Cost-effective share bioenergy 2030

How do other options compare to bioenergy?

CE Delft

Committed to the Environment

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Content

Summary

Introduction

The new 2030 climate and energy package includes a 27% renewables target at EU level. According to the Impact Assessment (IA) of the Commission, a relatively high share (over 60%) of this target will be met by bioenergy use. The expected share of bioenergy deployment in the IA in 2030 follows from calculations in the PRIMES model. Whilst the PRIMES model aims to calculate a price based equilibrium under different policy scenarios, it is questionable whether the published PRIMES output truly reflects a cost-effective renewable energy mix for 2030 from a societal perspective. The reason is that higher discount rates than the social optimum have been applied.
In addition, it is unclear which underlying assumptions have been made on the costs of the different technologies.
Transport and Environment, Birdlife Europe and the European Environmental Bureau therefore requested CE Delft to determine the most cost-effective optimal RES mix for the EU-28, Germany, France, Sweden, Spain, Poland and the UK, taking into account social discount rates and the most recent cost developments.

Central question and scope

The central question of this study is what the most cost-effective renewable energy mix in the chosen key Member States in 2030 is, given current and future cost structures. An additional question is how this mix compares with the current renewable energy demand and the projections of the EU reference scenarios 2013 and 2016.

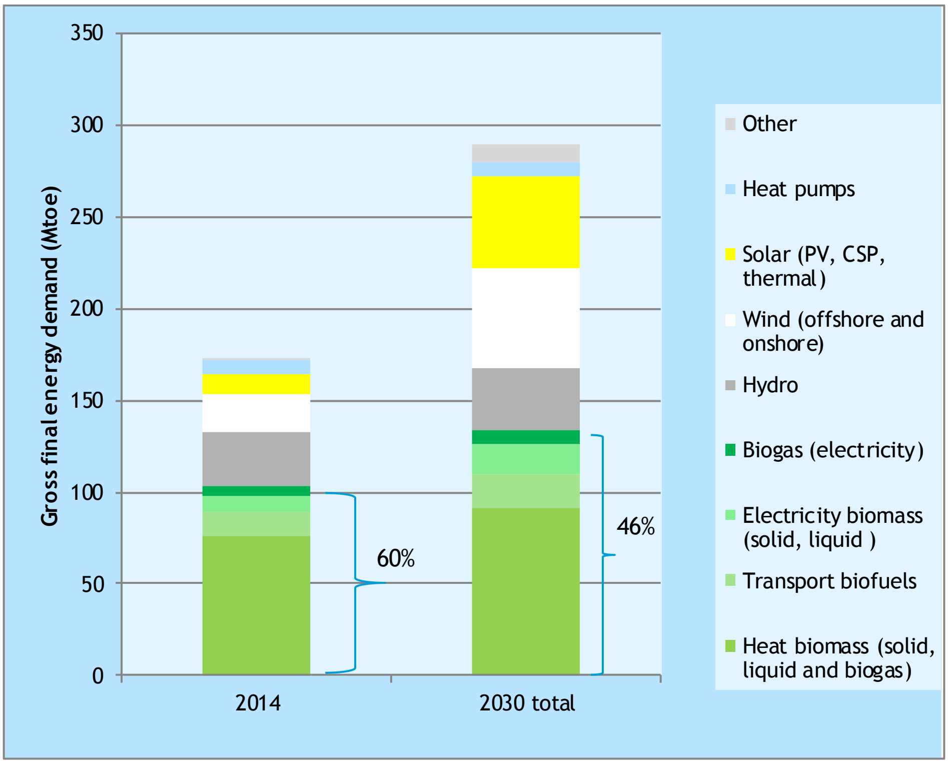
The optimal mix of renewables has been determined in terms of cost-effectiveness to meet the renewables target. Obviously, there are other factors that play an important role as well in the prioritization of technologies, such as greenhouse gas reductions (which may differ between renewable technologies), employment benefits, added value for the economy, a justified sharing of efforts between sectors and actors in the economy, etc. Other considerations than cost-effectiveness have not been considered in this study and should be assessed separately.

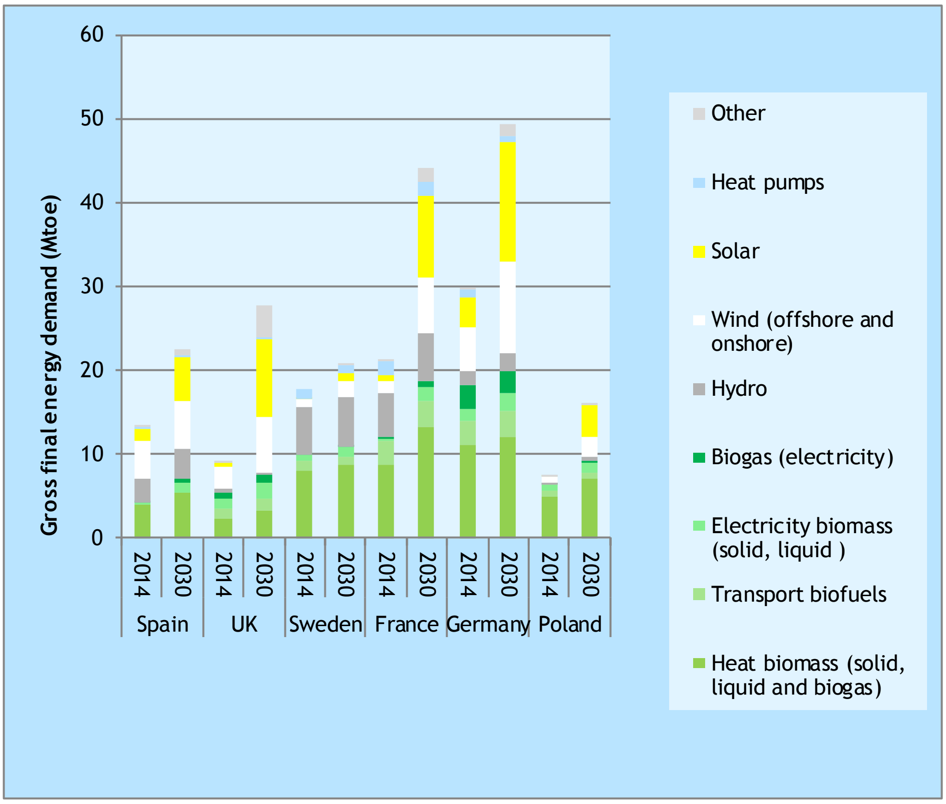
Results

Figure 1 presents the current demand (2014) and the 2030 optimal mix for the EU-28 (upper diagram) and six member states (lower diagram). The upper diagram shows that the total share of bioenergy in the mix will decrease from 60% in 2014 to 46% in 2030 in the EU-28; the growth of non-bioenergy options is significantly larger than bioenergy options. In particular solar energy and wind energy will increase in the most cost-effective mix. Wind energy will increase by more than a factor 2.5, while solar energy increases by nearly a factor 5 between 2014 and 2030.

