consumption levels which are temporarily significantly higher than OECD regions to construct new buildings and infrastructure (van Ruijven et al., 2016). The activity level moves gradually towards the trendline according following an S-curve.

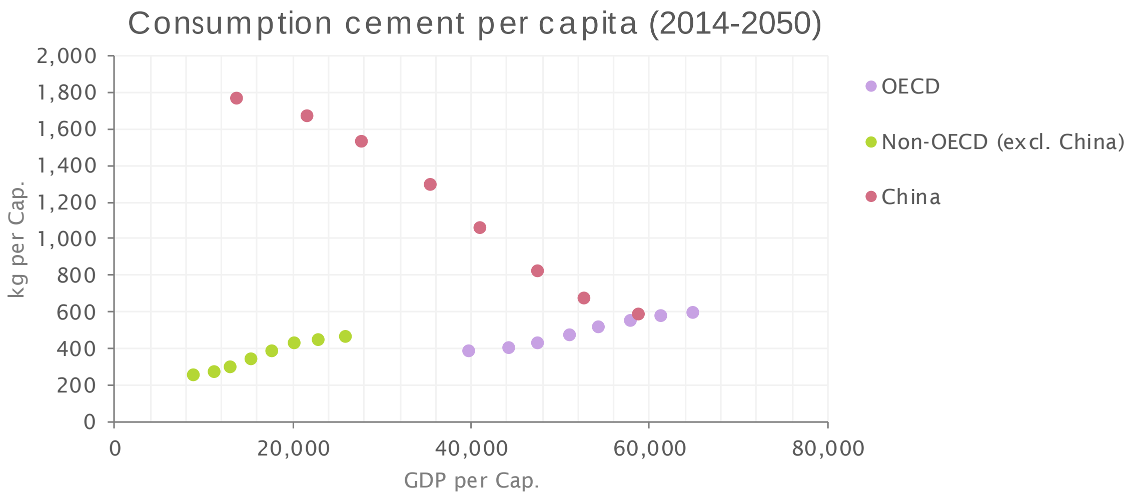


Figure 4.4 Example of relation between activity developments and GDP levels for industry

4.3 Total final consumption

The total final energy demand in each sector is calculated differently based on the decarbonization options available.

4.4.1 Buildings

The final energy demand in the buildings sector can be manipulated by three variable inputs. First of all, the *Efficiency improvement* of technologies in 2050 can be entered, as well as the *Thermal performance improvement* that is realized in buildings by 2050 (as a result of improved insulation). The third input are the *Technology shares* by 2050 for each function.

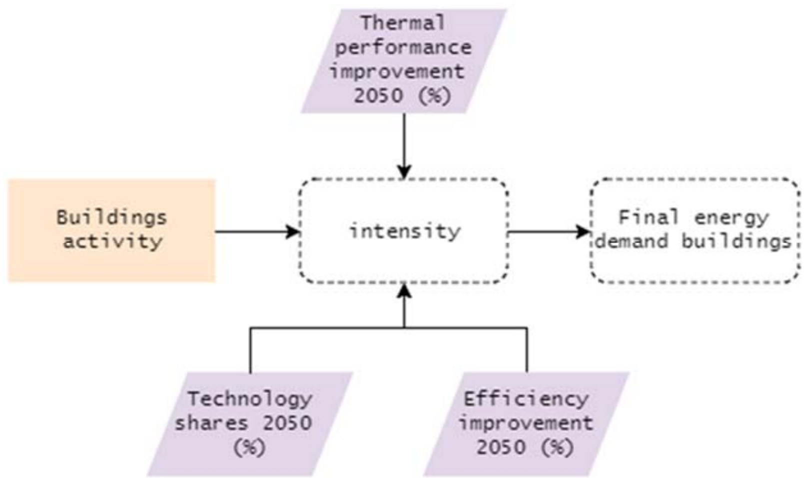


Figure 4.5 Overview of the input variables to model final energy demand for buildings

The efficiency improvement develops as described in section 4.2, while the energy savings due to retrofitting of the buildings progresses linearly, assuming a fixed part of the building stock is modified annually.

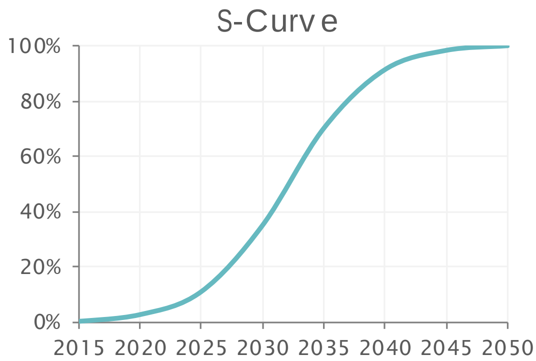


Figure 4.6 Applied S-curve in buildings sector

All technologies included in the buildings sector are already commercially available and can therefore be deployed from start of the model. The transition path from 2014 technology shares (*$BTechShare_{2014}$*) towards 2050 follows a symmetric S-curve. Of course, perfect symmetry is not found in real life, but it was actually found that applying symmetric S-curves often results in more accurate predictions than non-symmetric S-curves (Kucharavy and Guio, 2011). Kucharavy and Guido (2011) analysed hundreds of S-curves and proposed to use symmetrical S-curves for predictions of technological systems. One of the explanations is that with the simplicity of a symmetric S-curve there is no room for hidden biases.

$BTechShare_t$ = $BTechShare_{2014} + (BTechShare_{2050} - BTechShare_{2014}) \times SCurve_t$

With

$BTechShare_{2014}$ = *Technology share in 2014*

$BTechShare_{2050}$ = *Technology share in 2050*

$SCurve_t$ = *The value of the S-Curve at t (number between 0 and 1)*

Th S-Curve itself can be described with the following formula:

$$SCurve_t = \frac{1}{1 + e^{-0.2\left((t-2014)-\frac{2050-2014}{2}\right)}}$$

4.4.2 Transport

For the transport sector, intensity is determined by four inputs. *Efficiency improvements* by 2050 can be entered for all transport modes and different technologies. Furthermore, only a technology switch in the road transport subcategories (e.g. bus, freight road) is assumed. For the other sectors, no technology switch can be modelled. Although some electric or hydrogen alternatives are currently developed for air and shipping transport, these were found too premature to take into consideration. Alternatively, biofuels can be utilized to decarbonize all conventional combustion engines.

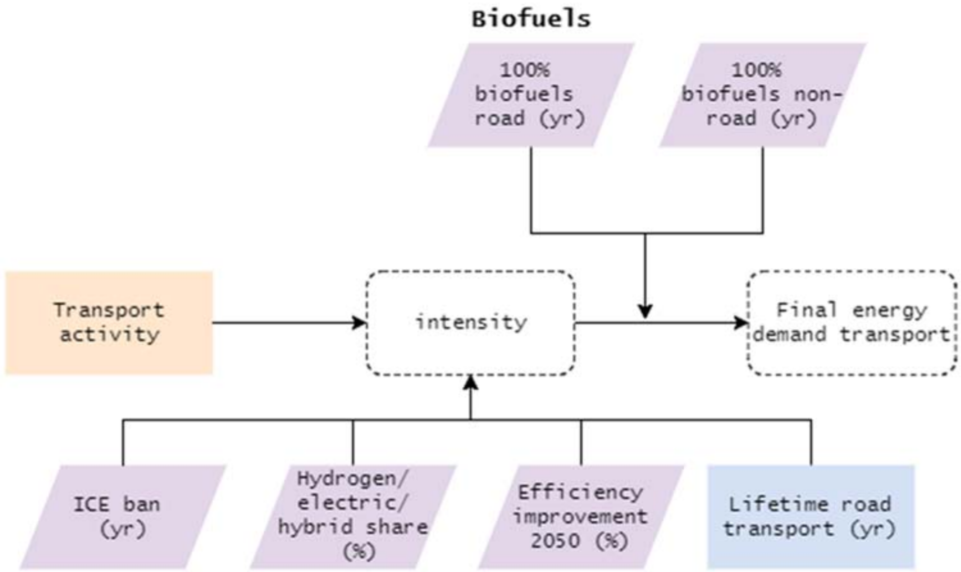


Figure 4.7 Overview of the input variables in finale energy demand for transport

For road transport modes, a ban on vehicles with an internal combustion engine (*ICE ban*) can be simulated as is already announced by for example India, France, the Netherlands and United Kingdom. Furthermore, the conventional combustion engine can be replaced with *Hydrogen / electric / hybrid share*.

The technology share of electric and fuel cell powered road transport is affected by the year in which ICE is prohibited. From that moment, market share of renewable technologies after ban ($TechShareRen_{AB}$) is affected by the *Lifetime road transport* and the desired final share:

$$TTechShareRen_{AB\,t} = TTechShareRen_{t-1} + (TTechShareRen_{2050} / Lifetime) \times (t - t_1)$$

With

$TTechShareRen_{t-1}$ = *Technology share in the previous year of renewable technology*

$TTechShareRen_{2050}$ = *The desired final market share of renewable technology*

Lifetime = *Typical lifetime of the type of road transport in years*

The following lifetimes are assumed based on Napp et al. (2017a).

Table 4.1 Assumed average lifetimes for different types of road transport.

Subcategory	Lifetime (years)
LDV	12.5
Light road	10
Bus	15
Freight road	15

Prior to the ICE ban, the market is expected to anticipate. In the run-up to road transport without internal combustion engines, the growth of the annual market share increases exponentially until it reaches the full growth rate at the ICE ban year.

$TTechShareRen_{BB\,t}$ = $TTechShareRen_{t-1} + RenGrowth_{t-1} \times (RenGrowth_{AB} / TTechShare_{2020})^{(Ban - 2020)}$

With

$TTechShareRen_{t-1}$ = *Technology share of low carbon technology in the previous year*

$RenGrowth_{t-1}$ = *Additional market growth of the previous year*

$RenGrowth_{AB}$ = *The growth rate when all ICE's are banned* $(TTechShareRen_{2050} / Lifetime_{years})$

$TTechShare_{2020}$ = *The assumed technology share in 2020*

Ban = *Year wherein ICE's are no longer sold on the market*

The year 2020 is chosen since it is the first point after 2014. The market share for electric vehicles in 2020 is still marginal and assumed to be 0.2% based on IEA (2017a). The market share for hydrogen fuel cells is expected to be very limited still in 2020 and set at 1% of the electric vehicle shares (0.002%) in 2020.

The share of road transport technologies powered by combustion engines are not modelled explicitly but adapts to the developments in the fuel cell and power sector: as the share of renewable technologies in transport (*TTechShareRen)* increases, the fossil powered technologies in road transport (*TTechShareFossil)* decreases proportional to their current share.

$TTechShareFossil_{t}$ = $TechShareFossil_{2014} \times (1 - TechShareRen_{t})$

A second strategy for decarbonizing (road) transport is the deployment of biofuels to propel internal combustion engines. The availability of biofuels in the transport sector is calculated based on the input of a year in which 100% of the fossil fuel demand is powered with biofuels. An exponential growth is assumed between the starting year and the 100% biofuel year. The available biofuels at a moment are calculated with the following formula:

$BiofuelsTransport_{t}$ = $BiofuelsTransport_{2014} \times (1 + GrowthRate_{bio})^{(t-2014)}$

With

$BiofuelsTransport_{2014}$ = *The biofuels used in transport in 2014*

$GrowthRate_{bio}$ = *The compound average annual growth rate required to reach 100% biofuels by the desired year:* $(Liquidfuels_{bioyear} / Biofuels_{2014})^{(1/(bioyear-2014))}$

4.4.3 Industry

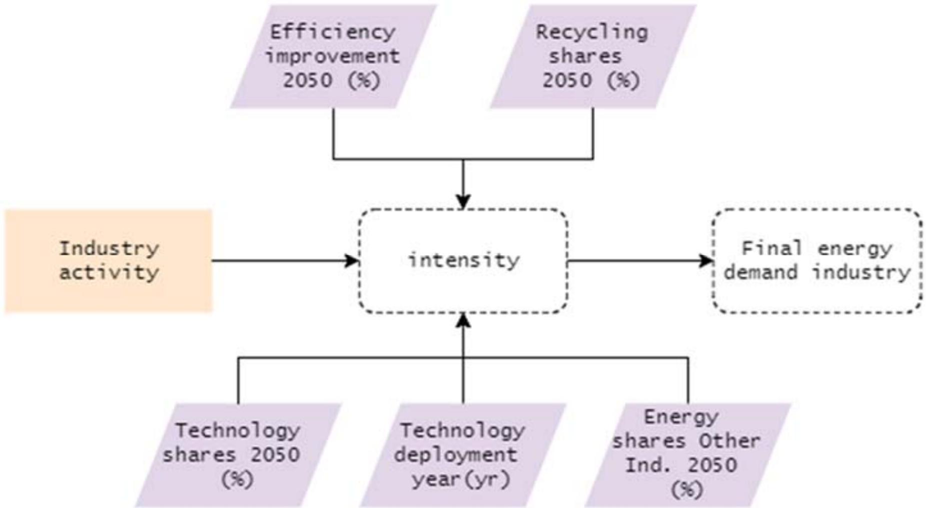


Figure 4.8 Overview of the input variables in energy for industry

The energy intensive production processes in industry are specified by technology. First of all, *Efficiency improvements* that are realized by 2050 can be entereed per sector. Furthermore, *Recycling shares* for iron and steel and aluminium in 2050 can be entered in the model. For the remaining primary production, *Technology shares* by 2050 should be specified. Furthermore, some technologies are not yet deployable at the start of this model and therefore a *Technology deployment year* should be provided in the input.

For the non-specified technologies, *Energy shares of other ind.* by 2050 can be entered as input. The transition from 2014 to 2050 follows the same S-curve as in buildings sector.

$IEShare_t = IEShare_{2014} + (IEShare_{2050} - IEShare_{2014}) \times SCurve_t$

With:

$IEShare_{2014}$ = *Energy share in 2014*

$IEShare_{2050}$ = *Energy share in 2050*

$SCurve_t$ = *The value of the S-Curve at t (number between 0 and 1)*

For the modelling of the transition in the industry between 2014 and 2050, an S-curve is used. But unlike the buildings sector, many low carbon technologies are not yet deployable on a commercial scale and are expected to be market-ready after 2020 or 2030. Furthermore, these technologies might become dominant after 2050 and this scenario only grasps its start-up phase. On the other hand, there are also proven low carbon technologies which are already widely applied (such as recycling). This makes determining the S-curve somewhat more complex and is partially based on the S-curve values in 2050 and the deployment year:

$$SCurve_t = \frac{1}{1 + e^{-10(Scurve_{Dt} + (Scurve_{2050} - Scurve_{Dt})\frac{t-Dt}{2050-Dt} - 0.5)}}$$

With

$Scurve_{Dt}$	= *Corresponding S-curve value of the tech. share in deployment year*
$Scurve_{2050}$	= *Corresponding S-curve value of the tech. share in 2050*
D_t	= *Deployment year*
t	= *in years*

An example of the different growth paths is presented in figure 4.9, where technology shares of two technologies both increase by 50%. However, one technology already covers 50% of the activity in the specific category while the other is a newly introduced technology. Both technologies have a deployment year in 2014.

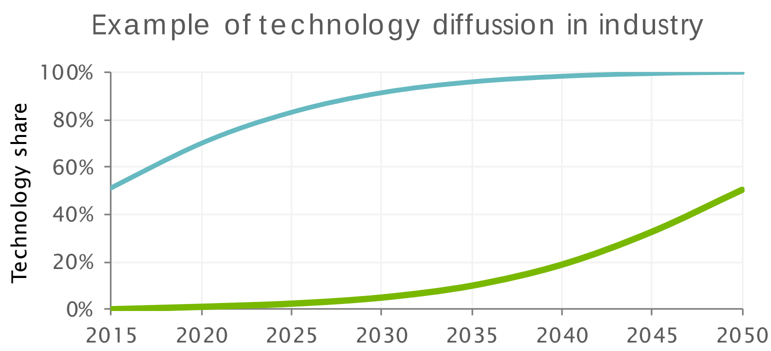


Figure 4.9 Example of two different technology diffusion paths in industry.

4.5 Power sector

Decarbonization of the power sector requires a transition towards renewable energy sources. In this section, the different components of the model are explained as well as the assumption of the growth rates.

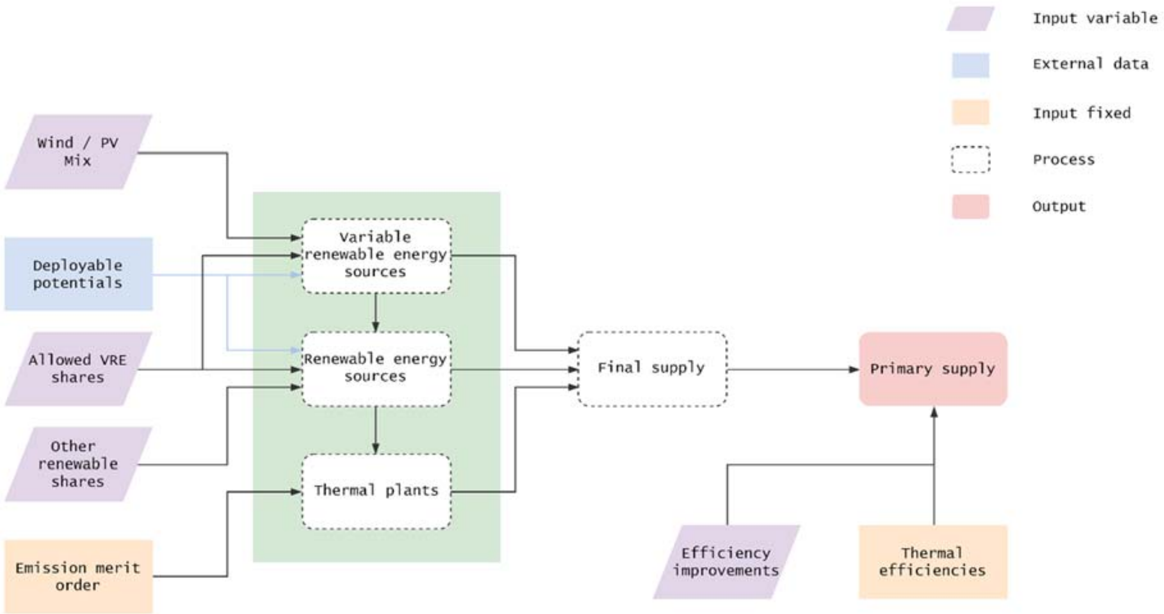


Figure 4.10 Overview of the power sector model

4.5.1 Power supply

The energy sources that are used for electricity production are divided into three categories:

1. *Variable renewables* Wind, Solar Photovoltaics
2. *Other renewables* Solar thermal, Hydro power, Geothermal, Ocean, wave and tidal
3. *Thermal power plants* Nuclear, Biofuels, Natural gas, Coal, Oil products, Other

Variable renewables consists of the two most promising renewable energy technologies due to high current growth rates, decreasing prices and sufficient remaining potential. An important disadvantage of these energy sources is that it is supply driven technology and dependent on solar radiation and velocity of the wind.

The *Other renewables* category consist of several energy technologies which can produce emission-free electricity and are more predictable or controllable than wind and solar photovoltaics. All technologies have been demonstrated on commercial scale, but its current deployment differs greatly. Hydropower is currently the largest renewable energy source (16% of the global final demand). In Non-OECD Americas hydro is responsible for 56% of the current power production. Ocean, wave and tidal produced only 0.0042% of the global electricity in 2014. The role of geothermal and solar thermal of 0.324% and 0.036% respectively in the global energy production in 2014 is also rather marginal. Nevertheless, developments in these technologies are fast resulting in decreasing prices and increasing production. An important advantage of these technologies is that they can provide baseload power which reduces the demand for additional storage capacity or transmission infrastucture (Matek and Gawell, 2015)

Thermal power plants, comprise of technologies which were responsible for 80% of the electricity production in 2014. These plants are able provide large supplies of electricity and adapt to demand fluctuations. Important disadvantages of these technologies are the emission of greenhouse gases (natural gas, coal and oil products) and safety issues (nuclear). Combustion of biofuels for electricity production is in principle a renewable energy source. However, biomass is a much wanted energy source throughout the total energy system, while the total supply is finite. Since there are sufficient alternatives to produce electricity, biofuels are preferably avoided for power production (see chapter 5).

4.5.2 Deployable potentials

One restriction of the total energy that can be derived from a specific renewable energy source in a specific area is referred to as the *Deployable potential*. Supply can be limited by the availability of land, availability of resources and the share of potential that can be captured by the specific technology (Deng et al., 2015). Establishing these potentials is not formalized in a methodology which results in enormous ranges in technical potential studies (Moriarty and Honnery, 2012). For this study, deployable potentials are based on a meta-analysis by Krewitt et al. (2009).

A correction is made for the potential of wind energy in China. Krewitt et al. (2009) set the deployable at 5 EJ, while other studies found significantly higher values. Liu et al. (2009) estimated the potential of wind in China between 10 and 28 EJ. Deng et al. (2015), assume the potential of on- and offshore wind combined to be between 21 and 75 EJ in East Asia. Therefore, it was chosen to set deployable potential of wind in China at 21 EJ. The deployable potential of wind in Middle East is also relatively small, but there are no indications found that suggest to adjust this number.

Table 4.2 Assumed deployable potentials for renewable energy sources in EJ

	Solar photovoltaics	Solar thermal	Wind	Hydro	Tide, wave and ocean	Geothermal
Africa	717	4,348	29	7	18	4
Asia (excl. China)	170	116	21	8	154	7
China	98	60	21	5	7	5
Middle East	127	1,153	5	1	8	1
Non-OECD Americas	113	287	45	9	42	5
Non-OECD Eurasia	116	204	75	5	0	6
OECD Americas	89	359	168	6	47	7
OECD Asia Oceania	225	1,513	57	1	30	4
OECD Europe	33	4	31	7	25	2
World	1,689	8,043	436	50	331	45

4.5.3 Allowed share of intermittent renewables

Another constraint that affect the growth of solar photovoltaics and wind is the maximum allowed share of intermittent renewables (*Allowed VRE share*). The electricity grid is actually a rather sensitive system and an important condition is that supply and demand have to be balanced at all time. Whereas production of power plants can be scaled up or down, the supply of electricity from wind and solar photovoltaics is much more volatile and uncertain. Critics argue that this intermittency is an important barrier to large scale penetration of PV and wind. However, this obstacle appears to be more of a social and politcal nature, rather than an actual technical one (Sovacool, 2009). According to (Jacobsen and Zvingilaite, 2010) intermittent energy systems can be balanced by applying several strategies:

- Expand the electricity grid
- Create a portefolio of different renewable sources
- Increase storage capacity (pumped hydro, batteries, heat pumps, hydrogen)
- Flexibilize demand

Developments in energy storage go fast: the costs of battery storage decreased spectacularly (Kittner et al., 2017), electric vehicles create an enormous storage potential (Richardson, 2013) and by producing hydrogen from electricity, 100% renewable energy grids should be well possible with limited required power-to-gas storage (Blanco and Faaij, 2018). The role of IT becomes very significant (Reinaud et al., 2017).

Including these option can thus enable a signficant share of intermittent renewables in electricity production. In theory even 100% of the electricity mix, though this would result in very high curtailment and large storage capacities (Kroposki et al., 2017). In the summer of 2017, a scientific disucssion did arise about a study by Jacobson et al. (2015). The study stated that wind and solar photovoltaics can produce 95% of the power production in the United States by 2050. Clack et al. (2017) judged this study as unrealistic. One of the main points of criticism is that the study by Jacobson et al. (2015) would only consider a limited amount of technologies while diversifying the portefolio of energy sources would be a much more affordable strategy according to Clack et al. (2017). Jacobson et al. (2017) responded to all the points of criticism and defended its previous research.

Looking at other simulations, the maximum share of intermittent renewables found is rather high. Mathiesen et al. (2011) proposed a share of 71% VRE for the Danish electricity system in 2050. 6 years later, 69% of the Danish electricity is expected to come from wind and solar photovoltaics by as soon as 2022 (IEA, 2017b). Connolly et al. (2016) state that a flexible electricity system could allow for 80% of variable renewable energy sources in Europe. This same ratio was found for the state of Texas (Denholm and Hand, 2011). A simulation for the German electricity grid found a combined share of solar and wind as high as 84% in combination with storage in electric vehicles, hydrogen, heat pumps and pumped storage (Klaus et al., 2010).

For this model, the maximum share of intermittent renewables is set at 75% which is a considerable share but still within the range found in literature. Production of hydrogen, demand side management strategies and (chemical) storage capacities are assumed to buffer the variable energy supply.

The maximum amount of variable renewables in the power sector of Non-OECD Americas was set at 45%, due to the high current utilization of hydro in the power sector.

4.5.4 Mix Wind / PV

As the maximum allowed share of intermittent renewables is set, an allocation is needed between wind and solar photovoltaics. Combining wind with solar photovoltaics also partly balances electricity supply since wind is generally stronger in cloudy periods and vice versa, wind speeds are lower on average at sunny days. In Europe, an energy mix with 45% solar and 55% wind smoothens seasonal fluctuations significantly (Heide et al., 2010). Jacobson et al. (2015) projects 52% wind and 48% photovoltaics by 2050 for the United States. The beyond two degrees' scenario by IEA (2017c) projects a division of 53% wind and 47% PV by 2060. These results indicate that more or less equal shares of both energy sources are commonly used in literature. This study will therefore assume a 50/50 share of wind and photovoltaics unless one energy source exceeds the deployable potential.

Only in Asia (excl. China), an adaptation had to be made since the potential of wind was constraint to provide 38% of intermittent renewables.

4.5.5 Shares of other renewables

For the other renewables, a mix of the energy technologies is used to generate the remaining electricity demand. Solar thermal is assumed to provide more than 50% of the remaining energy demand, due to its high deployable potential. Except in OECD Europe, where the average irradiation is rather low. Furthermore, additional hydropower is deployed in all regions. Geothermal and tide, wave and ocean are also used in all regions except for Africa and Middle East. The production does not exceed the deployable potentials in any of the regions.

Table 4.3 Assumed distribution of electricity production from other renewables

	Hydro	Geothermal	Solar thermal	Tide, wave and ocean
Africa	20%	0%	80%	0%
Asia (excl. China)	20%	25%	50%	5%
China	10%	25%	60%	5%
Middle East	10%	10%	75%	5%
Non-OECD Americas	50%	0%	50%	0%
Non-OECD Eurasia	20%	25%	55%	0%
OECD Americas	20%	25%	50%	5%
OECD Asia Oceania	20%	25%	50%	5%
OECD Europe	50%	25%	5%	20%

4.5.6 Emission merit order

The thermal plants are modelled to phase out as the market shares of renewable energy sources increases. From the perspective of the carbon emissions it was chosen to first phase out the most emission intensive energy carriers. The remaining energy demand is met by energy sources on descending order.

1. Nuclear
2. Biomass
3. Natural gas
4. Coal
5. Other

Electricity production from coal and other energy sources are therefore chosen to phase out first, while nuclear energy will be the last remaining energy source. Nuclear energy is in this case preferred over biomass, since the use of biomass is preferably utilized in other sectors.

4.5.7 Thermal efficiencies

In the conversion from thermal to electric energy, a considerable part of the potential energy is lost. The 2014 efficiency factors of thermal power plants for each region were derived by dividing the electricity output with the energy input. Due to the planned phase out of the thermal plants, not much efficiency improvements is expected. Towards 2050, efficiencies of all combustion plants are assumed to gradually improve towards the highest efficiency rate found in 2014.

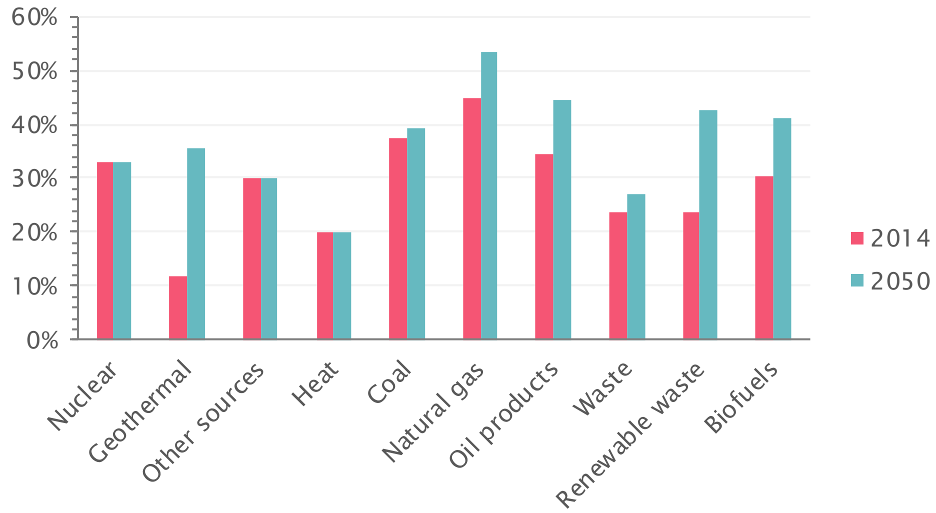


Figure 4.11 Global average efficiencies developments of power production between 2014 and 2050

4.5.8 100% renewable deployment year

An important variable input for the power sector is the year in which 100% of the power system is powered with renewables. Depending on this year, market share of renewable energy technologies will increase until 100% of market share is reached in that year. The development towards the full final market share follows a part of the S-curve based on the current market share and the final market share. This has as effect that in markets with relatively low shares of a specific renewable the early adopters phase can be simulated with relatively high growth shares. Also, in regions where a technology already plays a significant role much lower growth rates are expected. Figure 4.12 shows an example of the deployment of two renewable technologies with a high and a low current contribution to the electricity sector up to 2045. Growth rates of PV in China first accelerates before a steady growth is realised and finally decreases. For wind in Europe, the growth of annual additions declines slowly until the year 2045. To simulate these growth patterns, the S-Curve is calculated with the following formula:

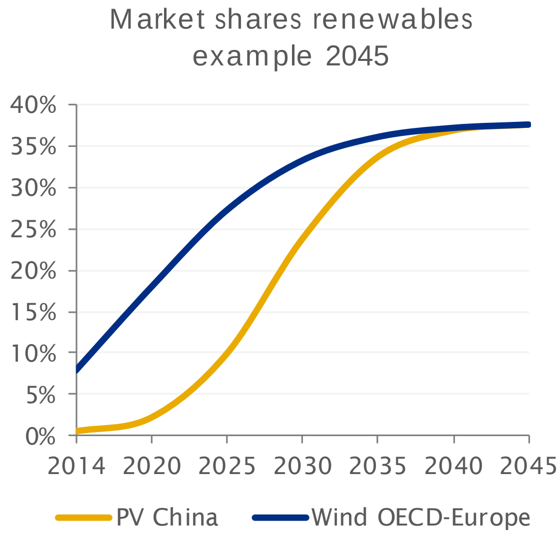


Figure 4.12 Example of deployment of renewable energy technologies in power sector to 38%

$$SCurve_t = \frac{1}{1 + e^{-10\left(SValue_{2014} + (1 - SValue_{2014})\frac{t-2014}{100\%Renyear-2014} - 0.5\right)}}$$

With

100%Renyear = *Year in which a 100% renewable power system should be realized.*

SValue2014 = *the initial value of x in 2014 in the logistic function of the Scurve* $\frac{1}{1+e^{-10(x-0.5)}}$

The $SValue_{2014}$ is calculated with the following formula.

$$SValue_{2014} = \frac{\ln\left(\frac{1}{TechShare_{2014}} - 1\right)}{-10} + 0.5$$

With

$TechShare_{2014}$ = *The share of the technology in 2014 of the specific technology relative to the final allowed share*

4.6 Energy industry own use and losses

Energy industry own use is defined by the IEA as the primary and secondary energy consumed by the transformation industries. Losses comprise of transportation losses of natural gas, electricity and coal. Energy industry own use and losses were responsible for 44 EJ in 2014.

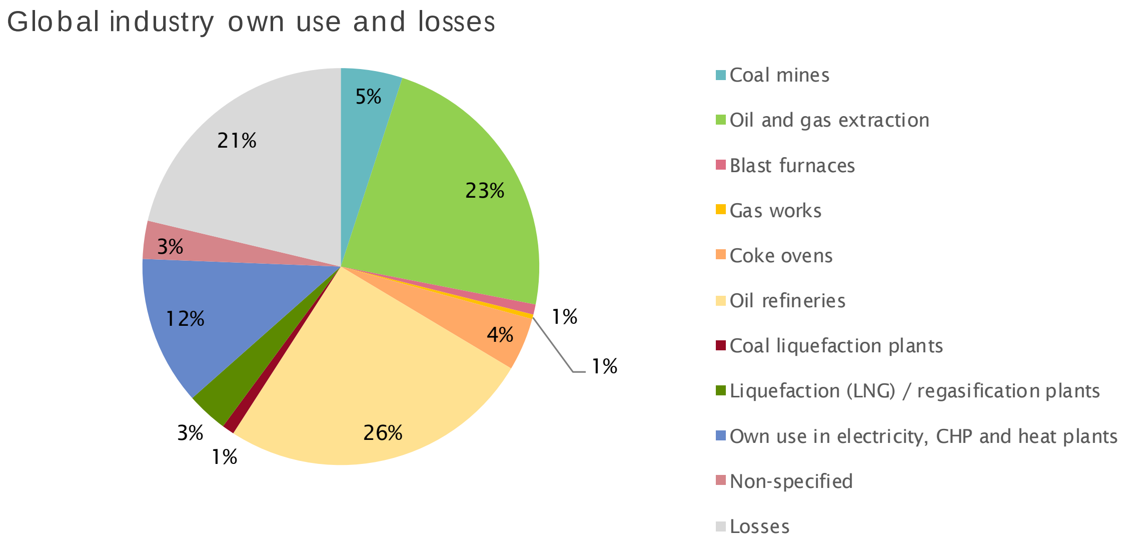


Figure 4.13 Distribution of energy use in energy industry own use and losses category in 2014

Future energy demand in this sector is calculated by linking the categories linearly to energy use in the corresponding categories. These links are provided in table 4.4.

Table 4.4 Indicators for activity in EIOUL categories

Category	Indicator category	Indicator energy carrier
Coal mines (energy)	Total final consumption	coal
Oil and gas extraction (energy)	Total final consumption	natural gas + oil products
Blast furnaces (energy)	Iron and steel	coal
Gas works (energy)	Iron and steel	coal
Coke ovens (energy)	Iron and steel	coal
Oil refineries (energy)	Total final consumption	oil products
Coal liquefaction plants (energy)	Total final consumption	oil products
Liquefaction (LNG) / regasification plants (energy)	Total final consumption	natural gas
Own use in electricity, CHP and heat plants (energy)	Total final consumption	electricity
Non-specified (energy)	Total final consumption	total
Losses	Total final consumption	total

4.7 Emission factors

The carbon budget is defined as the cumulative CO_2 emissions that have been produced between the start and the endpoint of the scenario. The slow degradation of atmospheric CO_2 makes the total emitted greenhouse gases a more important factor than annual emissions. The carbon budget is calculated by adding up all the annual emissions which is derived by multiplying the primary energy consumed with an emission factor

$$AnnualEmissions_t = \sum Ec_t \times EF_{ec}$$

With

Ec_t = *Energy Carriers consumed at (TJ)*

EF_{ec} = *Corresponding emission factor (tonnes* CO_{2e} */ TJ)*

Emission factors were derived from the emission factor database provided by the IPCC 2006. Since the energy carriers have been aggregated, the same has to be done for the emission factors. The global primary energy supply in 2014 is used to weigh the emission factors and aggregate them.

Table 4.5 Assumed emission factors

Energy carrier	Emission factor (tonne CO_{2e} / TJ)
Coal	96
Natural gas	56
Other oil products	79
Liquefied petroleum gases (LPG)	63
Motor gasoline excl. biofuels	70
Jet fuel	72
Gas/diesel oil excl. biofuels	74
Fuel oil	78
Waste	122
Renewable waste	102
Oil products	73
Coal CCS*	10
Natural gas CCS*	6
Biofuels**	5
Biofuels CCS**	-85

* *Emission factors for coal CCS and natural gas CCS is estimated to be 10% of the original emissions according to (Rubin et al., 2007)*

** *emission factors for biofuels and biofuels CCS are derived from (Caldecott et al., 2015)*

Besides these energy related emission factors, another important emission source in the industry is calcination of cement. This process emission is responsible for the annual emission of 2 Gt CO_2 (Taylor et al., 2006), which is about 6% of the global CO2 emissions. Therefore an emission factor of 0.54 tonne CO_2 / tonnes cement is considered derived from (Napp et al., 2014). Deployment of CCS technology in cement production can reduce this emission factor to a maximum of 90%.

4.8 Carbon budget

Finally, the annual emissions are accumulated into a carbon budget. The carbon budget is calculated by taking the average annual emissions of two consecutive periods (t1 & t2) and multiplying this by the amount of years in between. This is added to the previously calculated emissions

$$\sum E = E_{t-1} \frac{(E_{t2} - E_{t1})}{2} \times (t_2 - t_1)$$

5. Goals and Constraints

Formulation of goals and constraints is the first step in the energy backcasting methodology by Robinson (1982). Seven principles in total will give direction to the development of the energy scenario:

1. Limit the global average temperature increase to 1.5 °C
2. Provide sufficient energy to meet the expected future needs
3. Reduce energy intensity wherever reasonably possible
4. Rely on existing and proven low carbon technologies
5. Minimize the role of biomass in the energy system
6. Avoid burden shifting to future generations as much as possible
7. Incorporate political and societal acceptance and feasibility as a decision criteria

1. Limit the global average temperature increase to 1.5 °C

The main goal of this study is to develop a scenario in which the global average temperature increase is limited to 1.5 degrees by 2100. This requires a rapid decarbonization of the energy system. The allowed carbon budget between 2011 and 2100 is estimated to be 350 Gt CO_2 (199-415 Gt confidence interval) which is almost half of the allowed emissions for 2 °C scenarios (Rogelj et al., 2015). Considering that between 2011 and 2013 already 106 Gt CO_2 was emitted (Boden et al., 2017), the remaining carbon budget for the 2014-2100 period is around 244 Gt. Greenhouse gas emissions should reach net zero around 2050 according to the analysis by Rogelj et al. (2015).

Staying within this carbon budget appears to be infeasible without the deployment of negative emissions in the second half of the century (IEA, 2016; Lackner et al., 2016; Rogelj et al., 2015; van Vuuren et al., 2013). Several technologies are available to create negative emissions such as reforestation, using biomass in construction or capturing emissions from biomass combustion (BECCS). Negative emissions can therefore be used in the scenario to compensate for the overshoot of the budget in the first half of the century.

2. Provide sufficient energy to meet the expected future needs

An effective but rather blunt decarbonisation strategy would be to simply restrict energy intensive activities with financial or legal measures. But these options can potentially limit the development of the poorest countries considerably (Ditya et al., 2010; Weitzel et al., 2015). The energy transition is therefore not expected to limit future needs of people. The current consumption of energy across the world is very unevenly distributed: while in the United States there are 800 cars on the road for every 1,000 habitants, 1.2 billion people in developing countries still do not have proper access to electricity (IEA, 2016a). The lack of financial means makes large parts of Asia, Africa and South America, relatively small energy consumers. Economic growth in these regions is expected to unlock access to goods and services such as transportation, consumer goods and improved housing.

3. Reduce energy intensity wherever reasonably possible

Another important goal for this scenario is to reduce the energy intensity by improving energy efficiency. Efficiency improvements reduce the need for power supply capacity. Although wind energy is gaining a lot of tailwind and the future of solar energy looks sunny too, these technologies still play a minor role of less than 1% of the total primary energy supply. Supplying the energy demand with renewable sources, thus requires an immense scale up of the available technologies. And although there is sufficient deployable potential available (Deng et al., 2015; Krewitt et al., 2009), it still comes with undesirable side-effects. First of all, renewable energy technologies require vast amounts of land. Secondly, renewable energy technologies are not burden free. The production processes of photovoltaic panels and wind turbines are energy intensive (Pehnt, 2006; Peng et al., 2013) and require large amounts of (rare) natural resources (Alonso et al., 2012).

Improving energy efficiency is thus a priority for this scenario, but not at all costs. Efficiency potentials can be distinguished between hypothetical (what would in theory be the maximum reduction possible?), technological (what potential is technically possible to achieve?) and economic energy savings potential (what is the size of efficiency measures that result in a positive business case?) (Jaffe and Stavins, 1994).

This scenario only considers economic or technological efficiency potentials. First of all, this avoids being too overoptimistic about future technological improvements. Furthermore, extensive investments in efficiency measures might be unrealistic when there is an abundance of low-cost energy available.

4. Rely on existing and proven low carbon technologies wherever possible

As much as holy grails, such as nuclear fusion, could solve the clean energy issue, these are excluded in this research. Because of the tight carbon budget and the limited available time, only mature technologies which are ready to scale up are preferred. There is simply no time to invent, design, test and roll out new low carbon technologies. Also, betting on unproven technologies can have enormous negative consequences if they do not meet the expectations (Peters, 2016; Vaughan and Gough, 2016). The limited deployment of CCS is a good example: whereas most nations are well on track to keep their promises made at COP 21, CCS demonstration projects are seriously lacking behind which can put the carbon reductions after 2020 in danger (Peters et al., 2017).

Therefore, the application of CCS or other immature technologies are used with caution. In cases where there are no mature low carbon alternatives are available and CCS is the most realistic option, deployment of CCS is expected after 2020.

5. Minimize the role of biomass

Biomass is a very attractive energy source since it can be transformed into a wide range of products with similar physical properties as fossil energy carriers. This means that a significant part of the current energy infrastructure and technologies can be preserved. However, production of biomass requires arable land which conflicts with food production and/or nature preservation (van Dam et al., 2008). The potential of biomass that can be harvested in the future is topic of a heated scientific debate and fluctuates between 0 and 1,548 EJ per year depending on the study and scenario (Slade et al., 2011). The highest expected potential would require a global vegetarian diet and full utilization of the available arable land.

In this scenario, the incredibly broad range is interpreted as an indication for the enormous uncertainty of the available biomass and therefore it is chosen to stay within the safe margins. The sustainable potential deployment of primary biomass is estimated to be between 100 and 300 EJ (IPCC, 2014). Though this requires a fast scale up of the current biomass production: a demand of 300 EJ biomass would entail 0.5 Gha arable land dedicated to the production of energy crops, which is half the size of China plus an optimal use of organic waste streams (Slade et al., 2011). Minimizing the role of biomass, does not mean that biomass will not play an important role in the future energy system but addresses the scarcity of the resource and the importance of clever and strategic utilization.

6. Avoid burden shifting to future generations as much as possible

The relation between the current and the future generations plays a key role in the famous definition of sustainable development by the Brundlandt report in 1987. This is opposed to the current practices in which the consequences of issues such as climate change are passed through to future generations. In order to comply with the principles of the Brundlandt definition, another goal of the scenario is to limit the required efforts for future generations and complete the transition before 2050 as much as possible. This also means that the demand for negative emissions in the second half of this century should be minimized.

In the metareview of IAM's by Rogelj et al. (2015), large amounts of negative emissions are assumed since this is preferred from a least-cost perspective over steeper decarbonization in the first half of the century. Depending on the technology to produce negative emissions, it requires large amounts of capital, natural resources, land area and/or energy (Kartha and Dooley, 2016). Williamson (2016) argues that this rationale is unethical and impairs future generations. The scenario should therefore decarbonize as quickly as possible to limit the cumulative emissions and thereby the total required negative emissions to compensate an overshoot.