For the individual member states results differ, although the trends are more or less comparable. Wind and solar energy have the largest growth of demand, while the increase of bioenergy options are relatively more limited.

Figure 1 Gross final energy demand RES 2014 (actual demand) and 2030 optimal 2030 mix RES to meet the 27% EU renewables target (upper diagram) and six member states (lower diagram)

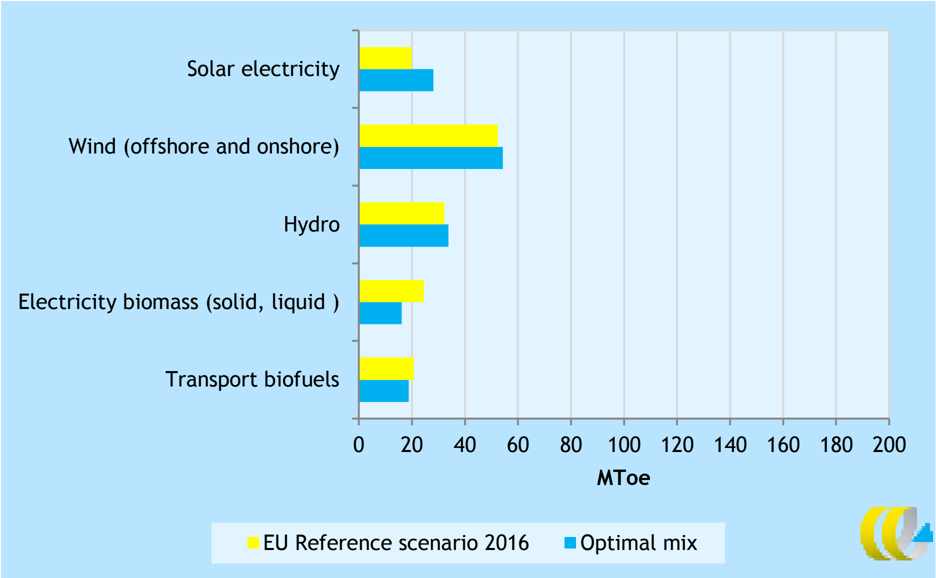


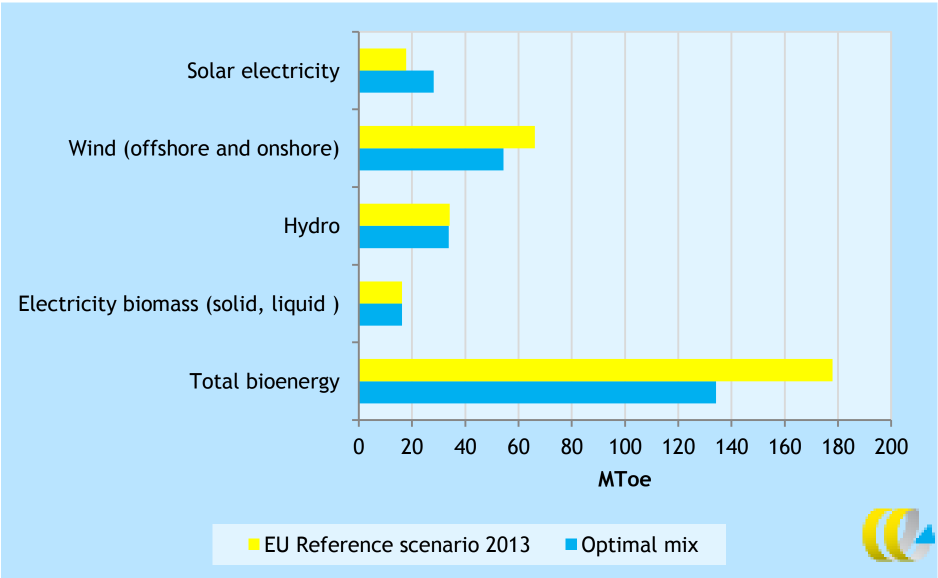


Comparison with EU reference scenarios 2013 and 2016

In Figure 2, our results are compared to the data that are publically available from the EU reference scenario 2016 (upper diagram) and 2013 (lower diagram).

Figure 2 **Comparison results with publically available information**





The main difference in results is the total demand for bioenergy. Demand in the optimal mix is approximately 45 Mtoe lower than in the EU reference scenario 2013. As demand in the EU reference scenario 2013 has not been published for all technologies separately, it was not possible to determine where these differences arise. The most probable explanation is a different demand of bioenergy in the heat sector, where our results indicate a large increase in solar thermal energy demand in the most cost-effective mix.

The comparison shows furthermore that for many technologies, demand in the optimal mix is more or less comparable to the EU reference scenario 2013 and 2016. This is the case for hydropower, wind energy (EU reference scenario 2016) and transport biofuels. Demand for solar electricity is higher in the optimal mix, while demand for biomass in electricity production is lower compared to the EU reference scenario 2016. Demand for wind energy is somewhat lower in the optimal mix compared to the reference scenario 2013.

For the EU reference scenario 2016, the total final demand of bioenergy is not presented. If the share of bioenergy in the EU reference scenario 2016 is still over 60%, it will implicate that an increase of bioenergy demand is particularly modelled in the heat sector. However, more detailed results are required for the EU reference scenario 2016 as well to make this comparison possible.

A major factor explaining the differences in our study with the reference scenarios, is the lower discount rate (3%), reflecting the social optimum. The (higher) discount rates in the PRIMES model, reflect decisions from a private perspective, subject to uncertainties, risk taking behaviours and limited access to funding. As the social optimum will not materialize under normal market conditions, interventions from the government are required to realize this optimal renewables mix.

1 Introduction

1.1 Background

The new 2030 climate and energy package includes a 27% renewables target at EU level. According to the Impact Assessment (IA) of the Commission, a relatively high share (approximately 60%)[1] of this target will be met by bioenergy use.[2]

The expected share of bioenergy deployment in the IA in 2030 follows from calculations in the PRIMES model. Whilst the PRIMES model aims to calculate a price based equilibrium for the modelled energy system under different policy scenarios, it is questionable whether the published PRIMES output truly reflects a cost-effective renewable energy mix for 2030 from a societal perspective. An important reason is that high discount rates have been applied. These rates are economically unfavourable for technologies requiring large upfront investment (such as wind, solar PV and geothermal energy).

In addition, it is unclear which assumptions have been made on current and future costs of the various renewables technologies. The most recent developments show that costs of some non-bioenergy technologies are decreasing much sharper than expected. For instance, in July 2016, the Dutch government announced that one of the major parks in the Netherlands, a 700 MW offshore wind park in Borssele, will produce 22.5% more electricity and require € 2.7 billion euros less then foreseen.[3] This means that the subsidy costs are 43% lower than recently was expected.

Taking into account social discount rates and the most recent developments may result in lower shares of bioenergy to meet the 27% target in a cost-effective manner. In this study, we will estimate cost-effective shares of bioenergy for the EU-28, Germany, France, Sweden, Spain, Poland and the UK.

1.1 Objective

The related research questions are:
- What are the current and forecasted costs structures of different renewables in the different parts of the energy sector in the EU-28 and six member states?
- What would be the most cost-effective renewable energy mix in the chosen key Member States given their resources and geographical location? How does that compare with the current renewable energy deployment in these countries and the projections of the EU reference scenarios 2013 and 2016?

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1 Own calculation.

2 In July 2016 the Commission has presented an updated reference scenario. However, with the information provided it is not possible to calculate the share of bioenergy in total demand for renewables.

3 www.rijksoverheid.nl/actueel/nieuws/2016/07/05/windpark-borssele-goedkoopste-ter-wereld

1.2 Scope

In this research, the optimal mix of renewables has been determined in terms of cost-effectiveness to meet the renewables target. Obviously, there are other factors that play an important role as well in the prioritization of technologies, such as greenhouse gas reductions (which may differ between renewable technologies), employment benefits, added value for the economy, a justified sharing of efforts between sectors and actors in the economy, etc. Other considerations than cost-effectiveness have not been considered in this study and should be assessed separately.

1.3 Approach

Predicting the future inherently bears uncertainties. Future costs and demand of renewables depend on technology developments, learning effects economies of scale. In addition, cost of renewable technologies vary within the EU, depending on geographical circumstances, wage costs, current deployment, costs of net integration, market structures, learning rates up to 2030, etc. While for technologies such as solar and wind energy the differences within the EU are already significant (offshore versus onshore wind, wind speed, type of turbines) within bioenergy technologies differences are very significant. Costs can vary widely depending on the geographical location of demand, the type of biomass which is consumed (woody crops, waste, grassy crops, etc.), the scale (e.g. bulk or domestic), the application (transport, electricity, heat, etc.) and therefore can only be compared taking into account a relatively large uncertainty margin.

In this study, we have estimated the most cost optimal renewable energy mix for the EU and six member states by constructing a (high level) cost curve ranking the technologies (additional potential) in terms of cost-effectiveness. For each technology marginal costs have been determined, as additional costs will normally increase for each extra unit of renewable energy that is produced.[4]

In this project, we aim to deliver a consistent dataset and up to date cost dataset for the six selected member states. The use of high quality data is crucial for reliable, comparable and credible results. In order to ensure consistency, for most technologies we have used costs data for the Dutch renewables subsidies as the basis for our costs calculation for the six member states. We have selected the Netherlands as a basis, because a sophisticated dataset for this country is available with a detailed breakdown of cost structures per technology (based on averages for many projects), which have been intensively checked after several consultation rounds with the industry. To our knowledge, this is one of the most complete, recent and detailed publically available datasets on cost structures of renewables.

The costs for the Netherlands have been translated to other member states by adjusting for the labour costs component of the technologies (labour costs include costs for procedures and planning). Wage rates per country have been compiled from Eurostat. By multiplying the labour costs share of the technologies with wage rates relative to the Netherlands, we have estimated

[4] For instance, costs of wind energy and solar energy will increase because of increasing grid connection costs, balancing power requirements, production losses, less optimal geographical locations, etc. On the other hand, costs are expected to decrease in future because of technological developments.

the labour costs components of the different technologies for other member states. By adding up the other costs (mostly cost for the 'hardware' component, such as the wind turbine), we have determined investment costs and O&M costs data for other member states.

We have assumed that costs for the 'hardware' component of technologies are comparable and do not differ between the member states, as the technologies are traded within international markets. However, we are aware that in reality this assumption may not be valid, as other factors can also play a role, such as the degree of competition in a specific market/country, the bargaining power of market actors/countries, site specific factors[5], transport costs, etc.

We have therefore cross-checked the results of our calculations with (IEA/NEA, 2015) Ecofys (2014) and other sources. IEA/NEA (2015) is an important source, as it presents levelised costs of electricity generation for 29 member countries.[6] Solar energy, wind energy, hydropower, and bioenergy electricity generation projects are included in the analysis. Important is to determine if similar definitions and technologies have been applied in the analysis.[7]
In addition, we have judged the reliability of the results for the different member states based on our own expertise.

Country specific circumstances also play a crucial role for generating renewable energy. In Southern European countries for instance, solar energy will be more productive than the EU-28 average, while in North West European countries like the UK, wind energy circumstances are favourable. The amount of full load hours for each of the technologies within the countries has been translated based on generation capacities in IEA/NEA (2015). Costs for the year 2030 have been estimated based on the technology roadmaps of the International Energy Agency (2012a;2012b;2015b;2015c;2015d), IEA-ETSAP and IRENA (2013), and DECC (2016).