7. Incorporate political and societal acceptance and feasibility as a decision criteria

An important critique on the current practice of modelling in Integrated Assessment Models is the fact that aspects such as political feasibility and social acceptance are not taken into account (Ackerman et al., 2009; Peters, 2016; Schubert et al., 2015).

In order to stay within 1.5 degrees there is insufficient time to swim against the current. On the contrary, an energy transition in top gear should go with the flow. Social and political resistance towards renewable energy technologies can cause severe delays for which there is simply no time. Important examples in Europe include the public resistance against wind turbines (Fast, 2013) and CCS technology (L'Orange Seigo et al., 2014) which hinder the deployment of these technologies.

And although concepts such as acceptance and feasibility are hard to express in a quantitative sense, nevertheless an attempt is made to incorporate these aspects in the argumentation and decision for specific technologies.

6. Current consumption and production

The second step of the energy backcasting scenario consists of mapping the current energy system and identifying the activity and intensity levels for buildings, industry and transport sector. The current activity levels are presented first and then a closer look is taken at the technologies and intensities at the start of the scenario.

6.1 Activity levels

Activity can be expressed in both monetary or physical terms. It was found that using physical units is a much more accurate indicator for energy scenarios (Neelis et al., 2007; Schenk and Moll, 2007). Physical units allow to add and check saturation levels of activity levels (Schenk and Moll, 2007). Additionally, the underlying reasons for variations in energy consumption can be studied better since there is a split between technology changes and activity changes (Neelis et al., 2007). Therefore, activity level is expressed in terms of physical indicators as much as possible. An overview of the activity levels that are explicitly modelled can be found in table 6.1.

Table 6.1 Subcategories for which activity levels are expressed and the corresponding units

Transport		Industry		Buildings	
Subcategory	*Unit*	*Subcategory*	*Unit*	*Subcategory*	*Unit*
LDV	pkm	Iron and steel	tonnes	Surface	m^2
Light road	pkm	Cement	tonnes	Space heating	m^2
Bus	pkm	High value chemicals	tonnes	Water heating	L hot water
Freight road	tkm	Ammonia	tonnes	Space cooling	CDD X GDP / m^2
Passenger rail	pkm	Methanol	tonnes	Lighting	Act_{index}
Freight rail	tkm	Paper, pulp and print	tonnes	Appliances	Act_{index}
World aviation bunkers	pkm	Aluminium	tonnes	Cooking	Act_{index}
Domestic aviation	pkm				
World marine bunkers	tkm				
Domestic navigation	tkm				

6.1.1 Transport

Activity in transport is expressed in terms of passenger kilometres (pkm) or tonnes kilometres (tkm) per capita. Although ships and airplanes transport both goods and passengers, ship transport is shared under freight transport and air transport under passenger transport. The activity levels are derived by dividing the total energy use with the specific energy intensities (discussed ahead in this chapter) derived from the ICCT (2012).

Table 6.2 Activity levels per capita for different transport modes and regions in 2014

	Africa	Asia (excl. China)	China	Middle East	Non-OECD Americas	Non-OECD Eurasia	OECD Americas	OECD Asia Oceania	OECD Europe	World aviation bunkers	World marine bunkers	World
LDV (pkm)	520	661	1,486	7,024	3,995	3,795	16,714	7,694	8,007	-	-	3,145
Light road (pkm)	59	1,005	313	243	690	162	116	431	249	-	-	595
Bus (pkm)	1,486	1,879	3,080	4,389	3,277	1,206	2,075	764	1,175	-	-	2,542
Freight road (tkm)	710	737	1,301	3,543	2,921	1,582	6,243	6,300	7,347	-	-	2,107
Passenger rail (pkm)	20	184	239	-	14	675	130	1,583	1,145	-	-	321
Freight rail (tkm)	124	243	869	-	469	3,315	5,259	1,137	969	-	-	936
World aviation bunkers (pkm)	-	-	-	-	-	-	-	-	-	461	-	461
Domestic aviation (pkm)	35	58	214	99	148	397	2,292	868	266	0	-	294
World marine bunkers (tkm)	-	-	-	-	-	-	-	-	-	-	22,574	22,574
Domestic navigation (tkm)	640	1,802	14,195	-	4,675	2,266	19,994	20,369	8,014	-	-	5,879

Looking at activity levels, most variation among the regions is found in activity levels of passenger cars (LDV) and domestic aviation. Non-OECD regions tend to have significantly lower activity levels per capita. Bus transport and light road per capita is more evenly distributed.

6.1.2 Industry

For the industry, production volumes are described in tonnes produced. The main source is the IEA ETP published in 2016 except for aluminium production for which the data by the International Aluminium Institute (IAI) (2017) was used. Data reported by the IAI provided more detailed information and did fit better with the intensity levels in combination with energy consumption in that sector. The ETP 2016 provides data for OECD and non-OECD, but not for China specifically. Therefore, additional data was collected for China.

Table 6.3 Chinese activity levels for industry in 2014 derived from literature

Material	Volume (Mt)	Source
Cement	2420	WBCSD (2017a)
High value chemicals	91.32577357	No data available: production volume calculated relative to China's global share in ammonia
Ammonia	47.3	USGS (2015)
Methanol	35	CIEC (2016)
Iron and steel	822	World Steel Association (2016)
Paper, pulp and print	107.1	RISI (2016)
Aluminium	36.789	IAI (2017)

Looking at the production per region, China is responsible for over 50% of the global iron and steel, cement and methanol production.

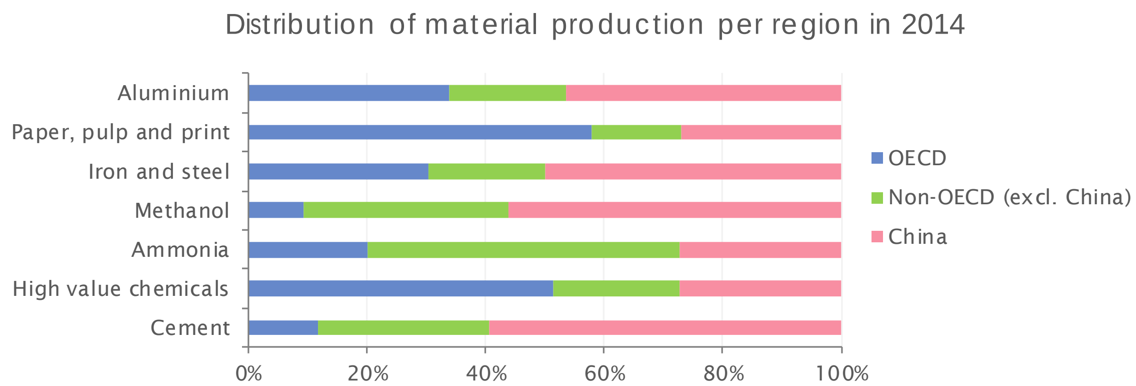


Figure 6.1 Distribution of materials that are produced per region in 2014. China is the largest producer of most materials

6.1.3 Buildings

Finding activity levels for functions within the buildings category was challenging. No detailed and complete data exists for activity levels in the buildings sector on a country or regional level. Nevertheless a few activity levels were compiled. The surface area per capita for different regions of residential and commercial buildings was derived from data by IEA (2013a).

Activity level of water heating is expressed in terms of litres 60 ˚C water by multiplying thermal energy with the specific heat of water and the temperature difference (ΔT) which is set at 45 ˚C. For cooking, lighting and appliances, no suitable measure for activity was found. Therefore, the useful energy was indexed based on the useful energy per capita. The region with the highest energy use per capita, ranked 100. The index of other regions at the start was set relative to this region.

Residential

Table 6.4 2014 activity levels residential sector per capita

Category	Unit	Africa	Asia (excl. China)	China	Middle East	Non-OECD Americas	Non-OECD Eurasia	OECD Americas	OECD Asia Oceania	OECD Europe	World
Surface	m^2 / cap	13	21	21	18	20	26	48	48	48	25
Water heating	L hot water / Cap. day	27	4	41	53	22	49	49	30	29	28
Lighting	Act_{index} / m^2	25	9	11	100	17	26	45	30	13	20
Appliances	Act_{index} / Cap.	4	8	20	54	15	36	100	71	33	22
Cooking	Act_{index} / Cap.	100	83	28	71	45	30	22	23	24	55

Commercial and public services

Table 6.5 2014 activity levels commercial and public service sector per capita

Category	Unit	Africa	Asia (excl. China)	China	Middle East	Non-OECD Americas	Non-OECD Eurasia	OECD Americas	OECD Asia Oceania	OECD Europe	World
Surface	m^2 / cap	1	4	4	5	2	3	18	18	18	6
Water heating	L hot water / Cap. day	2	1	2	4	5	11	15	22	17	5
Lighting	Act_{index} / m^2	77	16	19	22	100	54	36	46	23	30
Appliances	Act_{index} / Cap.	2	5	9	13	13	26	100	87	33	19

6.2 Technologies and intensities

To meet the activity demand, energy and materials are converted with specific technologies: a gas stove to prepare food or a blast furnace to produce steel. For all different functions that are analysed, different technologies are selected which are either currently used or appear to be a potential low carbon alternative mentioned in literature. Each technology has a specific energy intensity and requires specific energy carriers. By making these technologies and technology switches explicit and separating these from efficiency improvements, more transparency is created in the scenario and it is possible to trace down the effects of certain choices.

6.2.1 Buildings

A list of technologies that are included in the buildings sector for the different functions can be found in table 6.7. The appliances category in buildings encompass a variety of energy carriers which are not further specified to technology level. 100% of the appliances in residential buildings are powered with electricity, while for commercial and public services, 52% of the energy for appliances comes from electricity. The non-electric appliances comprise of several other functions that cannot be shared under the other functions. Think of gasoline lawn mowers or specific appliances used in the commercial and buildings sector.

Table 6.6 Overview of all the technologies for each function in buildings sector

Space and water heating	Space cooling	Lighting	Appliances	Cooking
Biomass stove	Air conditioner	Electric lamp	Biofuels app	Biomass stove
Coal stove	Biomass chiller	Oil lamp	Coal app	Coal stove
Electric heater	Gas chiller		Electricity app	Electric stove
Geothermal	Heat pump		Natural gas app	Natural gas stove
District heating			Oil products app	Fuel stove
Gas stove			Heat app	
Fuels stove				
Solar thermal				
Heat pump				

The performance (intensity) of the technologies was derived from (Rong et al., 2007). A study by (Ecofys and IEEJ, 2015) was used to complement the data. For light efficiencies indexes were used. Kerosene lamps which are typically found in rural areas have a much lower efficiency of around 20 times lower compared to electric lights (Mills, 2003). Other than for transport and industry, it was not possible to make a distinction between the different regions. Therefore, in this scenario a gas stove has the same efficiency all over the world, even though it is likely that there are regional differences. The average efficiency factors in 2014 are provided in table 6.8.

Table 6.7 Efficiency factors different technologies for functions in buildings 2014

Technology	Energy carrier	Space heating	Water heating	Space cooling	Lighting	Appliances	Cooking
Biomass stove	Biofuels	0.58	0.58				0.58
Coal Stove	Coal	0.58	0.58				0.58
Electric Res. Heating	Electricity	0.98	0.88				
Geothermal	Geothermal	1	1				
District heating	Heat	0.97	0.98				
Gas stove	Natural gas	0.87	0.56				
Fuel stove	Oil products	0.82	0.56				
Solar thermal	Solar thermal	0.4	0.4				
Heat pump	Electricity	3.2	1.8	2.8			
Air conditioner	Electricity			2.45			
Biomass space cooler	Biofuels			2.45			
Gas space cooler	Natural gas			2.45			
Electric lamp	Electricity				1		
Oil lamp	Oil products				0.04		
Biofuels app	Biofuels					1	
Coal app	Coal					1	
Electricity app	Electricity					1	
Natural gas app	Natural gas					1	
Oil products app	Oil products					1	
Heat app	Heat					1	
Electric stove	Electricity						0.99
Natural gas stove	Natural gas						0.87
Fuel stove	Oil products						0.9

The current technology shares that are used to provide the different functions are calculated by dividing the specific useful energy (total energy multiplied with efficiencies) by the total useful energy. Specific useful energy of technology could be easily derived in most cases since they are linked to a specific energy carrier (e.g. natural gas stove to natural gas). The only technologies that both require the same energy source are heat pumps and electric resistance heating. Based on the fact that the heat pump market share is still marginal in 2014 (EHPA, 2015), all heating with electricity is allocated to resistance heaters.

6.2.2 Transport

The included technologies for transport are a mix of conventional combustion engine practices and upcoming low carbon alternatives in the form of hydrogen and electric engines

Table 6.8 Overview of all the technologies for each function in transport sector

Road	Rail	Shipping	Air
Gasoline	Diesel	Gasoline	Kerosene
Diesel	Coal	Diesel	
CNG	Other	Bunkers	
LPG	Electric	Natural gas	
Hydrogen	Hydrogen		
Electric			

The different combustion engines require specific fossil fuels, but can also be powered with bio-based alternatives such as bioethanol, biodiesel or biogas.

Intensity levels of road transport (in MJ/pkm and MJ/tkm) are derived from the ICCT transport model and distinguishes different types of road transport, different engine technologies for each region. The intensities in 2014 are depicted in figure 6.2. The coloured bars show the global average intensities, while the error bars demonstrate the variation between the different regions. For bus, freight road and light road, the ICCT assumes the same efficiencies for fuel cells and electric engines.

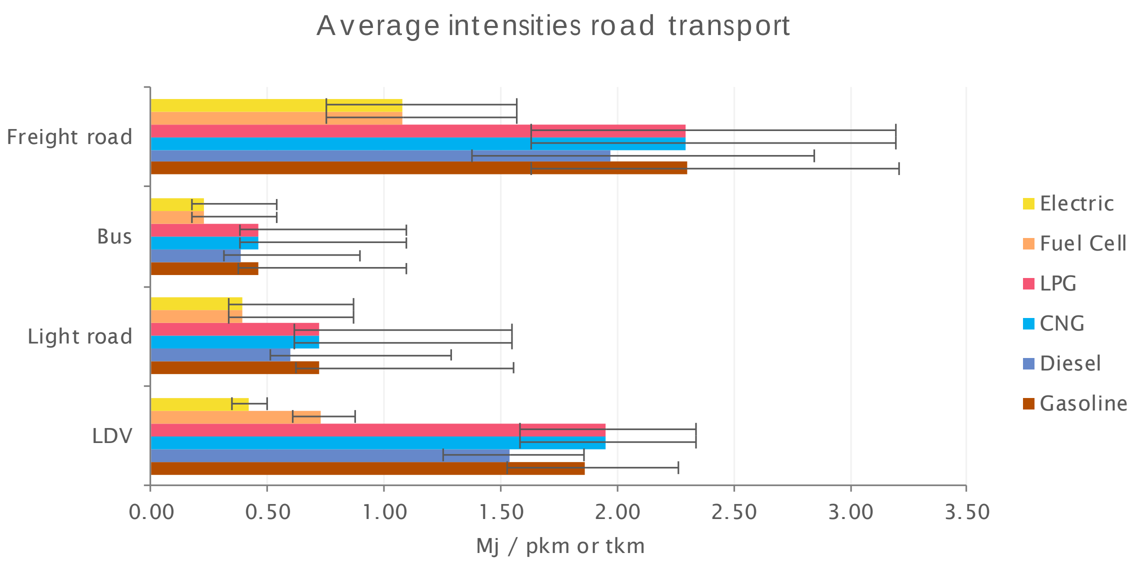


Figure 6.2 Average final energy intensities for different road modes and technologies in 2014 (Source: ICCT, 2012)

The ICCT model also contains average intensities of air and rail transport, but not for shipping. Shipping energy intensity was not provided by the ICCT database but was derived by dividing total ton kilometres of international marine transport from UNCTAD (2015) by the energy consumption in the energy balances which resulted in an average intensity of 0.05 MJ per tkm.

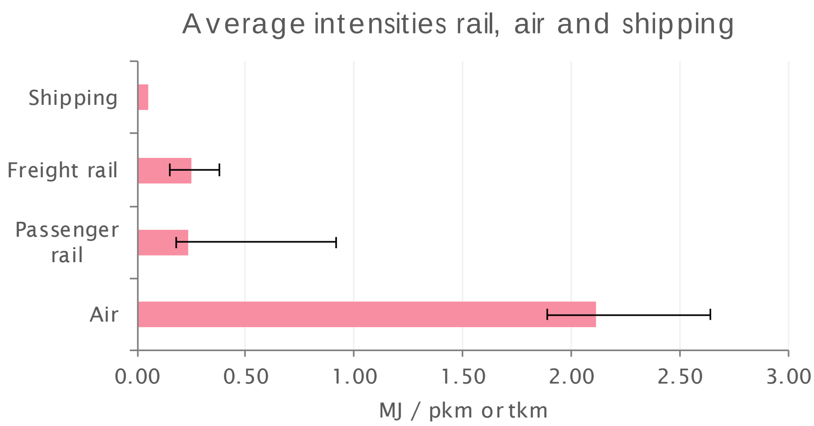


Figure 6.3 Average energy intensities for shipping, air, freight- and passenger rail in 2014

6.2.3 Industry

For the industry, this model explicitly focuses on seven of the most energy intensive production processes. The other industrial processes are included but no technologies are described for these processes. Currently, iron and steel is produced in a blast furnace (BF) or an electric arc furnace (EAF). Primary steel from iron ore is mostly made in blast furnaces, while most secondary steel comes from EAF plants (Fischedick et al., 2014). And although in reality scrap iron is also to a smaller extent mixed in BF processes, for this model the two routes are separated.

Production of aluminium consists of two steps: refining of bauxite to alumina and smelting of alumina to aluminium. Secondary aluminium only requires the smelting at significantly lower energy levels. The recycling of paper is not explicitly described in this model, although this certainly takes place on a large scale and provides clear energy reductions as well (Laurijssen et al., 2010). Unfortunately, there was insufficient data available to model this. The sustainable alternatives for the industry can be generally divided into carbon capture and storage options, application of biomass as feedstock and finally electrification/hydrogen use.

Table 6.9 Overview of all the technologies for each production process in industry

Iron and steel	Aluminium	Cement	Paper, pulp & print	Ammonia	Methanol and HVC
Primary BF	Primary	Conventional	Conventional	Conventional	Conventional
Secondary EAF	Secondary	With CCS	Electrification	Electrolysis	Biomass
Primary BF with CCS	Primary with CCS	Biomass CCS	Biomass CCS	Biomass	
Primary H2DR	Primary Solar thermal		Solar thermal		
Primary Electro winning					

The energy intensities for industrial processes were derived from a wide range of data sources as can be found in the table 6.11. Regional differences are described for currently used technologies, while for new technologies one general energy intensity was found.

Table 6.10 Energy intensities of different technologies in GJ / tonnes

Technology	OECD	Non-OECD (excl. China)	China
Secondary Aluminium[1]	3.7	3.4	3.7
Secondary Iron and steel[2]	4.6	4.6	4.6
CCS Aluminium[3]	73.8	68.1	73.4
Solar thermal Aluminium[3]	73.8	68.1	73.4
BF + CCS Iron and steel[4]	15.6	15.6	15.6
H-DR Iron and steel[4]	13.1	13.1	13.1
Electrowinning Iron and steel[4]	9.3	9.3	9.3
CCS Cement[5]	3.0	2.4	2.4
Biomass Cement[5]	3.0	2.4	2.4
Waste fired Cement[5]	3.0	2.4	2.4
Bio syngas High value chemicals[6]	50.3	50.3	50.3
Electrolysis Ammonia[7]	37.5	37.5	37.5
Bio syngas Ammonia[8]	58.6	58.6	58.6
Bio syngas Methanol[9]	30.3	30.3	30.3
Primary Aluminium[3]	73.8	68.1	73.4
Primary Iron and steel[5]	22.4	31.0	25.2
Primary Cement[5]	3.0	2.4	2.4
Primary Paper, pulp and print[5]	19.3	18.5	8.7
Primary High value chemicals[10]	42.0	42.0	42.0
Primary Ammonia[11]	33.2	35.9	35.9
Primary Methanol[11]	33.7	33.6	33.6

[1] (Van Der Voet et al., 2014) Secondary production is 5-10% of energy intensity of primary production, [2] (Worrell et al., 2008) Used best practices technology. Assumed EAF route only, [3] (IAI, 2017), [4] (Fischedick et al., 2014), [5] (IEA, 2016b) Derived by dividing energy use by production, [6] (Daioglou et al., 2014) 47 GJ of biomass is required to produce 1 tonne of olefins. 7% electricity use is added to account for non-process energy and machine drive, [7] (Pfromm, 2017), [8] (Gilbert et al., 2014), [9] (Hasegawa et al., 2010), [10] (Ecofys, 2012), [11] (Saygin, 2012) provided fuel use. 7% electricity use is added to account for non-process energy and machine drive.

7. Future demand for energy services

In this third step of the energy backcasting scenario, the expected future demand for energy services is analysed and expressed as a function of GDP per capita. This is done by analysing the historic or present activity levels and the corresponding GDP per capita in regions or countries. In figure 7.1, the GDP and energy consumption per capita of all countries are mapped on a logarithmic scale. A clear correlation can be seen between GDP per capita and energy use. Looking at activity levels provides even greater detail.

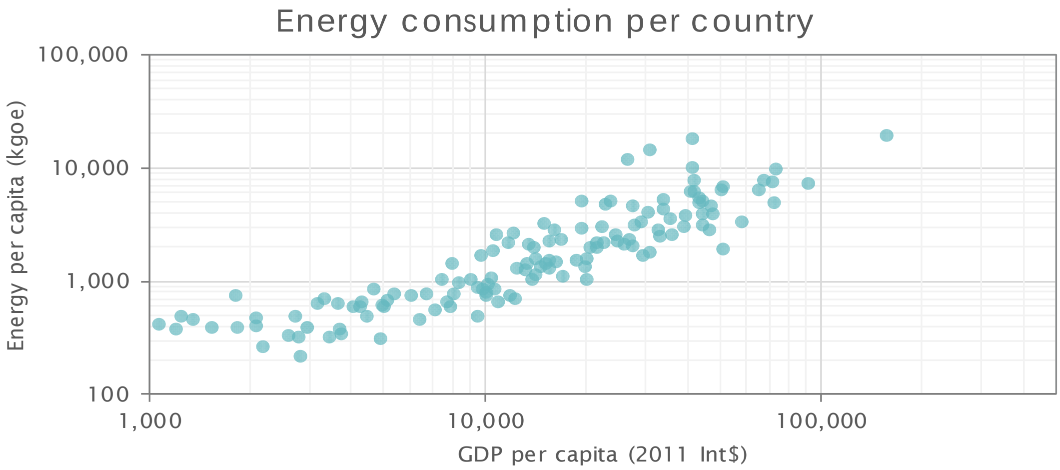


Figure 7.1 Relation between energy per capita and GDP per capita

This section consists of two parts: first, the future economy is outlined by looking at GDP and population projections. In the second part, the relations between activity and GDP are determined for each sector.

7.1 Future economy

7.1.1 Population growth

By 2050, the planet is expected to inhabit 9.16 billion people in the SSP2 scenario by (Riahi et al., 2017). An increase of 27% compared to 2014. Large differences in terms of growth projections were found across the regions. The population size is stabilized or even declines in most OECD regions, China and Eurasia. In Africa and Middle East, the population is expected to increase by 75% and 64% respectively. Asia and Africa are responsible for 85% of the total global population increase between 2014 and 2050.

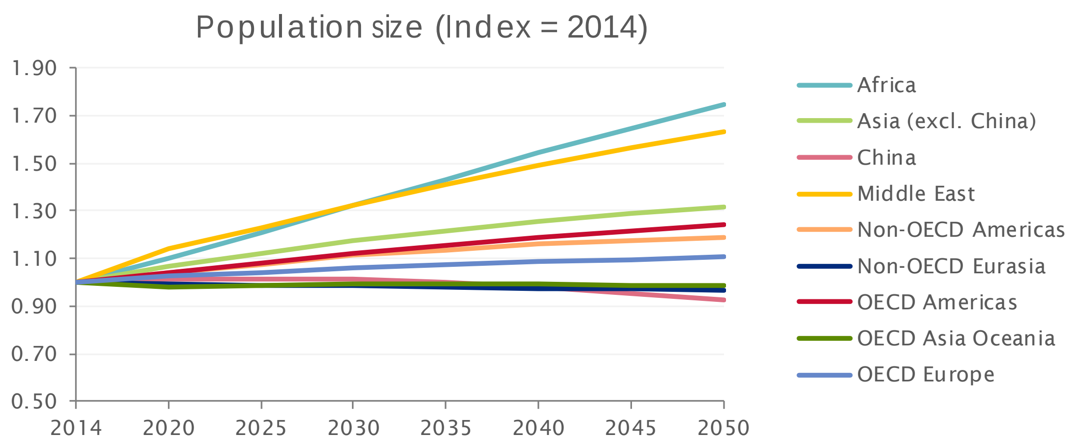


Figure 7.2 Indexed regional population size growth between 2014 and 2050

7.1.2 GDP projections

The 2014 GDP levels are derived from the World Bank (2017) and corrected for purchasing power (PPP). The future growth rates are derived from the SSP2 scenario consistent with the population growth projections. Growth projections are provided for every ten years. All growth rates are expected to slowly decrease over time (see figure 7.3), while growth rates in Africa remain relatively high by 2050.

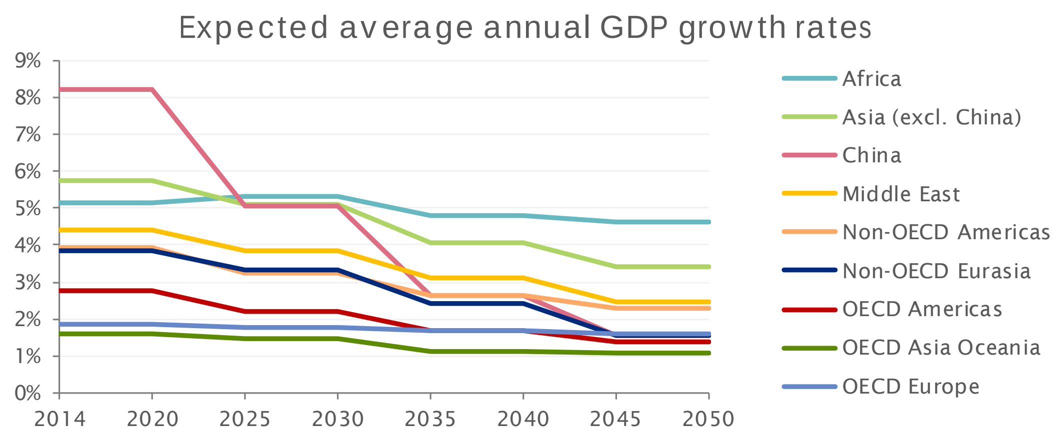


Figure 7.3 Assumed average annual GDP growth rates per region (source: Riahi et al. (2017))

The result of these economic growth rates is an increase of the global economy with 207% between 2014 and 2050. The combination of increased welfare and population size make Asia (excl. China) the largest economic region in 2050, closely followed by China. The total GDP in Africa is expected to grow with 470%, but is still relatively small role compared to other regions of equal population size.

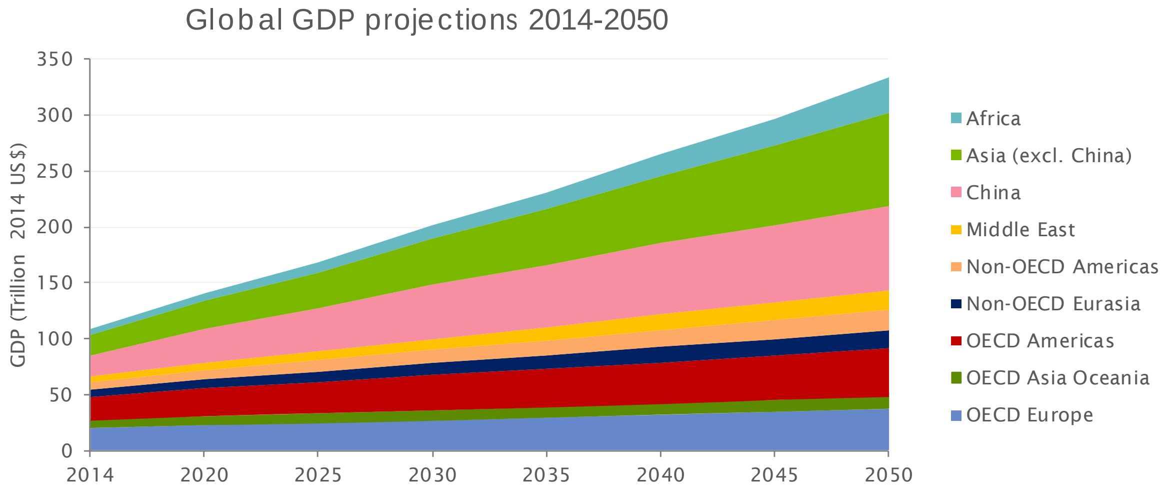


Figure 7.4 Global expected GDP projection 2014-2050

The total growth of an economy is not a measure for personal welfare. GDP per capita is derived by dividing the total GDP by population size. Between 2014 and 2050, GDP per capita increases substantially in all regions. The biggest percental increase is found in China, Asia (excl. China) and Africa. Asia (excl. China) and Africa remain nevertheless regions with the lowest average GDP per capita in 2050.

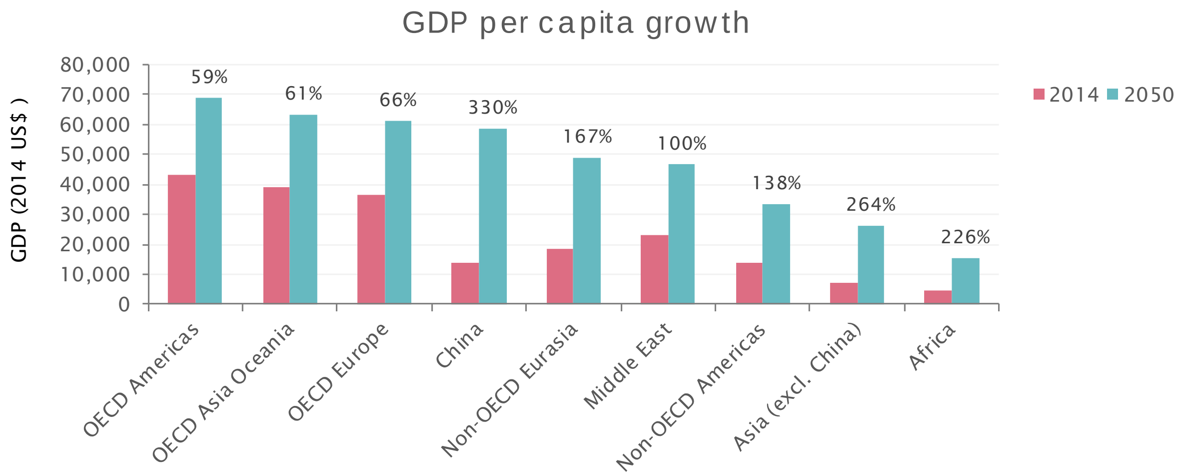


Figure 7.5 Assumed GDP per capita for different regions in 2014 and 2050. The three OECD regions remain the top in terms of highest GDP level per capita

7.2 Future activity demand

In this section, the links between GDP and economic activity in industry, buildings and transport are studied to determine a trendline which is later used to project future activity levels. Whenever available, projected activity levels are then matched with literature. Especially when there is high variance in the data (low R^2).

7.2.1 Industry

Analysis was conducted with historic data from producer associations.

Aluminium

Period: 1990-2014

Regions: United States (US), Europe, China, Rest of the world (ROW)

R^2: 0.76

Source: IAI (2017)

Consumption of aluminium per person is relatively low compared to other products studied. There is a quite strong logarithmic relation found between GDP and consumption ($R^2 = 0.76$).

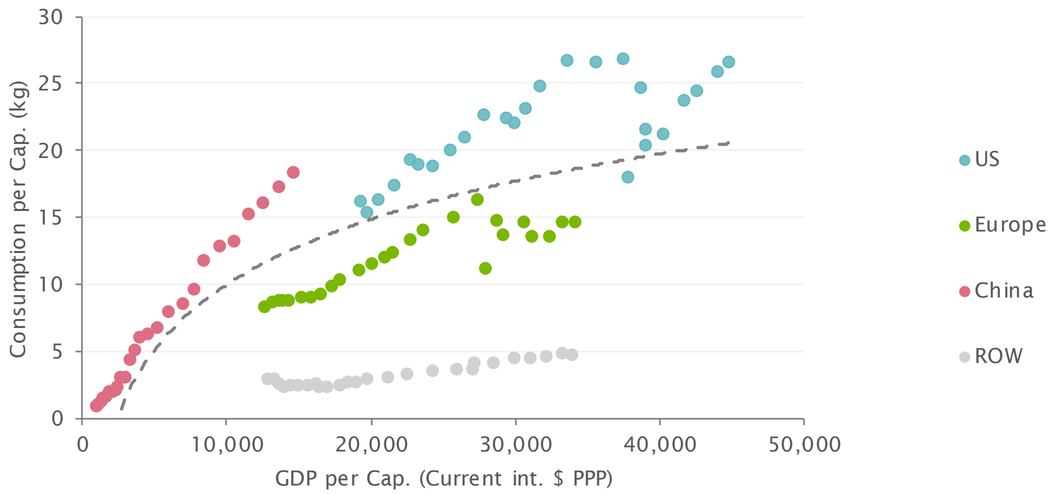


Figure 7.6 Average aluminium consumption per capita for several regions between 1990 and 2014 and trendline

Extrapolating this trend to the future results in an increase of aluminium demand up to 169 Mt per year, which is more than a doubling compared to 2014. The growth is predominantly found in non-OECD countries.

Comparing this outcome with other projections it appears that the expected demand in this study is on the lower side of other estimates. The IEA (2016) has a higher relative demand, while the estimates by Sverdrup et al. (2015) match with the estimates in this model.

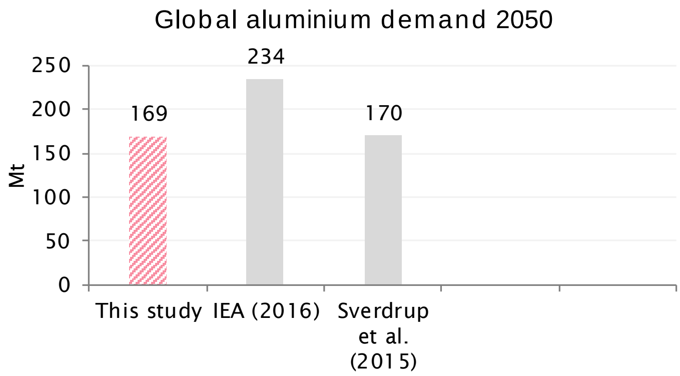


Figure 7.7 Comparison global aluminium demand 2050

Iron and steel

Period: 2014

Regions: Austria, Canada, Mexico, United States, Czech Republic, France, Germany, Italy, Netherlands, Poland, Romania, Spain, Sweden, United Kingdom, Turkey, Russian Federation, Ukraine, Argentina, Brazil, Venezuela, China, India, Japan, Korea, Rep.

R^2: 0.25

Source: World Steel Association (2016)

Looking at the steel consumption per capita and GDP in 2014 for different countries, a logarithmic relation was found. Though, the coefficient of determination is very low. The Chinese consumption can be found, in the upper left corner of figure 7.8.

This can be explained by the economic growth and associated construction activities that take place to build new infrastructure. But this growing demand for materials is coming to a halt: the Chinese steel consumption declined between 2009 and 2015 and this trend is expected to continue once the infrastructure is put in place (Yin & Chen, 2013; Zhang et al., 2016).

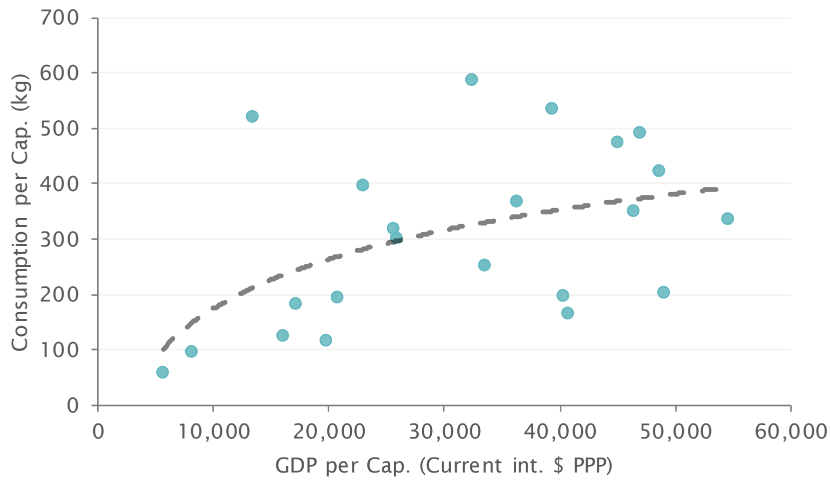


Figure 7.8 Average iron and steel consumption per capita in 2014 and trendline. Each dot represents one country

Following the growth path, the total demand increases from 1600 Mt per year up to nearly 2900 Mt per year in 2050.

The future iron and steel demand has been the subject of many studies since it is such a key material in society. A study from 1999 modelled a demand between 3,000 and 4,500 mega tonnes of steel in 2050 (Van Vuuren et al., 1999). However, most estimates of future steel demand found in more recent literature are lower: Van Ruijven et al. (2016) predicts an annual steel production of 2,160 Mt. IEA (2016b) assumes 2,234 Mt of steel up to 2050. Oda et al. (2013) estimates 2050 world steel demand between 2,194 and 3,191 Mt per year. Analysis by Morfeldt et al. (2015) found an average steel demand of 300 kg per capita per year in 2050 which corresponds to around 2,910 Mt per year.

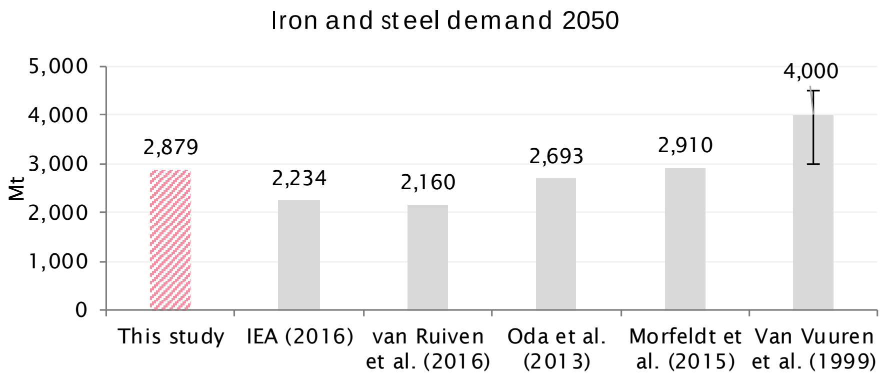


Figure 7.9 Comparison of global iron and steel demand scenarios in 2050

Cement

Period: 2000-2014

Regions:	Brazil, China, Egypt, Arab Rep., France, Germany, India, Indonesia, Iran, Islamic Rep., Italy, Japan, Mexico, Pakistan, Russian federation, Spain, Thailand, Turkey, United States
R^2:	0.13
Source:	CSI (2017a)

Cement consumption varies significantly among countries in the world. High consumption levels per capita are found in regions which go through a period of high economic growth. At present, the Chinese consumption is responsible for almost half of the total world cement consumption.

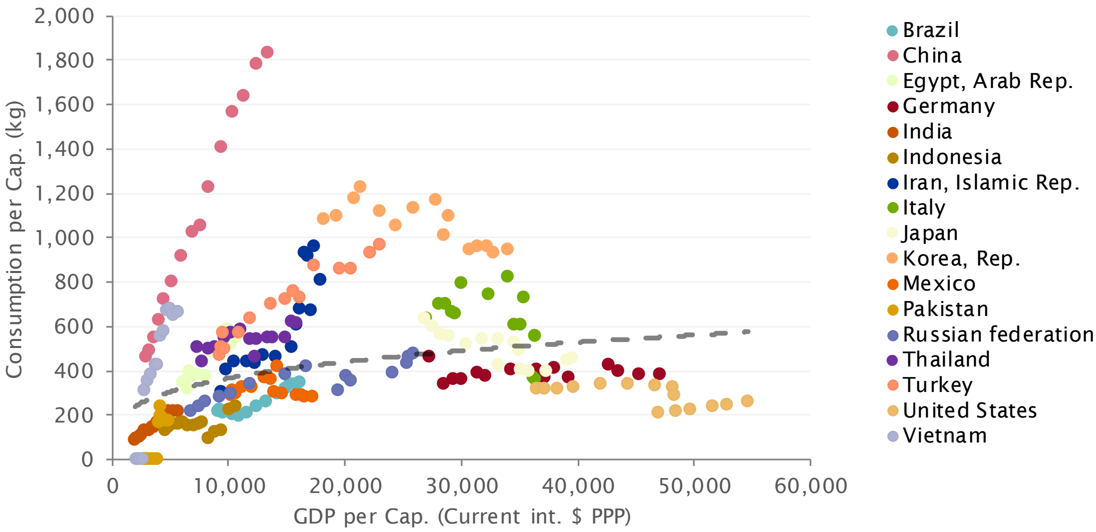


Figure 7.10 Average cement consumption per capita between 2000 and 2014 and trendline

Just as for iron and steel, it is expected that this peak of cement consumption in China will decline as was found by (van Ruijven et al., 2016).

On a global scale, cement demand is not expected to increase much in the future compared to the current production level (+7%). A shift is expected to take place from China as main consumer to other Non-OECD regionds. Comparing the results with other studies, this growth projection is 1.75% and 10% higher than respectively IEA (2016) and van Ruijven et al. (2016)

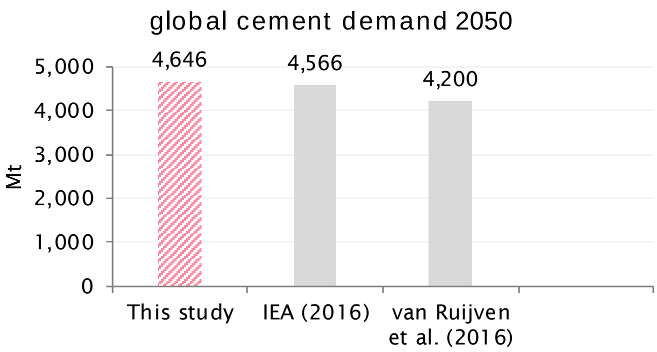


Figure 7.11 Comparison global cement demand 2050

Paper, pulp and print

Period: 2014

Regions: 110 countries

R^2: 0.42

Source: FAO (2017)

Data from the FAO was used to analyse use of paper per capita in 2014. A wide variety in consumption was found, but in general higher activity levels were found in countries with higher GDP per capita levels. Some strange outliers were found, such as Belgium (average of 337 kg per capita). Furthermore, a decrease in paper consumption was found between 2005 and 2014, which may be explained by digitalisation.