In order to determine the most cost-effective mix in 2030, one should ideally model the optimal trajectory up to 2030, based on replacement investments of current installations and investments in new installations. However, such a modelling would require detailed information on the age structure of existing installed renewable technologies (such as wind turbines). As such detailed information is not available for this project, we have made the assumption that current demand of renewable energy will remain up to 2030, and determined the most cost-effective mix to meet the 2030 target by adding up the most cost-effective technologies of the additional potential in 2030. We have not carried out a dynamic modelling exercise for intermediate years within the period 2014 (most recent year data available in Eurostat) up to 2030.

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5 For example soil conditions for wind turbine foundations, length of grid connection cables because of distance to the shore for offshore wind, etc.

6 Investment costs and O&M cost data are based on questionnaires.

7 For instance, IEA/NEA (2015) results show that the investment costs of solar PV rooftop are more than twice as high in France than in Spain. The question is where these differences originate from and if similar definitions have been taken into account for solar PV within the study.

1.4 Outline

The report is structured as follows:

- Chapter 2 presents the current share of bioenergy in the mix for the EU-28 and the six selected member states, as well as an overview of the 2030 results of existing scenario studies on renewables in the mix, including the most recent EU reference scenario 2016 that has been published in July 2016.
- Chapter 3 is the core of the study. In this chapter, we present the costs of the renewable technologies and the most optimal renewables mix in 2030
- Chapter 4 finally concludes.

2 Bioenergy in the RES mix

2.1 Current shares of bioenergy in the EU

According to the most recent renewable progress report (EC, 2015), bioenergy was the most dominant type of renewable energy in 2014. The lion's share of bioenergy was consumed for heating purposes, followed by transport (biofuels), electricity and biogas. Total bioenergy demand equals 106 Mtoe in 2014, contributing 60% of total RES deployment. Of the other renewable technologies, hydro, wind, solar and heat pumps are the dominant sources.

Gross final energy demand of bioenergy differs significantly between the six member states. While in Spain total contribution is relatively limited (33% of all renewables), in Poland the majority of renewables demand is sourced by biomass (88%). In Germany (61%), the UK (59%), Sweden (57%) and France (56%) the share does not deviate much from the EU average (60%).

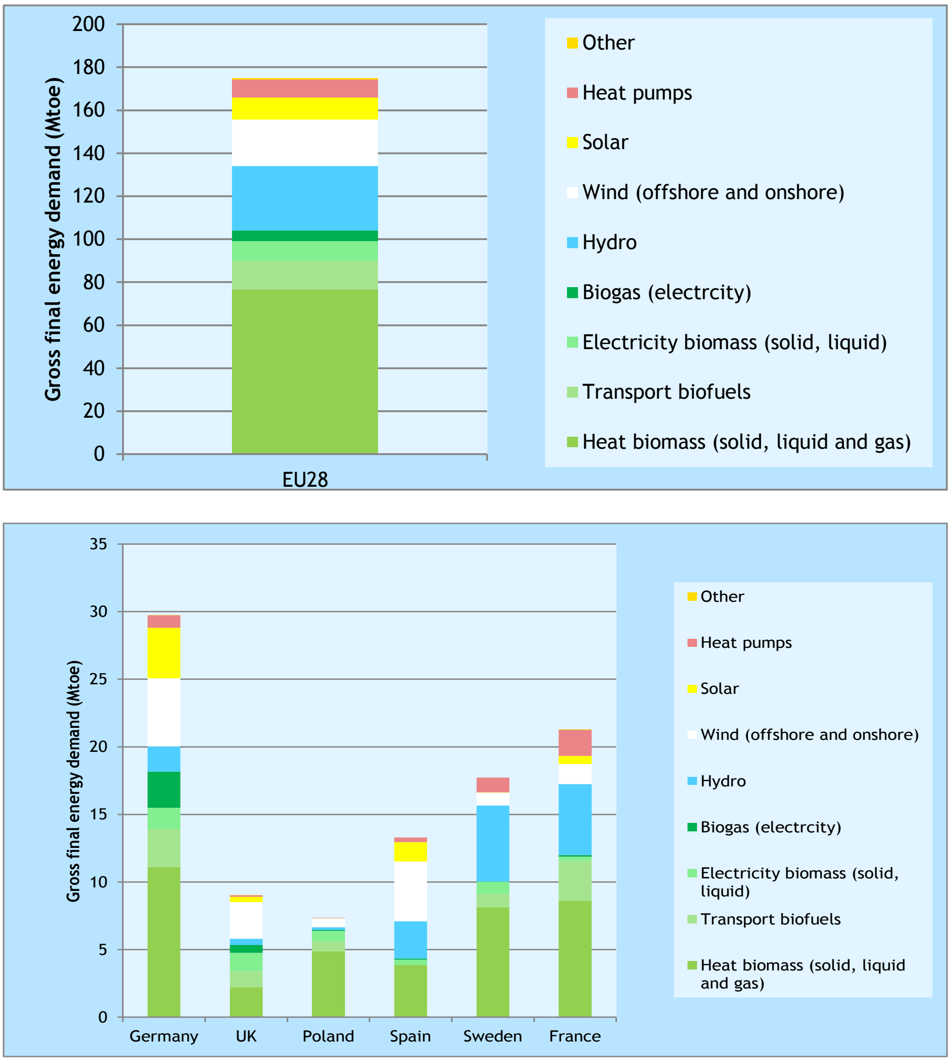
Solid biomass makes up the largest share of biomass demand. [8] According to the European observatory on renewable energy, in 2013, solid biomass accounted for 3% of the electricity produced in the EU and 15% of the heat produced in industrial units. The major share of heat energy from biomass was produced by domestic users. Most of the solid biomass consumed has been produced on European soil, although net imports have increased in the last years, mainly as a result of rising wood pellet imports (33.3% of total consumption of wood pellets) from countries such as the United States, Canada and Russia.

Figure 3 shows the gross final energy demand of renewables in the EU-28. Four categories of bioenergy consumption are presented:
1. Biomass for heat purposes (solid, liquid and biogas).
2. Transport biofuels.
3. Biomass for electricity purposes (solid, liquid).
4. Biogas for electricity purposes.

In all six member states, biomass for heat purposes is the dominant application of these four categories of bioenergy. The second largest category differs between member states. In the UK and Poland and Spain biomass for electricity is the second largest source of bioenergy, while in France and Sweden biomass for heat is followed by biofuels for transport. In Germany, biogas for electricity production is the second largest category of bioenergy, making up more than half of total biogas production for electricity in the EU-28.