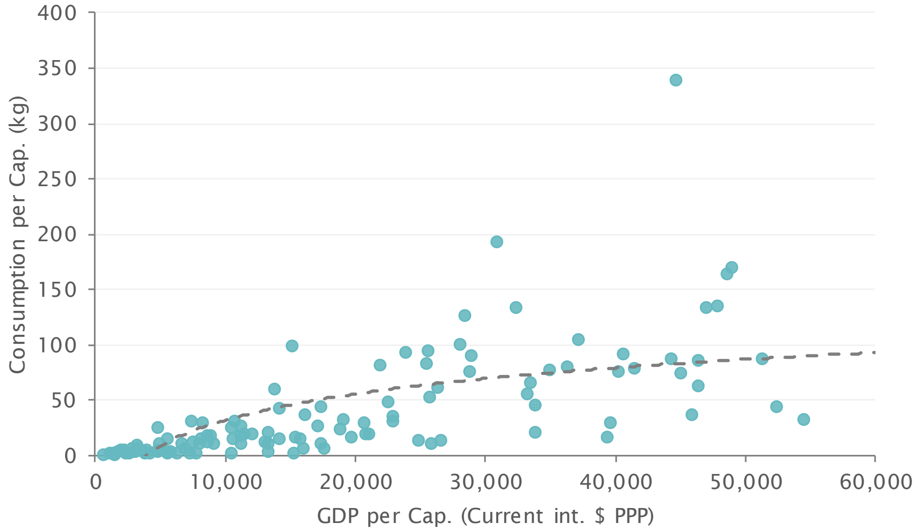


Figure 7.12 Average paper, pulp and print consumption per capita for different countries in 2014.

This recent decline in consumption strengthens the idea that demand per capita might be even further decreased than following the current trendline, but this effect is not considered in the projections. The demand for paper, pulp and print increases from 400 Mt in 2014 up to 654 Mt in 2050. This projection is in between the estimates by IEA (2016) and FAO (2017).

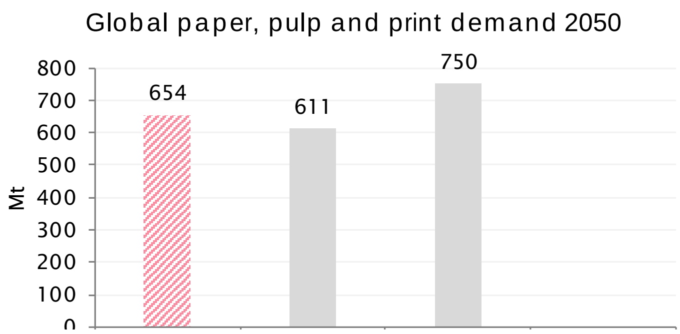


Figure 7.13 Comparison of global paper, pulp and print demand scenarios in 2050

High value chemicals, methanol and ammonia

Consumption data for chemicals is limited and no valid datasets were found. Therefore, the scenarios by the IEA (2016) are used to derive a growth factor for 2050. Furthermore, demand per capita is expected to increase between 2014 and 2050 with the following factors:

Product	Factor
High value chemicals	1
Ammonia	1.17
Methanol	2.5

Other sectors

Besides the production of these seven materials, there are thousands of other industrial processes which are not explicitly modelled. These are divided into four different categories of which the activity level is indexed.

- Other non-metallic minerals
- Other chemical and petrochemical
- Other non-ferrous metals
- Other

For the first 3 categories, indexed activity develops accordingly to the explicitly modelled material in the same category (e.g. if demand for aluminium doubles, indexed demand of other non-ferrous metals doubles as well).

Category	Corresponding production
Other non-metallic minerals	Cement
Other chemical and petrochemical	Ammonia, Methanol, HVC
Other non-ferrous metals	Aluminium

The remaining Other category is the aggregated energy use of eight categories including non-specified energy use. This category covers a 47 EJ, which is one third of the total energy use in industry. 50% of the energy use in this category is non-specified.

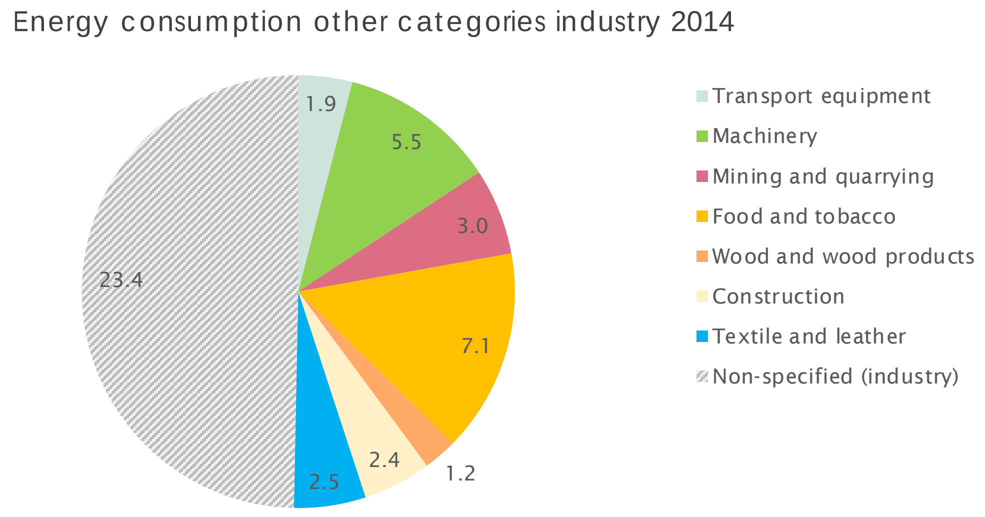


Figure 7.14 Final energy consumption of other industrial categories 2014 in EJ

Looking at the relation between energy use per capita of the aggregated other industries and GDP, a logarithmic relation was found with a high determination coefficient (R^2 = 0.82). The energy consumption in OECD Europe (bottom right) is the only important outlier. This trendline is used to project future energy demand of the other industries.

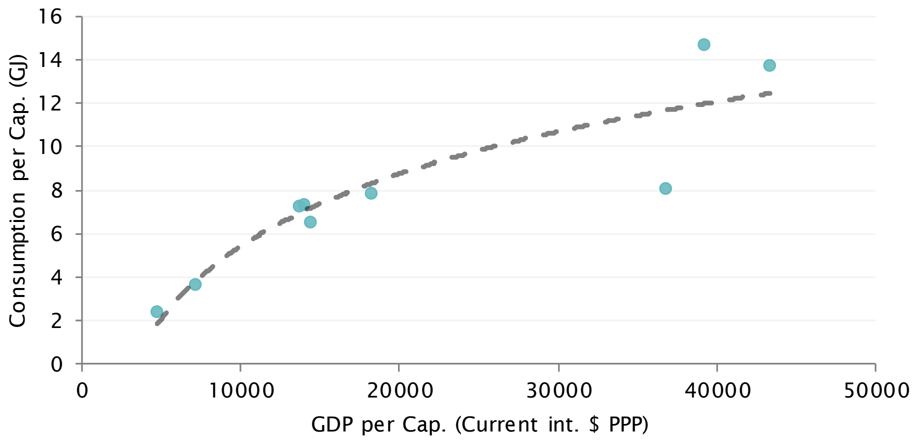


Figure 7.15 Energy consumption other industries and GDP per capita 2014

Conclusion

Activity correlations have been found for all industries. R^2 values of the trendlines were sometimes rather low which indicate that the trendline might not be useful. However, a validation check demonstrated that all growth projections are within or very close to other studies. Finally, the following formulas are used.

Table 7.1 Equations used to model relation between GDP per capita, time (t) and activity in industry

Category	Equation	Type of correlation
Cement	$3.2 \times GDP^{0.26}$	power
Iron and steel	115.97 x ln(GDP) -893.59	logarithmic
Paper, pulp and print	32.55 x ln(GDP) -267.65	logarithmic
Aluminium	7.04 x ln(GDP) -54.82	logarithmic
Other	4.8 x ln(GDP) -38.76	logarithmic
High value chemicals	1.49 x t	factor
Ammonia	1.17 x t	factor
Methanol	2.50 x t	factor

7.2.2 Buildings

As mentioned before, there is limited data regarding historic activity levels of the energy use in buildings. Therefore, the 2014 activity levels of all nine regions are used which were calculated based on the total energy consumption and assumed technologies. Due to the lack of reference literature, validation with other scenarios is not possible.

Surface areas

For both, the residential and the commercial floor area, a logarithmic relation was found with GDP at relatively high R^2 values (0.69 and 0.68 respectively).

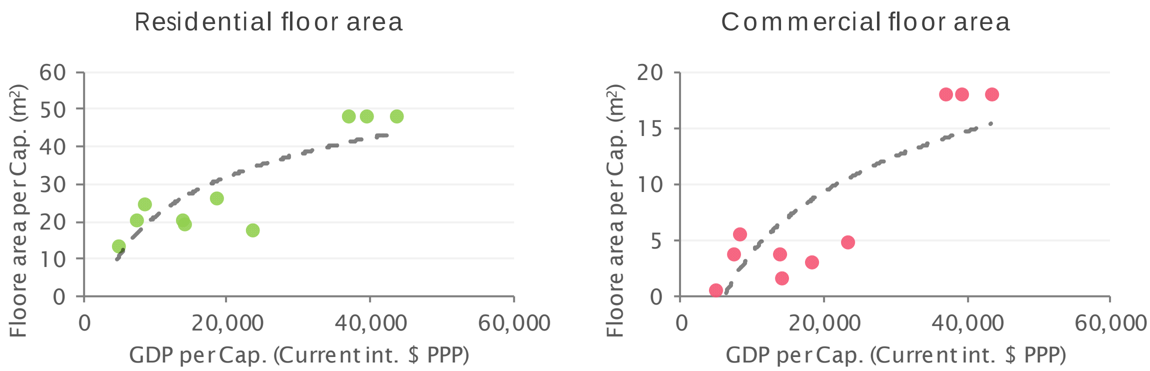


Figure 7.16 Residential and commercial floor areas and GDP per capita of different regions and a trendline

Residential surface area increases in the different regions from between 13 and 48 m^2 per capita to 22-59 m^2 per capita. The commercial floor area increases as well up to between 5 and 23 m^2 per capita in 2050.

Space heating and cooling

To determine the future activity level of heating and cooling demand, local climate plays an important role. Heating degree days (HDD) and cooling degree days (CDD) are used as indication of the demand for heat and cooling respectively. Country specific HDD and CDD were derived from CAIT (2011) and aggregated into the 9 different regions weighted by population size.

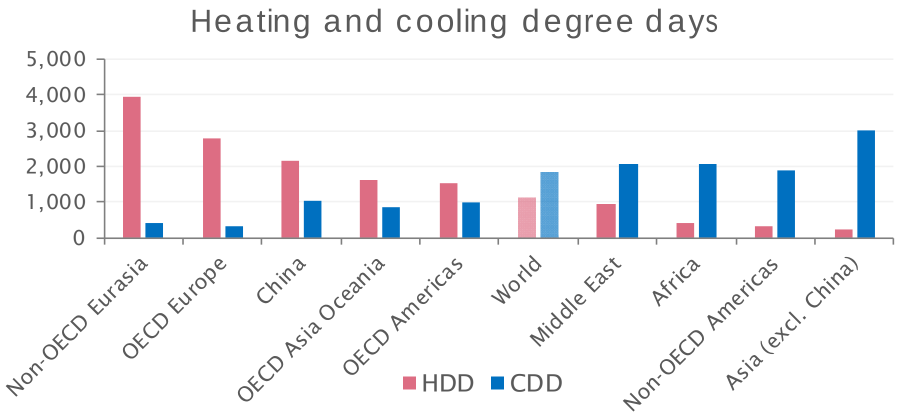


Figure 7.17 Annual heating and cooling degree days per region in 2011

While analysing demand and relation with GDP and degree days, it was found that space heating demand and GDP were not correlated, while a strong relation was visible between HDD and heating demand in commercial and residential space heating (R^2 = 0.71 & 0.83) as can be seen in figure 7.17. Indoor heating is a basic need and does not require capital intensive technology, which explains the lack of difference between high and low income regions.

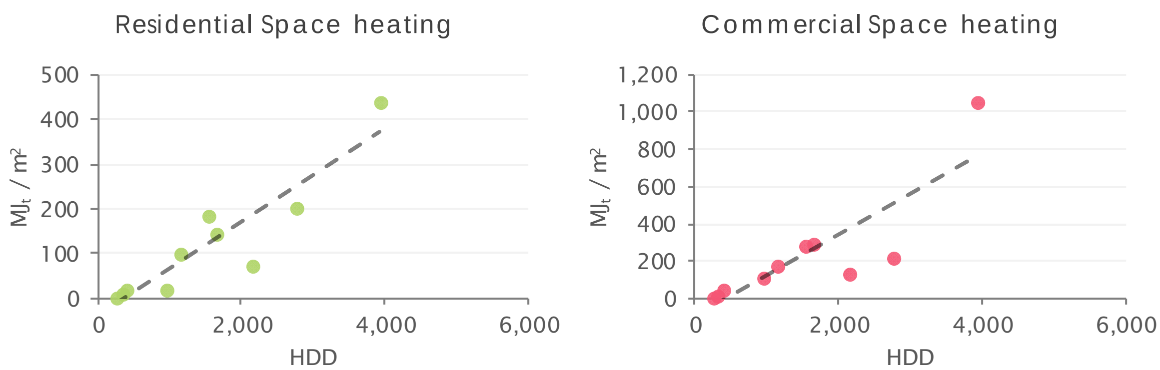


Figure 7.18 Residential and commercial space heating activity and GDP per capita of different regions and a trendline

Therefore, HDD was assumed as a more accurate predictor of the heating demand than GDP or GDP in combination with HDD. Since there is no change in HDD assumed in this model, heating demand (MJ_t per m^2) remains constant until 2050

For space cooling, more advanced (and expensive) technology is required such as air conditioning. Therefore, the cooling demand is dependent on both CDD as well as GDP (Isaac and van

Vuuren, 2009). The best fit was found by multiplying CDD with GDP. Outlier in commercial space cooling is OECD Americas with more than 1,100 MJ_t per m^2.

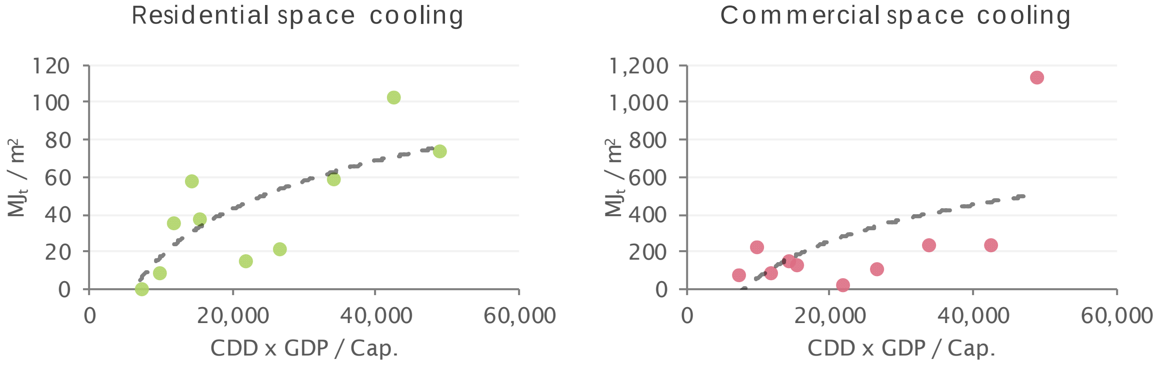


Figure 7.19 Residential and commercial space cooling activity and GDP per capita of different regions and a trendline

Following this trendline, average cooling demand in 2050 almost doubles compared to 2014 for both residential and commercial buildings. An increase is found throughout all regions.

Water heating

For commercial hot water use, a low variability was found (R^2 = 0.70). The variability in residential hot water demand and GDP was rather high (R^2 = 0.28). This could be explained by local climates as well. Almost no hot water is used in Asia (excl. China), where the amount of heating degree days is very low, while hot water use in the colder regions Non-OECD Eurasia and China are above the trendline.

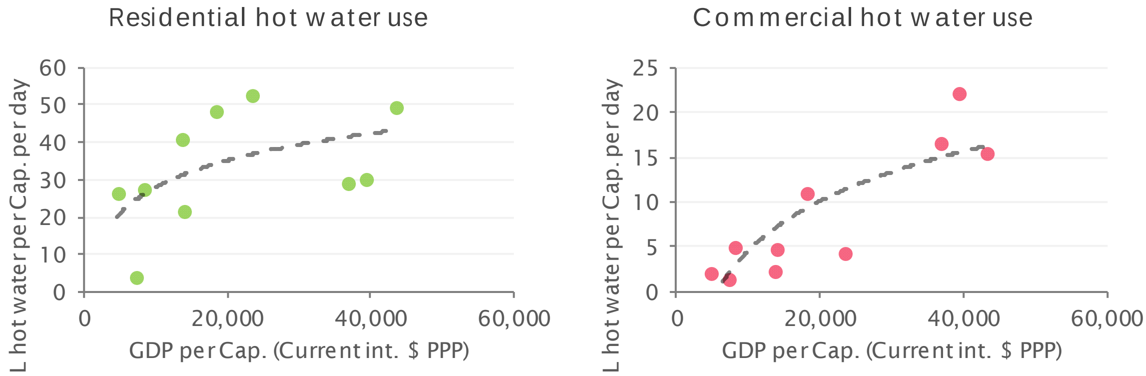


Figure 7.20 Residential and commercial water heating activity and GDP per capita of different regions and a trendline

Global demand of warm water is expected to increase by 32%. With most relative growth expected in non-OECD regions, especially Asia (excl. China) warm water demand increases significantly up to18 litres hot water per person per day in 2050 but still remains below the global average of 36 litres.

Lighting

For lighting, a weak logarithmic relation was found between GDP and indexed residential activity per square meter (R^2 = 0.24). For commercial lighting a logarithmic relation was found with an R^2 value of 0.61.

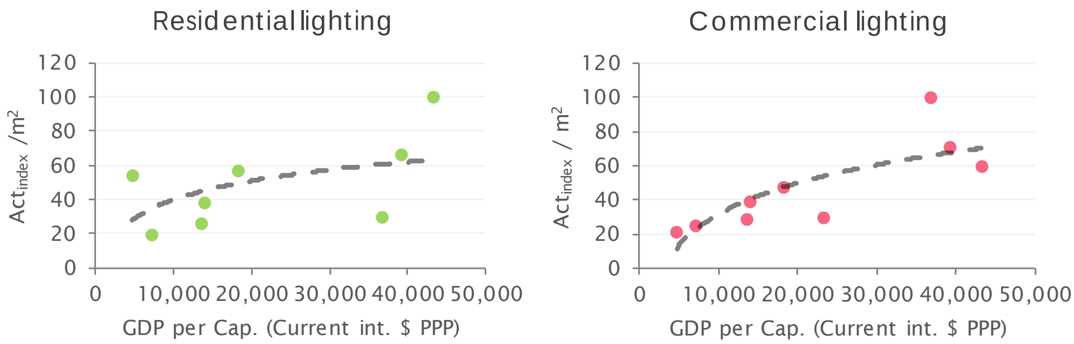


Figure 7.21 Residential and commercial lighting activity and GDP per capita of different regions and a trendline

Global average demand for residential lighting per square meter surface is expected to grow with 68% up to 2050. In the commercial and public services, 74% growth is expected based on this analysis.

Appliances

The energy use for appliances in commercial and residential buildings follows a power trendline with high R^2 values of 0.79 and 0.83 respectively. Appliances includes all kinds of electronics, kitchen appliances and household equipment which are generally rather capital intensive. This explains the steep curve.

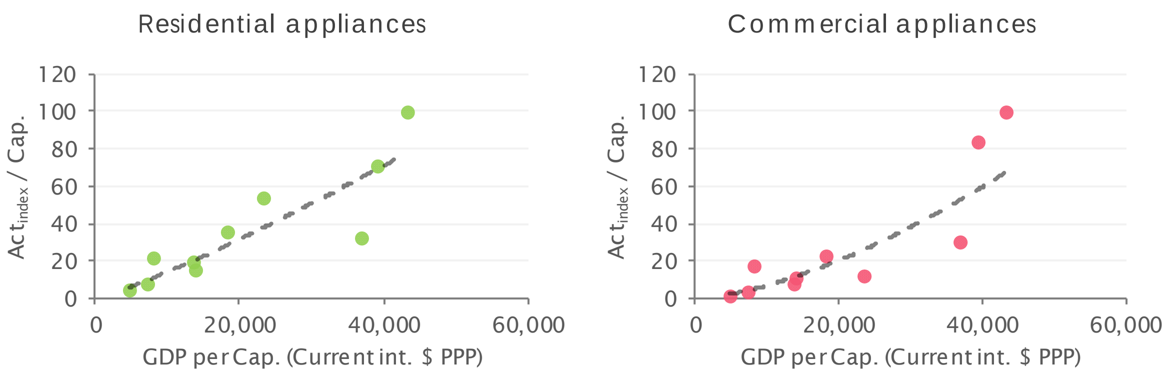


Figure 7.22 Residential and commercial appliances activity and GDP per capita of different regions and a trendline

This steep trendline results in a significant growth in activity demand of appliances in buildings. Demand in appliances is expected to become the fastest growing function in the building sector.

Cooking

Cooking demand, which is only provided for the residential sector, does not seem to be affected by growth in GDP. A slight decrease appears to be visible, but with a very low determination coefficient ($R^2 < 0.1$). Therefore, residential cooking is assumed to be unaffected by growth in GDP per capita. The Middle East is an outlier with the highest activity of cooking of all regions. This might be explained by lack of reliable data sources.

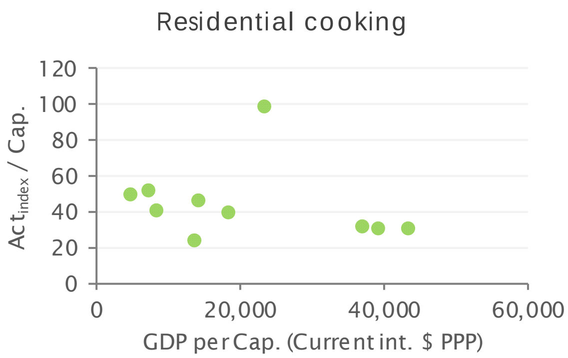


Figure 7.23 Residential cooking heating activity and GDP per capita of different regions.

Conclusion

The analysis of the activity levels in the buildings sector showed for most categories that a saturation occurs when a certain GDP level is reached. Saturation for demand of appliances was not found yet at the current GDP levels. Furthermore cooking and space heating were found to be life necessities and appeared unaffected by GDP levels.

Table 7.2 Equations used to model relation GDP and activity in buildings

Category	Commercial and public services	Residential	Type of relation
Surface	7.8 x ln(GDP) -67.91	15.2 x ln(GDP) -118.15	Logarithmic
Space heating	-	-	-
Water heating	7.98 x ln(GDP) -68.93	10.4 x ln(GDP) -67.86	Logarithmic
Space cooling	280.5 x ln(GDP x CDD) - 4459.21	37.1 x ln(GDP x CDD) - 581.03	Logarithmic
Appliances	$4.0 \times 10^{-6} \times GDP^{1.56}$	$3.0 \times 10^{-4} \times GDP^{1.17}$	Power
Lighting	26.46 x ln(GDP) -212.26	16.02 x ln(GDP) -107.63	Logarithmic
Cooking	-	-	

R^2 values of the correlations were in some cases (e.g. demand for lighting) rather low, but unfortunately there were no other sources available to validate the results with.

7.2.3 Transport

The activity in transport is expressed in passenger kilometres (pkm) for passenger transport and freight kilometres (tkm) for freight transport. The activity correlations were determined by analysing the activity levels and GDP per capita in 2014. For world marine bunkers and world aviation bunkers, additional data points were used, since these are not divided over different regions.

Road

Road transport is the largest energy consumer in the transport sector of which LDV and freight road are the largest categories within road transport. For LDV and freight a logarithmic relation was found between activity and GDP (R^2 = 0.7 & 0.8). The outlier in LDV is Non-OECD Americas where activity per capita is double as high as in regions with similar GDP levels (OECD-Europe).

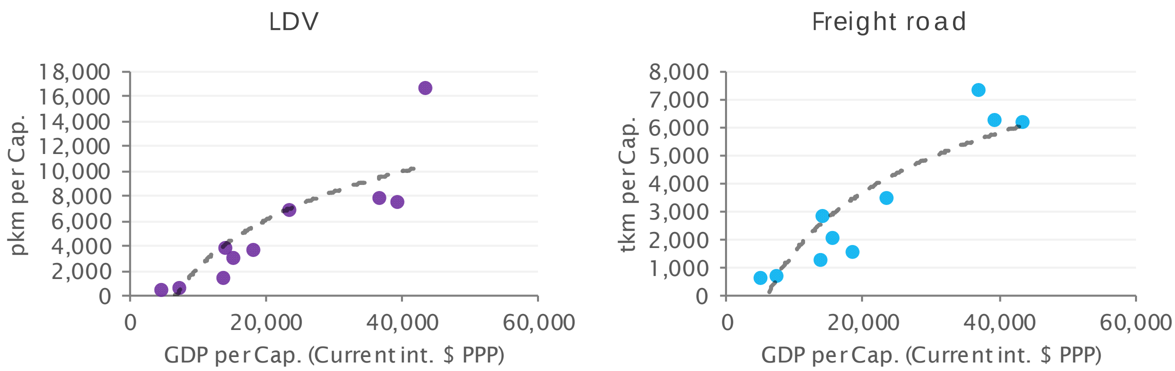


Figure 7.24 LDV and freight road activity and GDP per capita of different regions and a trendline

Looking at 2050, global activity of Freight road and LDV per capita will triple. The main increase in activity per capita is found in Africa and Asia, where activity is currently limited.

Light road and bus transport, is currently responsible for about 10% of the total energy consumption in road transport. When activity for these two categories is plotted against GDP, no correlation was found with a R^2 value > 0.1. For light road, the region with the highest activity per capita in 2014 was Asia (excl. China).

These transport modes appear to be culturally determined, rather than affected by income. Since no correlation was found (negative nor positive), the activity per capita was set constant between 2014 and 2050.

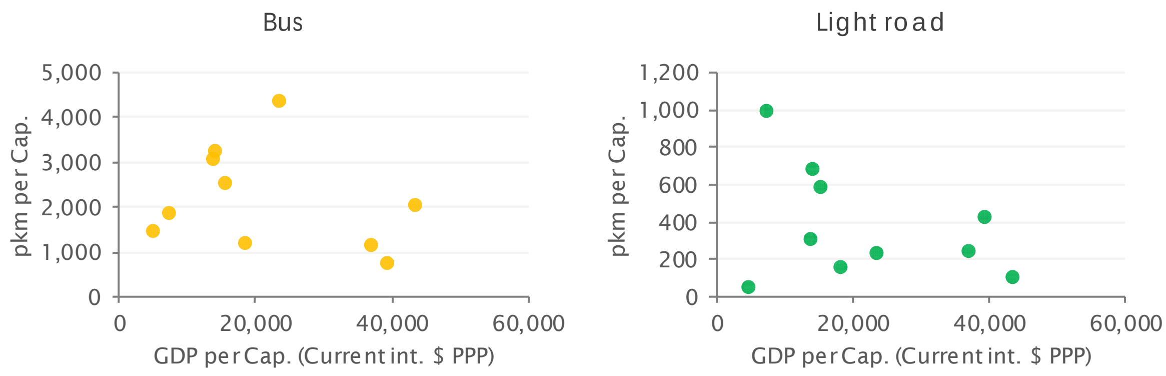


Figure 7.25 Bus and light road activity and GDP per capita of different regions and a trendline

Rail

Just as for light road and bus, significant variations are found in rail transport (2% of total transport energy demand) across the regions regardless of GDP levels. Nevertheless, a logarithmic trendline was assumed.

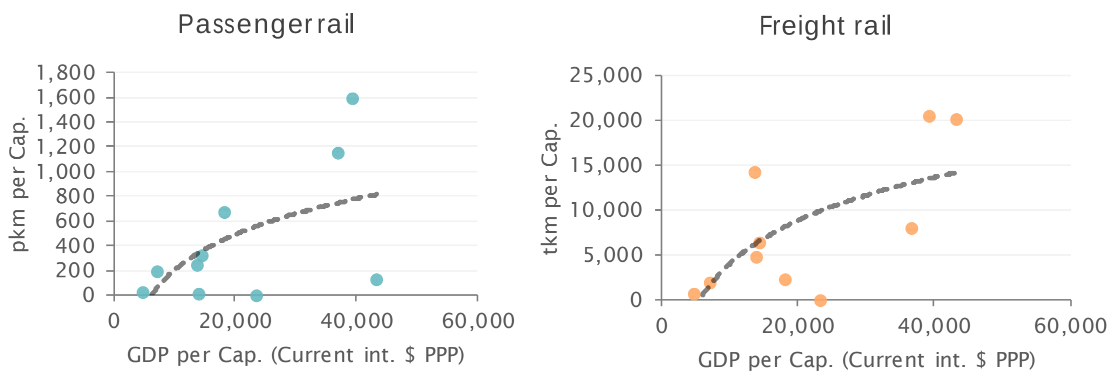


Figure 7.26 Passenger rail and freight rail activity and GDP per capita of different regions and a trendline

As a result, passenger rail and freight rail increase with 235% and 191% respectively relative to 2014.

Aviation

In figure 7.26, the annual air passengers per inhabitant are plotted against GDP over a period between 1990 and 2014, in which the total amount of passenger carried increased by 215% (Worldbank, 2017). Air transport seems to accelerate as GDP increases and a power trendline shows a very strong correlation with a high determination coefficient (R^2= 0.95).

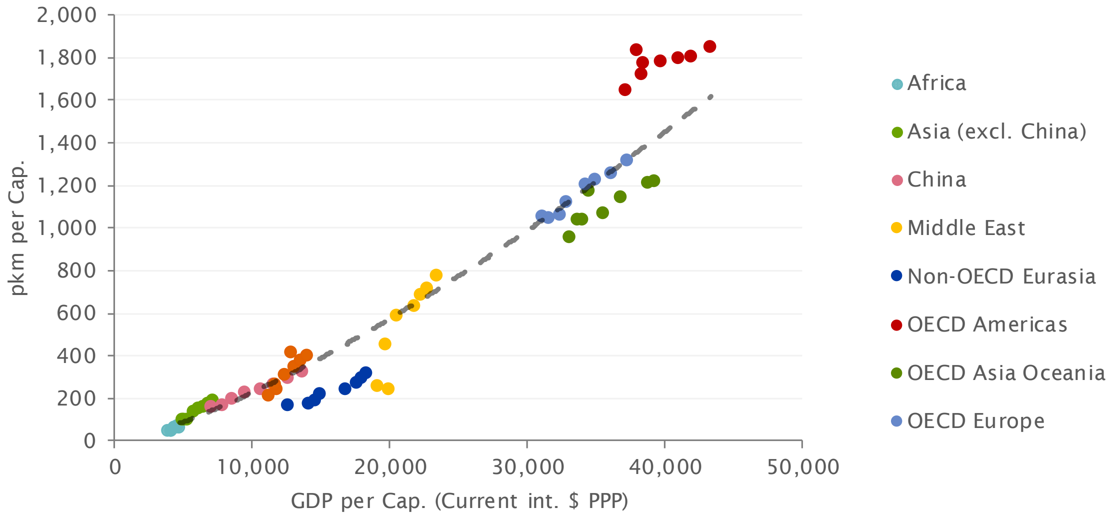


Figure 7.27 International and domestic air transport activity and GDP per capita of different regions and a trendline

The same growth trend is found in domestic navigation with United States as an important outlier, with almost 2,500 passenger kilometres per capita travelled in 2014.

As a result, activity in air transport increases significantly between 2014 and 2050.

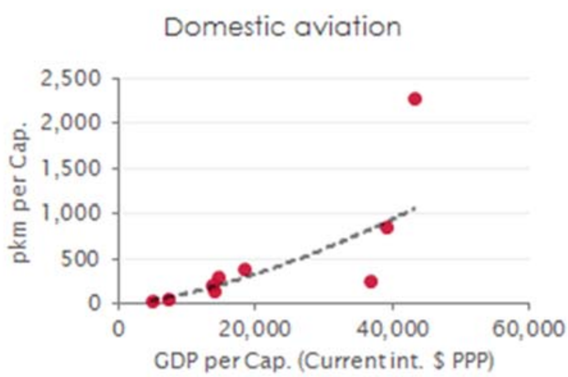


Figure 7.28 Domestic air transport activity and GDP per capita of different regions and a trendline

Shipping

For World marine bunkers and domestic navigation, a logarithmic relation was found between freight carried and GDP. World marine bunkers data was analysed between 2000 and 2015 and derived from UNCTAD (2015). The data showed a close fit to the logarithmic trendline. Domestic navigation was analysed on a regional level in 2014 and a logarithmic trendline was drawn with a R^2 of 0.57.

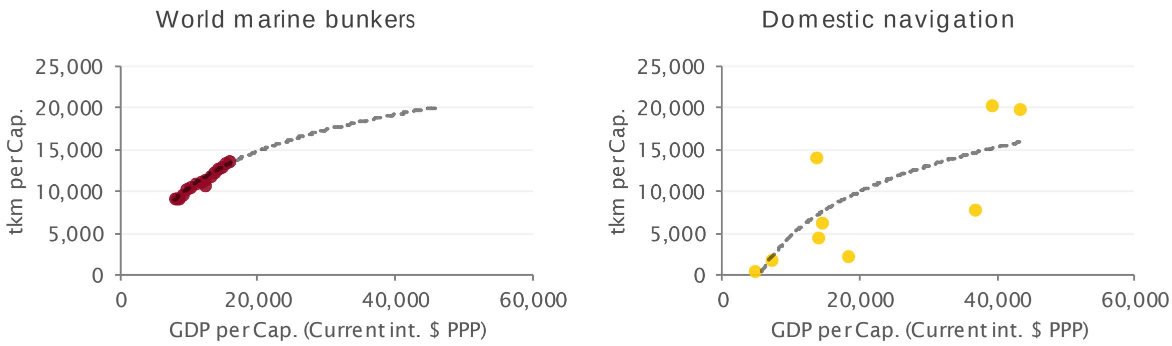


Figure 7.29 International and domestic shipping activity and GDP per capita of different regions and a trendline

Conclusion

Just as in the buildings sector, most activity levels saturate as a certain welfare is reached. Exception is aviation transport of which the activity is expected to accelerate and a limit is not yet in sight.

Table 7.3 Equations used to model relation GDP and activity in transport

Category	Equation	Type of equation
LDV	5619.16 x ln(GDP) - 49582.94	Logarithmic
Light road	-	-
Bus	-	-
Freight road	2701.2 x ln(GDP) -23334	Logarithmic
Passenger rail	457.74 x ln(GDP)-3975.9	Logarithmic
Freight rail	1192.6 x ln(GDP)-9613.9	Logarithmic
World aviation bunkers	$9.0 \times 10^{-4} \times GDP^{1.34}$	Power
Domestic aviation	$9.0 \times 10^{-5} \times GDP^{1.52}$	Power
World marine bunkers	6310.4 x ln(GDP) -47663	Logarithmic
Domestic navigation	7625.7 x ln(GDP) -65548	Logarithmic

Finally, the growth projections up to 2050 in this model are compared with global growth rates from the ICCT transport model. The growth rates are derived from business as usual scenario between 2015 and 2050. The comparison indicates that growth rates assumed in this model are generally higher than the ICCT business as usual scenario. An exception is the expected growth in air transport. The ICCT expects an increase of 368% between 2015 and 2050, whereas in this model a growth of 256% is assumed.

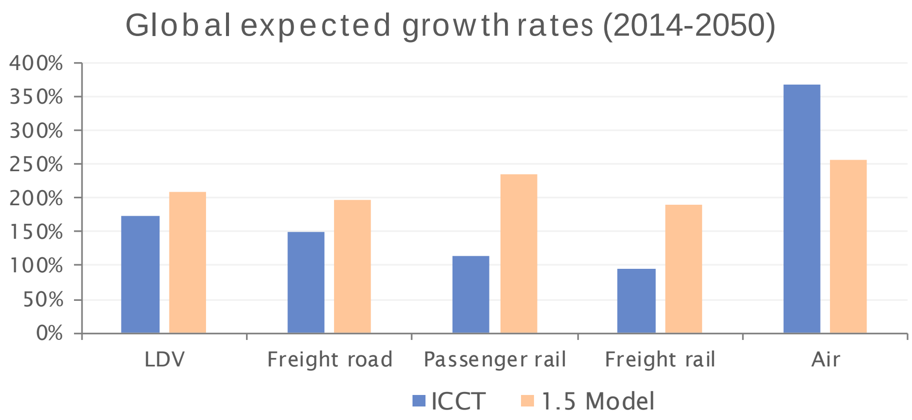


Figure 7.30 Comparison growth rates 2014-2050 1.5 model and ICCT BAU scenario

7.2.4 Other

The other sector contains three categories: *Agriculture/forestry*, *Fishing* and *Non-specified (other).* No useful units were identified to express activity. Therefore, energy per capita was used as a proxy.

Agriculture/forestry

A logarithmic correlation was found for energy use in agriculture and forestry and GDP (R^2 = 0.67).

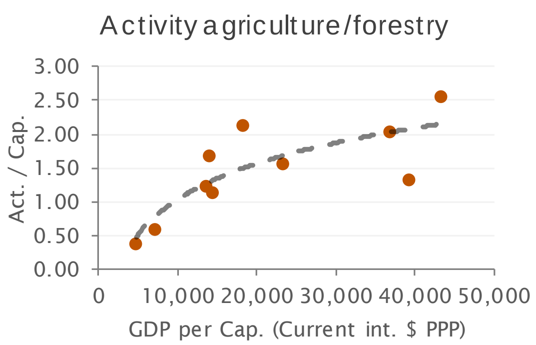


Figure 7.31 Agriculture/forestry activity and GDP per capita of different regions and a trendline

Fishing & Non-specified (other)

For fishing and non-specified activity in terms of energy use appears really dispersed. Therefore the energy demand per capita in this sectors was assumed to be constant.

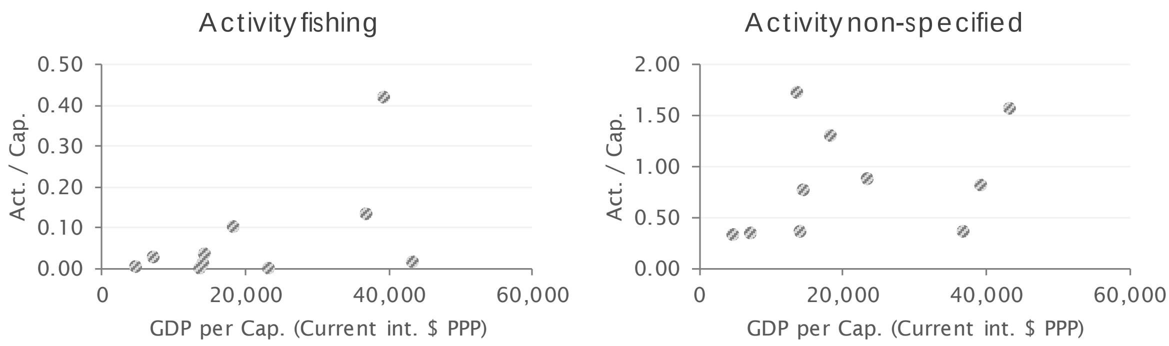


Figure 7.32 Fishing and non-specified activity and GDP per capita of different regions. No clear correlation was found between GDP and activity per capita.

Conclusion

From the three categories in this sector, only agriculture/forestry is specified. For the two other categories, no increase is expected.

Table 7.4 Equations used to model relation GDP and activity in Other

Category	Equation	Type of equation
Agriculture/forestry	0.76 x ln(GDP) - 5.97	Logarithmic
Fishing	-	-
Non-specified (other)	-	-

8. Final energy demand

Now the future activity levels have been determined, an energy demand analysis is conducted on a sector level. For each sector the expected efficiency improvements are described first. Subsequently, the technology switches are discussed and finally an overview is provided of the final energy consumption in the sector. At the end of this chapter, the total final consumption is described.

8.1 Industry

8.1.1 Efficiency improvements

The potential for improving the energy performance in industry is significant (IEA, 2016c; Saygin, 2012; Worrell and Carreon, 2017). By switching to the best practice technologies alone, a total efficiency improvement between 20% and 35% can be achieved (Worrell and Carreon, 2017). Several strategies are available to reduce energy demand further such as improving the performance of electric motors (IEA, 2016), optimizing the use of waste streams in industrial symbioses (Chertow, 2008), or by reducing the pressure in production processes (Abdelaziz et al., 2011).

Iron and steel

According to Worrell and Carreon (2017), efficiency of iron and steel production can be improved in EU and North America with 20% and 26% respectively and by 30% in China. Similar efficiency improvement potential for the EU was found by Moya and Pardo (2013). In Non-OECD regions, the expected intensity reductions potential is expected to be between 35% and 55% according to Worrell and Carreon (2017). This is also in line with the more conservative estimates of the efficiency improvement potential for India (Pal et al., 2016). Based on these findings, efficiency improvements by 2050 are expected to be 23% in OECD, 30% in China and 40% in Non-OECD (excl. China).

Aluminium

The aluminium production process consists of the refining of bauxite into alumina and subsequently the smelting of alumina into aluminium. Aluminium is one of the most energy intensive products in terms of energy per tonnes. The alumina smelting process is responsible for 86% of the aluminium energy demand (IAI, 2017). Due to the high energy intensity, a lot of efforts already have been made to improve the energy performance in the past. The remaining improvement potential is therefore limited. Most efficient production of aluminium currently takes place in Non-OECD regions due to newly installed plants. The remaining energy improvement potential for the smelting process is 13% in industrialized countries (OECD) (UNIDO, 2010) According to Worrell and Carreon (2017), an efficiency improvement of 4% is possible in the non-industrialized countries (China and non-OECD).

Other non-ferrous metals

Energy use in the other non-ferrous metals category can be attributed for the larger part to the production of zinc and copper. For copper, a total efficiency improvement potential of 46% was found (UNIDO, 2010). In zinc production, significant differences are found in the specific energy intensity across the world: whereas in Western Europe zinc is produced at 15.2 GJ per tonne, Chinese zinc production demands 37 GJ per tonne produced. Global improvement potential for zinc is assessed at 36% (UNIDO, 2010). Total energy demand of zinc and copper is about equal in size. The total efficiency potential has been distributed among the regions with reduction potential of China at 50%, whereas OECD reduction potential is set at 15% and non-OECD 35%.

Cement

Several energy efficiency measures are available for cement production of which clinker substitution with minerals appears to be very effective (Kajaste and Hurme, 2016) as well as using a dry rather than wet calcination process (Benhelal et al., 2012). In China, where half of the global cement production takes place, cost-effective efficiency measures could cumulatively save 5 EJ between 2010 and 2030 (Hasanbeigi et al., 2013). No distinctions were found in efficiency improvements across the regions. The global average efficiency potential is 25% according to Worrell and Carreon (2017).

Other non-metallic minerals

For other non-metallic minerals (glass, lime and ceramics), there is still a high efficiency improvement potential, due to the relatively small scale (China has 90,000 kilns for brick production) and outdated production plants, significant proportion of energy is currently lost. According to (UNIDO, 2010), intensity reductions for all materials can be around 50%, regardless of the region.

Paper, pulp and print

For paper, pulp and print it is difficult to get a grip on energy intensity due to the integration production process of feedstock and energy. The cost-effective energy savings potential for the paper production in China is estimated to be 22% (Kong et al., 2015) which congregates with the global efficiency potential (Kong et al., 2016).

Chemical and Petrochemical

In the chemical and petrochemical sector, efficiency can be improved by optimizing utilities, heat exchangers and heat transmissions (Worrell and Carreon, 2017).