8 According to EurObserv'er (2015), Primary energy consumption of solid biomass in the EU was 91.5 Mtoe in 2013. Although this figure is not totally comparable to gross final demand statistics, as energy is lost during conversion processes, the figure indicates that the majority of bioenergy demand originates from solid sources.

Figure 3 **Gross final energy demand of renewables 2014 in the EU-28 (upper diagram) and in the six selected member states (lower diagram)**



Demand for other renewables than bioenergy differs significantly between member states as well. In Germany and Spain, wind, solar and hydro energy are the dominant sources of non-bioenergy renewables, while in France and Sweden hydropower is the largest source. In the UK and Poland wind energy is almost solely responsible for total demand of other renewables. In both these countries, demand for renewables is limited compare to the other member states. Heat pumps have a significant share of demand in France, Sweden and Germany, and to a lesser extent Spain.

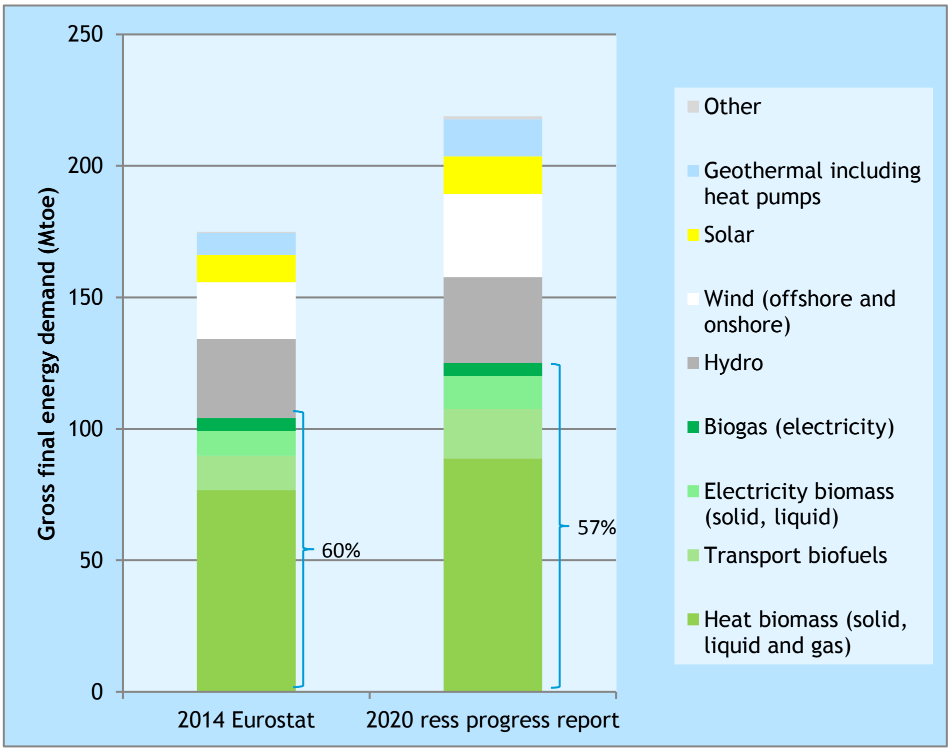
2.2 Projected demand of renewable energy

There are several projections of future demand of renewables. For most EU-wide projections, detailed information, for instance information on the share of bioenergy in renewables demand, is presented on EU level. Although many publications with projections, based on for instance PRIMES modelling, do present information for various technologies on member state level, no detailed information is presented making a country specific comparison possible between bioenergy demand and other renewables. We therefore focus on EU projections in this section.

According to the EU renewables progress report, total renewables demand will increase from 175 Mtoe in 2014 up to 220 Mtoe in 2020. The corresponding share of bioenergy in total RES demand will decrease from 60% in 2014 to 57% in 2020, because other renewable technologies are expected to increase more rapidly, most notably wind, solar and heat pumps. Total demand of bioenergy will increase by 20% (from 104 Mtoe in 2014 to 125 Mtoe in 2020), while demand for other renewables increases by 30% (from 73 Mtoe in 2020 to 94 Mtoe in 2020).

The 2020 projections in the RES progress report 2015 have been determined in a modelling exercise and differ from the targets in the National Renewable Action Plans (NREAP's). The most important reason is that demand of land based biofuels in the modelling exercise is expected to be lower than those in the NREAP targets. However, if the NREAP targets would be met, the share of bioenergy would still decrease. We can therefore conclude that the relative share of bioenergy demand will decrease both based on the modelling exercise and the NREAP targets.

Figure 4 Projected EU renewables demand in 2014 and 2020 according to RES progress report 2015



For the trajectory after 2020, (up to 2030), several projections have been carried out. In this study we focus on four scenarios that have recently been developed by the European Commission:

1. The EU reference scenario 2016: this scenario projects the impact of current EU policies on several energy related topics, among others the share of renewable energy sources or levels of energy efficiency.
   The Reference Scenario provides a benchmark against which new policy proposals can be assessed and is developed by a consortium led by the

National Technical University of Athens. The PRIMES model has been used for energy and CO_2 projections in the reference scenario.[9]

2. The EU reference scenario 2013: this scenario is the predecessor of the PRIMES reference scenario 2016. The EU reference scenario has been used, among others, for the impact assessment of the for the 2030 framework for climate and energy policies.
3. The GHG 40 scenario: this scenario has been studied in the impact assessment for the 2030 framework for climate and energy policies. It assumes additional policies compared to the reference scenario 2013 and thereby meeting a 40% greenhouse gas reduction in 2030. The share of renewables in this scenario is equal to the EU target (27%) that has been agreed upon. Similar to the reference scenario 2013 and 2016, PRIMES has been used in the modelling of the scenario.
4. The GHG 40 EE scenario: in this scenario for the impact assessment of the 2030 framework for climate and energy policies, final demand of renewables is close to the agreed target as well (26% modelled in the GHG40 EE scenario versus an agreed target of 27%). A major difference with the GHG40 scenario is that additional energy efficiency policies are foreseen, reducing total final demand of energy. As total final demand is lower (numerator), final demand of renewables (operator) can be lower as well to meet the renewables target (which is expressed in %).

Beside the four scenarios that have been described above, other scenarios exist such as the Energy Revolution scenario (Greenpeace and EREC, 2012), the EREC baseline and advanced scenario (EREC, 2011), scenarios developed by the International Energy Agency (IEA) and various scenarios presented in impact assessments of the European Commission. However, we have presented more detailed information on the four scenarios presented in Table 1, as we focus in our study on scenarios modelled with PRIMES. In addition, the projected renewables share in these scenarios is most in line with the 27% renewables target (and therefore most interesting to compare with the optimal mix).

Table 1 shows that the differences between the studies are significant, which is not surprising given that reference scenarios are based on reference developments while the GHG40 and GHG40 EE other assume additional policies. Demand in 2030 for bioenergy ranges from 166 Mtoe in the Energy Efficiency scenario of the 2030 impact assessment to 182 Mtoe in the GHG40 scenario. The share of bioenergy in total renewable energy demand is 63% in the EU reference scenario 2013 and GHG 40EE scenario, and 64% in the GHG40 EE scenario. The published information in the EU reference scenario 2016 does not allow to calculate shares of bioenergy in total demand.

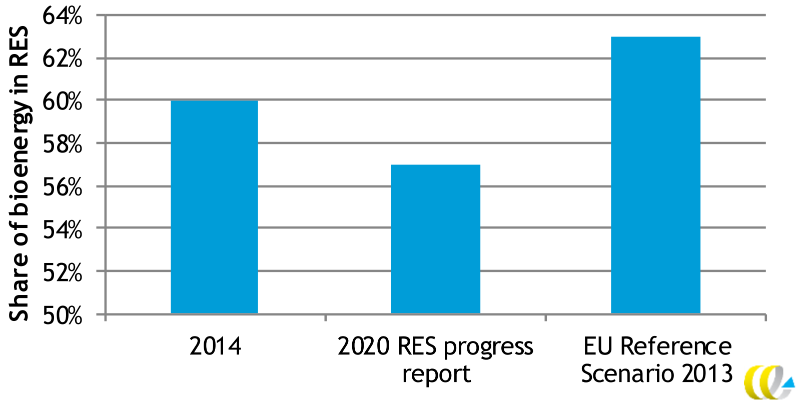
[9] In addition, several other models have been used for projections in the reference scenario: the GAINS model for non-CO_2 greenhouse gas projection the GLOBIOM/G4M models for emissions and greenhouse gas removals related to land use, land use change and forestry; the GEM-E3 model which projects macroeconomic developments; the PROMETHEUS model which projects world energy prices and the CAPRI model which projects changes in agricultural activities.

Table 1 **Share of bioenergy according to various scenarios 2030**

	EU reference scenario 2016	EU reference scenario 2013	GHG 40 scenario IA 2030	GHG 40 EE scenario IA 2030
Total final demand (Mtoe)	1081	1126	1073	991
RES share	24%	24%	27%	26%
Total RES demand (Mtoe)	259	275	284	262
Final demand Bioenergy (Mtoe)	Not published	178	182	166
Bioenergy share in RES (%)	Not published	63%	64%	63%

The relatively high share of bioenergy based on these scenarios, would mean a reversal of downward trend presented in the progress report up to 2020 (see Figure 5). This figure compares the 2014 demand (Eurostat figures) with the projected 2020 share of bioenergy in the RES progress report and the EU reference scenario 2013.

Figure 5 **Share of bioenergy in RES for 2014, 2020 (progress report) and EU reference scenario 2013**



The share of bioenergy in renewables demand is expected to decrease between 2014 and 2020, while the EU reference scenario 2013 (but also the GHG40 and GHG40EE scenarios) predict the share of bioenergy to increase to over 60% in 2030.

2.3 Conclusion

In this chapter we have compared 2030 bioenergy demand of with current demand (Eurostat figures) and projected 2020 demand in the 2015 progress report. We conclude that total bioenergy energy demand in the EU reference scenario 2013, the GHG40 and GHG40EE scenarios, show an increase of the share of bioenergy demand in the renewables mix, while the renewables progress report is forecasting a relative decrease up to 2020. In the next chapter, we will estimate the most cost-effective renewables mix for six member states and the EU, based on own calculations and compare these to the scenarios presented in this chapter.

3 Cost-effective mix 2030

3.1 Introduction

This chapter presents an assessment of the most cost-effective mix to meet the (indicative) renewables targets of 2030 in the six selected member states and the EU-28. In order to determine the most cost optimal mix, we first determined additional realisable potential. The realisable potential represents the achievable potential in 2030 assuming that all existing barriers can be overcome and all driving forces are active; it is limited only by maximum market growth rates, planning constraints and technical boundary conditions (e.g. available land to install wind turbines). In this study, we base the realisable potential on the Green-X database, showing potentials per RES technology on EU and member state level Ragwitz et al. (2011). Information from the Green-X database has been used for modelling in the RES progress report 2015 as well.[10] By ranking the technologies in a cost curve, we determined the most cost-effective additional potential to meet the EU 2030 target.[11] As no individual targets on member state level exist (and it is as yet undecided whether any targets will be set, and what the status of these targets will be), we have assumed that renewables targets for the member states increase with the same amount of percentage points as the EU renewables target (7 percentage points), resulting in the following targets per member state (see Table 2). For Sweden, we have assumed a higher target, as final demand of renewables in Sweden has already met the 2020 target increased by 7 percentage points.

Table 2 Targets for 2020 and 2030 (very indicative) per member state

	2020	2030
EU-28	20%	27%
Germany	18%	25%
Spain	20%	27%
Poland	15%	22%
UK	15%	22%
Sweden	49%	66%
France	23%	30%

As already indicated in the approach in Section 1.3, one should ideally model the optimal trajectory up to 2030, based on replacement investments of current installations and investments in new installations, in order to determine the most cost-effective mix in 2030. As such detailed information is not available for this project, we have made the assumption that current

[10] Although the Green-X database has been updated since 2011, the updated potentials on member state level are not publically available. We therefore have used the 2011 database in our study as a basis. Source: Personal communication Mr Ortner, TU Wien, 13 October 2016.