For ammonia production, an annual efficiency improvement of 0.5% was found over the last years (UNIDO, 2010). Extrapolating this trend results in a reduction of 20% between 2014 and 2050. For the production of high value chemicals (crackers), a global efficiency potential of 25% seems feasible (UNIDO, 2010). This efficiency potential is more or less the same across the different regions. Production of methanol is a relatively small energy consumer compared to ammonia and steam crackers and there are important data gaps concerning energy intensity. Nevertheless, UNIDO estimates that intensity can be reduced with 25% in upcoming economies and 10% in Europe (OECD). For the other chemical and petrochemical production processes, an average reduction potential of the other chemical sectors is assumed of 20% in OECD and 22% in China and other Non-OECD regions.

Other

The category *Other* comprises for a significant part of *non-specified* processes and several other industries such as food, drinks and tobacco, machinery and textile, leather and clothing. These industrial processes require mainly low or medium temperature heat (see figure 8.1) and energy costs are relatively low compared to operation costs (Blok and Nieuwlaar, 2017). Therefore, energy efficiency improvements might not have been a priority in the past which could mean there is sufficient potential left. According to (ICF, 2015), 45% of energy savings are technically possible in both the food and machinery industries in the EU by 2050, which are the largest specified categories. This number was assumed for all other industrial energy services.

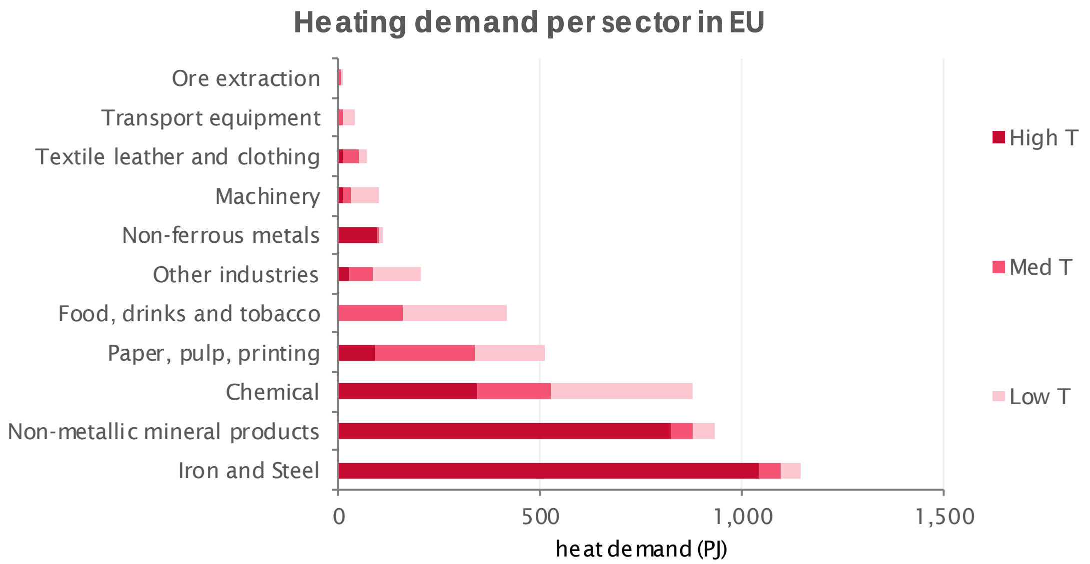


Figure 8.1 Heating demand in EU industry per sector. The industrial sectors that are shared under the Other category generally only require medium and low temperature heat

In table 8.1, all the efficiency improvements (energy / output) are listed for each industry. These improvements only concern the currently available technologies. No efficiency improvements were found for new technologies such as hydrogen direct reduction.

Table 8.1 Assumed efficiency improvements realized by 2050 in industry compared to 2014

Industry	OECD	China	Non-OECD (excl. China)
Iron and steel	23%	30%	40%
Aluminium	13%	4%	4%
Other non-ferrous metals	15%	50%	35%
Cement	25%	25%	25%
Other non-metallic minerals	50%	50%	50%
High Value chemicals	25%	25%	25%
Ammonia	20%	20%	20%
Methanol	15%	25%	25%
Other chemical and petrochemical	20%	22%	22%
Paper, pulp and print	22%	22%	22%
Other	45%	45%	45%

8.1.2 Technology switches

Iron and steel

Iron and steel production is one of the largest energy consumers in industry and almost completely coal based. The main production method for iron and steel production is currently via blast furnaces (BF) wherein coal products are used to reduce iron and to generate high temperature heat. Production of steel from scrap is done in electric arc furnaces (EAF), where electricity is the most important energy source. Secondary steel can also be used in BF, however for simplicity it is assumed this only occurs in EAF.

Looking at the availability of steel scrap for 2050, most of the produced steel remains in the society as stock in the form of construction beams, cars etc. Taking this into account, studies found a maximum recycling percentage of 50% possible in the future (Oda et al., 2013; Pauliuk et al., 2013). By 2050, recycling efforts are maximized and 50% of the total iron and steel production is assumed to come from secondary steel since it saves both materials and energy.

For the remaining 50%, there are three low-carbon alternatives found in literature:

- Blast furnace route with CCS (BF + CCS)
- Direct reduction with hydrogen (Hydrogen-DR)
- Electrowinning (EW)

Hydrogen direct reduction and electrowinning are preferred over CCS due to social acceptance, economic and environmental performance (Weigel et al., 2016). However, both EW and Hydrogen-DR are still in a premature phase and require significant further development. A techno-economic study of these three innovative steel making processes expects that BF with CCS will enter the commercial market first from 2020 and from 2030 Hydrogen-DR will become the most attractive route (Fischedick et al., 2014). In the below 2 degrees model by (IEA, 2017c), steel and iron with CCS is implemented from 2020 and reaches a market share of 55% in 2060.

The socio-economic and environmental benefits of Hydrogen-DR one side, and the more proven technology of BF-CCS on the other side make that a 50/50 share of these technologies is assumed for primary iron and steel production in 2050, with BF-CCS coming up in 2020 and Hydrogen-DR in 2030. Electrowinning is not included in this scenario due to its current premature status and is expected to become economically attractive after 2050 (Fischedick et al., 2014).

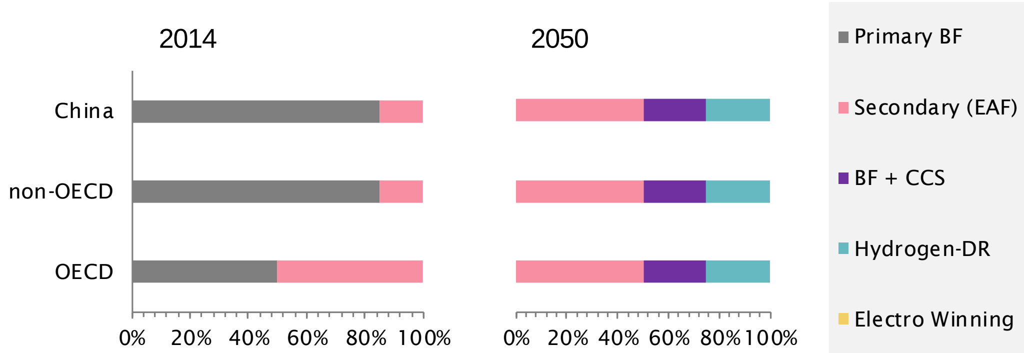


Figure 8.2 Technology shares iron and steel production 2014 (l) and 2050 (r)

Aluminium

Production of aluminium is highly energy intensive in terms of production per ton. The smelting process is completely powered with electricity, but fossil fuels are used in the bauxite refining process. For secondary aluminium production, the refining step can be avoided and the smelting process requires substantially less energy of only 5-10% of the energy of primary aluminium production (Liu et al., 2011; Van Der Voet et al., 2014).

In order to reduce energy demand, it is important to increase collection and utilization of secondary aluminium as much as possible. However, the availability is limited due to the sink in society and increasing demand. Therefore, a maximum recycling rate of 50% is assumed by 2050.

CCS and solar thermal are mentioned in literature as solutions to decarbonize the refining of bauxite. Several experiments are executed with high temperature solar thermal (IEA, 2011; Murray, 2001; Padilla et al., 2014). Experiments with solar thermal are promising but are still in a preliminary phase and therefore are expected to only play a small role in 2050 of 10% of the production. For the remaining production, CCS is applied as has been studied in literature (Jilvero et al., 2014; Mathisen et al., 2014).

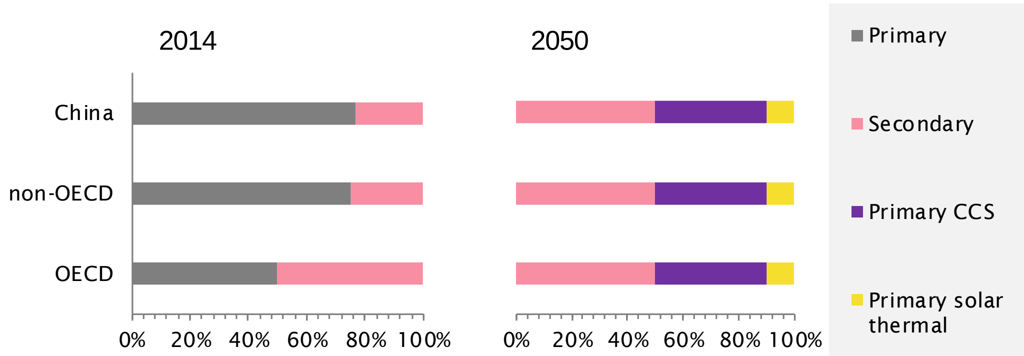


Figure 8.3 Technology shares aluminium production 2014 (l) and 2050 (r)

Cement

The CO_2 emissions related to cement production come from the combustion of fossil fuels and a significant part of the emissions comes from the calcination process. Switching towards renewable energy sources is therefore insufficient when aiming for full decarbonization. The implementation of CCS appears to be the only solution which can both decrease the process and energy related emissions significantly (Leeson et al., 2017; Schneider et al., 2011).

Cement production requires high temperatures and cement kilns are currently mainly fired with fossil fuels. However, there is an opportunity to utilize alternative fuels as well. Already 40% of the cement production is fired with biomass and waste in Europe (de Beer et al., 2017). Combining the application of biomass as fuel with carbon capture storage could result in negative emissions. Utilizing this technology in the energy intensive industry reduces capacity in the power sector for which there are sufficient low-carbon alternatives. A limitation of biomass is the relatively low calorific value (Moses, 2011), but this hurdle can be overcome by pre-processing the biomass first, for instance with torrefaction (Phanphanich and Mani, 2011). With CCS as the only decarbonization option, an additional benefit can be created in the form of negative emissions by (co-)firing biomass. In 2050, CCS technology is assumed to be applied on all the cement production sites, in line with IEA (2017c). By 2050, 70% of the energy is supplied by biomass.

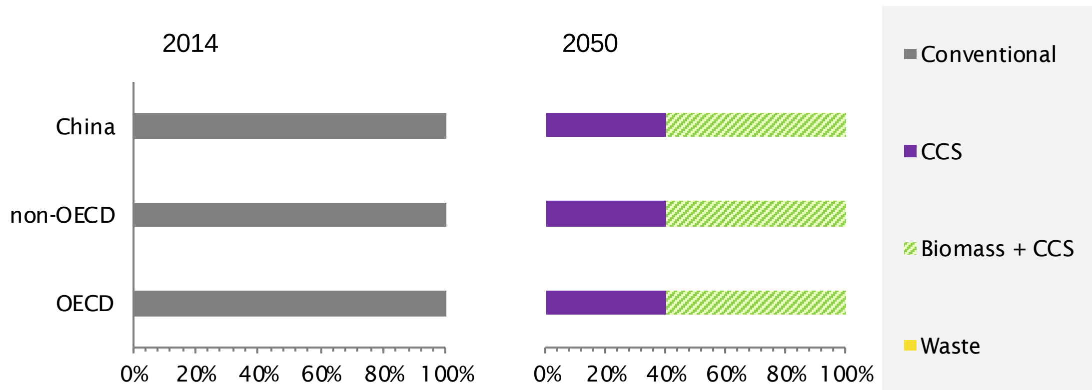


Figure 8.4 Technology shares cement production 2014 (l) and 2050 (r)

Paper, pulp and print

For production of paper, pulp and print, no specific technologies are distinguished, instead the energy mix in 2050 is adjusted. Looking at the global energy consumption of this sector in 2014, biomass and electricity are the predominant energy carriers globally and together responsible for 76% of the energy demand. In China, 45% of the energy is derived from coal.

Paper pulp and print has been assigned as a potentially interesting industry to generate negative emissions (CSI, 2017b; Jönsson and Berntsson, 2012; Leeson et al., 2017; Möllersten et al., 2006; Onarheim et al., 2017). CO_2 emissions can be captured in the gasification process of black liquor. From an economic perspective, a disadvantage of applying CCS in this sector is the fact that most plants are located in remote areas where there is no possibility to connect to other storage infrastructure (Leeson et al., 2017). From a social acceptance perspective, the remote location can be an advantage, since there may be less public resistance against CCS in these areas (van Os et al., 2014).

Towards 2050, energy from gas, coal, oil products and waste which are currently used are replaced by biomass. 50% of the biomass combusted is combined with CCS technology. Furthermore, the heat that is used in 2014 is produced with electricity as proposed by Bakhtiari (2010).

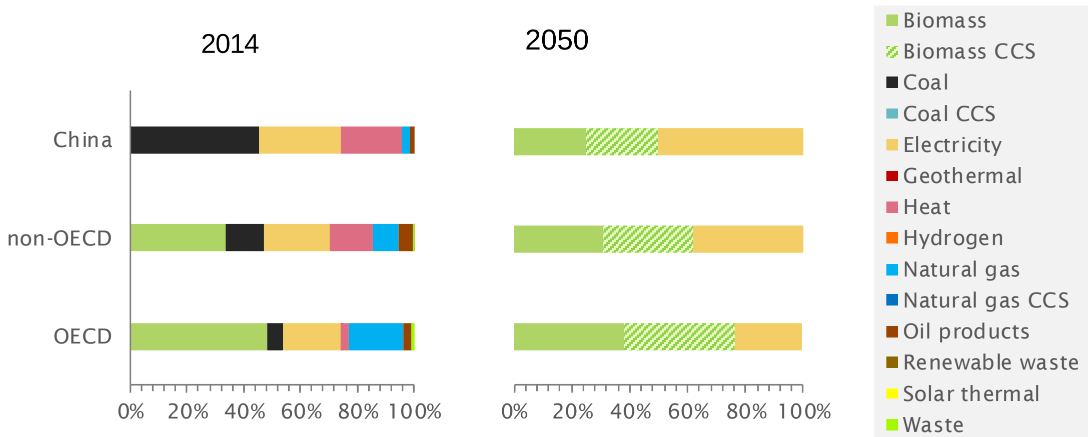


Figure 8.5 Energy shares assumed for paper, pulp and print production 2014 (l) and 2050 (r)

Ammonia, high value chemicals & methanol

Ammonia is produced in the Haber-Bosch process binding hydrogen to nitrogen. Currently, hydrogen is derived by steam reforming natural gas or coal (in China). Alternatively, a biomass gasification process can be used which is already cost competitive (Gilbert et al., 2014). A second substitute would be to create hydrogen from electricity via electrolysis. In this process, the existing Haber-Bosch process remains intact but the steam reforming is eliminated (Pfromm, 2017).

Since the supply of biomass is limited and most of the technology in ammonia plants can remain intact, the electrolysis is preferred. In 2050, 100% of the ammonia is produced from electrolysis.

An additional advantage of hydrogen is that flexible production helps stabilizing the electricity grid.

The steam cracking process to produce high value chemicals nowadays is completely fossils based. Naphtha derived from refineries are cracked into different chemicals.

A low carbon alternative would be to derive carbon from biomass. Via gasification or pyrolysis it is possible to create a syngas and form hydrocarbons in a Fischer-Tropsch process (Daioglou et al., 2014).

For methanol, biomass is used as well as feedstock, replacing natural gas and coal (Bergins et al., 2016; Hasegawa et al., 2010; IEA, 2013b). Deployment of all these technologies in the chemical industry is expected to start in 2020.

Other sectors

The other sectors in the industry comprise a significant part of the total energy demand in industry (47% in 2014). Nonetheless, the technologies are not explicitly described in this model since it covers thousands of different production processes. Furthermore, it is often unclear which processes are actually used: the largest energy consumer in the other sectors is the non-specified category (23 EJ).

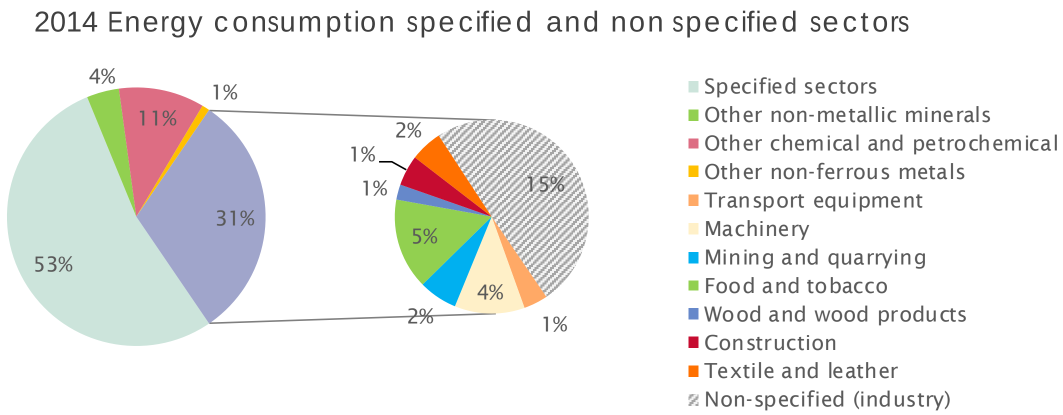


Figure 8.6 Global distribution of energy consumption Industry 2014

Due to this uncertainty, a conservative approach is chosen to determine the energy mix in 2050. By 2050, the currently used fossil energy carriers are replaced with low emission alternatives that are related. Oil products are replaced with biofuels with similar properties and can serve as a liquid fuel or as a feedstock in chemical sector. In energy intensive industry sectors, CCS can be applied. But the production processes in these categories are generally smaller and produce less concentrated emissions, which make CCS not very suitable everywhere. Furthermore, there is a limited demand of high temperature heat in this category (See figure 8.1). For instance in the food industry - the biggest specified sector within the Other category – the heat that is required to bake, pasteurize or rinse, is typically low or medium temperature (< 400 °C). Industrial heat pumps or electric ovens can provide these temperatures rather efficiently. Nevertheless, 50% is non-specified which could be all different kinds of industrial processes. Therefore it is assumed that 50% of all coal and natural gas is replaced with electricity while the remaining 50% is replaced with CCS technology.

Table 8.2 Assumed low-carbon alternatives for used energy carriers in 2014

Energy carriers 2014	Other chemical and petrochemical 2050	Other non-ferrous metals 2050	Other non-metallic minerals 2050	Other 2050
Biomass	Biomass	Biomass	Biomass	Biomass
Coal	Coal CCS	Coal CCS	Coal CCS	Coal CCS / Electricity
Electricity	Electricity	Electricity	Electricity	Electricity
Geothermal	Geothermal	Geothermal	Geothermal	Geothermal
Heat	Heat	Heat	Heat	heat
Natural gas	Natural gas CCS	Natural gas CCS	Natural gas CCS	Natural gas CCS / Electricity
Oil products	Biomass	Biomass	Biomass	Biomass
Waste	Biomass	Biomass	Biomass	Biomass

Other chemical and petrochemical

As a result of the previously mentioned replacement strategies, biomass becomes the most important energy source in OECD regions by 2050.

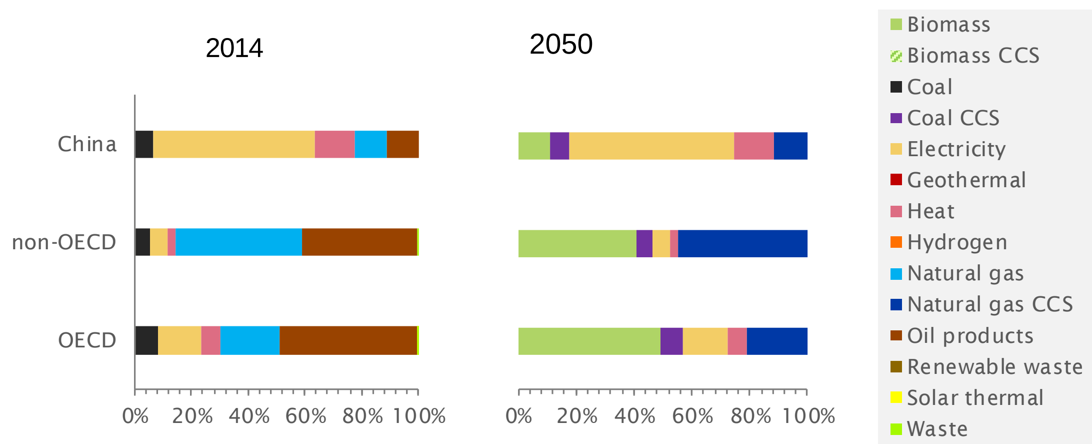


Figure 8.7 Energy shares other chemical and petrochemical production 2014 (l) and 2050 (r)

Other non-ferrous metals

The Other non-ferrous metals production generally requires high temperatures and therefore coal and natural gas are the dominant energy carriers. Therefore CCS is applied to reduce the emissions by 2050.

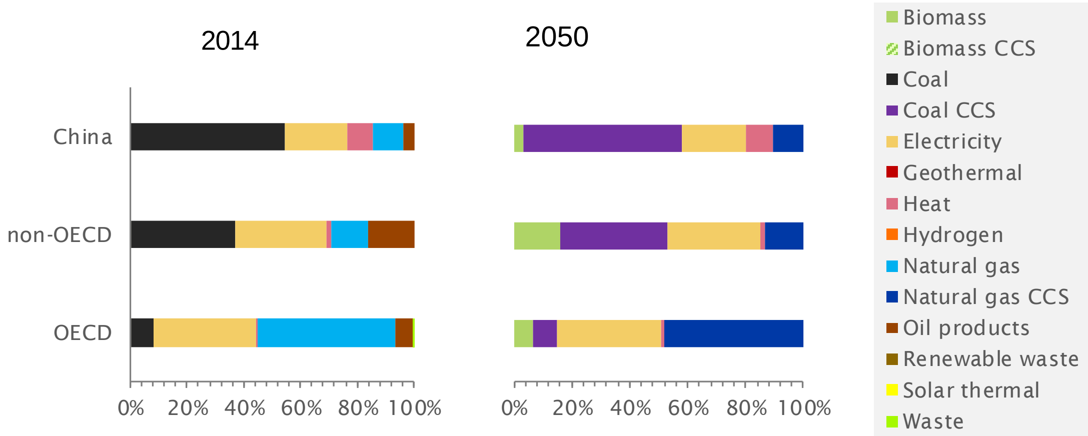


Figure 8.8 Energy shares other non-ferrous metals production 2014 (l) and 2050 (r)

Other non-metallic minerals

Just as other non-ferrous metals, this sector also typically requires high temperatures with coal as the dominant energy carrier by 2014.

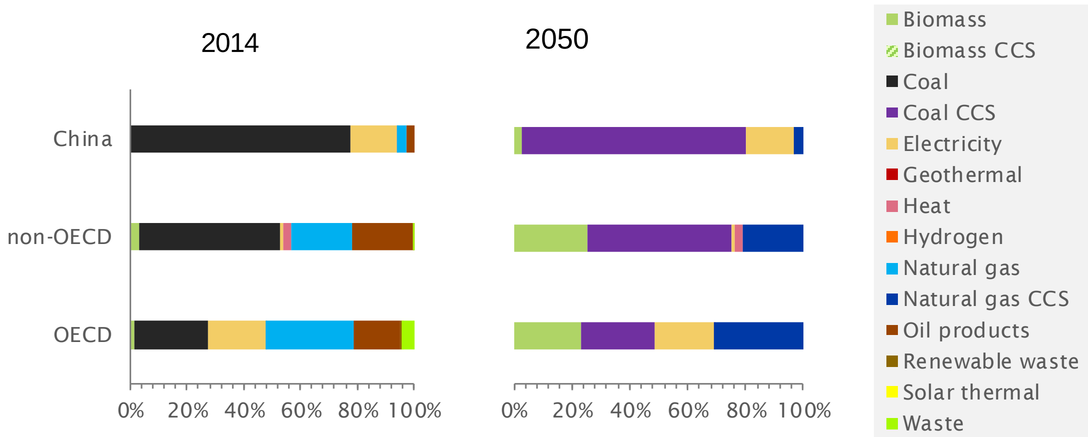


Figure 8.9 Energy shares other non-ferrous metals production 2014 (l) and 2050 (r)

Other industries

In the other industries, an electrification is assumed towards 2050 related to the low temperature demand. In OECD and China, electricity provides 58% and 63% respectively of the total energy demand in this sector.

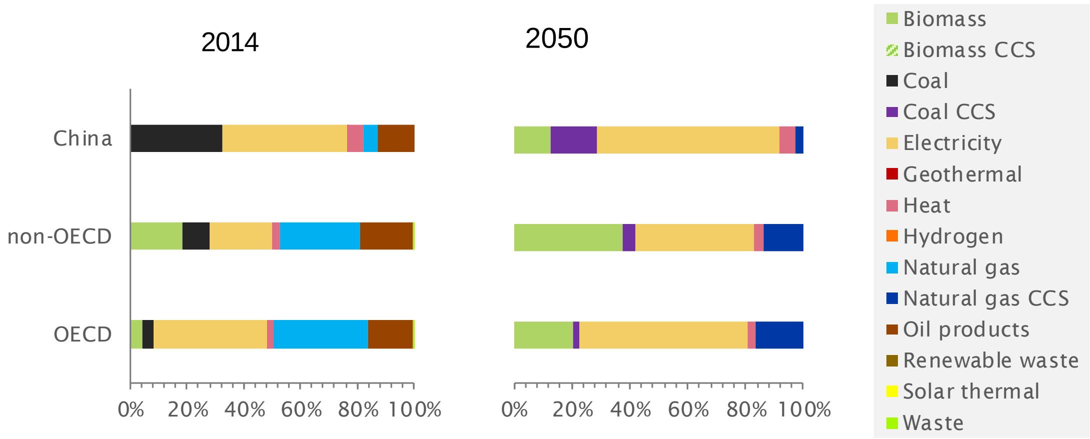


Figure 8.10 Energy shares other industries production 2014 (l) and 2050 (r)

8.1.3 Final energy demand industry

Despite an enormous increase in production, total final energy consumption in the industry increases by only 5% in 2050 compared to 2014. In 2040 the peak consumption is reached of 173 EJ per year. Coal, natural gas and oil products are gradually replaced by low-carbon alternatives. CCS is used in different sectors where no realistic alternative was available. By 2050 67 EJ of biomass is used as feedstock for chemicals or as source of negative emissions in combination with CCS. The role of electricity also increases from 20% of the total final consumption in 2014 up to 29% in 2050.

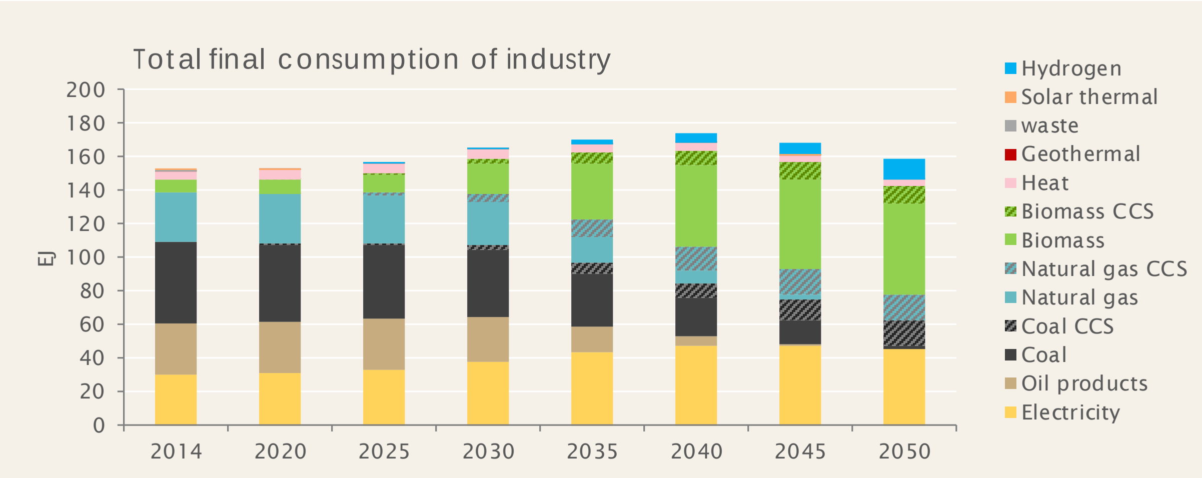


Figure 8.11 Global final energy consumption industry (EJ)

The relatively stable total energy demand of the industry can be explained by the significant reductions in energy intensities of products. Most reductions are realized in the production of iron and steel of which the average required energy per ton declined from 20.46 GJ in 2014 to 6.55 GJ in 2050. This is explained by increased recycling rates, improved efficiencies as well as the introduction of hydrogen reduction.

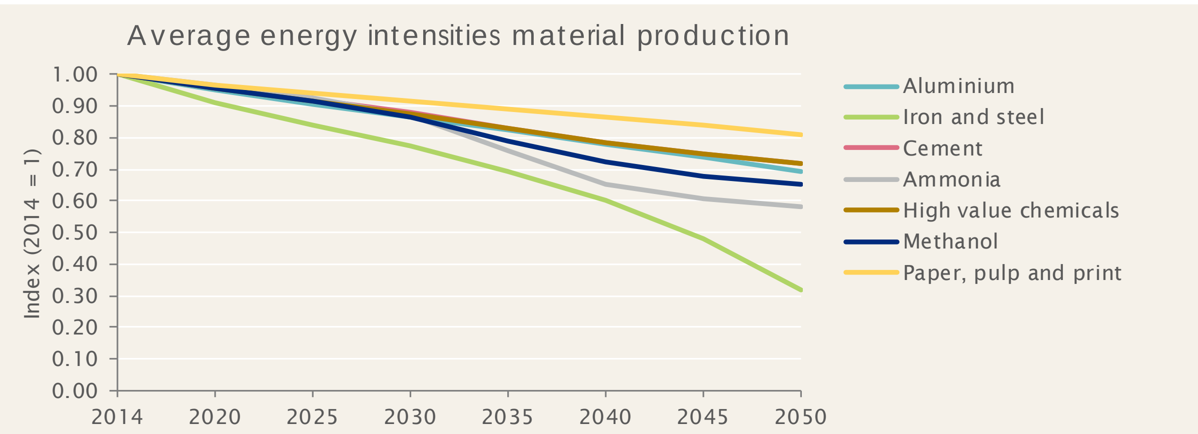
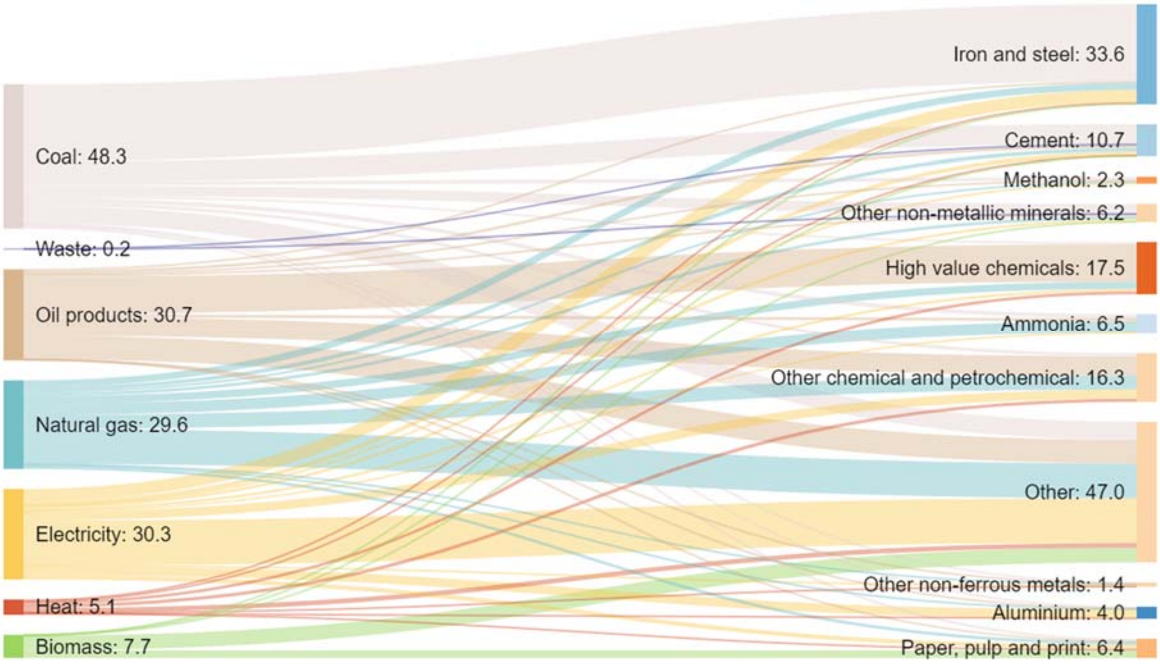


Figure 8.12 Average energy intensities material production 2014-2050

Total final energy flows industry

2014



2050

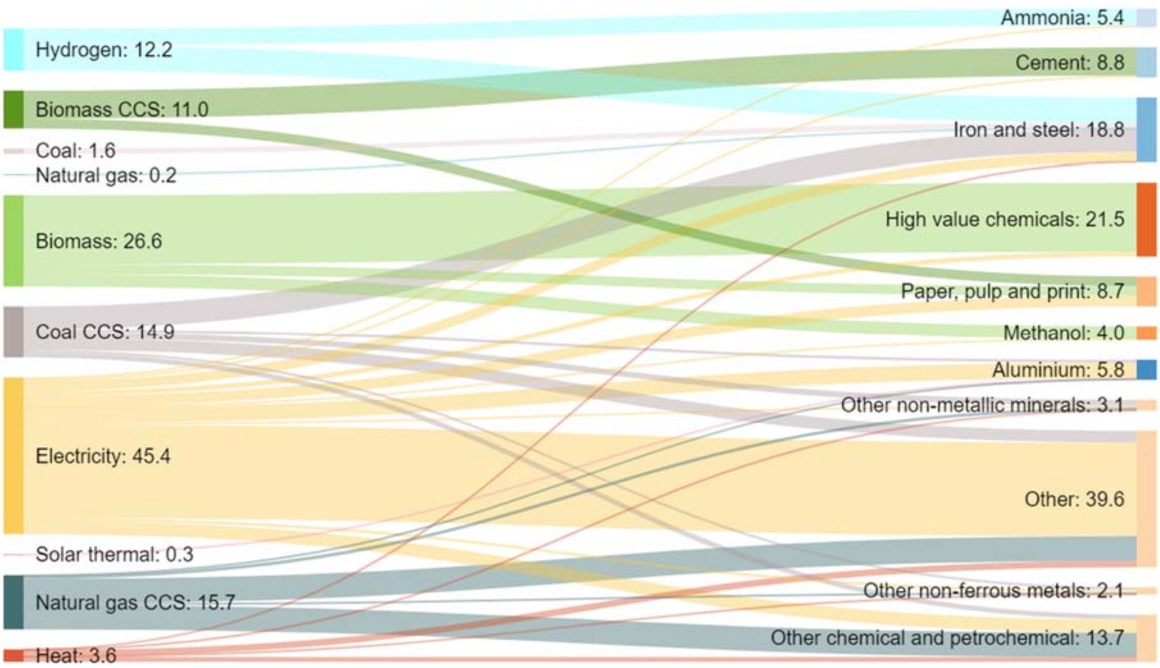


Figure 8.13 Energy flows in global industry sector in 2014 and 2050 in EJ including feedstocks. A wide variety of energy carriers is required. By 2050, the remaining fossil fuels are only used in combination with CCS

8.2 Buildings

8.2.1. Efficiency improvements

Thermal performance

Energy demand of space heating and cooling in buildings can be reduced significantly by improving the thermal performance of the buildings. In developed countries there are already strict policies in place that restrict the energy performance of new building projects which have proven to be effective (Filippini et al., 2014; Iwaro and Mwasha, 2010; Nejat et al., 2015). Furthermore, these policies are increasingly adopted in developing regions as well (Nejat et al., 2015). According to the Global Buildings Performance Network (GBPN, 2017), deep renovation of existing building stock and high performance standards for new constructions can reduce space cooling and heating demand between 75% and 90% compared to the current average building stocks in all regions (see figure 8.14).

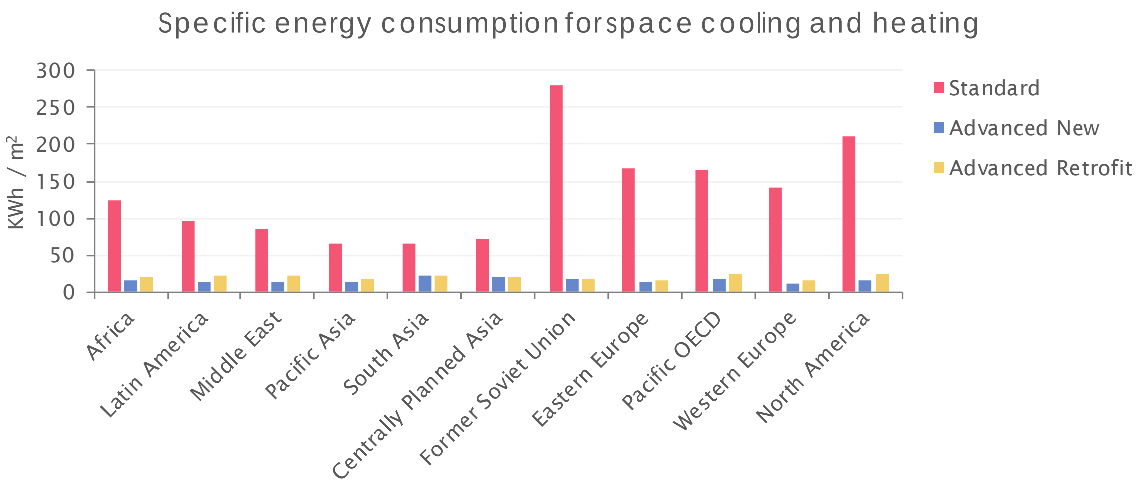


Figure 8.14 Energy consumption for space cooling and heating for standard, advanced new and retrofit in different regions (Source: GBPN, 2017)

However, as these advanced insulation might improve the energy performance of buildings drastically, achieving the full theoretical potential might not be desirable. First of all, the additional required materials can have a significant contribution to the total environmental impact of the building (Audenaert et al., 2012; Blengini and Di Carlo, 2010). Secondly, advanced retrofit is capital intensive and is less cost optimal than applying less extensive insulation measures (Delmastro et al., 2016), especially in regions where there is less heating demand (Baglivo et al., 2015).

There is thus a trade-off between significant energy reduction on the one hand and additional required capital and materials on the other hand. Therefore, it was chosen to determine the level of insulation based on the amount of heating degree days. In regions with more than 1000 heating degree days, 70% of the thermal demand is reduced by 2050 relative to 2014. In the other regions, 35% reduction is realised in 2050 compared to 2014.

Looking at the efficiency improvements potential of technologies, not much savings can be expected by improving the existing techniques (Ecofys and IEEJ, 2015). Improvements of boilers and stoves are expected to be in the range of 5-10%, since these have already been optimised close to their efficiency limits (IEA, 2013a). For relatively new technologies such as heat pumps, there is still potential to advance.

Heat pumps

The coefficient of performance (COP) of heat pumps can be improved by 50% and 38% for space heating and water heating respectively in 2030 (Ecofys and IEEJ, 2015). According to Ecofys and IEEJ, COP of air conditioners can also be improved by 45%. These performance improvements of best available technologies in 2030 are used to express the average performance values by 2050.

Appliances

Looking at the historic energy performance of appliances (electronics, kitchen equipment, IT, etc.), annual improvements of 2-3% have been found over a longer period of time (IEA, 2016d). According to the study by IEA, further annual efficiency improvements between 0.5 and 1% are very well possible. According to Waide (2011) 40% of energy use in appliances can be saved between 2010 and 2030. For this scenario an annual efficiency improvement of 2.5% is assumed which results in a total indexed performance improvement of 150%.

Lighting

Significant energy savings can be realized in lighting. LED is around 13 times more efficient than incandescent light and 2 times more efficient compared to fluorescent lamps (Blok and Nieuwlaar, 2017). The savings potential that can be derived by replacing all inefficient lights is estimated between 40% and 78% around 2030 (IEA, 2016c; IEEJ, 2011; UNEP, 2014; Waide, 2011). This efficiency improvements is extrapolated towards 2050 with an annual performance improvement of 2% per year, resulting in a total improvement of 104% more lumen per watt.

In table 8.3, the assumed performance improvements (output / energy) for the buildings sector are presented. For heat pumps and air conditioners, the assumed average COP by 2050 is provided between parentheses.

Table 8.3 Assumed performance improvements by 2050 in buildings

Function	Technology	Performance Improvement rate
Space heating	Heat pump	50% (COP = 4.8)
Water heating	Heat pump	38% (COP = 2.75)
Space cooling	Air conditioner	45% (COP = 4)
Appliances	All appliances	150%
Lighting	Lighting	104%

8.2.2. Technology switches

Residential

For the residential sector the transition in space heating, hot water use and cooking are looked at more closely. Lighting, space cooling and appliances are 100% powered with electricity.

Space heating

Looking at the current shares of technologies, biomass is still the predominant fuel source in poor regions (see figure 8.15), whereas in OECD countries the main energy source to heat residential dwellings is natural gas. District heating plays a significant role in non-OECD Europe and Eurasia; 34% of the total final energy demand in buildings is derived from heat which is centrally generated. In the transition towards 2050, a switch has to be made towards more efficient and renewable energy sources. Electric heat pumps are considered as a promising technology. First of all, the very high efficiency of heat pumps reduce the required additional investments in the electricity grid infrastructure that is needed to electrify the built environment. Furthermore, heat pumps can play an important role in the integration of intermittent renewables: by utilizing the thermal energy storage capacity in combination with a smart grid, peak demands can be reduced significantly (Arteconi et al., 2013; Blarke, 2012; Hedegaard et al., 2012). On the other hand, heat pump systems are very capital intensive and electric boilers might be more attractive from an individual economic point of view if the heating demand is low (Hawkes et al., 2011; Nielsen et al., 2015; Ten Cate, 2012). Also, air source heat pumps do not perform very well in cold climates (Hawkes et al., 2011).

Solar thermal, already plays a considerable role in space heating in Asia and China of more than 10%. Advantages of solar thermal is that it can reduce electricity demand and is installed on site and therefore does not require transportation infrastructure. The technology does require improvements in terms of costs and performance (IEA, 2013a).