[11] As investment costs decrease between now and 2030, and the additional potential will be realized in the period 2014-2030, we have taken the average of current (2015) and future (2030) costs as a proxy for average costs for installing additional potential in the period 2014-2030.

demand of renewable energy will remain up to 2030, and determined the most cost-effective mix to meet the 2030 target by adding up the most cost-effective technologies of the additional potential.

3.2 Current demand and realisable potential

As explained in Section 3.1, realisable potentials have been based on the Green-X database. This database has initially been set up in 2001 for the EU 15, based on a detailed literature survey and a development of an overall methodology with respect to the assessment of specific resource conditions of several RES options. The figures were updated in 2005, based on among others, reviews of national experts. Within the scope of the EU research futures-e-again potentials have been reshaped, validated and complemented.[12]

Biomass potentials include imports of primary solid biomass to the EU of on average (at EU level) of 30% compared to the domestically available additional potential. The total biomass resource potential available domestically has been allocated to specific technologies.

However, the biofuels potential in the Green-X data (Ragwitz et al, 2011) contains both land based biofuels and advanced biofuels. Based on the recent communications[13] of the European Commission and the cap on land based biofuels as set by the ILUC Directive, it is unlikely that a large potential for land based biofuels in 2030 can be expected. The European Commission has indicated that land based biofuels have a limited role in decarbonising the transport sector, should not receive public support after 2020 and should be gradually phased out.

We have therefore corrected for the land based of biofuels in the Green-X database. The energy potential of land based biofuels in Ragwitz et al. (2011), in terms of final demand, is approximately 15 Mtoe[14] (rape and sunflower, maize and wheat (corn). In order to correct for the land based biofuels, we have subtracted the potential of land based biofuels (approximately 15 Mtoe) from the total potential of biofuels (approximately 50 Mtoe), resulting in a potential of advanced biofuels in the EU-28 of approximately 35 Mtoe.

The Green-X database presents several types of feedstock for biofuels production:
- rape and sunflower are being used for the production of biodiesel;
- maize, wheat (corn) for the production of bioethanol;
- maize, wheat (whole plant) for the production of advanced bioethanol;
- several sources for the production of biomass to liquid (BTL), such as miscanthus, switchgrass and forest residues.

The first and second types of biofuel production are classified as land based biofuels in this study and have been excluded from the total potentials.

12 Based on feedback processes, six workshops and active involvement of key stakeholders.

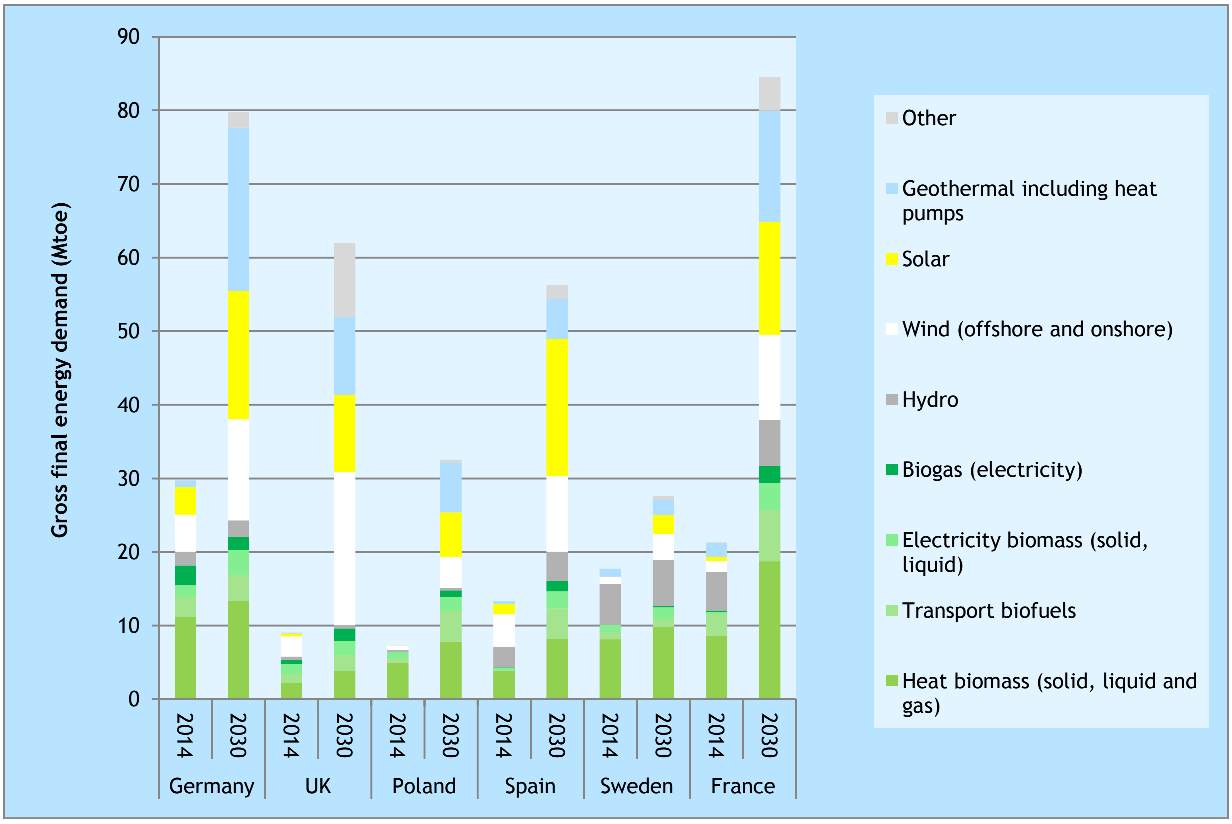
13 A European Strategy for Low-Emission Mobility Brussels, 20.7.2016 COM(2016) 501 final.

14 The Green-X database does not present a distinction between land based and advanced biofuels in terms of final demand. However, the primary input of feedstocks for the Green-X database is presented in Hoefnagels et al. (2011), as well as the types of biofuels that are being produced with these feedstocks. Based on the production efficiencies (Resch et al.(2014)) of land based biofuels (66% of a biodiesel plant and 57%-65% for a bioethanol plant), we have calculated the 2030 potentials of land based biofuels in terms of final demand.