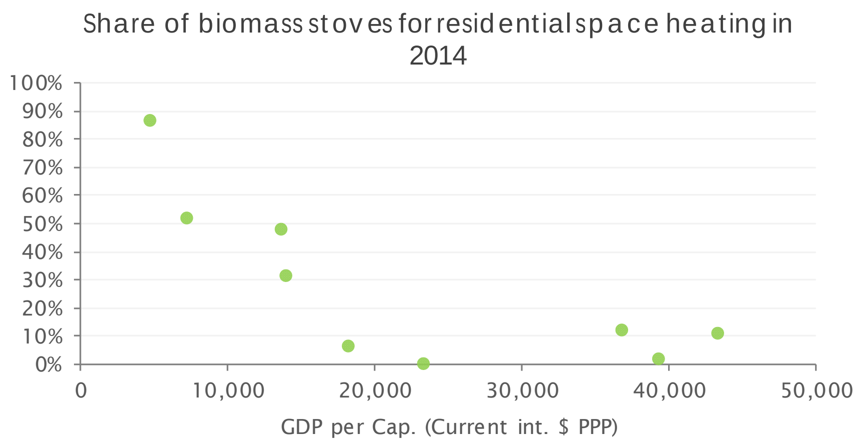


Figure 8.15 Share of biomass stoves in residential space heating and GDP per capita in 2014

In 2050, a mix of heating technologies is assumed. First of all, combustion of biomass is phased out slowly in all regions except in Africa. The GDP per capita in Africa is still relatively low by 2050 and therefore, 40% of the heating is still assumed to come from fired biomass (see the trend in figure 8.16). 20% of the heating demand is provided by solar thermal in regions with high irradiation: Non-OECD Asia (excl. China), China Africa and Middle East. District heating can also well be applied in renewable energy systems under certain conditions (Lund et al., 2010). Therefore, district heating from industrial waste streams provides a share of the heat demand in all regions except for Africa, Non-OECD Americas and Middle East, where there is very little heating demand and the investments of an heat network are unlikely to pay off. And even though the heating demand in Asia is also marginal, infrastructure is already present in cities. The remaining heat demand is matched with heat pump systems and electric resistance heaters. In all OECD regions and China two thirds of the remaining heat demand is expected to be supplied by heat pumps and one third by electric resistance heating or electric boilers. In Non-OECD regions, the partition is 50/50.

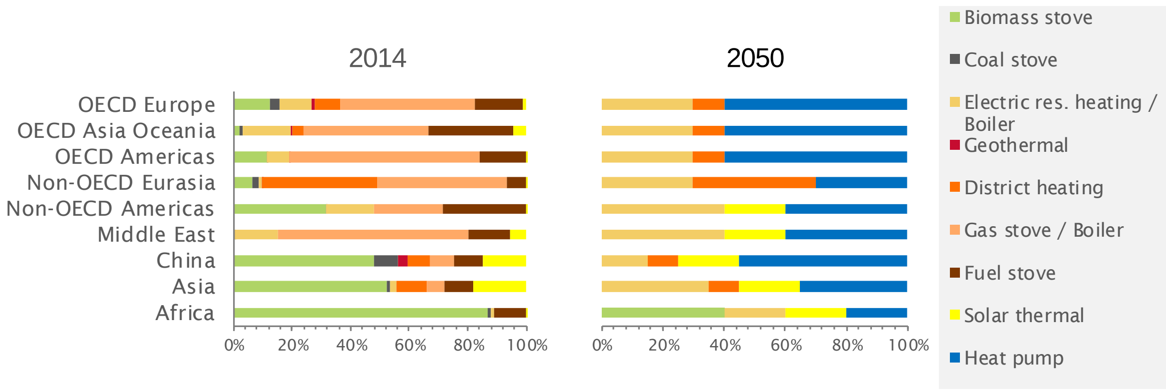


Figure 8.16 Technology shares used to provide space heating in residential buildings per region

Water heating

In the transition towards 2050, technologies for heating, cooling and hot water are combined as much as possible to minimize investments and production of additional equipment. Hybrid heat pumps can heat water efficiently, however these require additional investments as well. Solar thermal is assumed to provide 20% of the hot water in regions with high radiation. District heating only plays a role in Non-OECD Eurasia. Furthermore hybrid heat pumps are assumed to provide 50% of the warm water demand in regions with heating demand over 1000 heating degree days.

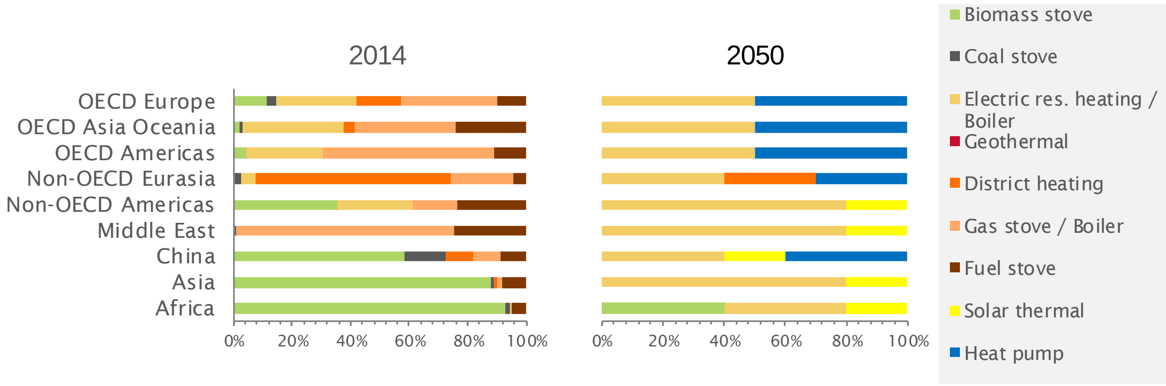


Figure 8.17 Technology shares used to provide water heating in residential buildings per region

Cooking

For cooking, natural gas, biomass and electricity are currently the main energy sources with significant differences throughout the regions. As was found for space heating, the use of biomass in cooking appears to also have a negative correlation with GDP per capita (figure 8.19). In 2014, there is also a considerable amount of fuels used to heat food.

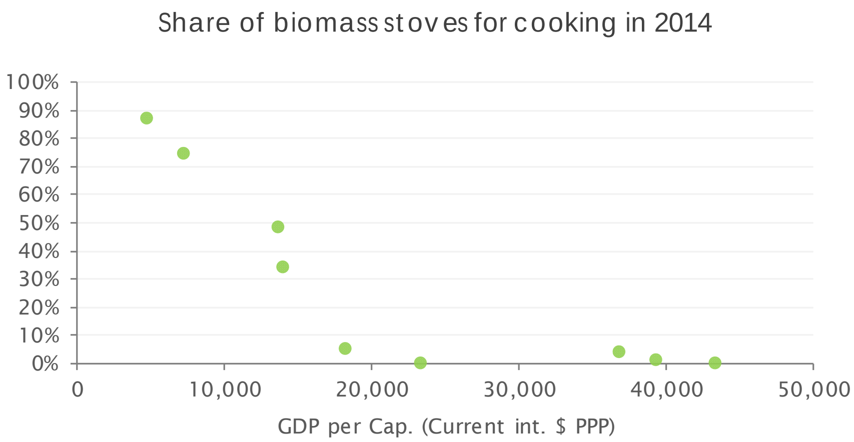


Figure 8.18 Share of biomass stoves in residential cooking and GDP per capita in 2014

By 2050, all natural gas and coal stoves are replaced with electric heating technologies. The fuel stoves are replaced with (liquid) biofuel alternatives. Liquid energy carriers have a very high energy density and avoids high electricity storage capacities in remote areas, where biomass and petroleum are still the main energy sources for cooking. The traditional biomass stoves are phased out in all regions except in Africa where 50% of the cooking is still powered with traditional biomass.

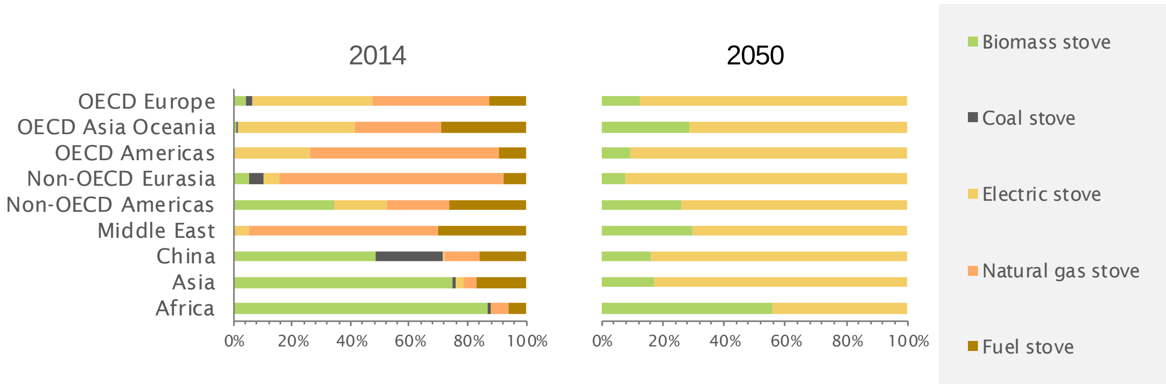


Figure 8.19 Technology shares used for cooking in residential buildings per region

Commercial and public services

The main lines of reasoning for technology choices have been explained. However, this section will briefly describe the consequences for the transition in commercial and public services buildings.

Space heating

Other than in the residential sector, biomass plays a significantly smaller role in space heating of commercial buildings. Furthermore there is relatively less solar thermal used in this sector.

Towards 2050, efficient heat pumps and conventional electric heating systems are assumed to be the dominant technologies. With the same distribution as in the residential sector: two thirds is provided by heat pumps in regions with high heating demand (>1000 HDD) and 50% in regions with lower heating demands.

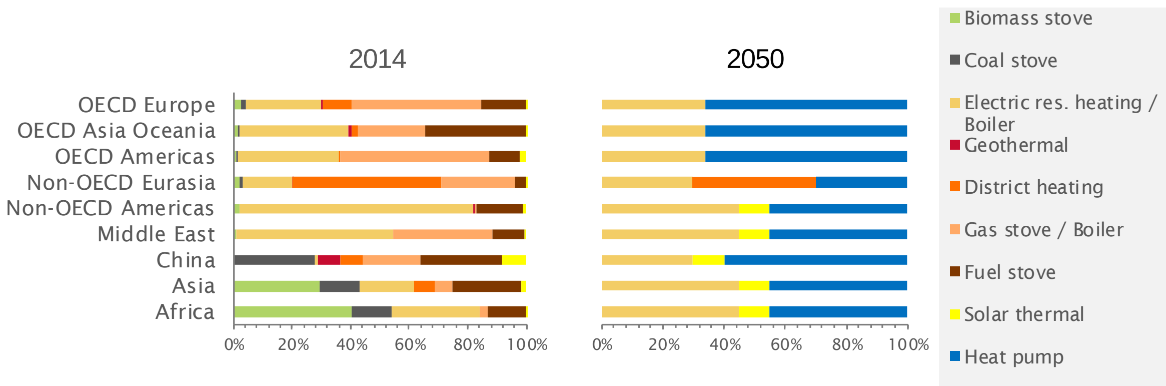


Figure 8.20 Technology shares used to provide space heating in commercial buildings per region

Water heating

Water heating requires 12% of the total current energy demand in commercial and public services. Towards 2050, hybrid heat pumps will generate 50% of the warm water in regions with high heating demand, whereas in regions with low heating demands no hybrid heat pumps are expected to provide warm water. The current infrastructure of district heating in Non-OECD Eurasia is assumed to stay in operation with district heating used to heat water in offices.

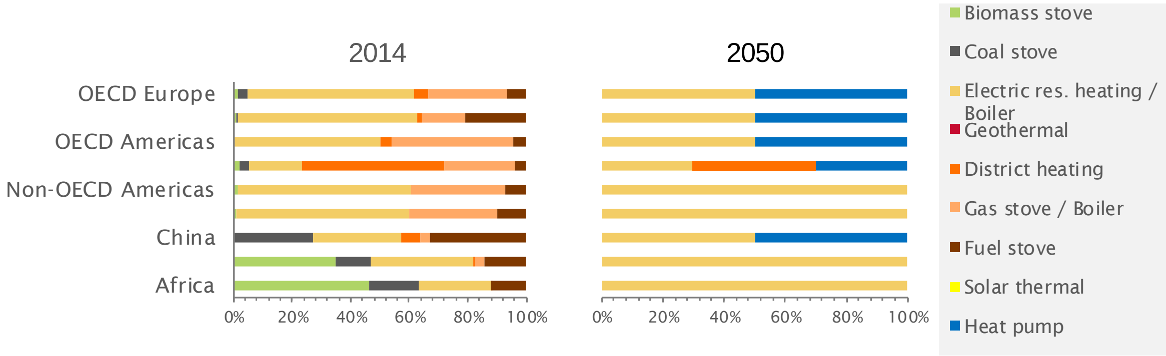


Figure 8.21 Technology shares water heating commercial buildings 2014 (l) and 2050 (r) per region

Appliances

Appliances is the largest energy consumer within commercial and public services (40%). The dominant energy carrier in most regions is currently electricity except for Africa. Some fuels are also used which might be complicated to replace with electric alternatives. Therefore these oil products are expected to come from bio based energy carriers in 2050. The other energy carriers are replaced with electric alternatives.

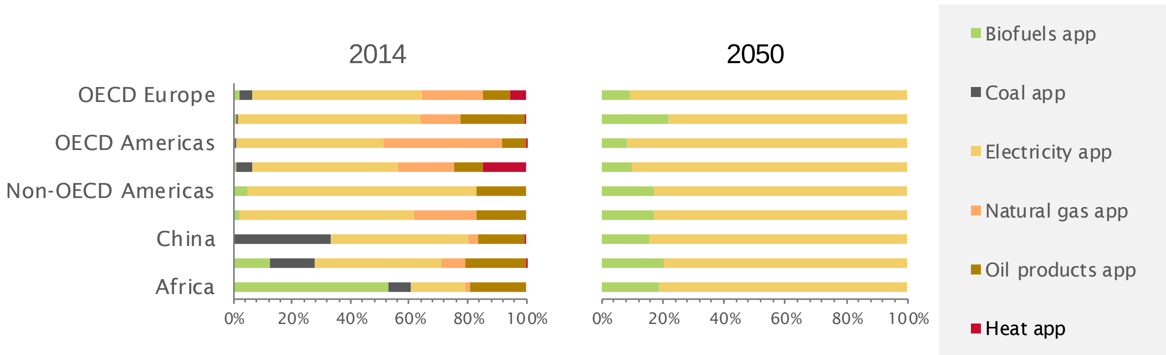


Figure 8.22 Technology shares appliances commercial buildings 2014 (l) and 2050 (r) per region

8.2.3 Final energy demand buildings

The total final energy consumption in buildings increases slightly up to 133 EJ in 2050, an 11% growth relative to 2014. The transition in the buildings sector is characterized by the electrification: by 2050, 78% of the final energy consumption in the buildings sector will consist of electricity. In most regions, energy in buildings will be even 100% electric. Natural gas, which currently contributes to almost 50% of the energy use in developing countries is marginalised already by 2040. Also the application of biomass is reduced as a result of increasing welfare.

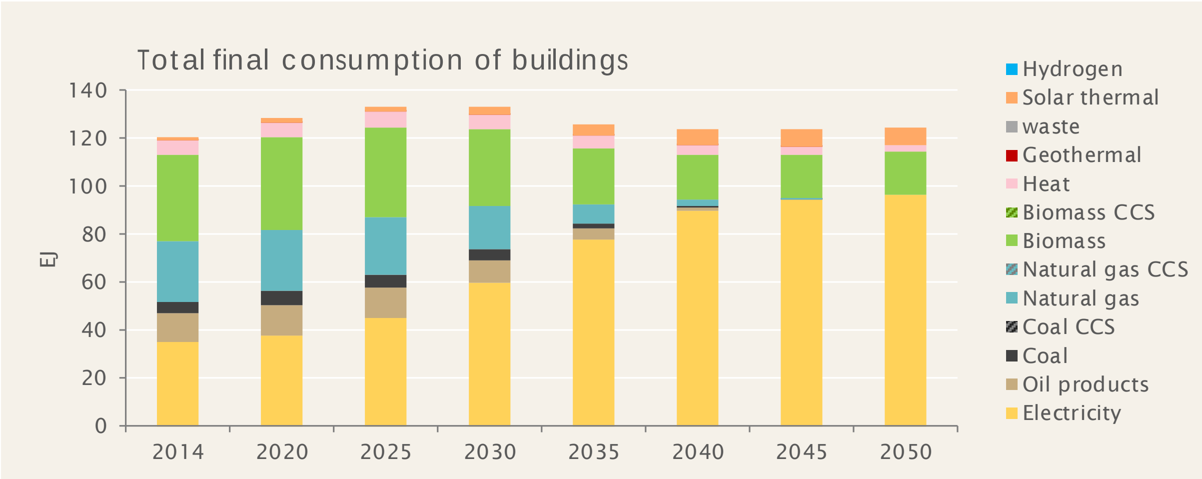


Figure 8.23 Global final energy consumption buildings 2014-2050 in EJ

The technology changes and efficiency improvements result in a significant decline in the energy consumption per capita in OECD regions. The energy consumption across the regions move more towards each other by 2050 and were found to be between 11 and 22 GJ per capita.

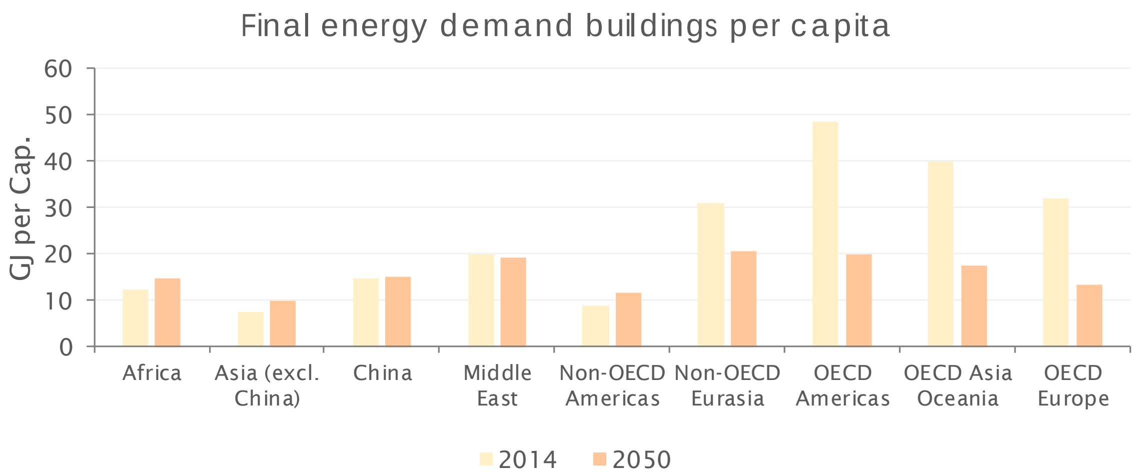
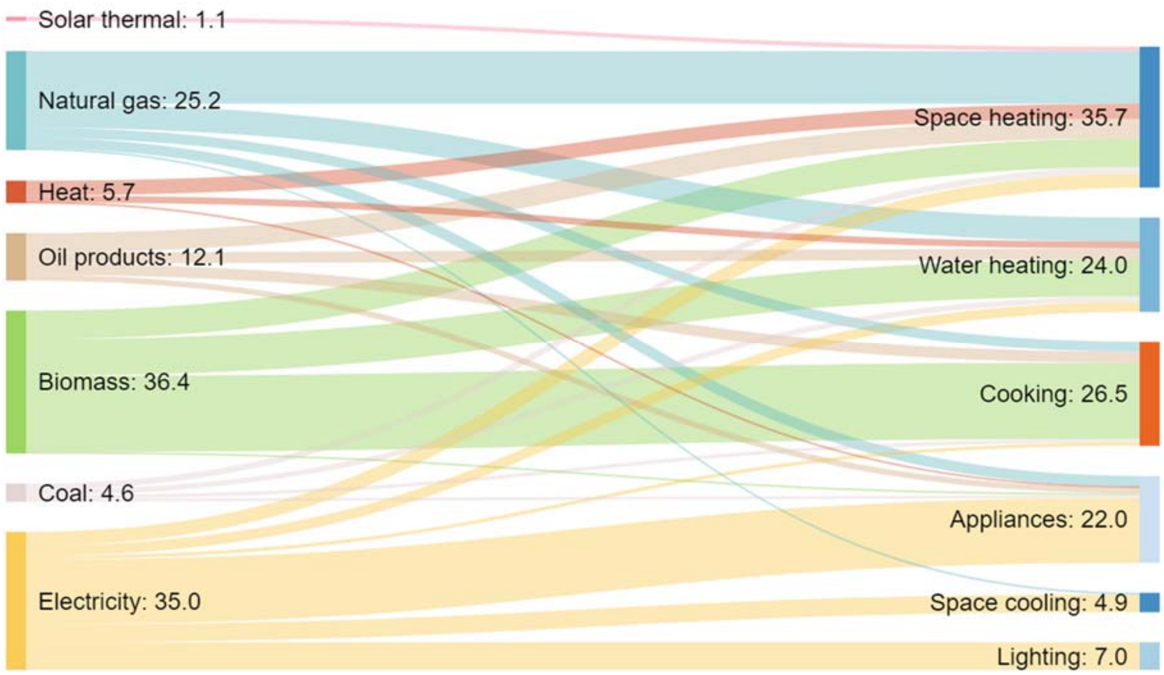


Figure 8.24 Final energy demand for buildings per capita 2014 and 2050. The regional differences decrease towards 2050

Energy demand for appliances is expected to increase with 54%, despite the efficiency improvements. Appliances will become a larger energy consumer than space heating or cooking. Energy demand for space heating is reduced due to thermal insulation and highly efficient heat pump technology.

Final energy flows buildings

2014



2050

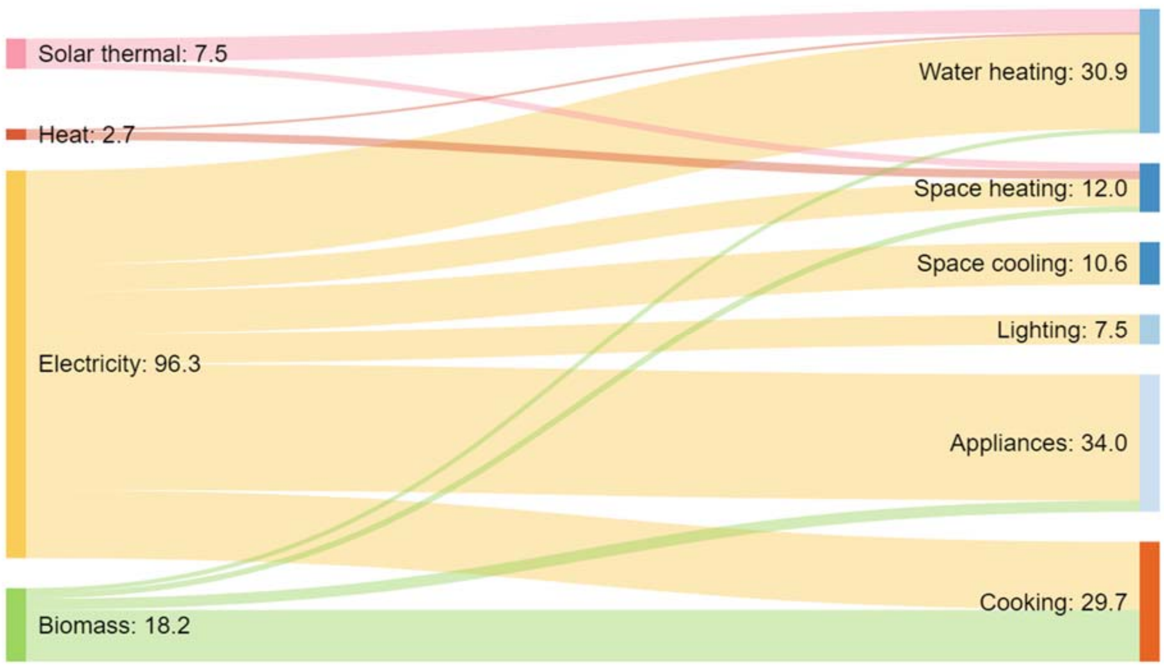


Figure 8.25 Final energy flows in global buildings sector in 2014 and 2050 in EJ. Towards 2050, almost all energy services are powered by electricity.

8.3 Transport

8.3.1 Efficiency improvements

Just as in the other sectors, substantial efficiency improvements can be realised in the transport sector (Greene and Baker, 2011).

Road

For the efficiency improvements in road transport, an extensive literature study by Hill et al. (2012) is used which was prepared for the Committee on Climate Change as well as ICCT (2016) for freight road. This study assessed the efficiency potential between 2010 and 2050 for different road transport modes. The results have been translated in an average annual improvement rate which then was used to define efficiency potentials for the period of this model (2014-2050), which can be found in table 8.4.

Table 8.4 Assumed efficiency improvements by 2050 in road transport. Reduction of the energy per activity

	Gasoline	Diesel	CNG	LPG	Fuel cell	Electric
LDV	47%	45%	47%	47%	31%	24%
Light road*	33%	33%	-	-	21%	8%
Bus	21%	21%	-	-	21%	14%
Freight road	-	45%**	-	-	22%	18%

* *Efficiency improvements for light road is based on motor cycles.*

** *Derived from report by ICCT* (2016) *on fuel efficiency potential of heavy-duty trucks*

Rail

According to Green and Baker (2011), energy efficiency of rail transport can be improved by 50% between 2007 and 2050. The international Union of railways has set itself the target of 50% efficiency improvement for Europe in 2050 compared to 1990 (UIC, 2012). This more conservative efficiency improvement by the IUC of 0.6% per year is assumed for all rail transport modes and regions, which results in an overall efficiency improvement of 26%.

Air transport

For air transport, a maximum theoretical average annual fuel efficiency improvement of 2.7% between 2010 and 2030 (Façanha et al., 2012) is possible under stringent policies. This would result in a total reduction of 42% between 2010 and 2030. For this scenario, a more conservative estimate is used by expecting the 42% efficiency improvement to be realized in 2050.

Shipping

For shipping, there are currently enormous differences found in efficiency: The top 5% most efficient ships emit 38% less CO_2 than industry average while the bottom 5% emits 48% more CO_2 than industry average (ICCT, 2013). There is a significant potential to reduce energy intensity and most of the measures that can be applied are cost-effective as well. According to the ICCT (2013) an efficiency improvement of 50% can be realized by 2040 compared to 2010.

Extrapolating this to 2014-2050, an efficiency improvement of 56% in total is assumed.

Table 8.5 Assumed efficiency improvements by 2050 in rail, air and shipping

Transport type	Efficiency improvement
Rail	26%
Air	42%
Shipping	56%

8.3.2 Technology switches

In this section, the technology switches for transport are described and motivated. Technology switches are expected in road and rail transport modes only. Before 2050 it is assumed that shipping and air transport are powered with combustion engines propelled with biofuels. The development of hydrogen and electric alternatives in air and shipping is still too premature.

Road

There are three options for the decarbonization of road transport:

- Internal combustion engines with biofuels
- Electric engine (with renewable power)
- Hydrogen fuel cell (electrolysis with renewable power)

The first option: use of biofuels in road transport by 2050 is preferably as limited as possible since there is a finite amount of biomass available and biofuels are required for air and marine transport as well.

Therefore, liquid fuels are preferably avoided in the future which would require a phase out of the internal combustion engines (ICE) for road transport. Some policies are already announced which direct to this phase out. Norway has set the most ambitious targets and only allows plug-in hybrids or full electric vehicles on the market from 2025. The Dutch government aims for 100% emission reduction of the newly sold vehicles by 2030. France and the United Kingdom intend to phase out ICE's by 2040. Germany, the largest car manufacturing country of Europe, announced policies to ban the combustion engine by 2030. But this announcement immediately led to an intensive political debate which is still going on. And not only in OECD countries electric vehicles will gain market share: Indian president Modi announced a similar ban by 2030 (WEF, 2017), the Chinese possess a third of the global electric car fleet in 2016 (IEA, 2017c) and are currently formulating regulations.

Also, manufacturers move towards electric vehicles in a rapid pace. Figure 8.26 provides an overview of all the electric models available until 2020.

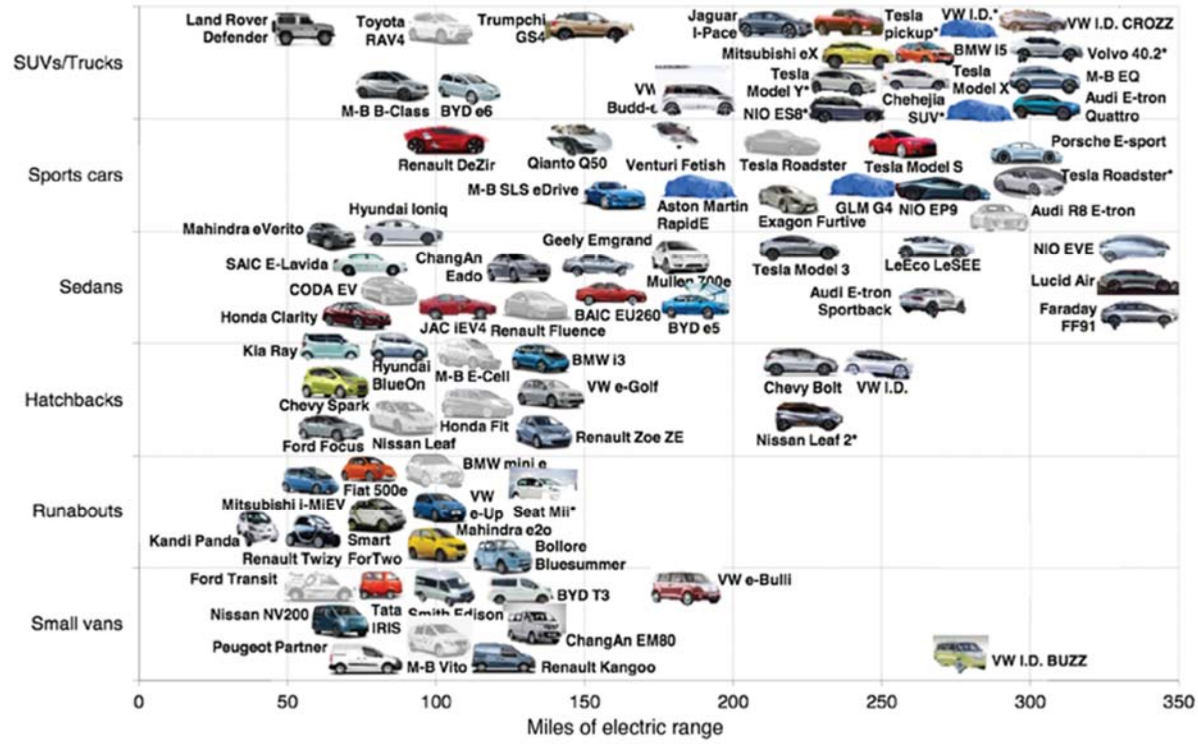


Figure 8.26 Electric and plug-in vehicles announced on the market up to 2020 (Source: Bloomberg, 2017)

Given the assumed average lifetime of vehicles, a ban of ICE's in 2040 would be too late to phase out all liquid fuels by 2050. A transition by 2030, as proposed by some governments already, would lead to a complete phase out of ICE's before 2050. On the other hand, this transition might be too early for developing regions. The average age of the vehicle fleet in Ethiopia and Kenya is for instance 20 years (Deloitte, 2016). In these countries, the majority of the car fleet consists of imported occasions from developed countries. But as the manufacturers from automobiles adapt to the policies of their main sales markets (mainly developed countries and China), combustion engine models are likely to phase out in developing countries as well.

In this scenario, it is assumed that in Asia (excl. China), China and all OECD regions, combustion engines will not be sold after 2030. In the other regions, combustion engines are no longer available for sale from 2040. This does not only applies to passenger transport but for heavy transport as well.

Subsequently, a division has to made for the distribution between fuel cell powered, electric and hybrid vehicles.

Both technologies have different characteristics and additional advantages and disadvantages. First of all, the current production capacity and sales of electric vehicles is much higher than for hydrogen fuel cells: for every 80 electric vehicles only one hydrogen fuel cell vehicle was sold in the US in 2016 (AP, 2017). Also the infrastructure for hydrogen vehicles stays behind in the

United states: hydrogen fuel stations are available in 3 states only opposed to public electric stations which are spread over the entire country (AFDC, 2017). This might be explained by the significantly lower lifecycle costs of electric vehicles compared to hydrogen fuel cell cars (Offer et al., 2010). Furthermore, the costs of batteries are expected to decline drastically in the coming decades (Nykvist and Nilsson, 2015).

Storage and costs remain the most important barriers of the adoption of hydrogen (Alaswad et al., 2016; Sharma and Ghoshal, 2015). Nevertheless, hydrogen fuel cell cars have some major advantages over electric vehicles: refuelling is fast which make fuel cell technology more suitable for long distances (Thomas, 2009). Secondly, hydrogen fuel cells can play an important role in balancing energy systems with high shares of intermittent renewables at relatively low costs since they do not extract electricity from the grid but can actually generate electricity (Alavi et al., 2017; Oldenbroek et al., 2017). According to a study by Oldenbroek et al. (2017), only 20% of the vehicle fleet has to be provided with fuel cell technology to balance an electricity grid with high shares of variable renewables.

Plug-in hybrids, which have both an internal combustion and electric engine, are not expected to play a large role on the longer term, since the complexity and costs do not outweigh the benefits of a longer range, but can play an important role in the transition (Bloomberg NEF, 2017). Though, in the "Below 2 degrees scenario" by IEA (2017c), plug-in hybrids play a significant role in most road transport categories especially in freight transport. Furthermore, hydrogen fuel cell cars only play a very marginal role in the IEA (2017c) scenario's.

Given the current head start of electric vehicles, battery powered cars are assumed to become the dominant technology in all modes of transport. Electric vehicles are sometimes combined with combustion engines to extend the range. Also, a share of hydrogen vehicles in the car fleet is still desirable for grid balancing purposes as described by Oldenbroek et al. (2017) and also for buses and freight road to cover long distances.

The following distribution was made between electric, plug-in hybrid and hydrogen technologies for the different road modes that replace the internal combustion engines after the proposed ban. For LDV, electric vehicles are expected to become the dominant replacement of the ICE (60%), due to its expected favourable costs. 20% of the passenger cars are expected to be plug-in hybrids with both an combustion and electric engine. One fifth of the passenger cars without an combustion engine is expected to be equipped with hydrogen fuel cells. As an alternative for combustion engines in light road, only electric battery powered engines are assumed. Buses will be mostly electricity driven as well: 60% will be full electric and 20% hybrid. Also 20% of the buses are expected to run on hydrogen. In freight transport, which entails both small urban minivans as well as long distance heavy trucks, 40% of the vehicles sold after the ban are plug-in hybrids to cover longer distances. 40% of the freight road is expected to be fully electric (especially small vans) and the remaining 20% of freight road is powered by hydrogen.

Furthermore, it is assumed that the plugin-hybrids use 50% of the time its electric engine and 50% the combustion engine.

Table 8.6 Assumed distribution of electric, plug-in hybrid and hydrogen vehicles per mode of road transport that replace the current internal combustion engines.

	Electric	Hydrogen	Plug-in hybrid
LDV	60%	20%	20%
Light Road	100%	0%	0%
Buses	60%	20%	20%
Freight road	40%	20%	40%

Rail

Rail is currently responsible for a small share of the energy use and emissions in the transport sector (2%), but still responsible for 2 EJ and expected to increase in the coming years. Electricity and diesel are the two major energy sources. In OECD Americas, 90% of the train transport is powered by diesel. Fossil fuels in rail transport can be replaced with electricity or biodiesel. Several initiatives are already undertaken to produce biodiesel for train transport such as in India and the United States (ETIP Bioenergy, 2017). Nevertheless, one of the goals of this scenario is to reduce the use of biomass as much as possible. Therefore, it is assumed that of all non-electric rail transport 50% is electrified and 50% is powered by biodiesel.

8.3.3 Biofuels

To power shipping, air transport, plug-in hybrids and a remainder of the combustion engines in road transport, 58 EJ of biofuels is required by 2050. However, increasing the share of biofuels before that period could significantly reduce the total emissions from the transport sector. Biofuels would then function as a bridging fuel and peak before 2050. In this trade-off, two goals described in chapter 5 conflict with each other: minimize emissions and reduce the use of biomass. In the most extreme scenario, in which biofuels would replace all liquid fuels in 2025, cumulative emission of 168 Gt CO_2 is avoided compared to 100% biofuels by 2050. However, the 2025 and 2030 peak scenario require very high annual growth rates of 41% and 26% respectively and the peak is more than three times the capacity required in 2050.

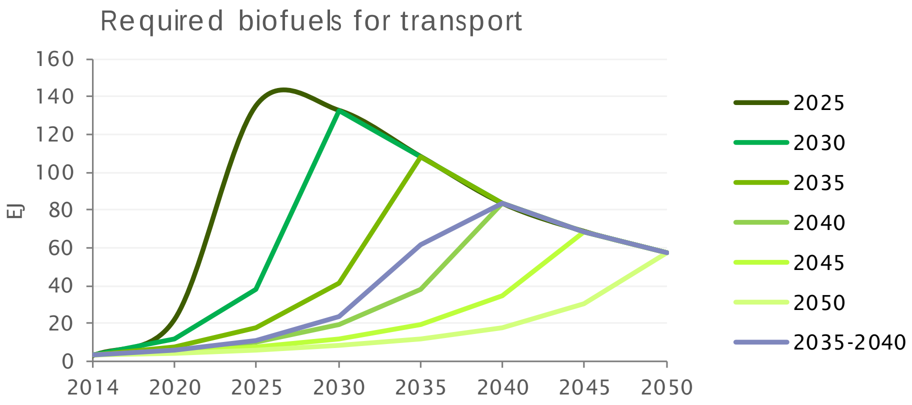


Figure 8.27 Global demand of biofuels under different 100% biofuels years in transport sector

Therefore, a compromise is made by setting a peak biofuel demand for shipping, marine and rail transport at 2035, while 100% biofuels in road transport is expected in 2040 (see purple line in figure 8.29). This still requires a peak of 25 EJ per year for biofuels compared to 2050 and an average annual growth rate of 14%. This additional effort results in a cumulative emission reduction of 66 Gigatons CO_2 in the transport sector.

8.3.4 Energy demand transport

The global final energy consumption in transport peaks at 142 EJ in 2030 in this scenario. As the market share of efficient electric and fuel cell vehicles increases substantially, the total final energy demand in transport decreases.

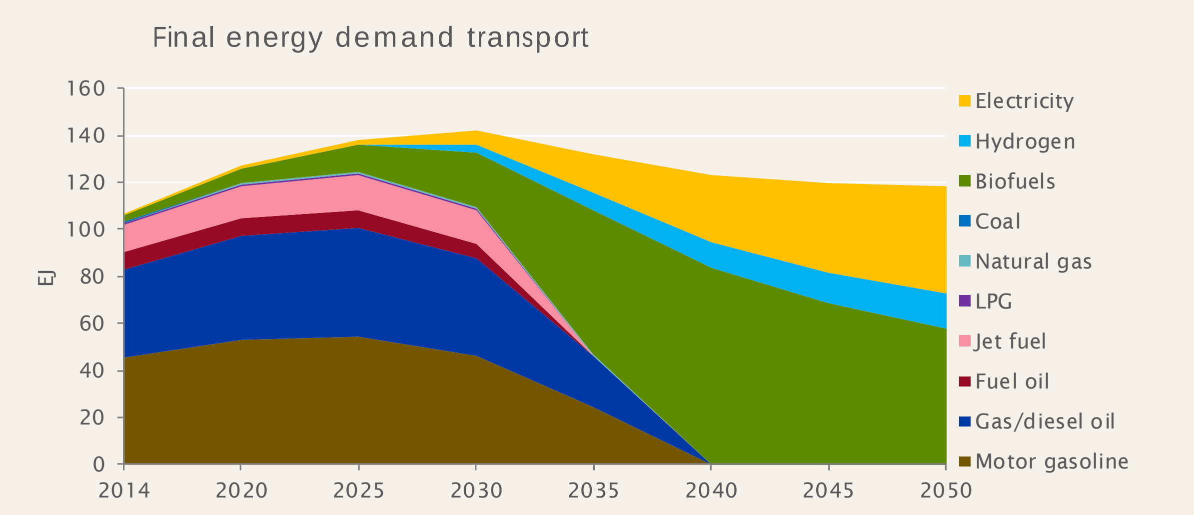


Figure 8.28 Global final energy consumption transport 2014-2050 in EJ.

When looking at the final consumption of transport, the role of electricity seems modest, but this is explained by the significantly higher efficiency of electric vehicles: by 2050, 69% of the driven passenger kilometres of LDV is provided by electric engines.

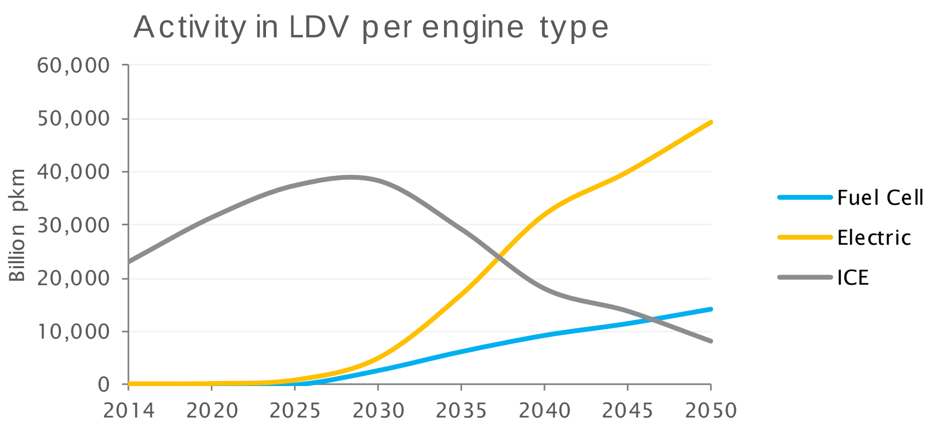


Figure 8.29 Global passenger kilometres driven for different engines between 2014 and 2050

The combination of efficiency improvements and switches towards more efficient engine types (e.g. ICE to electric) result in substantial decrease of the average energy consumption per kilometre. By 2050, the average energy intensity per mode decreased between 23% and 78% compared to 2014. As can be seen in figure 8.30, most energy reduction is realized in LDV due to the high expected efficiency improvement and the switch to electric and hydrogen powered engines.

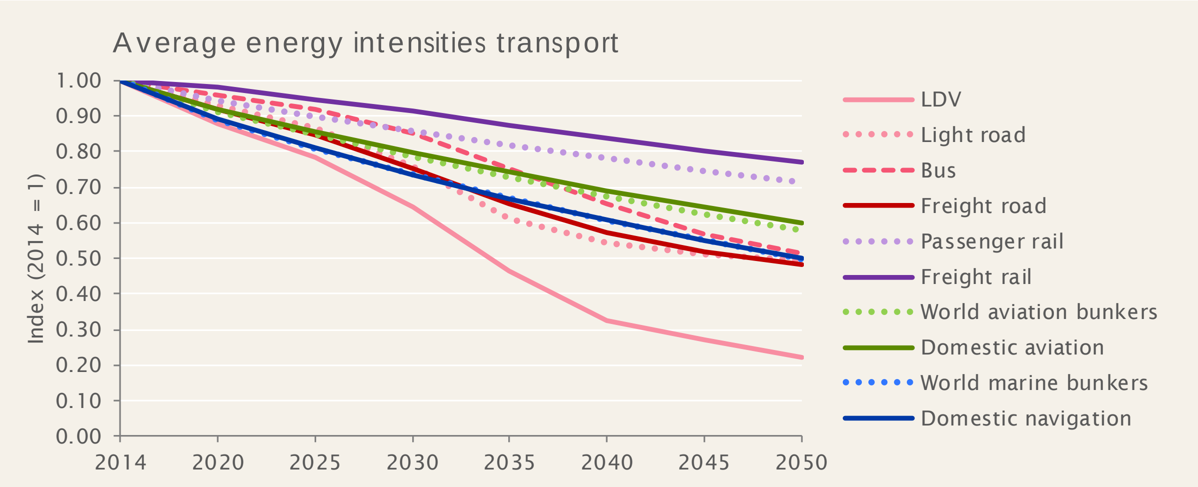


Figure 8.30 Average global energy intensities per unit of activity. Most reduction is found in passenger cars (LDV) due to efficiency improvements as well as switch to electric and fuel cells.

Looking at the different regions, The efficiency improvements lead to a reduction of the total energy demand in OECD with -51%, while energy demand in Africa for transport is expected to increase by 275%. Nevertheless, in terms of energy per capita, Africa is still behind the other regions. Furthermore, the energy demand for world aviation bunkers increases substantially between 2014 and 2050.

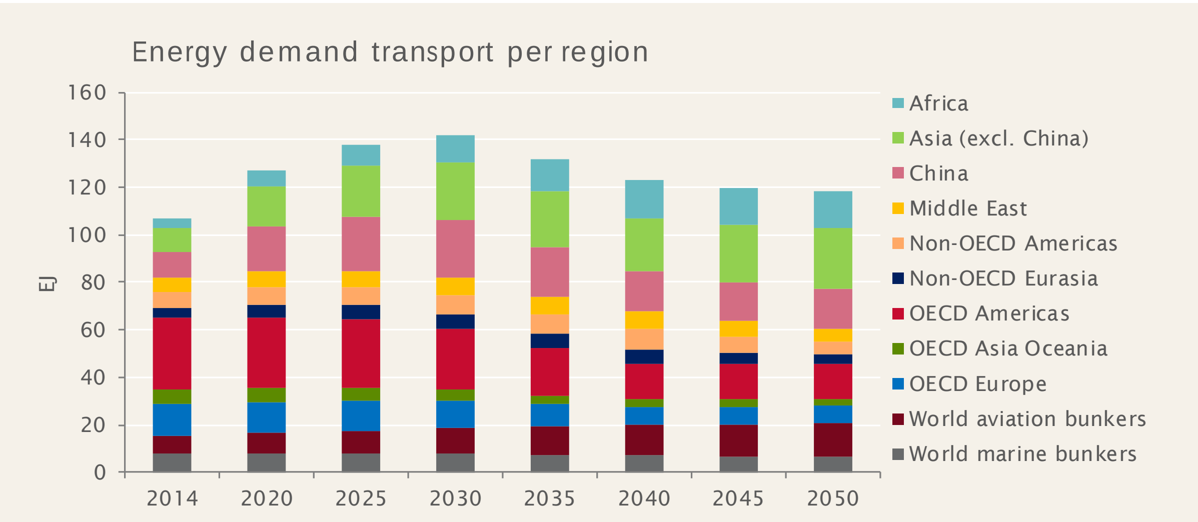
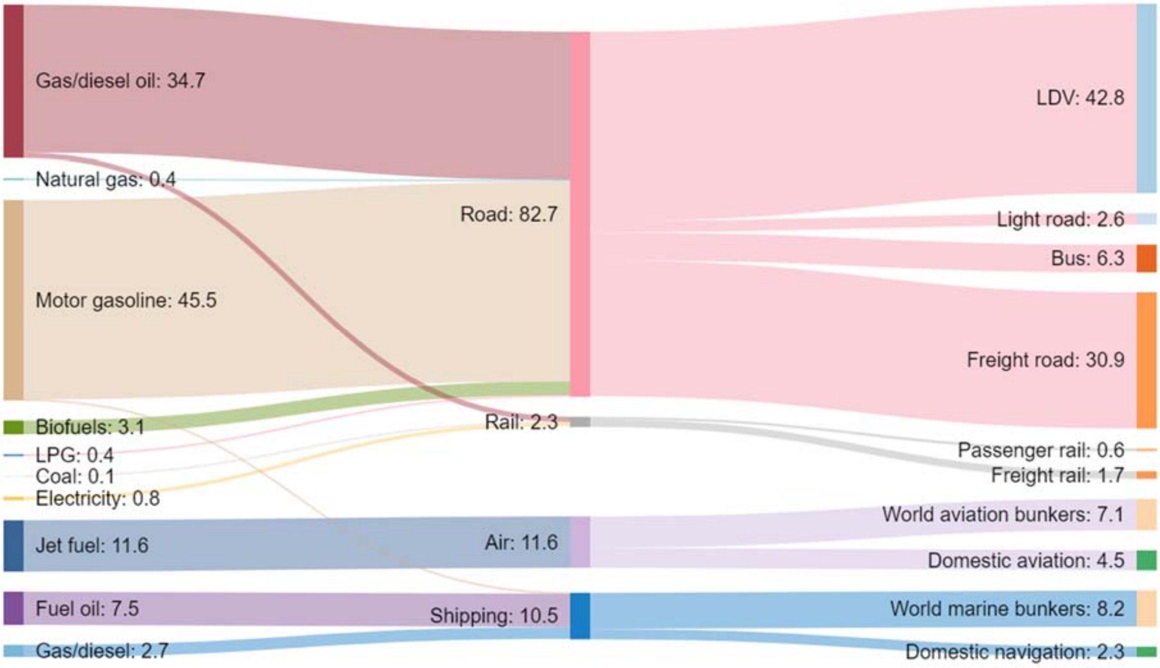


Figure 8.31 Energy demand for transport per region 2014-2050

Final energy flows

2014



2050

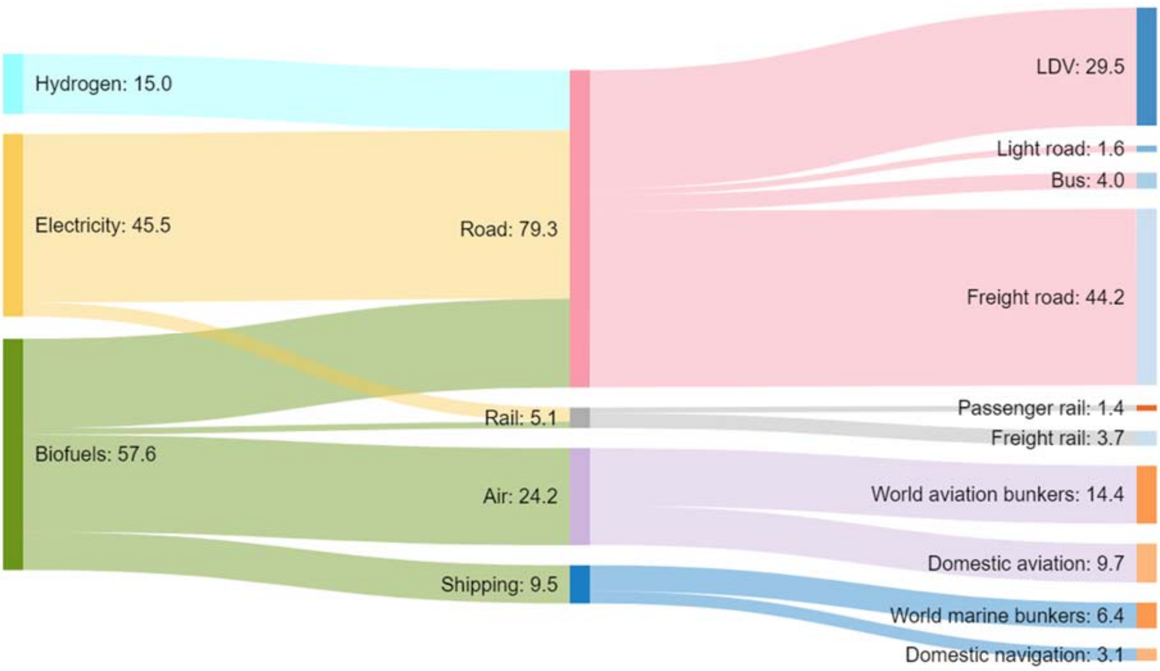


Figure 8.32 Final energy flows in global transport sector in 2014 and 2050 (in EJ). Between 2014 and 2050, a shift takes place from gasoline and diesel as main energy carriers towards electricity and biofuels.

8.4 Other

8.4.1 Efficiency improvements

Efficiency improvements in the fishing sector can be realized by improving the performance of the ships and the catch technology (Priour and Khaled, 2009; Sterling, 2009). Yet, little research has been published on the efficiency potentials. Therefore, the same efficiency improvement for ship transport are assumed of 56% in total between 2014 and 2050.

The global energy efficiency potential in agriculture has not been studied extensively either. According to Gallaher et al. (2009), fuel consumption in US agriculture could be reduced with 43% and 48% for petroleum and electricity respectively. An average efficiency improvement of 45% is assumed (1% per year).

Finally, for the non-specified sector an annual efficiency improvement of 1% is assumed which corresponds to 43% efficiency improvement between 2014 and 2050.

Table 8.7 Assumed efficiency improvements by 2050 in Other

Sector	Efficiency improvement (energy / product)
Fishing	56%
Agriculture/Forestry	45%
Non-specified (other)	43%

8.4.2 Technology switches

Looking at the current energy consumption in these categories, Diesel provides 49% and 76% of the energy in agriculture/forestry and fishing respectively and only 5% in the non-specified (other) category. No technologies are specified for this category, thus the following assumptions are made for replacing fuels:

- All fossil liquid fuels are replaced by biofuels
- All solid and gaseous fossils are replaced by electricity

8.4.3 Energy demand Other

The other category plays a relatively small role in the total final consumption. In 2050, 49% of the energy is provided by biomass, while the remaining 51% comes from electricity.

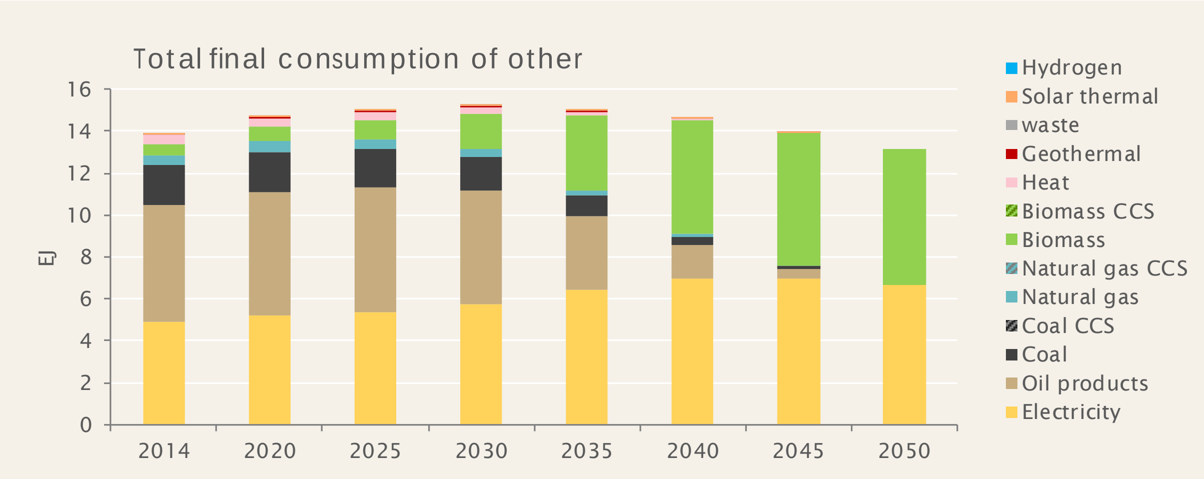


Figure 8.33 Global final energy consumption Other 2014-2050 in EJ

9. Total primary energy supply

Primary energy supply is presented in this section. First of all, the developments in the power sector are looked at, secondly the energy industry own use is reviewed and finally the total primary energy supply is depicted.

9.1 Power sector

In this scenario, demand for electricity increases with 184% between 2014 and 2050 up to 241 EJ. In 2050, 15% of the electricity is used to produce a of total 27 EJ hydrogen. 38% of the total final consumption in 2050 is provided by electricity. The electrification in transport and buildings are the main reasons for this enormous increase in demand, as well as the additional economic welfare.

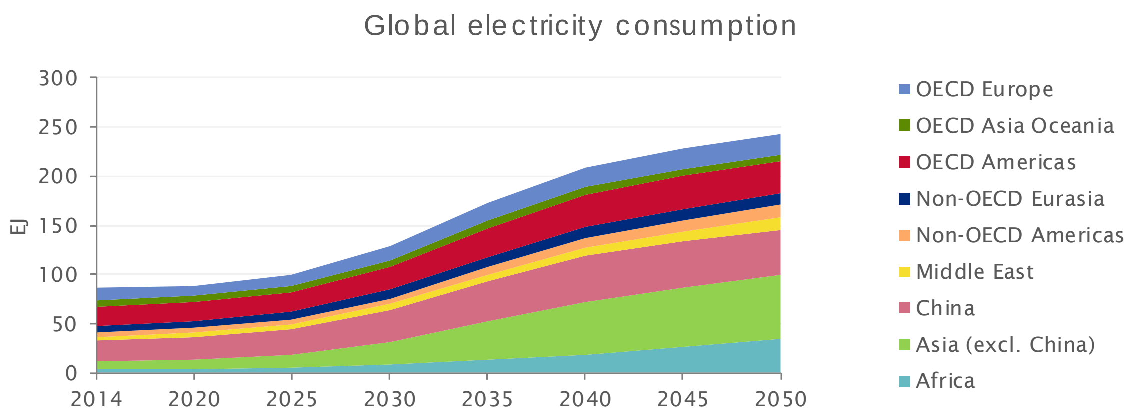


Figure 9.1 Global electricity consumption between 2014 and 2050 per region

Especially in Africa and Asia (excl. China), substantial relative growth of electricity demand is expected although the electricity consumption per capita is still modest compared to other regions. Figure 9.2 shows the electricity consumption per capita in 2014 and 2050. OECD Americas and OECD Asia Oceania remain the largest electricity consumers in terms of energy per capita.

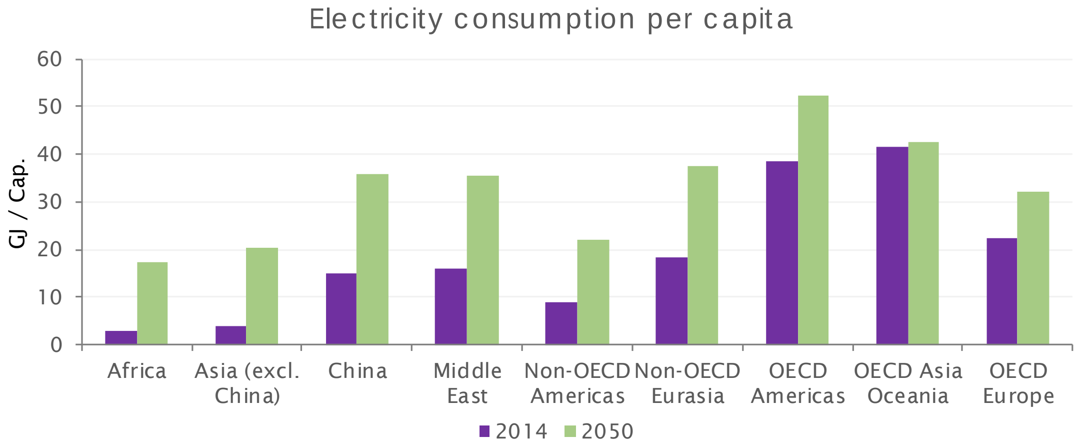


Figure 9.2 Electricity consumption per capita in 2014 and 2050. The consumption gap between developing and developed countries is expected to be reduced towards 2050

9.1.1 Deployment of renewables

Rapid decarbonization of the power system is a must to reduce the cumulative GHG emissions. First an analysis is done, to decide in which year the power system will be based on 100% renewable energy sources. This is done by looking at the implications of shifting the 100% renewables year for the cumulative emissions of the power sector on one hand and the required capacity of wind and solar (the largest renewable energy sources) on the other hand.

Looking at the cumulative emissions for the power sector, significant savings can be realized if a 100% renewable power supply is realized before 2050. In the most extreme case (100% renewable by 2030), 138 Gt of CO_2 emissions can be saved compared to a 2050 scenario. However, this requires an incredible scale up of production capacity before 2020.

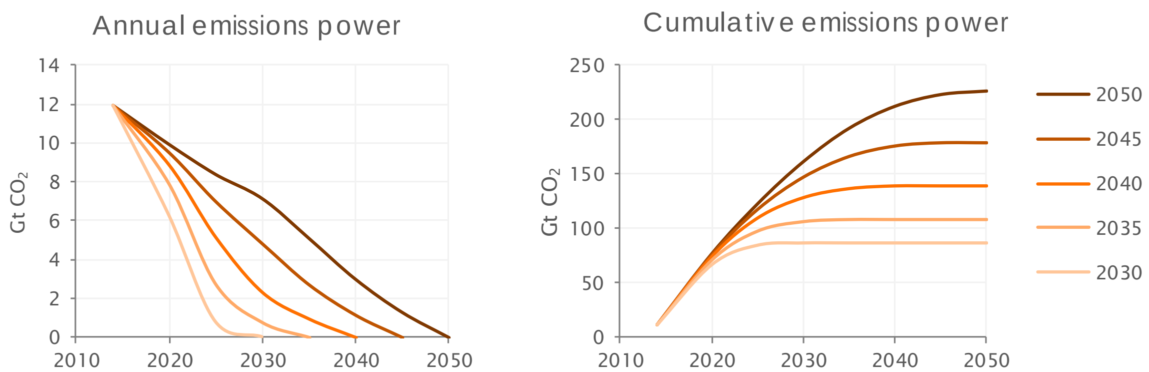


Figure 9.3 Annual emissions and cumulative emissions under different 100% renewable power years

Looking at the required annual newly installed capacities for solar and wind in the different cases, the 2050 and 2045 scenarios peak just after 2035. Required capacities for wind are smaller than for photovoltaics due to the higher capacity factor. The peak of annual average demand in 100%

renewable power grid by 2035 and 2040 requires a lower peak demand compared to the other scenarios. 2035 is an incredibly short timeframe and therefore a compromise is found by assuming 100% of the electricity will be derived from renewable sources by 2040. This still results in 88 Gt of avoided cumulative CO_2 emissions compared to achieving a 100% renewable energy grid by 2050. Yet, it still requires immense scale up of production: around 2040, the required yearly additions for solar photovoltaics are four times higher than the total capacity installed in 2016.

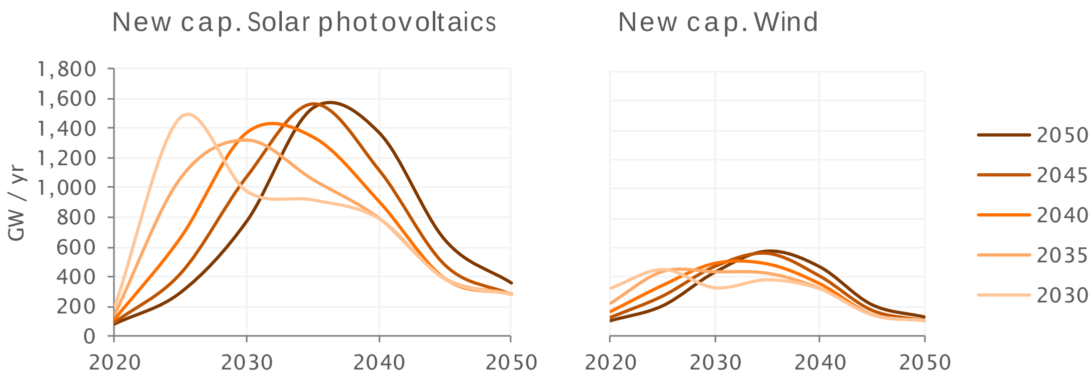


Figure 9.4 Required additional capacities PV and wind under different 100% renewable power years

9.1.3 Energy sources

Looking at the total final consumption in the power sector, a rapid phase out of fossil fuels is required from the start of the scenario. Even though coal fired power plants are one of the first plants to close, coal fired power plants are operational until 2040. This is mainly explained by the power production in China. Capacities of nuclear, natural gas or biofuels in China are relatively small and are insufficient to replace coal before 2040. In countries, where natural gas and nuclear energy already provide a significant share of the current energy consumption, coal fired plants can theoretically be phased out by 2025 if nuclear plants would remain open.

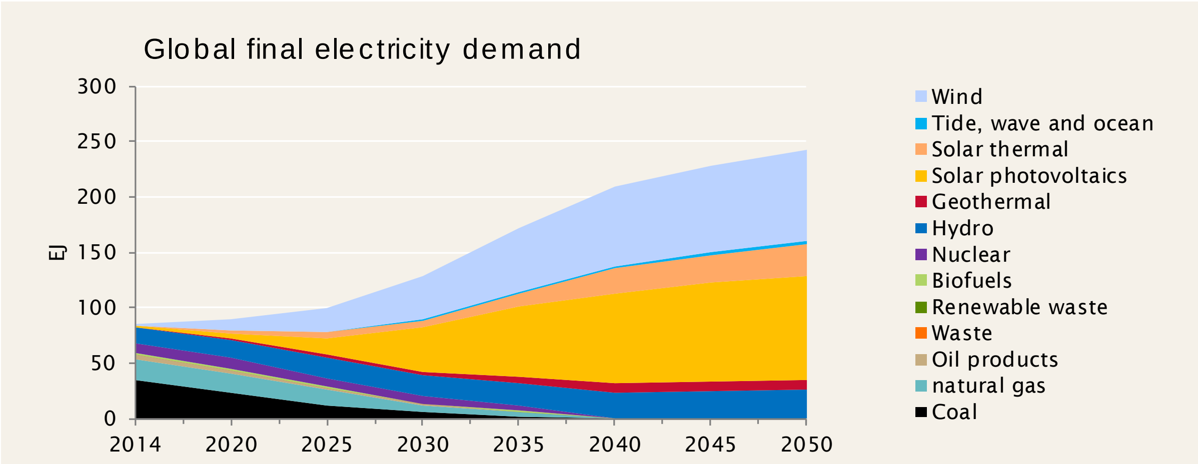


Figure 9.5 Global final electricity demand by source between 2014 and 2050 increases to 243 EJ.

By as soon as 2025, more than 63% of the electricity demand is powered with renewable energy sources in this scenario. Wind and solar photovoltaics have already become the main renewable energy sources by 2050.

Looking at the required capacities of renewables (table 9.1), most absolute growth is required for solar photovoltaics and wind. For hydro power, the relative growth rates is much lower as capacity doubles in 36 years' time. High relative growth paths are required for solar thermal, geothermal and tide, wave and ocean, but the absolute growth is still limited in the start of the scenario.

Table 9.1 Capacities renewable energy technologies between 2014 and 2050 in GW

Energy source	2014	2020	2025	2030	2035	2040	2045	2050
Solar photovoltaics	194	895	4,216	11,054	17,733	22,254	24,183	25,606
Solar thermal	1	103	154	206	371	713	818	909
Wind	363	1,365	3,104	5,597	8,068	9,866	10,600	11,132
Hydro	1,110	1,347	1,498	1,543	1,658	1,834	1,934	2,012
Tide, wave and ocean	0	11	14	19	36	68	72	72
Geothermal	9	51	70	90	156	282	298	303

Most additional capacity is required for solar photovoltaics: between 2020 and 2025 664 GW of new photovoltaic panels have to be installed annually and between, 2025 and 2035 the required additional capacity is doubled. The main growth is found in Asia and China (figure 9.6) where there is limited amount of wind energy available and a steep increase in demand. From 2035 onwards, the additional capacity that needs to be installed declines. Even small negative new capacities are found in OECD regions. The production capacity that has become available can then be used to replace photovoltaics that reached the end of their lives.

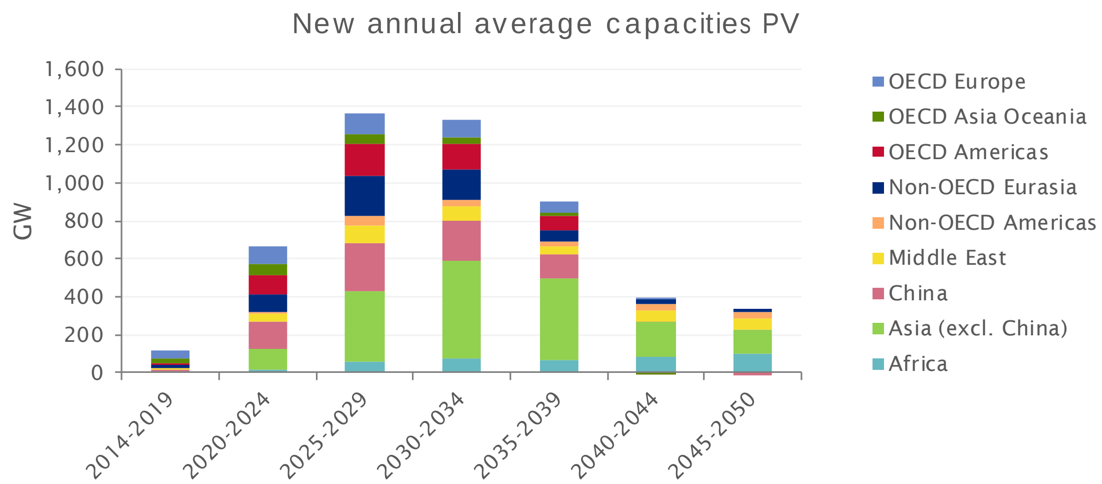


Figure 9.6 Additional annual capacities solar photovoltaics per region

The global required average annual growth rates of consumption from wind energy decreases from 25% between 2014 and 2020 almost linearly to around 1% by 2050. Growth rates in Middle East is an outlier which is explained by the marginal contribution of wind in the current electricity production.

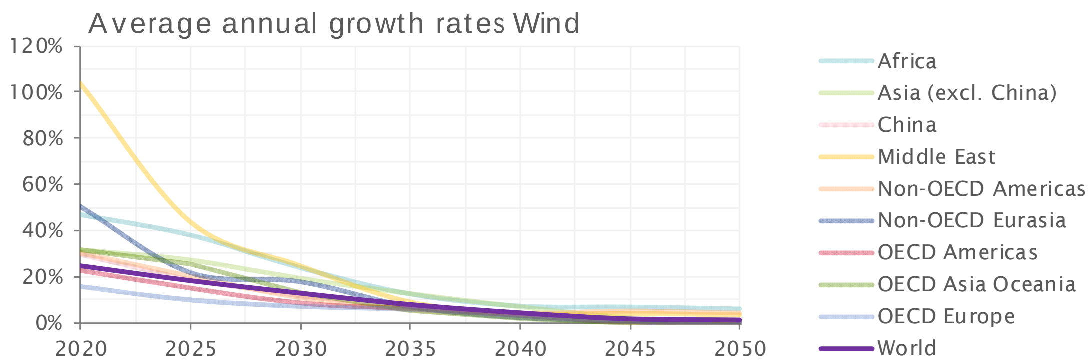


Figure 9.7 Average annual growth rates for consumption of power from wind

Other than for wind, deployment of solar photovoltaics requires high average annual growth rates that peak between 2020 and 2025. Especially in Asia (excl. China), Africa and Middle East, high annual growth rates are required.

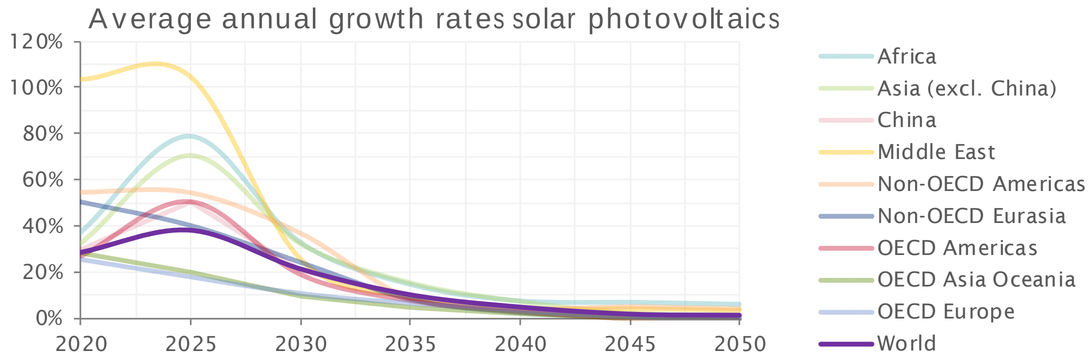


Figure 9.8 Average annual growth rates for consumption of power from solar photovoltaics

9.1.4 Comparison with other scenarios

In this section, the electricity scenario is compared with other low carbon scenarios. First of all, a closer look is taken at electricity production in three low carbon scenario's. Subsequently, the scenario is compared with the most stringent IAM scenario's from the fifth assessment report (AR%) by the IPCC (2014).

When comparing the energy mix for the power sector with other renewable energy scenarios, it is first of all noticeable that the electricity demand is higher than in all other scenarios. This is partly explained by the advanced electrification in the transport sector. By 2050, 65 EJ of electricity (incl. hydrogen production) is required for transport which is 21 EJ higher than the Greenpeace advanced revolution scenario (2015) accounted for and 38 EJ higher than the projections by the IEA B2D scenario (2017). Furthermore, the generation of photovoltaics and wind energy is higher than in the other scenario's.

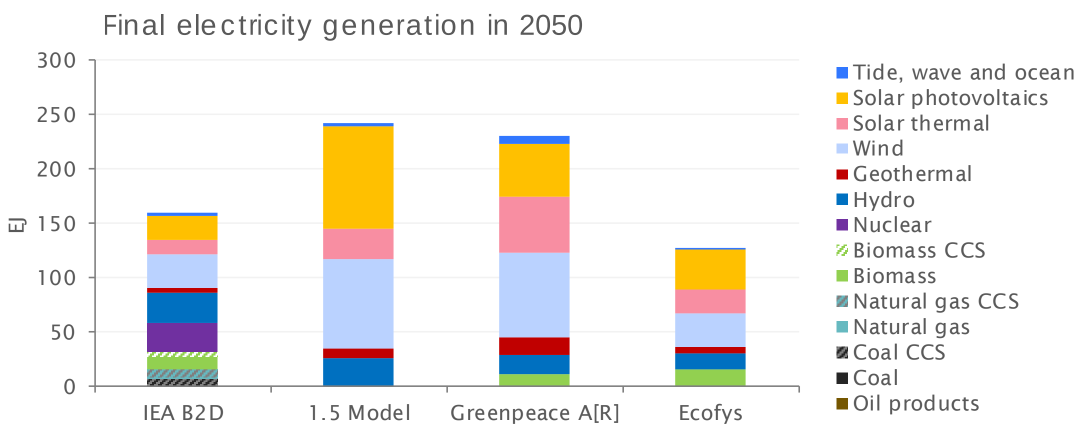


Figure 9.9 Comparison scenarios global final electricity consumption 2050

The amount of hydro power in the 1.5 model is also relatively high compared to most other scenarios, but just below the amounts used in the B2D scenario. Another important difference is that the 1.5 model is the only model in which there is no biomass used for electricity production.

For a comparison of electricity generation with low carbon IAM scenarios, 34 scenarios from the latest IPCC report (2014) were selected with a probability of exceeding 1.5 °C below 66%. Of these scenarios, only six had a chance higher than 50% to stay within 1.5°C. Looking at the total final electricity production (figure 9.10), this scenario remains within the margins of other scenarios. For wind and solar (PV and solar thermal), this electricity scenario exceeds the growth trends in the selected AR5 scenarios. The same production level of wind and solar is found only after 2060 in the AR5 scenarios. Furthermore, coal, nuclear and natural gas for power generation is phased out earlier than in most IAM scenarios. For electricity production from hydro, the proposed scenario is near the average consumption in comparison to the AR5 scenarios. Electricity from nuclear and biomass plays a considerable role in most IAM scenarios, while it is phased out in this scenario.

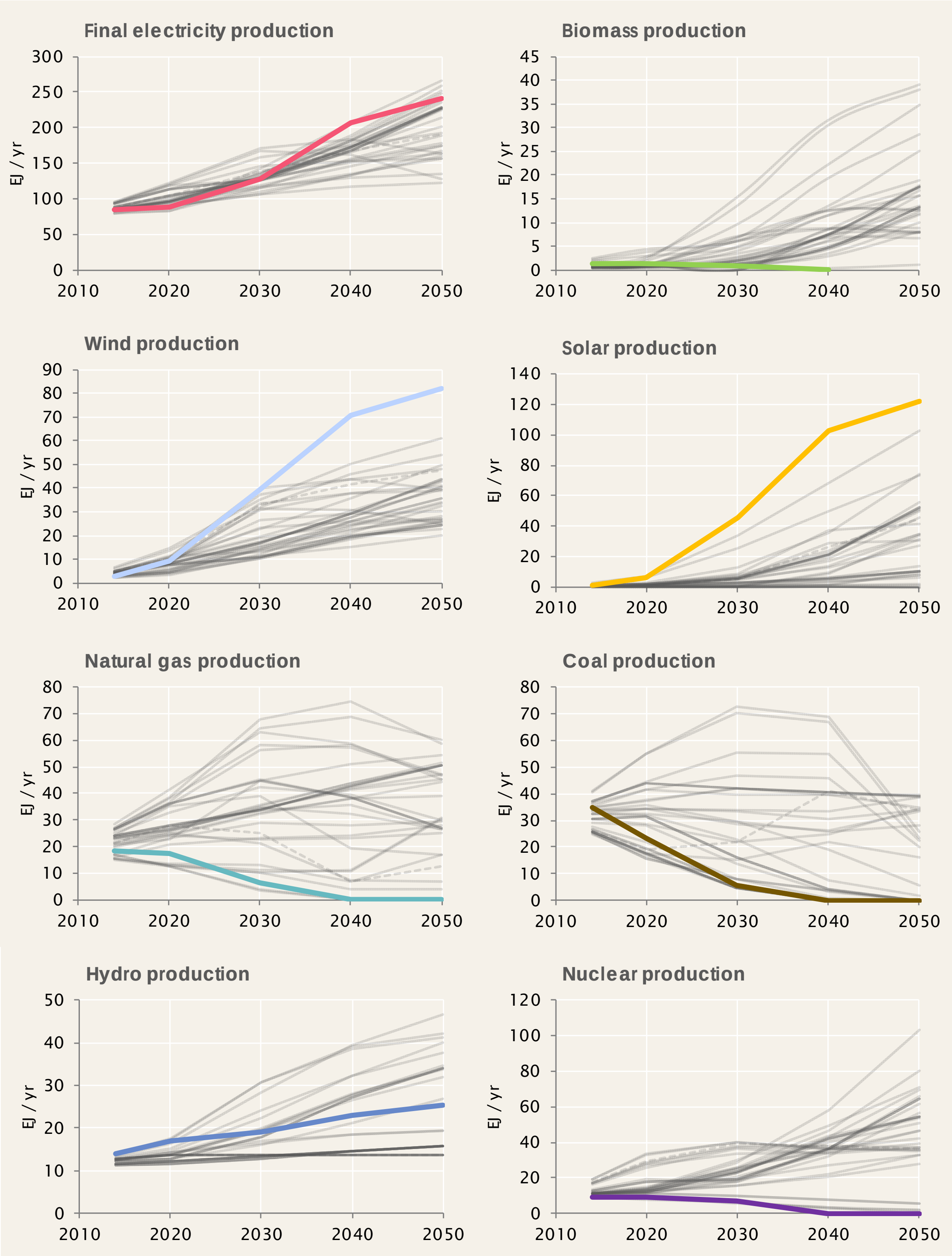


Figure 9.10 Developments in electricity production from different energy carriers. Comparing the 1.5 model (coloured lines) with the most ambitious AR5 scenarios

9.2 Energy industry own use and losses

The total energy demand for energy industry own use and losses (EIOUL) is reduced with 64% between 2014 and 2050. The reduced energy use in oil and natural gas extraction and oil refineries combined are responsible for 80% of the reduction. The only sector in which the energy industry own use is increased is in electricity from 5.4 EJ to 8.8 EJ. With the decentralization of the electricity grid it can be argued whether the percentage of losses is still the same: large central plants are replaced with smaller installations.

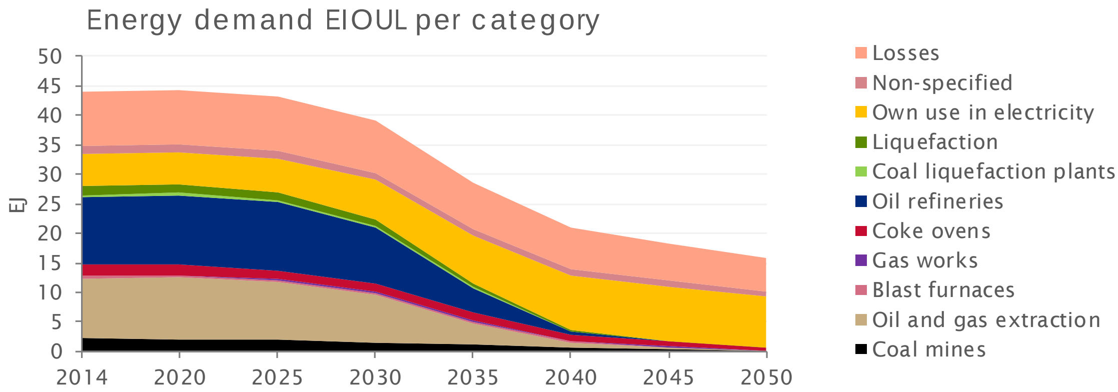


Figure 9.11 Global energy demand energy industry own use and losses between 2014 and 2050

9.3 Total Primary energy supply

Now, the total final consumption of all sectors are calculated as well as the power sector and energy industry own use, the total primary energy supply is presented.

9.3.1 Description of total primary energy supply

Despite, an additional 1.9 billion people and a tripling of the global economy, the total primary energy actually decreases between 2014 and 2050 by 21%.

Between 2014 and 2025, the use of coal is already reduced significantly, mainly due to the phase out in the electricity sector. Furthermore, the capacity of renewable energy sources increases between 2014 and 2025 with high growth rates but with still a relatively small contribution. The oil consumption peaks around 2025. Between 2025 and 2030, the consumption of coal and natural gas is further reduced to 54% of the consumption level in 2014. By 2030, coal and natural gas consumption is almost equal in size. The share of wind and solar photovoltaics are also of equal sizes in 2030 and provide each 40 EJ. Each of these two energy carriers have become double as big as nuclear (21 EJ) or hydro (19 EJ) in 2030.

From 2030 until 2040, oil demand is in a free fall. This rapid decrease is explained by two phenomena taking place in the transport sector: the ban on internal combustion engines in most regions by 2030 and the full deployment of biofuels by 2035 for non-road transport and 2040 for road transport. In line with the current IEA convention, the primary source for biofuels production is not taken into account in the primary supply. Biofuels for transport peaks in 2040 with 83 EJ of annual consumption. The use of other biomass in industry and buildings remains relatively constant. Though, the use of biomass decreases in buildings, more biomass is used in the industry as feedstock and for high temperature heat.

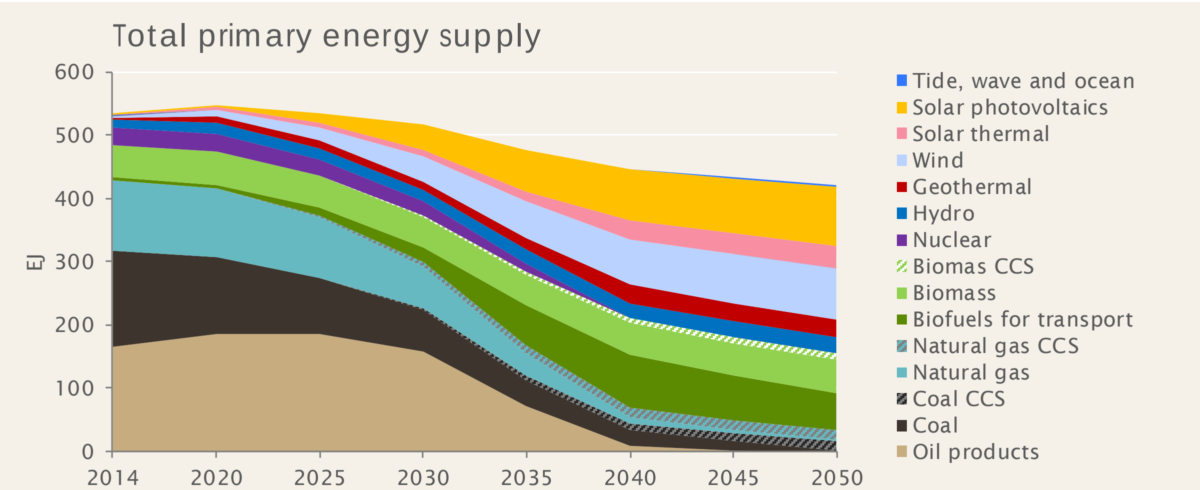


Figure 9.12 Global total primary energy supply between 2014 and 2050 reduces despite the increased activity

Between 2040 and 2050, the developments are relatively small compared to the previous years. In this period, most changes are found in the industry sector where CCS technologies are further deployed and biomass is increasingly used as feedstock in the chemical sector. Furthermore, biofuels for road transport are phased out as hydrogen and fuel cell cars gain market share. At the end of the scenario, biofuels demand is reduced to 58 EJ.

Table 9.2 Global primary energy supply between 2014 and 2050 per energy source in EJ

Energy carrier	2014	2020	2025	2030	2035	2040	2045	2050
Oil products	165	187	186	158	72	9	2	0
Coal	153	121	88	65	41	25	14	2
Coal CCS	0	0	1	4	8	11	14	16
Natural gas	111	108	96	66	36	10	3	0
Natural gas CCS	0	1	2	7	13	16	17	17
Biomass	51	53	51	49	47	49	51	52
Biofuels for transport	3	6	11	23	62	83	69	58
Biomass CCS	0	0	1	2	6	9	11	11
Nuclear	28	28	24	21	14	0	0	0
Hydro	14	17	19	19	21	23	24	25
Geothermal	3	10	12	13	19	30	29	27
Wind	3	10	22	40	57	71	77	82
Waste	1	1	0	0	0	0	0	0
Solar thermal	1	5	7	10	17	29	33	36
Solar photovoltaics	1	3	15	39	64	80	88	94
Other sources	0	0	0	0	0	0	0	0
Tide, wave and ocean	0	0	0	1	1	2	2	2
Total	534	550	535	517	478	447	434	422

The global energy system is completely transformed by 2050 and 100% powered by low carbon energy sources (see figure 9.13). The role of coal and natural gas is substantially reduced and only used in the industry in combination with CCS technology. Perhaps the most significant change is the phase out of oil and oil products in the energy system. Until the year 2030, oil products are the largest energy source. But as the electrification of road transport takes off and the petrochemical industry also switches towards bio-based feedstocks, the utilization of oil products is rapidly phased out.

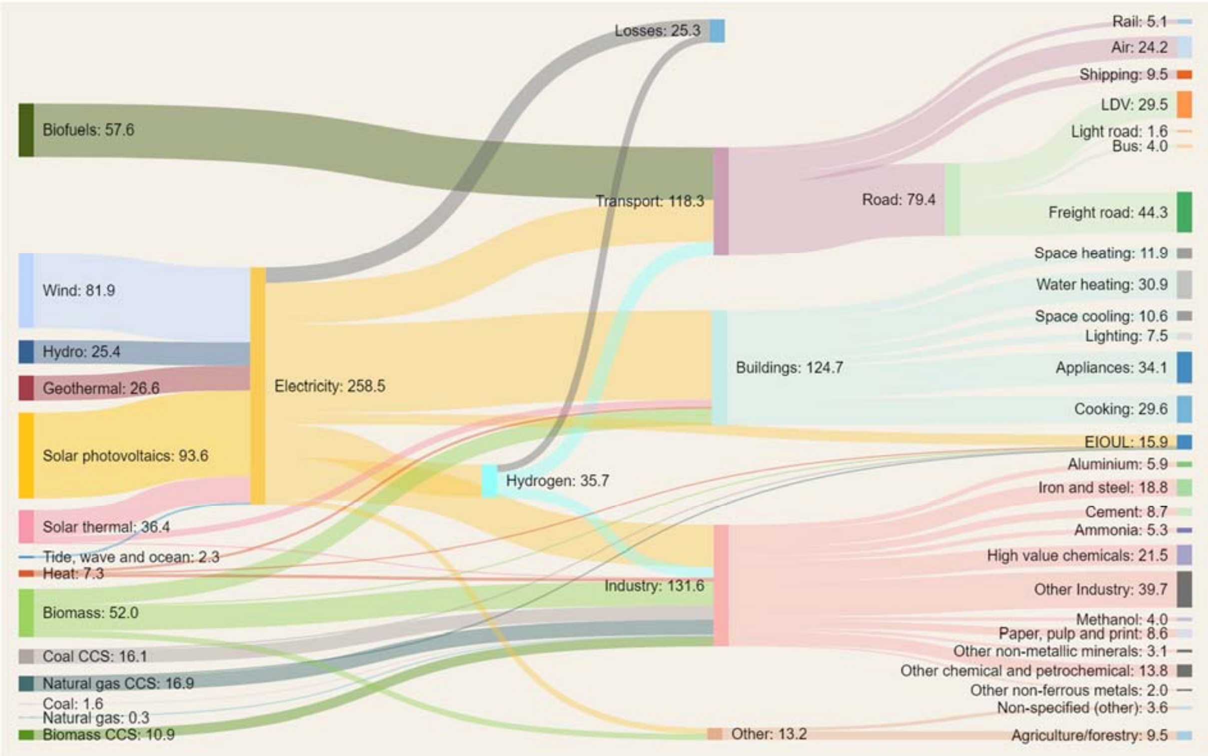


Figure 9.13 Global overview of the energy system by the year 2050 in EJ. Biomass, wind and solar photovoltaics have become the dominant energy sources.

The role of biomass in the energy sector

By 2050, 63 EJ of primary biomass and 57.6 EJ of biofuels is used in the energy system. In 2040, a peak in demand takes place and 84 EJ of biofuels is used. The traditional use of biomass for space heating and cooking decreases over time, while the application for biomass increases in industry as feedstock in the chemical sector or combustible to provide high temperatures. Furthermore, 11 EJ of the used biomass is combined with CCS to create negative emissions.

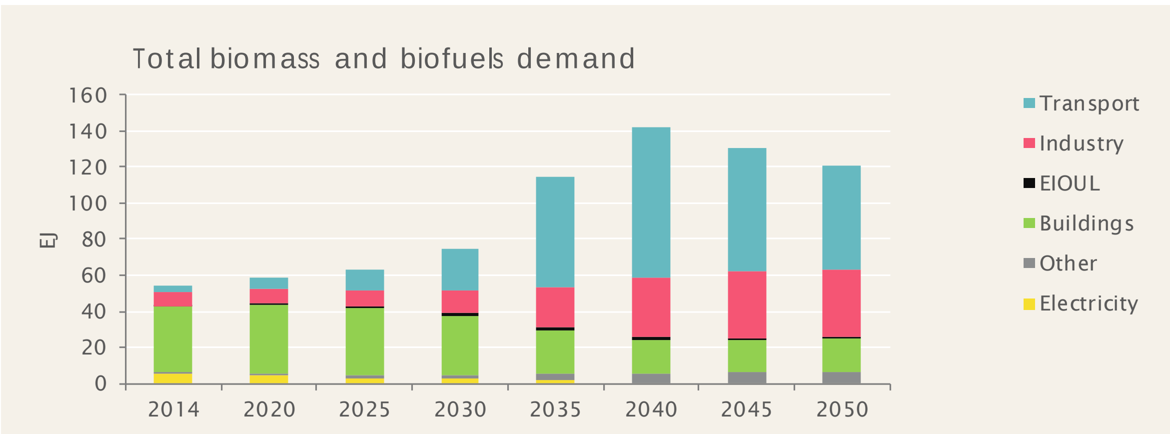


Figure 9.14 Overview of the demand for biomass and biofuels per sector

When looking at the biofuels in the transport sector by 2050, 39% of the biofuels is needed for road transport, 3% for rail transport, 42% for air and 16% of total transport biofuels demand is required for shipping.

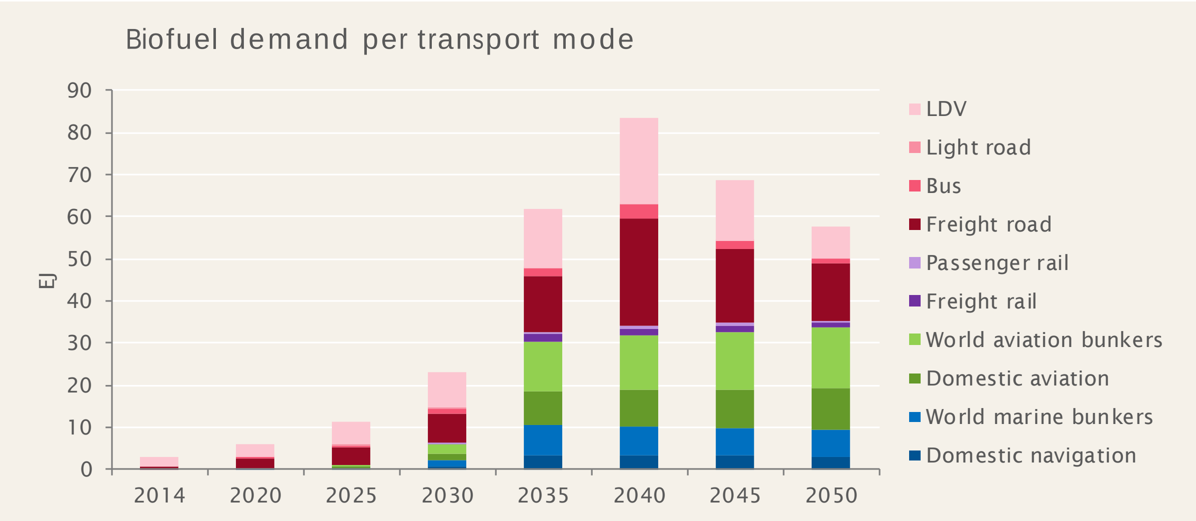


Figure 9.15 Total biofuel demand for different transport modes peaks in 2040 and decreases afterwards due to electrification in road transport

The production of biofuels could be derived from different sources with different conversion ratios, which makes it difficult to calculate the required primary biomass that would be required to produce sufficient biofuels. The conversion efficiency of most biofuels production is around 40% to 50% (Daioglou, 2016). Algae and microalgae would be a promising option to create biofuels on a large scale since it requires limited amount of space (Quinn and Davis, 2015; Schenk et al., 2008). Based on the average rates by Daioglou (2016), a total maximum amount of between 225 and 266 EJ of primary biomass would be required in the energy sector in peak year 2040. This is still within the bandwidth of between 100 and 300 EJ of primary biomass that can be sustainably produced according to the IPCC (2014).

The role of energy efficiency and technology switches

The decrease in total primary energy supply can be explained by the implemented efficiency improvements and technology switches. If energy intensities would have remained constant, TPES in 2050 would reach 917 EJ, an increase of 118%. TPES could even reach almost 1,373 EJ by 2050 in the case no technology switches or efficiency improvements would have been realized. Most technology switches also result in an energy efficiency improvement. This difference is mainly explained by the significant conversion losses in the power sector that are avoided and the switch to hydrogen fuel cells and electric vehicles in the transport sector which are significantly more efficient modes of transport. It should be noted that such a technology freeze is not a business as usual scenario.

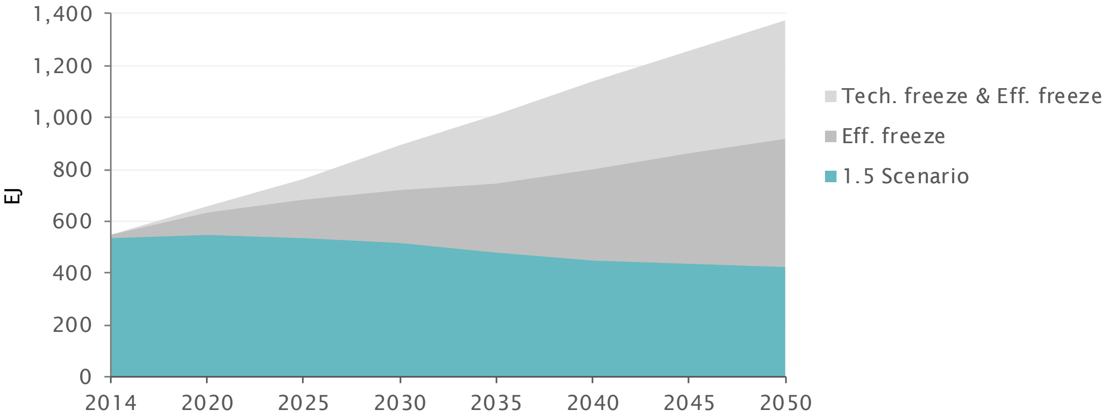


Figure 9.16 The technology switches and efficiency improvements reduce the total primary energy supply in this scenario substantially

9.3.2 Comparison with other scenarios

To place the energy supply in perspective, the results are compared with other scenarios. First of all, the most ambitious scenarios by IEA, Greenpeace (GP) and the world energy council (WEC) are looked at. Unfortunately, no data was available regarding the primary supply of the Ecofys scenario (2012). When it comes to primary energy, this scenario follows more or less the line of the advanced revolution (A[R]) scenario by Greenpeace (2015). But in terms of total final consumption, the 1.5 Model is more in the upper range of the scenarios. It should be noted that the production of coke for steel production is added to the TFC of the 1.5 Model, whereas in IEA convention this is a transformation process.

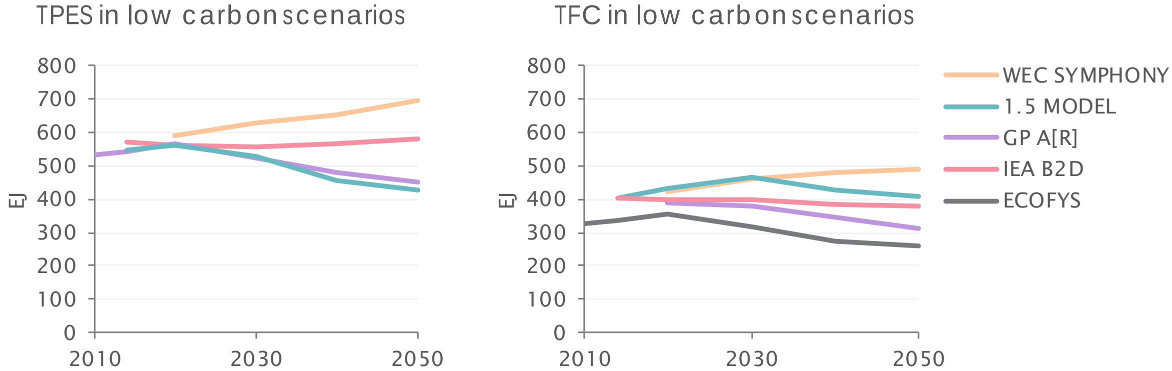


Figure 9.17 Comparison of total primary energy supply (TPES and total final consumption (TFC) in different low carbon scenarios

Subsequently, the results are compared with IAM scenarios. In the upper left graph of figure 9.18, the TPES is compared with 24 baseline scenarios from Riahi et al. (2017). By 2050, the TPES in this scenario is 53% lower than the average energy supply of the baseline scenarios. In the most ambitious scenarios from the IPCC AR5 (2014), the total primary energy supply is in general significantly lower than the baseline scenarios. The TPES in this scenario remains within the bandwidth of the low carbon scenarios (upper right graph in figure 9.18), though it moves from the higher side in 2014 to the lower side of the range by 2050. In terms of TFC (bottom figures in 9.18), the scenarios are less dispersed than TPES, this difference can be explained by the reduced thermal conversion losses for electricity production in the low carbon scenarios.

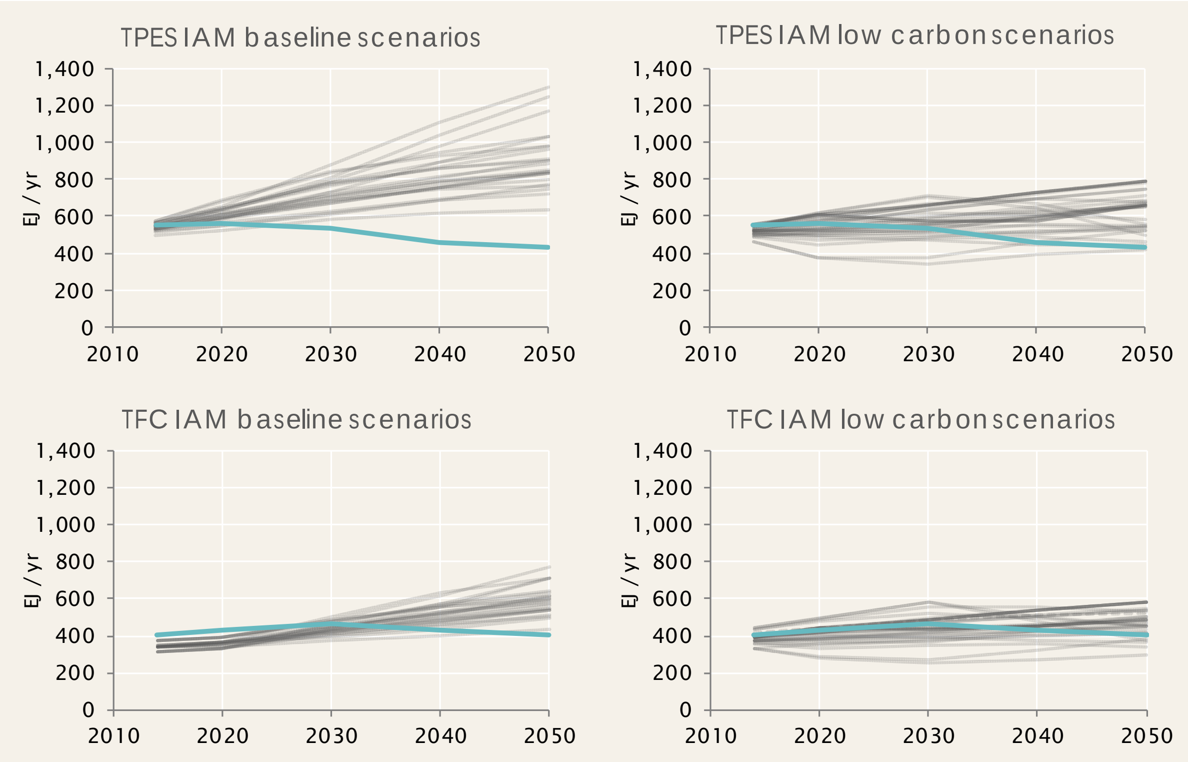


Figure 9.18 Above: comparison of TPES with baseline scenarios from IAM's by Riahi et al. (2017) and the low carbon IAM scenarios from IPCC AR5 (2014). Below: comparison of TFC with baseline scenarios and the low carbon IAM scenarios.

10. Emissions and carbon budget

Annual emissions CO_2 emission pathways between 2014 and 2050 are presented in this chapter as well as the cumulative emissions. A comparison with other scenarios concludes this last chapter of the results.

10.1 Annual CO_2 emissions

The annual emissions from energy and cement industry accounted for 35.4 Gt of CO_2 in 2014 with electricity production as the largest source of emissions (11.9 Gt CO_2). The process related emissions from calcination of cement accounted for 2 Gt CO_2 in 2014. The fast deployment of renewable electricity technologies results in a steady decline of emissions in the power sector. The annual emissions from the transport sector peak in 2025, but decrease fast after 2030 as the internal combustion engines are phased out and biofuels replace all liquid fossils. Mainly due to the rapid decarbonization of the energy sector, the average annual emissions between 2014 and 2050 is limited to 17.7 Gt CO_2. By 2040, the energy system is already practically decarbonized: the annual emissions in 2040 are only 11% of the emissions in 2014.

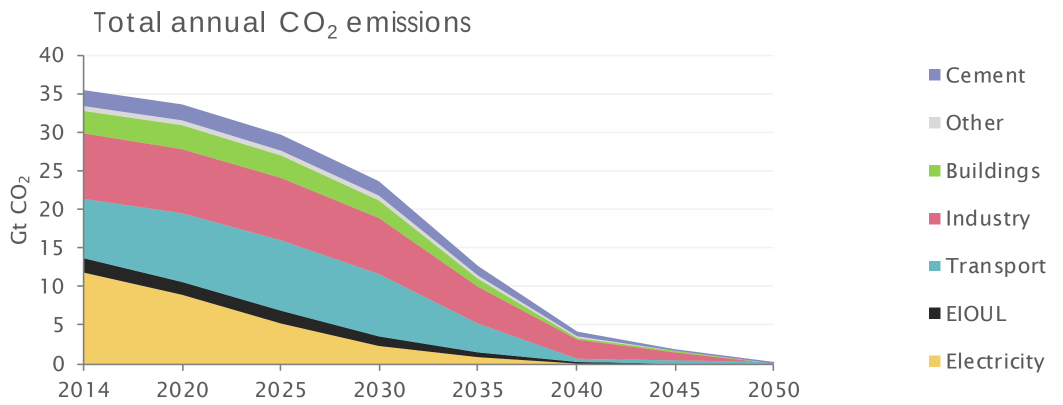


Figure 10.1 Total annual CO_2 emissions per source between 2014 and 2050

Emissions from industry, the third largest emitter, decreases relatively slow compared to other sectors. This is explained by the late assumed availability of low carbon technologies in this sector. However, some negative emissions in the industry (in cement and paper production) are responsible for 1.2 Gt CO_2 of negative emissions in 2050. which results in net emissions of -0.39 Gt for the entire sector by 2050 (see figure 10.2).

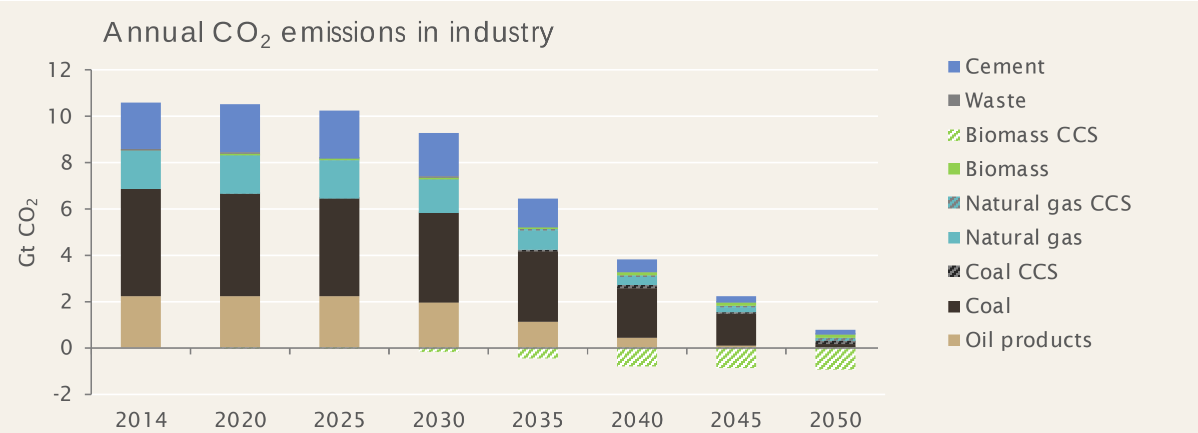


Figure 10.2 Annual CO_2 emissions in industry between 2014 and 2050

10.2 Cumulative emissions

Due to the rapid decarbonization of the energy system, the cumulative CO_2 emissions between 2014 and 2050 account for 680 Gt. In the first 16 years, already 78% of the cumulative emissions are realized, while between 2040 and 2050, only 17 Gt CO_2 is added to the carbon budget. Oil products were found to be the main contributor to the total emissions. Furthermore, a cumulative 14.7 Gt negative emissions were realized before 2050.

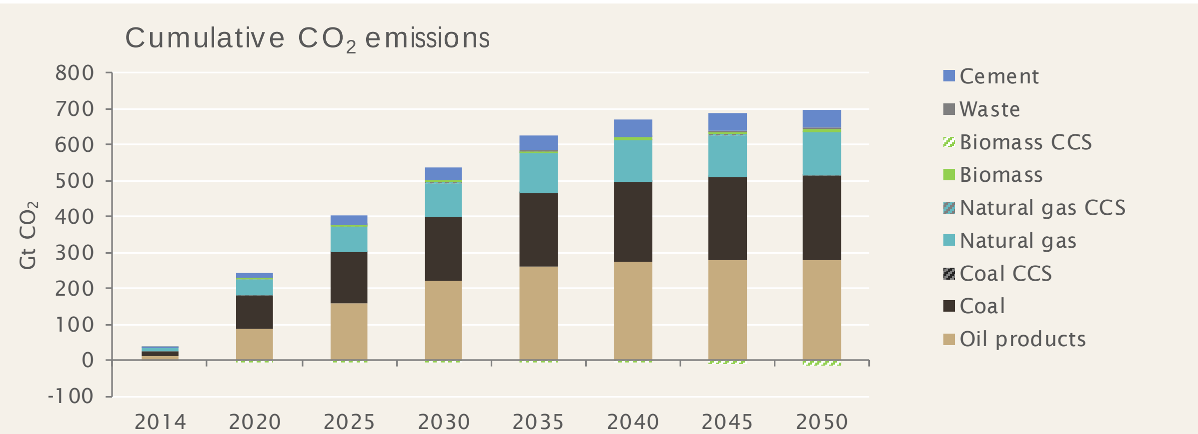


Figure 10.3 Total cumulative CO_2 emissions between 2014 and 2050

The results overshoots the net carbon budget proposed by Rogelj et al. (2015). Therefore, further deployment of negative emission technologies is needed in the second half of the century.

Given the cumulative emissions between 2014 and 2050, the net carbon budget between 2011 and 2100 from Rogelj et al. (2015) and the CO_2 that has been emitted between 2011 and 2014 (106 Gt), between 371 and 587 Gt of additional negative emissions have to be realized to compensate for the fossil fuels and industr (see table 10.1).

Table 10.1 Required cumulative negative emissions

Cumulative CO_2 emissions 2011-2014	**106**
Cumulative CO_2 emissions 2014-2050	680
Carbon budget 2011-2100	199/415
Required cumulative emission	**-371/-587**

If the full capacity of negative emissions would be deployed in 2030, average required annual negative emissions would be between -5.3 and -8.4 Gt.

10.3 Comparison with other scenarios

Finally, the annual and cumulative emissions from fossil fuels and industry are compared with other IAM scenarios. Just as for the total energy supply, emissions are compared with baseline scenarios from Riahi et al. (2017) and low carbon scenarios from IPCC AR5 (2014) with a chance of exceeding 1.5˚C under 66%.

Looking at the annual emissions in the baseline scenarios, it becomes clear that this scenario substantially deviates already by 2020 (figure 10.4). For most low carbon scenarios (right graph in figure 10.4), it is noticeable that most scenarios already assume substantially lower emissions by 2014, than actually found. The emissions in this scenario are relatively high at the start in comparison to the other scenarios, but by 2050 these have been substantially reduced.

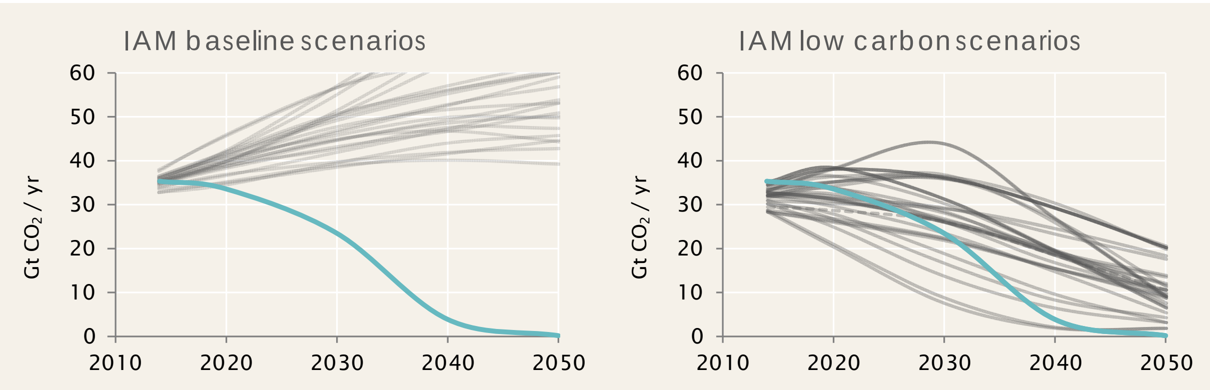


Figure 10.4 Comparison of annual CO_2 emissions from fossil fuels and industry with baseline scenarios (Riahi et al., 2017) and most ambitious AR5 IPCC (2014) scenarios

When looking at the total cumulative emissions from fossil fuels and industry by 2050, the total emissions in this scenario are 61% lower than the average baseline scenarios and 25% lower than the average cumulative emissions in the low carbon scenarios.

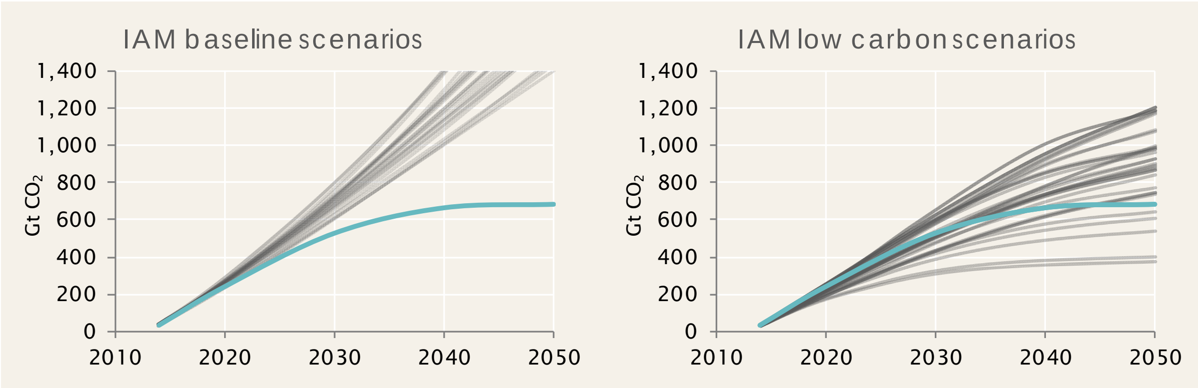


Figure 10.5 Comparison of cumulative CO2 emissions from fossil fuels and industry with baseline scenarios (Riahi et al., 2017) and most ambitious AR5 IPCC (2014) scenarios. Starting year is 2014

11. Sensitivity analysis

Finally, a sensitivity analysis is conducted to complement the results. This analysis is conducted on three aspects. First of all, the effect of different GDP and population scenarios is looked at. Secondly, the impact of different material demand projections in industry are reviewed. Finally, more high efficient space heating and water heating is looked at for buildings.

11.1 Shared Socio-economic pathways

For this scenario, the 'middle of the road' socio-economic pathway is used which is referred to as SSP2. Besides, there are four other pathways with different narratives and GDP and population growth assumptions (figure 11.1).

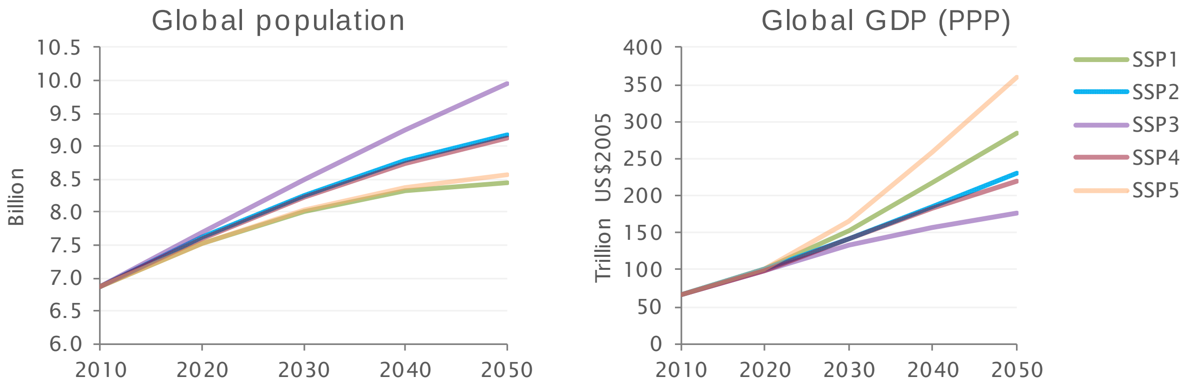


Figure 11.1 Global population and GDP growth in different shared socio-economic pathways

The results demonstrate that a higher level of global GDP results in a higher level of primary energy supply and cumulative emissions. For primary energy supply in 2050, values were found between 373 EJ and 525 EJ. In terms of cumulative CO_2 emissions, a total difference of 50 Gt CO_2 was found between the lowest and highest scenarios by 2050. The deviation of cumulative emissions is maximum 5% from the proposed scenario (SSP2).

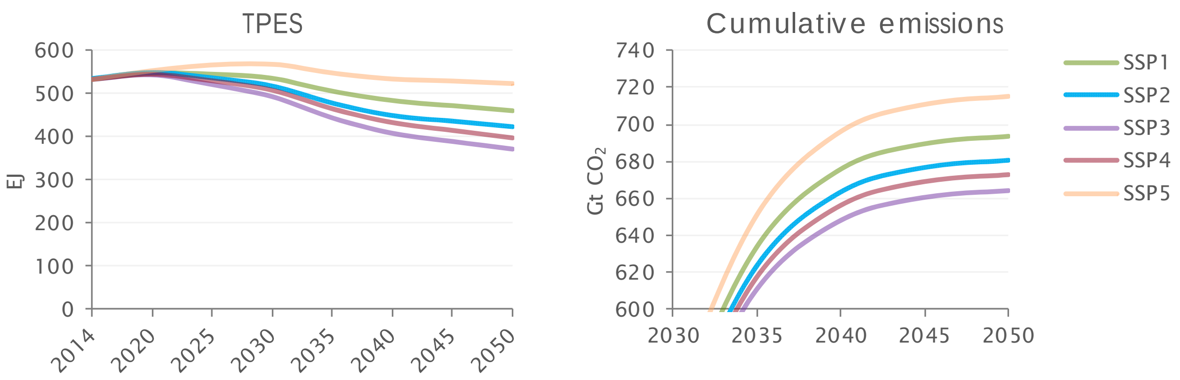


Figure 11.2 Comparison of total primary energy supply (TPES) and cumulative emissions for different socio-economic pathways. The SSP2 line is used in this scenario

This sensitivity analysis demonstrates that different economic growth levels clearly have an effect on emissions and primary energy supply, though it is relatively small: in the SSP 5 scenario, the global economy is twice the size of SSP3 by 2050, yet the TPES is 41% higher and cumulative emissions 8%. This can be explained by the fact that the main deviation takes place after 2030 when decarbonization is already quite progressed.

11.2 Material demand in industry

In chapter 7, the future activity demand was determined. For most materials in industry, literature studies were used to validate the findings. And though, the results were usually pretty close to reference literature, a sensitivity analysis is conducted to explore the lower and upper boundaries of other studies. An overview of the variety found in literature for four key materials is visualised in figure 11.3. Most variety was found in literature, for steel demand in 2050.

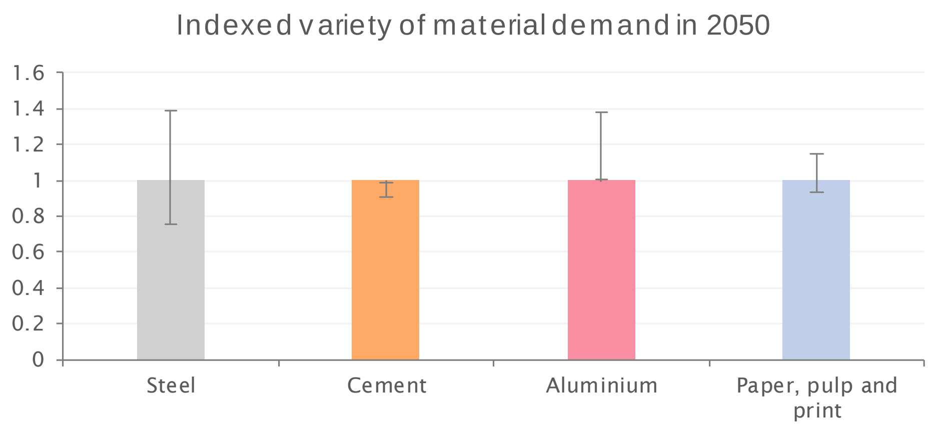


Figure 11.3 Indexed variety in literature for steel, cement, aluminium and paper pulp and print demand by 2050

In order to conduct this sensitivity analysis, the upper and lower boundaries were used as factors to scale the global demand by 2050. Therefore, no additional difference in regional distribution was taken into account.

In the high material demand scenario, TFC of the industry is 12 EJ higher in 2050 compared to this scenario. In the low material demand scenario, TFC of the industry is 6 EJ lower. The total cumulative emissions in the low and high material scenarios are 11.1 Gt CO_2 lower and 17 Gt CO_2 higher respectively by 2050 compared to this scenario. This is a maximum deviation of 3%.

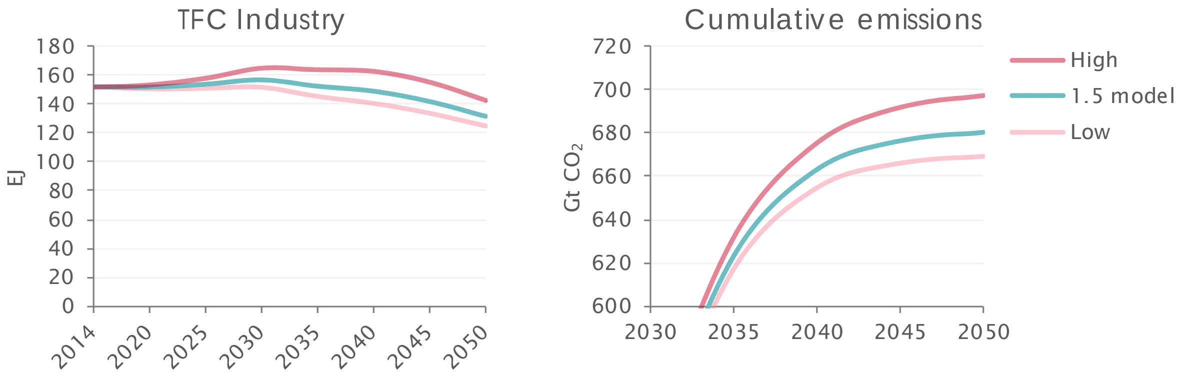


Figure 11.4 Comparison of high and low material demand with the 1.5 scenario

11.3 High efficient heating in the building sector

A third and final sensitivity analysis is conducted to explore the impact of the chosen technology switches in electric space heating and water heating in buildings. In chapter 8, a distribution was made for different heating technologies in different regions. By 2050 most technologies are assumed to be powered with electricity. A distribution was made for space and water heating between highly efficient technologies (heat pumps) and more low efficient technologies (electric boilers or resistance heating) for each region. Reasoning that some part would always be provided by low efficient technologies especially in developing countries with low heating demand, due to lack of capital or practical reasons.

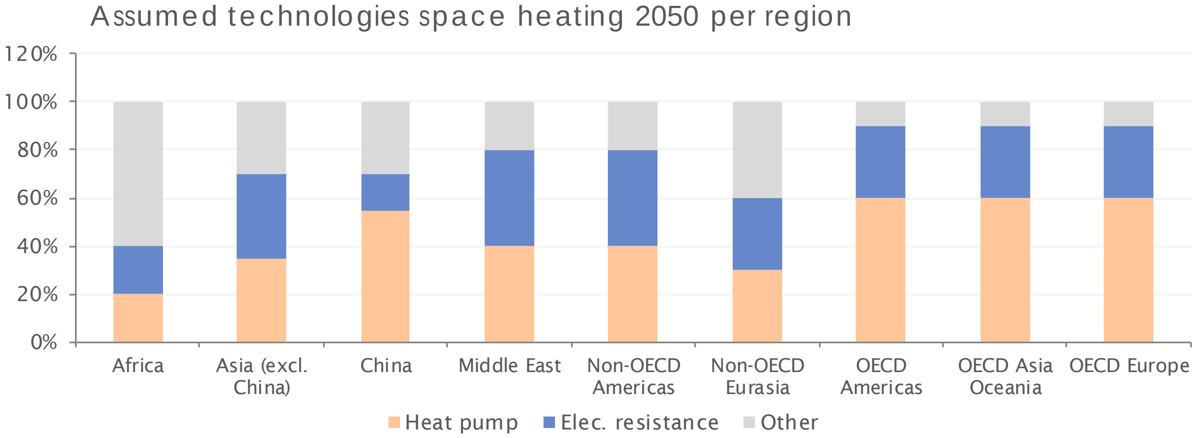
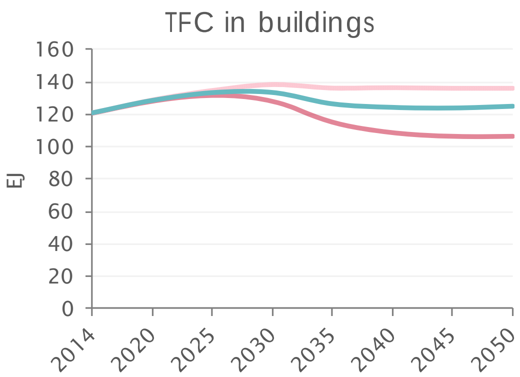
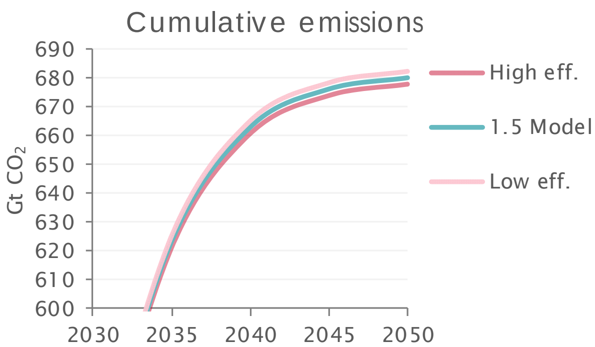


Figure 11.5 Assumed distribution of technologies for residential space heating per region by 2050

In order to see the impact of using high efficient technologies on energy and emissions, two extremes scenarios were developed: one in which all electric space and water heating uses low efficient technologies and another in which all electric water and space heating is provided by highly efficient heat pumps. The total final consumption of buildings in the high efficiency scenario, is 30 EJ lower than the low efficiency scenario and 18 EJ lower than this scenario. In terms of cumulative emissions, the difference is much smaller (only 5 Gt CO_2). This is explained by the fact that all electricity is derived from renewable sources by 2040.





12. Discussion

The aim of this study was to develop a scenario and explore the required transition path of the energy system within 1.5 degrees in which the amount of required negative emissions is minimized. The results demonstrate that total emissions should be substantially reduced by as soon as 2040 in which the power and transport sector have been completely transformed. This steep decarbonization path in the first half of the century results in significantly lower cumulative emissions than other low-carbon scenarios. Yet even in this scenario, additional negative emissions are required of between 371 and 587 Gt CO_2 to compensate for the surplus of emissions from fossil fuels and industry.

A combination of both energy efficiency measures as well as technology switches are required to stay close to the carbon budget as much as possible. The sensitivity analysis demonstrated that economic growth does significantly affect the cumulative emissions. For the uncertainty in future material demand or electric space heating and water technologies, the effect on emissions is relatively limited. Though this can have other benefits (such as lower electricity grid costs).

In the next part of this discussion section, first the limitations of this study specifically are discussed in more detail. Then, the concerns regarding several specific aspects of decarbonization scenarios are explained. Finally, some important concerns are addressed regarding renewable energy technologies.

Limitations of the study

To keep this research manageable, choices were made to simplify certain processes and mechanisms. And although this is inevitable when modelling the global energy system for a master thesis, it may have led to inaccuracies. An example is the modelling of efficiency improvements in the industry sector. In this model, equal improvements are assumed for all energy carriers, while in real life efficiency improvement options reduce the demand of specific energy carriers: an improved industrial heat pump affects electricity demand, while the application of coke dry quenching influences the input of coal in the iron and steel industry (Moya and Pardo, 2013). Another barrier to further specify the processes or add regional details, was the limited amount of available data.

Furthermore, the exclusion of costs as decision criterion might also have led to different decisions than normally would have been made in the current economic rationale. This is partly done, since making accurate cost predictions is very challenging and inadequate cost projections can have major consequences for the scenario outcomes (Creutzig et al., 2017). Nevertheless, some rough cost estimations could have been taken into account in for instance the decision process of technology switches for the different sectors. According to Deng et al.

(2012), the upfront investments of an energy transition are significant but still less than 2% of global GDP.

Durance and Godet (2010) argue that the plausibility is one of the five conditions for credible scenarios. This has been taken into account as much as possible by preferring demonstrated technologies over options that are still in a premature phase. Yet in order to stay within the carbon budget, fast deployment rates of low carbon technologies are required across all sectors, which might therefore be less plausible. On the other hand, breaking with the current trends as is done in backcasting scenarios is sometimes even more realistic than other scenario approaches (Höjer and Mattsson, 2000).

A final limitation of the research is the fact that the study focuses solely on the energy system and industry, while other emissions should be considered as well. Also the interaction between biofuels and food production is not included here.

A realistic scenario

In order to stay within 1.5 °C scenario with a reduced amount of negative emissions, the required transition path is much steeper than almost all other low-carbon scenarios. This raises the question whether the proposed scenario is actually realistic. Five aspects are discussed: the deployment rates of renewables, the share of variable renewables, the use of biomass, the dependence on unproven technologies and finally the costs.

Loftus et al. (2015) denounce the high deployment rates of renewable energy sources and argue this is not in accordance with historic findings. Looking at the actual historic track record of photovoltaics, energy scenarios have actually significantly underestimated the growth of PV (Creutzig et al., 2017). According to the study by Creutzig et al. (2017), correcting for this underestimation results in a much higher supply of PV between 30% and 50% of the global electricity production by 2050. In this scenario, 39% of the electricity demand is provided by photovoltaics. One of the drivers of this enormous growth are the stalling costs: solar photovoltaics with battery storage becomes compatible with fossil fuels in the very near future (Kittner et al., 2017). As electricity demand in regions in Africa and Asia (excl. China) is expected to grow steeply between 2014 and 2050, new additions can cost-effectively be supplied by renewables. This disruptive nature of renewable energy technologies is incomparable with previous transitions (Green and Newman, 2017; Napp et al., 2017b).

A limitation of this scenario is the fact that no simulations have been conducted to make sure the electricity demand can be met consistently. Instead, a maximum of intermittent renewable shares was derived from literature. This is further explained by the great potential for storage capacity in the future in the form of hydrogen (Jentsch et al., 2014; Kavadias et al., 2017; Oldenbroek et al., 2017; Walke et al., 2016), electric vehicles (Diouf and Pode, 2015; Mwasilu et al., 2014; Sternberg and Bardow, 2015) and heat pumps (Arteconi et al., 2013; Sternberg and Bardow, 2015). Though in this study no actual quantification is provided.

A concern of this scenario is the high amount of biomass. In order to reduce the amount of cumulative emissions, biofuels are used by 2035 in all transport sectors for a short period. Even though this amount could potentially be derived sustainably (Cigolotti, 2012; IPCC, 2014; Slade et al., 2011), one of the goals of this scenario was to preferably avoid the utilization of biomass as much as possible. Three options could be considered to reduce the required amount of biomass in the transport sector.

A first option could be to implement the ban on internal combustion engines by as early as 2025. This would be sooner than the most ambitious plans so far and requires significant additional efforts of manufacturers to design new models and also for governments to build the required infrastructure. A second option would be to improve the energy efficiency of road transport even further, especially before 2035. If the assumed efficiency improvements for 2050 would have been realised by 2035, 17% of the liquid fuels for LDV could be saved. Also for freight transport, higher efficiency improvements seem realistic (Delgado et al., 2017). A third option would be to stimulate public transport over private transport. To keep up with the growing activity of passenger and tonnes kilometres would require an enormous investment in extending the current infrastructure. A shift towards clean public transport, but also cycling and walking in urban areas was found to be one of the most significant and cost-effective mitigation options (Replogle and Fulton, 2014).

Although one of the aims was to utilize proven technologies only, this was not achieved in all sectors. In transport and buildings sectors, most used technologies have been demonstrated on a commercial scale. However, the limited availability of low carbon technologies in the industry forced to rely heavily on technologies which have not been tested on commercial scale yet and are assumed to be deployable after 2020. An example is the stagnating deployment of CCS technology (Cozier, 2017; Peters et al., 2017), which is used in the production of iron and steel, the chemical industry and in combination with biomass to realize negative emissions. The delay of CCS can significantly increase costs of mitigating climate change (Krey, 2014). Enhancing material efficiency and increasing recycling rates could decrease the reliance on these technologies (Ekins et al., 2016).

Environmental concerns of renewables

An important risk of mitigating climate change lies in the burden shifting towards other environmental concerns such as biodiversity loss, ecotoxicity or eutrophication (UNEP, 2016). This especially needs attention if you consider the research by Steffen et al. (2015) on planetary boundaries, which argues that problems regarding biosphere integrity and biochemical flows might be even more alarming than climate change.

Furthermore, the decarbonization of the energy system requires a significant additional amount of materials (Berrill et al., 2016), including the demand of finite rare earth metals for transport, renewables and storage (Alonso et al., 2012; Kleijn and van der Voet, 2010; Stegen, 2015). Also, the mining capacities of steel and copper are expected to become a constraint (Kleijn and van der Voet, 2010). But according to Hertwich et al. (2015) the additional copper and iron requirements can be relatively limited.

Arversen et al. (2011) state that most low carbon energy models are too simplistic, since lifecycle emissions of renewable energy technologies such as photovoltaics, wind and CCS are not taken into account. This model did include the direct emissions from CCS and the process emissions for biomass utilization, but indeed neglects the lifecycle emissions of wind and photovoltaics. However, the life cycle emissions of power from wind and photovoltaics are small: respectively a factor 250 and 25 less than coal (Arversen et al., 2011). Furthermore the emissions can be reduced significantly once the production and transportation processes are decarbonized (Nugent and Sovacool, 2014; Peng et al., 2013).

Heard et al. (2017) and Loftus et al. (2015) argue that many of the published scenarios assume unrealistically low total primary energy demands compared to reference scenarios. But this is a very limited indicator for these types of scenarios due to the fact that most renewable energy technologies have no efficiency losses (Brown et al., 2017). Total final consumption would therefore be a much more accurate criterion to see if the demand for energy is realistic or not.

The results from this scenario support the claim by Figueres and many other climate and energy scientists (2017), that the next three years are crucial. Even then, the goal is extremely challenging. Yet, a recent publication by Millar et al. (2017) suggests that the carbon budget to stay within 1.5 degrees is perhaps much larger than previously thought. This would mean, that no or little additional negative emissions would be required after 2050 in this scenario. However it is too early to start applauding yet, the article led to an immediate discussion and was criticised by many renowned climate scientists (Hausfather, 2017; Peters, 2017; Stern, 2017). Future research should tell whether the small window of opportunity has become a bit bigger.

13. Conclusion and recommendations

This study provides a decarbonization pathway to stay within 1.5 ˚C global average temperature increase with a relatively limited amount of required negative emissions. This requires a rapid break with the current practice and net decarbonization of the global energy system by 2050. All countries on this planet, rich or poor, warm or cold, densely or sparsely populated should contribute. This is asking a lot, yet the steep technological advances make this transition not unrealistic.

Policy makers should engage in a simultaneous exhibition to reduce emissions in all sectors. In the buildings sector, policies can already focus on the renovation and adaptation of the buildings stocks and improvement of all energy consumers. For the transport sector, bans on internal combustion engines in all countries should be announced. Furthermore infrastructure should be installed to power the vehicles of the future. In the power sector it is important that electricity from wind and solar photovoltaics can unrestrictedly grow. Storage capacities and demand side management options should be upscaled to meet the fluctuating demand.

Perhaps the greatest challenges are found in decarbonization of the industry and the supply of biomass. Intensified research and development of low carbon technologies in the industry is much needed. The high demand for biomass in this scenario requires careful planning to realize a sustainable supply.

Further research could elaborate on the different subjects addressed in this study. Furthermore, the global energy system could be analysed on a country level. However, this requires an increase in the availability of data. Especially regarding energy consumption and activity levels in industry, which are very dispersed and often undisclosed. A central database could lower the threshold of conducting studies. Another important contribution would be to study the effect of reducing the demand for certain energy services, for instance a shift from private to public transport.

Above all, this study emphasises that there is no time to loose and a global decarbonization path should preferably be taken today rather than tomorrow to avoid spilling our chances of staying within 1.5 degrees. It is time for action!

14. List of figures

15. List of tables

16. References

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Appendix A: Regions for energy consumption

To further disaggregate the energy consumption in buildings and transport, additional data sources were used. The regions that were described in these regions, did not overlap completely with the regions that are defined in this thesis. And therefore a choose had to be made to assign the regions modelled needed to the regions described. An overview of the assumptions that were made is listed below.

Transport

ICCT region	1.5 C region
U.S.	OECD Americas
Canada	OECD Americas
Mexico	OECD Americas
Brazil	Non-OECD Americas
Latin America-31	Non-OECD Americas
EU-27	OECD Europe
Russia	Non-OECD Eurasia
Non-EU Europe	Asia (excl. China)
China	China
Japan	OECD Asia Oceania
India	Asia (excl. China)
South Korea	Asia (excl. China)
Australia	OECD Asia Oceania
Asia-Pacific-40	Asia (excl. China)
Middle East	Middle East
Africa	Africa

Buildings

IEA ETP 2014 region	1.5 C region
United States	OECD Americas
OECD	OECD Asia Oceania
EU	OECD Europe
South Africa	Africa
Brazil	Non-OECD Americas
Non-OECD	Middle East
Russia	Non-OECD Eurasia
AESEAN	Asia (excl. China)
China	China

Appendix B: Socio-economic factors

Population (millions)								
Region	2014	2020	2025	2030	2035	2040	2045	2050
Africa	1,150	1,264	1,392	1,521	1,647	1,774	1,892	2,010
Asia (excl. China)	2,435	2,605	2,732	2,859	2,961	3,062	3,134	3,205
China	1,372	1,387	1,389	1,390	1,369	1,349	1,311	1,273
Middle East	223	254	275	295	314	333	349	365
Non-OECD Americas	483	502	520	537	550	562	568	574
Non-OECD Eurasia	342	339	338	337	336	334	332	330
OECD Americas	498	518	539	559	576	593	606	619
OECD Asia Oceania	168	165	166	166	166	166	166	165
OECD Europe	562	577	587	596	604	611	616	621
World	7,232	7,612	7,937	8,262	8,523	8,785	8,974	9,163

Gross Domestic Product (billion $US\$_{2014}$)								
Region	2014	2020	2025	2030	2035	2040	2045	2050
Africa	5,438	7,345	9,520	12,338	15,599	19,720	24,723	30,995
Asia (excl. China)	17,545	24,535	31,448	40,308	49,206	60,067	71,074	84,098
China	18,702	30,062	38,493	49,288	56,135	63,934	69,105	74,694
Middle East	5,196	6,731	8,127	9,814	11,443	13,342	15,062	17,005
Non-OECD Americas	6,763	8,514	9,995	11,735	13,374	15,241	17,085	19,152
Non-OECD Eurasia	6,279	7,870	9,274	10,927	12,312	13,871	14,991	16,202
OECD Americas	21,567	25,384	28,314	31,581	34,310	37,275	39,892	42,692
OECD Asia Oceania	6,584	7,247	7,799	8,392	8,880	9,396	9,922	10,477
OECD Europe	20,658	23,088	25,188	27,479	29,878	32,487	35,135	37,998
World	108,732	140,776	168,157	201,863	231,135	265,333	296,989	333,314

Gross Domestic Product per Capita ($US\$_{2014}$)								
Region	2014	2020	2025	2030	2035	2040	2045	2050
Africa	4,729	5,809	6,836	8,114	9,470	11,117	13,069	15,423
Asia (excl. China)	7,206	9,420	11,511	14,097	16,619	19,614	22,681	26,241
China	13,636	21,666	27,722	35,470	40,994	47,389	52,705	58,667
Middle East	23,313	26,515	29,601	33,235	36,420	40,056	43,178	46,639
Non-OECD Americas	14,000	16,967	19,235	21,833	24,331	27,129	30,074	33,344
Non-OECD Eurasia	18,340	23,187	27,401	32,382	36,648	41,478	45,095	49,029
OECD Americas	43,309	48,960	52,553	56,489	59,581	62,896	65,826	68,927
OECD Asia Oceania	39,277	43,953	47,096	50,464	53,427	56,564	59,888	63,407
OECD Europe	36,754	40,022	42,933	46,068	49,482	53,157	57,024	61,177
World	15,034	18,219	20,785	23,753	26,261	29,062	31,746	34,693

Appendix C: Total final consumption per region

World - Total Final Consumption (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	74,784	84,888	108,719	143,613	172,914	186,845	193,803
Oil products	178,452	183,920	161,860	77,677	12,011	3,348	71
Coal	56,900	55,065	49,841	36,701	24,799	14,490	1,621
Coal CCS	215	1,006	3,120	6,458	9,428	11,889	14,991
Natural gas	56,460	54,124	43,929	23,870	9,332	3,388	282
Natural gas CCS	341	1,415	4,838	10,325	14,243	15,542	15,775
Biomass	53,251	58,888	70,233	113,087	145,063	136,430	128,535
Biomass CCS	183	723	2,272	5,880	9,337	10,623	10,920
Heat	11,787	11,906	11,653	10,312	8,910	7,609	6,266
Geothermal	382	359	269	124	38	8	0
waste	312	295	246	143	58	21	2
Solar thermal	1,503	1,902	3,148	5,123	6,595	7,264	7,726
Hydrogen	1	230	3,859	9,569	15,649	20,242	27,113
Total	434,572	454,719	463,988	442,881	428,376	417,700	407,104

Africa - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	2,082	3,449	6,000	9,663	13,219	17,828	22,942
Oil products	8,117	10,420	11,838	9,407	863	298	0
Coal	390	461	431	246	91	23	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	402	418	354	197	56	13	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	13,391	14,573	15,448	18,261	27,368	25,026	21,474
Biomass CCS	0	0	0	0	0	0	0
Heat	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0
waste	0	0	0	0	0	0	0
Solar thermal	40	161	577	1,308	1,921	2,297	2,580
Hydrogen	0	1	7	46	294	1,080	2,133
Total	24,422	29,484	34,654	39,128	43,811	46,565	49,129

Asia (excl. China) - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	5,709	8,357	14,243	24,107	33,665	39,036	42,506
Oil products	20,680	25,091	24,157	12,305	1,817	582	0
Coal	932	1,000	886	500	185	48	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	874	960	833	414	91	20	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	14,079	15,156	15,570	17,380	18,305	17,615	18,966
Biomass CCS	0	0	0	0	0	0	0
Heat	42	49	47	33	22	17	16
Geothermal	0	0	0	0	0	0	0
waste	0	0	0	0	0	0	0
Solar thermal	44	103	314	695	1,040	1,251	1,417

Hydrogen	0	24	869	2,106	3,436	3,866	4,260
Total	**42,360**	**50,740**	**56,920**	**57,539**	**58,561**	**62,435**	**67,166**

China - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	7,835	9,909	14,464	20,568	25,401	26,035	25,141
Oil products	22,748	24,985	21,947	9,213	918	246	0
Coal	8,227	8,494	7,425	4,049	1,551	424	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	2,314	2,410	1,944	877	237	44	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	9,300	9,458	10,032	13,348	14,050	12,896	12,846
Biomass CCS	0	0	0	0	0	0	0
Heat	1,058	1,062	940	656	445	318	230
Geothermal	248	241	184	83	24	5	0
waste	0	0	0	0	0	0	0
Solar thermal	1,095	1,286	1,777	2,386	2,682	2,598	2,399
Hydrogen	0	25	807	1,719	2,466	2,450	2,388
Total	**52,825**	**57,870**	**59,521**	**52,900**	**47,776**	**45,018**	**43,005**

Middle East - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	2,591	3,016	3,817	4,874	5,812	7,068	8,277
Oil products	7,371	7,654	7,313	5,144	351	104	0
Coal	11	12	12	8	4	1	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	2,284	2,329	1,909	986	291	64	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	430	757	1,584	3,816	8,373	6,291	4,102
Biomass CCS	0	0	0	0	0	0	0
Heat	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0
waste	0	0	0	0	0	0	0
Solar thermal	19	55	168	351	489	555	595
Hydrogen	0	1	5	27	150	481	837
Total	**12,706**	**13,824**	**14,807**	**15,207**	**15,471**	**14,565**	**13,811**

Non-OECD Americas - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	2,598	3,097	3,854	4,732	5,542	6,883	8,173
Oil products	9,108	9,279	8,685	5,768	483	145	0
Coal	12	14	13	8	3	1	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	661	663	538	279	72	15	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	1,651	1,943	2,696	5,155	9,766	7,413	5,007
Biomass CCS	0	0	0	0	0	0	0
Heat	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0
waste	0	0	0	0	0	0	0

Solar thermal	34	63	156	301	403	448	474
Hydrogen	0	1	5	28	156	495	855
Total	14,065	15,059	15,947	16,271	16,426	15,400	14,509

Non-OECD Eurasia - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	2,575	3,058	4,088	5,329	6,042	6,496	6,735
Oil products	6,574	6,740	6,276	4,030	339	98	0
Coal	398	373	284	137	44	10	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	3,790	3,504	2,566	1,156	320	63	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	876	1,081	1,626	3,429	6,537	4,807	3,119
Biomass CCS	0	0	0	0	0	0	0
Heat	4,135	4,135	3,883	3,310	2,810	2,378	1,983
Geothermal	5	5	4	2	1	0	0
waste	2	2	2	1	0	0	0
Solar thermal	5	5	3	1	0	0	0
Hydrogen	0	1	4	20	107	330	550
Total	18,359	18,902	18,734	17,414	16,201	14,181	12,387

OECD Americas - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	11,280	11,711	13,618	17,119	19,758	19,787	18,960
Oil products	33,079	30,771	23,459	9,249	930	272	0
Coal	74	71	58	33	13	4	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	9,376	8,465	6,078	2,692	745	143	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	2,747	3,633	5,409	9,891	10,185	9,356	9,228
Biomass CCS	0	0	0	0	0	0	0
Heat	66	101	193	299	327	289	229
Geothermal	10	9	6	2	1	0	0
waste	0	0	0	0	0	0	0
Solar thermal	97	84	58	24	6	1	0
Hydrogen	0	31	872	1,760	2,363	2,344	2,305
Total	56,729	54,876	49,750	41,069	34,328	32,196	30,721

OECD Asia Oceania - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	3,325	3,288	3,505	4,015	4,363	4,283	4,018
Oil products	7,330	6,650	4,954	2,024	241	64	0
Coal	54	48	33	15	4	1	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	1,257	1,092	753	321	85	16	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	417	616	1,023	1,902	2,080	1,883	1,853
Biomass CCS	0	0	0	0	0	0	0
Heat	101	97	93	86	74	61	46
Geothermal	14	12	9	4	1	0	0

waste	0	0	0	0	0	0	0
Solar thermal	67	56	37	15	4	1	0
Hydrogen	0	6	172	342	463	454	441
Total	12,565	11,863	10,578	8,724	7,316	6,762	6,358

OECD Europe - Total Final Consumption excl. Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	6,025	6,491	7,860	10,265	11,967	12,166	11,707
Oil products	16,130	14,903	11,339	4,967	599	170	0
Coal	673	603	437	205	64	14	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	5,782	5,088	3,567	1,568	436	85	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	2,372	2,609	3,093	4,469	4,874	4,458	4,535
Biomass CCS	0	0	0	0	0	0	0
Heat	1,151	1,062	884	635	454	344	259
Geothermal	89	77	56	27	9	2	0
waste	0	0	0	0	0	0	0
Solar thermal	90	76	51	21	6	1	0
Hydrogen	0	16	448	910	1,253	1,249	1,229
Total	32,312	30,926	27,736	23,067	19,661	18,489	17,730

OECD - Total Final Consumption Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	10,504	10,579	11,166	11,913	12,272	11,986	11,405
Oil products	13,347	13,019	11,315	6,470	2,155	465	20
Coal	6,370	6,096	5,528	4,456	3,375	2,176	341
Coal CCS	37	193	586	1,217	1,785	2,283	2,941
Natural gas	12,073	11,340	9,360	5,449	2,307	896	102
Natural gas CCS	126	502	1,627	3,323	4,431	4,760	4,788
Biomass	2,622	2,616	3,309	6,470	9,988	11,317	11,494
Biomass CCS	128	338	750	1,508	2,241	2,504	2,538
Heat	993	985	991	992	996	979	952
Geothermal	9	7	5	3	1	0	0
waste	279	261	212	117	42	11	1
Solar thermal	12	11	8	7	10	23	52
Hydrogen	0	24	130	511	963	1,448	2,308
Total	46,500	45,972	44,985	42,437	40,567	38,851	36,941

Non-OECD (excl. China) - Total Final Consumption Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	9,237	11,043	14,807	19,295	22,990	24,043	23,640
Oil products	13,016	13,258	11,889	6,998	2,650	782	48
Coal	12,231	13,768	15,460	14,682	12,710	8,456	922
Coal CCS	69	348	1,233	2,839	4,577	6,231	8,356
Natural gas	15,500	15,862	14,391	9,030	4,367	1,936	174
Natural gas CCS	196	837	2,963	6,502	9,160	10,110	10,342
Biomass	5,205	5,512	5,741	6,400	7,865	8,570	8,723
Biomass CCS	37	218	918	2,866	5,223	6,418	6,942
Heat	2,085	2,317	2,601	2,588	2,393	2,049	1,531

Geothermal	0	0	0	0	0	0	0
waste	31	32	32	24	16	9	1
Solar thermal	1	1	1	7	22	60	149
Hydrogen	0	69	376	1,474	2,875	4,491	7,577
Total	57,607	63,264	70,413	72,707	74,848	73,155	68,405

China - Total Final Consumption Industry (PJ)

	2020	2025	2030	2035	2040	2045	2050
Electricity	11,023	10,889	11,298	11,735	11,881	11,235	10,298
Oil products	4,532	4,350	3,758	2,099	662	123	3
Coal	27,528	24,127	19,274	12,363	6,757	3,331	358
Coal CCS	109	466	1,301	2,401	3,065	3,375	3,693
Natural gas	2,149	1,995	1,635	901	322	91	6
Natural gas CCS	19	76	248	500	653	672	645
Biomass	18	201	963	3,292	5,696	6,442	6,383
Biomass CCS	18	167	604	1,506	1,873	1,701	1,441
Heat	2,156	2,098	2,021	1,712	1,389	1,173	1,019
Geothermal	8	7	6	3	1	0	0
waste	0	0	0	0	0	0	0
Solar thermal	0	0	0	5	12	28	61
Hydrogen	0	32	166	627	1,123	1,554	2,228
Total	47,560	44,407	41,273	37,144	33,436	29,727	26,135

World marine bunkers - Total Final Consumption Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	0	0	0	0	0	0	0
Oil products	7,995	7,574	6,181	0	0	0	0
Coal	0	0	0	0	0	0	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	0	0	0	0	0	0	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	70	330	1,548	7,422	7,118	6,741	6,380
Biomass CCS	0	0	0	0	0	0	0
Heat	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0
waste	0	0	0	0	0	0	0
Solar thermal	0	0	0	0	0	0	0
Hydrogen	0	0	0	0	0	0	0
Total	8,065	7,905	7,729	7,422	7,118	6,741	6,380

World aviation bunkers - Total Final Consumption Industry (PJ)

Energy carrier	2020	2025	2030	2035	2040	2045	2050
Electricity	0	0	0	0	0	0	0
Oil products	8,423	9,225	8,750	0	0	0	0
Coal	0	0	0	0	0	0	0
Coal CCS	0	0	0	0	0	0	0
Natural gas	0	0	0	0	0	0	0
Natural gas CCS	0	0	0	0	0	0	0
Biomass	74	402	2,191	11,853	12,859	13,615	14,427
Biomass CCS	0	0	0	0	0	0	0

Heat	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0
waste	0	0	0	0	0	0	0
Solar thermal	0	0	0	0	0	0	0
Hydrogen	0	0	0	0	0	0	0
Total	8,497	9,627	10,941	11,853	12,859	13,615	14,427

Appendix D: Emissions

	Annual Emissions (Mt CO_2)							
Energy carrier	2014	2020	2025	2030	2035	2040	2045	2050
Oil products	12,012	13,550	13,516	11,496	5,250	629	158	5
Coal	14,689	11,580	8,430	6,228	3,910	2,354	1,378	155
Coal CCS	0	3	11	35	75	108	130	154
Natural gas	6,246	6,061	5,403	3,716	2,013	554	196	16
Natural gas CCS	0	3	12	37	72	89	95	95
Biomass	254	263	256	245	237	246	257	260
Biomass CCS	0	-16	-61	-193	-500	-794	-903	-928
Waste	165	91	56	40	21	8	3	1
Cement	0	0	0	0	0	0	0	0
Total	33,365	31,536	27,622	21,604	11,077	3,194	1,315	-243

	Annual Emissions per Sector (Mt CO_2)							
Sector	2014	2020	2025	2030	2035	2040	2045	2050
Electricity	11,924	8,844	5,122	2,289	939	0	0	0
Energy industry own use and losses	1,853	1,828	1,697	1,292	524	142	54	21
Transport	7,493	8,723	9,106	8,069	3,699	418	344	288
Industry	8,580	8,402	8,116	7,189	4,734	2,482	1,035	-386
Buildings	2,916	3,125	2,998	2,304	1,108	381	146	91
Other	614	643	638	576	383	189	81	33
Total	33,381	31,566	27,678	21,720	11,385	3,612	1,659	46

	Cumulative Emissions (Mt CO_2)							
Energy carrier	2014	2020	2025	2030	2035	2040	2045	2050
Oil products	12,012	88,696	156,360	218,890	260,755	275,451	277,420	277,828
Coal	14,689	93,496	143,521	180,165	205,509	221,170	230,501	234,335
Coal CCS	0	9	44	161	437	893	1,487	2,198
Natural gas	6,246	43,167	71,829	94,628	108,950	115,365	117,241	117,771
Natural gas CCS	0	10	48	168	440	844	1,304	1,778
Biomass	254	1,806	3,103	4,355	5,558	6,765	8,024	9,317
Biomass CCS	0	-47	-239	-876	-2,608	-5,842	-10,083	-14,661
Waste	165	932	1,300	1,539	1,690	1,762	1,789	1,798
Cement	0	0	0	0	0	0	0	0
Total	33,365	228,069	375,965	499,030	580,732	616,409	627,682	630,364

	Annual Emissions per Sector (Mt CO_2)							
Sector	2014	2020	2025	2030	2035	2040	2045	2050
Electricity	11,924	74,231	109,148	127,676	135,746	138,092	138,092	138,092
Energy industry own use and losses	1,853	12,893	21,706	29,180	33,721	35,386	35,874	36,059
Transport	7,493	56,143	100,717	143,656	173,075	183,366	185,271	186,851
Industry	8,580	59,528	100,825	139,088	168,894	186,933	195,727	197,349
Buildings	2,916	21,040	36,347	49,602	58,132	61,854	63,172	63,763
Other	614	4,386	7,589	10,625	13,022	14,451	15,125	15,408
Total	33,381	228,222	376,332	499,827	582,590	620,082	633,260	637,522

Appendix E: Activity levels per sector

Transport

World - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	23,153	31,565	38,338	46,073	52,422	59,308	65,348	71,733
Light road (pkm)	3,657	3,864	4,022	4,180	4,300	4,419	4,497	4,574
Bus (pkm)	15,303	16,093	16,728	17,364	17,845	18,326	18,638	18,951
Freight road (tkm)	15,432	21,280	25,656	30,379	34,253	38,376	41,990	45,787
Passenger rail (pkm)	2,012	2,936	3,616	4,352	4,952	5,591	6,152	6,744
Freight rail (tkm)	6,642	9,105	10,940	12,922	14,534	16,250	17,753	19,333
World aviation bunkers (pkm)	3,337	4,402	5,379	6,594	7,705	9,015	10,296	11,768
Domestic aviation (tkm)	999	1,533	2,039	2,724	3,349	4,124	4,873	5,774
World marine bunkers	163,261	181,054	195,383	210,341	222,399	234,842	244,898	255,192
Domestic navigation	45,502	61,210	72,767	85,259	95,230	105,866	115,014	124,655

International Bunkers - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
World aviation bunkers (pkm)	3,337	4,402	5,379	6,594	7,705	9,015	10,296	11,768
World marine bunkers (tkm)	163,261	181,054	195,383	210,341	222,399	234,842	244,898	255,192

Africa - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	598	1,150	1,774	2,612	3,588	4,829	6,331	8,177
Light road (pkm)	68	75	82	90	97	105	112	119
Bus (pkm)	1,709	1,879	2,069	2,260	2,448	2,636	2,811	2,986
Freight road (tkm)	817	1,601	2,375	3,298	4,260	5,356	6,538	7,845
Passenger rail (pkm)	23	145	263	406	557	730	918	1,128
Freight rail (tkm)	143	467	785	1,168	1,568	2,028	2,528	3,083
Domestic aviation (pkm)	40	61	87	123	168	230	312	423
Domestic navigation (tkm)	735	2,791	4,804	7,232	9,775	12,696	15,873	19,401

Asia (excl. China) - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	1,609	3,696	5,759	8,360	10,898	13,873	16,747	19,929
Light road (pkm)	2,447	2,618	2,746	2,874	2,976	3,078	3,149	3,221
Bus (pkm)	4,575	4,894	5,133	5,373	5,563	5,754	5,888	6,022
Freight road (tkm)	1,794	3,805	5,470	7,290	8,865	10,540	12,015	13,550
Passenger rail (pkm)	449	800	1,089	1,405	1,678	1,968	2,222	2,487
Freight rail (tkm)	593	1,466	2,191	2,984	3,671	4,403	5,048	5,720
Domestic aviation (pkm)	141	239	347	500	667	888	1,130	1,436
Domestic navigation (tkm)	4,388	10,016	14,682	19,786	24,204	28,904	33,048	37,362

China - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	2,037	5,252	7,309	9,497	10,591	11,532	11,848	11,947
Light road (pkm)	429	434	434	435	428	422	410	398
Bus (pkm)	4,224	4,274	4,277	4,280	4,218	4,155	4,038	3,921
Freight road (tkm)	1,785	3,541	4,468	5,396	5,853	6,295	6,495	6,675
Passenger rail (pkm)	328	626	783	941	1,018	1,092	1,125	1,155
Freight rail (tkm)	1,191	1,971	2,381	2,791	2,987	3,176	3,253	3,321
Domestic aviation (pkm)	294	534	742	1,039	1,250	1,507	1,699	1,918

Domestic navigation (tkm)	19,469	24,595	27,224	29,856	30,933	31,967	32,131	32,240

Middle East - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	1,566	1,980	2,332	2,726	3,084	3,467	3,787	4,113
Light road (pkm)	54	62	67	72	76	81	85	88
Bus (pkm)	978	1,114	1,205	1,296	1,379	1,462	1,531	1,600
Freight road (tkm)	790	988	1,150	1,329	1,492	1,667	1,817	1,975
Passenger rail (pkm)	-	-	-	-	-	-	-	-
Freight rail (tkm)	-	-	-	-	-	-	-	-
Domestic aviation (pkm)	22	45	71	106	141	186	229	280
Domestic navigation (tkm)	-	-	-	-	-	-	-	-

Non-OECD Americas - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	1,930	2,450	2,872	3,346	3,771	4,228	4,645	5,075
Light road (pkm)	333	346	358	371	379	387	392	396
Bus (pkm)	1,583	1,644	1,703	1,761	1,801	1,841	1,861	1,882
Freight road (tkm)	1,411	1,726	1,964	2,215	2,426	2,645	2,833	3,024
Passenger rail (pkm)	7	51	83	117	147	178	207	236
Freight rail (tkm)	227	350	441	537	620	707	784	864
Domestic aviation (pkm)	72	104	133	170	207	251	297	353
Domestic navigation (tkm)	2,259	3,082	3,688	4,334	4,886	5,461	5,969	6,487

Non-OECD Eurasia - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	1,299	1,729	2,067	2,419	2,673	2,916	3,058	3,183
Light road (pkm)	56	55	55	55	54	54	54	54
Bus (pkm)	413	409	408	407	405	403	401	398
Freight road (tkm)	542	752	902	1,052	1,160	1,266	1,334	1,401
Passenger rail (pkm)	231	266	291	316	333	351	361	372
Freight rail (tkm)	1,135	1,220	1,284	1,347	1,391	1,434	1,459	1,483
Domestic aviation (pkm)	136	172	207	252	292	339	375	416
Domestic navigation (tkm)	776	1,376	1,803	2,228	2,535	2,839	3,034	3,227

OECD Americas - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	8,323	9,004	9,526	10,029	10,408	10,761	11,014	11,234
Light road (pkm)	58	60	62	65	67	69	70	72
Bus (pkm)	1,033	1,076	1,118	1,160	1,195	1,229	1,257	1,285
Freight road (tkm)	3,109	3,409	3,645	3,892	4,091	4,297	4,469	4,644
Passenger rail (pkm)	65	96	118	140	159	178	195	212
Freight rail (tkm)	2,619	2,802	2,957	3,117	3,247	3,380	3,489	3,600
Domestic aviation (pkm)	1,141	1,284	1,400	1,529	1,639	1,759	1,866	1,981
Domestic navigation (tkm)	9,957	10,851	11,567	12,311	12,914	13,535	14,051	14,579

OECD Asia Oceania - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	1,290	1,379	1,446	1,508	1,547	1,579	1,598	1,607
Light road (pkm)	72	71	71	72	72	72	71	71
Bus (pkm)	128	126	126	127	127	127	127	126
Freight road (tkm)	1,056	1,089	1,124	1,160	1,185	1,210	1,232	1,255
Passenger rail (pkm)	265	269	276	282	286	291	294	298

Freight rail (tkm)	191	210	224	239	250	261	272	282
Domestic aviation (pkm)	145	167	185	204	221	239	258	279
Domestic navigation (tkm)	3,414	3,500	3,602	3,705	3,775	3,845	3,907	3,969

OECD Europe - Activity Transport (billion pkm or tkm)

Transport mode	2014	2020	2025	2030	2035	2040	2045	2050
LDV (pkm)	4,501	4,925	5,253	5,575	5,862	6,123	6,320	6,468
Light road (pkm)	140	144	146	149	150	152	153	155
Bus (pkm)	660	678	689	701	709	718	724	730
Freight road (tkm)	4,129	4,371	4,557	4,746	4,921	5,099	5,258	5,418
Passenger rail (pkm)	644	683	714	745	774	803	829	856
Freight rail (tkm)	545	618	678	739	800	861	920	980
Domestic aviation (pkm)	150	210	267	331	403	485	572	670
Domestic navigation (tkm)	4,504	4,998	5,397	5,808	6,208	6,618	7,002	7,391

Buildings

Africa - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	13	17	19	22	24	26	29	31
Space heating (MJ_t / m^2)	52	52	52	52	52	52	52	52
Water heating (L / Cap. day)	27	29	30	32	34	35	37	39
Space cooling (MJ_t / m^2)	9	17	23	29	35	41	47	53
Lighting (Act_{index} / m^2)	100	113	124	135	145	156	166	177
Appliances (Act_{index} / Cap.)	100	136	171	216	265	326	401	493
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

Asia (excl. China) - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	21	25	28	31	33	36	38	40
Space heating (MJ_t / m^2)	2	2	2	2	2	2	2	2
Water heating (L / Cap. day)	4	7	9	11	13	15	16	18
Space cooling (MJ_t / m^2)	15	25	33	40	46	52	58	63
Lighting (Act_{index} / m^2)	100	149	186	224	254	285	311	338
Appliances (Act_{index} / Cap.)	100	145	189	245	302	371	444	530
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

China - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	21	28	32	35	37	40	41	43
Space heating (MJ_t / m^2)	127	127	127	127	127	127	127	127
Water heating (L / Cap. day)	41	46	48	51	52	54	55	56
Space cooling (MJ_t / m^2)	58	75	84	93	99	104	108	112
Lighting (Act_{index} / m^2)	100	165	199	234	254	274	289	304
Appliances (Act_{index} / Cap.)	100	171	227	303	358	424	480	543
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

Middle East - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	18	20	22	23	25	26	27	29
Space heating (MJ_t / m^2)	19	19	19	19	19	19	19	19
Water heating (L / Cap. day)	53	54	55	56	57	58	59	60
Space cooling (MJ_t / m^2)	74	79	83	87	91	94	97	100
Lighting (Act_{index} / m^2)	100	102	104	106	107	109	110	111
Appliances (Act_{index} / Cap.)	100	111	122	135	147	161	173	186
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

Non-OECD Americas - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	20	23	24	26	28	30	31	33
Space heating (MJ_t / m^2)	13	13	13	13	13	13	13	13
Water heating (L / Cap. day)	22	24	25	26	28	29	30	31
Space cooling (MJ_t / m^2)	21	29	33	38	42	46	50	54
Lighting (Act_{index} / m^2)	100	118	130	142	152	162	172	181
Appliances (Act_{index} / Cap.)	100	134	161	192	223	258	296	338
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

Non-OECD Eurasia - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	26	30	32	35	37	39	40	41
Space heating (MJ_t / m^2)	461	461	461	461	461	461	461	461
Water heating (L / Cap. day)	49	51	53	54	56	57	58	59
Space cooling (MJ_t / m^2)	1	9	16	22	26	31	34	37
Lighting (Act_{index} / m^2)	100	115	125	135	143	151	156	161
Appliances (Act_{index} / Cap.)	100	125	147	174	197	225	246	268
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

OECD Americas - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	48	50	51	52	53	54	55	56
Space heating (MJ_t / m^2)	200	200	200	200	200	200	200	200
Water heating (L / Cap. day)	49	51	51	52	53	53	54	54
Space cooling (MJ_t / m^2)	103	107	110	112	114	116	118	120
Lighting (Act_{index} / m^2)	100	104	107	109	111	113	115	116
Appliances (Act_{index} / Cap.)	100	112	119	128	134	142	148	155
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

OECD Asia Oceania - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	48	50	51	52	53	54	55	56
Space heating (MJ_t / m^2)	151	151	151	151	151	151	151	151
Water heating (L / Cap. day)	30	31	32	33	33	34	35	35
Space cooling (MJ_t / m^2)	59	63	66	68	70	72	75	77

Lighting (Act_{index} / m^2)	100	106	110	113	116	119	123	126
Appliances (Act_{index} / Cap.)	100	113	123	133	142	151	161	172
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

OECD Europe - Activity Residential Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	48	50	51	52	53	54	55	56
Space heating (MJ_t / m^2)	223	223	223	223	223	223	223	223
Water heating (L / Cap. day)	29	30	31	31	32	33	33	34
Space cooling (MJ_t / m^2)	36	39	42	44	47	50	52	55
Lighting (Act_{index} / m^2)	100	110	118	127	135	144	152	161
Appliances (Act_{index} / Cap.)	100	120	138	158	179	203	228	256
Cooking (Act_{index} / Cap.)	100	100	100	100	100	100	100	100

Africa - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	1	2	4	5	6	7	9	10
Space heating (MJ_t / m^2)	68	68	68	68	68	68	68	68
Water heating (L / Cap. day)	2	4	5	6	8	9	10	11
Space cooling (MJ_t / m^2)	229	287	333	381	424	469	515	561
Lighting (Act_{index} / m^2)	100	107	113	118	124	129	135	140
Appliances (Act_{index} / Cap.)	100	133	168	216	272	346	442	568

Asia (excl. China) - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	4	6	8	9	10	12	13	14
Space heating (MJ_t / m^2)	9	9	9	9	9	9	9	9
Water heating (L / Cap. day)	1	4	5	7	8	9	11	12
Space cooling (MJ_t / m^2)	31	106	162	219	265	311	352	393
Lighting (Act_{index} / m^2)	100	144	177	210	237	264	288	312
Appliances (Act_{index} / Cap.)	100	146	194	262	335	430	536	670

China - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	4	7	9	11	12	14	14	15
Space heating (MJ_t / m^2)	137	137	137	137	137	137	137	137
Water heating (L / Cap. day)	2	6	8	10	11	12	13	14
Space cooling (MJ_t / m^2)	156	286	355	424	465	505	535	565
Lighting (Act_{index} / m^2)	100	165	199	233	254	274	289	304
Appliances (Act_{index} / Cap.)	100	226	341	510	644	812	961	1,140

Middle East - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	5	6	7	8	8	9	10	10
Space heating (MJ_t / m^2)	114	114	114	114	114	114	114	114
Water heating (L / Cap. day)	4	5	6	7	8	9	9	10
Space cooling (MJ_t / m^2)	1,136	1,172	1,203	1,235	1,261	1,287	1,308	1,330
Lighting (Act_{index} / m^2)	100	115	128	142	153	165	173	183
Appliances (Act_{index} / Cap.)	100	145	191	249	303	367	426	493

Non-OECD Americas - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	2	3	4	5	6	7	8	8
Space heating (MJ_t / m^2)	17	17	17	17	17	17	17	17
Water heating (L / Cap. day)	5	6	7	8	9	10	11	12
Space cooling (MJ_t / m^2)	109	163	198	233	264	294	323	352
Lighting (Act_{index} / m^2)	100	105	108	112	115	118	120	123
Appliances (Act_{index} / Cap.)	100	132	158	190	223	263	307	359

Non-OECD Eurasia - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	3	5	6	8	9	10	10	11
Space heating (MJ_t / m^2)	1,070	1,070	1,070	1,070	1,070	1,070	1,070	1,070
Water heating (L / Cap. day)	11	13	14	16	17	17	18	19
Space cooling (MJ_t / m^2)	75	141	188	235	269	304	328	351
Lighting (Act_{index} / m^2)	100	111	120	128	134	140	144	148
Appliances (Act_{index} / Cap.)	100	130	159	196	231	273	306	344

OECD Americas - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	18	19	20	20	20	21	21	22
Space heating (MJ_t / m^2)	289	289	289	289	289	289	289	289
Water heating (L / Cap. day)	15	16	17	18	18	18	19	19
Space cooling (MJ_t / m^2)	238	272	292	312	327	343	355	368
Lighting (Act_{index} / m^2)	100	109	114	119	123	127	130	134
Appliances (Act_{index} / Cap.)	100	114	123	134	143	152	161	170

OECD Asia Oceania - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	18	19	19	20	20	21	21	22
Space heating (MJ_t / m^2)	292	292	292	292	292	292	292	292
Water heating (L / Cap. day)	22	23	24	24	25	25	26	26
Space cooling (MJ_t / m^2)	242	274	293	313	329	345	361	377
Lighting (Act_{index} / m^2)	100	106	110	114	118	121	124	128
Appliances (Act_{index} / Cap.)	100	113	121	131	140	150	161	172

OECD Europe - Activity Commercial and Public Buildings

Function	2014	2020	2025	2030	2035	2040	2045	2050
Surface (m^2 / Cap.)	18	19	19	20	20	21	21	22
Space heating (MJ_t / m^2)	226	226	226	226	226	226	226	226
Water heating (L / Cap. day)	17	17	18	18	19	19	20	21
Space cooling (MJ_t / m^2)	95	119	139	159	179	199	218	238
Lighting (Act_{index} / m^2)	100	110	118	126	135	143	151	159
Appliances (Act_{index} / Cap.)	100	122	143	166	192	221	253	289

Industry

World - Activity Industry (Mt)

Material	2014	2020	2025	2030	2035	2040	2045	2050
Cement	C	4,176	4,243	4,315	4,375	4,468	4,550	4,646
High value chemicals	C	359	389	435	478	523	550	570
Ammonia	C	184	194	208	220	233	241	248
Methanol	C	72	86	108	130	153	165	174
Iron and steel	C	1,754	1,889	2,108	2,331	2,579	2,744	2,879
Paper, pulp and print	C	419	449	495	542	593	627	654
Aluminium	C	87	96	113	130	148	160	169

OECD - Activity Industry (Mt)

Material	2014	2020	2025	2030	2035	2040	2045	2050
Cement	C	511	556	626	694	765	810	845
High value chemicals	C	183	198	221	244	267	282	293
Ammonia	C	36	38	40	42	44	46	47
Methanol	C	7	8	10	12	14	16	17
Iron and steel	C	512	522	530	536	541	545	550
Paper, pulp and print	C	226	217	197	176	153	140	131
Aluminium	C	28	29	30	30	31	32	33

Non-OECD (excl. China) - Activity Industry (Mt)

Material	2014	2020	2025	2030	2035	2040	2045	2050
Cement	C	1,348	1,565	1,893	2,233	2,596	2,849	3,056
High value chemicals	C	80	89	103	116	131	141	150
Ammonia	C	99	107	116	126	135	143	149
Methanol	C	26	32	42	52	63	70	76
Iron and steel	C	435	596	867	1,155	1,466	1,678	1,845
Paper, pulp and print	C	84	120	183	250	322	371	409
Aluminium	C	22	32	48	66	85	98	108

China - Activity Industry (Mt)

Material	2014	2020	2025	2030	2035	2040	2045	2050
Cement	C	2,317	2,123	1,796	1,447	1,108	891	745
High value chemicals	C	96	102	111	118	125	127	127
Ammonia	C	49	50	51	52	53	52	51
Methanol	C	40	46	57	66	76	80	81
Iron and steel	C	807	771	711	640	572	521	483
Paper, pulp and print	C	110	112	115	117	118	116	114
Aluminium	C	37	36	35	33	31	30	29