On member state level however, we do not have insight in the potential of advanced biofuels. We have therefore scaled down total biofuels potentials (land based and advanced biofuels, which are available on member state level) on member state level based on the relative share of land based biofuels (30%) on EU level. As this factor may differ between member states in reality, an uncertainty boundary has to be taken into account for country specific biofuels outcomes.

The current demand and estimated realisable potential in 2030 for each of the member states are presented in Figure 6. The figure shows that the realisable potential in the member states is in particular large for wind, solar energy, and geothermal heat including heat pumps. The additional potential for bioenergy renewables is smaller compared to the other renewables.

Figure 6 Current gross final demand and realisable potential 2030

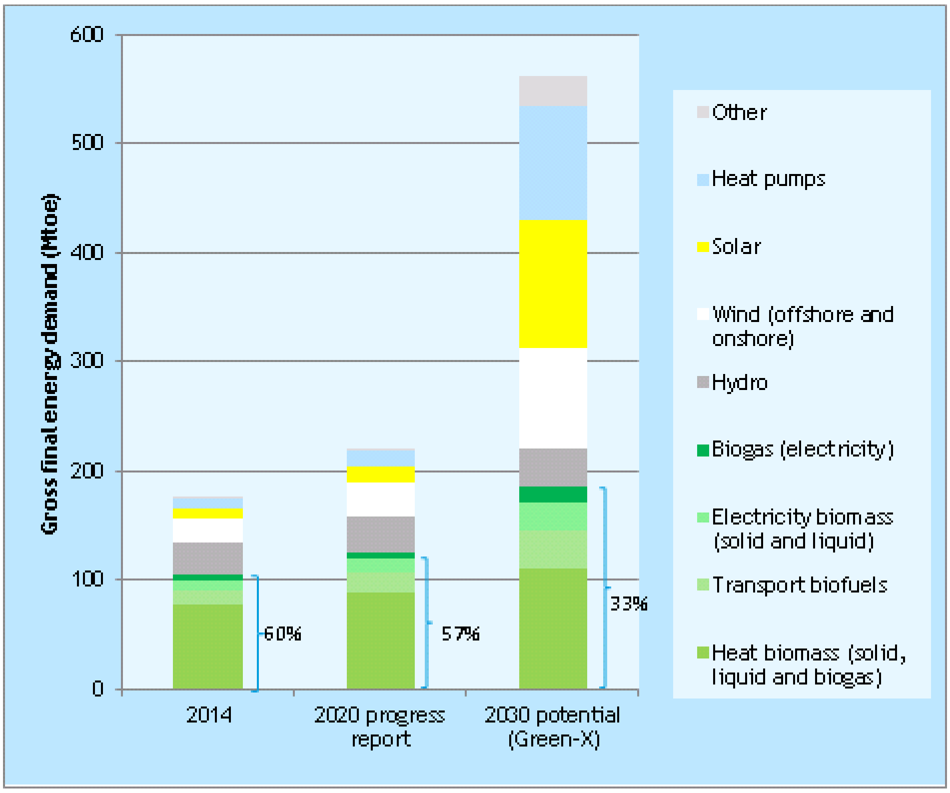


Based on the Green-X database, we can conclude that the additional realisable potential for non-bioenergy options is larger than for bioenergy options. Demand for bioenergy options can increase by less than a factor two up to 2030, while the growth potential for non-bioenergy options is more than a factor five. The difference in growth potential between bioenergy and non-bioenergy options might be even larger, as it is unclear to what extent considerations for sustainability criteria have been taken into account in the Green-X database of 2011 for biogas, bio-heat and biomass for electricity. The realisable potential for these options could therefore be lower. For non-bioenergy options, in particular wind energy, solar and heat pumps have a significant larger additional potential.

Given the figures in Table 1, we can also conclude that total final demand for bioenergy in the scenarios based on PRIMES modelling in 2030 is rather close to the maximum realisable potential presented in the Green-X database of 2011.

Of the other technologies on the other hand, only a limited share of the realistic potential is realized in 2030 with the PRIMES modelling. In the scenarios based on PRIMES, total demand of non-bioenergy renewables is approximately 100 Mtoe, while the total realistic potential is over 375 Mtoe. In other words, while in most scenarios over 90% of bioenergy potential is realized, less than 30% of the potential of other technologies is exploited.

Figure 7 **Current final demand, 2020 final demand (progress report) and 2030 potential on EU level**



3.3 Current and future costs

In order to determine the most cost-effective mix, the net costs of each of the technologies have been determined. The net costs are the costs of the technologies minus the income of energy production, these represent the additional costs for the various renewable technologies on top of the energy incomes.

To determine the current costs we have used several sources. Important data are the costs calculations for the FIP subsidy scheme in the Netherlands, the most recent IEA/NEA (2015) study presenting costs for renewable electricity technologies, IEA ETSAP and IRENA (2013) and Ecofys (2014). For bioenergy, reports on prices in the EU-28 have been consulted, such as JRC et al. (2015), Forest Research (2015), SEAI (2016) and BTC (2014). This has resulted in a coherent dataset has been created on current costs in the six member states and the EU.

Costs for the year 2030 have been estimated based on sources such as the technology roadmaps of the International Energy Agency, IEA ETSAP and IRENA (2013) and DECC (2016).

Costs have been determined based on the LCOE method (Levelized Costs of Energy). This is a method calculating costs by accounting for all of a system's expected lifetime costs (including construction, fuel, operation and maintenance, etc.), which are then divided by the system's lifetime expected power output. This method is widely used for comparing the costs of different electricity generating technologies. The LCOE methodology can also be applied to heat generating technologies and biofuels for transport. For instance, in the Netherlands, the methodology is used for determining the level of subsidies for renewable electricity and heat generating technologies.

In the LCOE methodology, the costs for energy both the costs (nominator) and the energy production (denominator) are being discounted. The formula is presented below.

$$\text{Costs excluding energy benefits } (€/GJ) = \frac{\Sigma[(\text{Capitalt} + \text{O\&Mt} + \text{Fuelt}) * (1+r)]^{-t}}{\Sigma\ \text{Gj} * (1+r)^{-t}}$$

In which:

$Capital_t$	=	Capital construction costs in year t;
$O\&M_t$	=	Operation and maintenance costs in year t;
Fuelt	=	Fuel costs in year t;
$(1+r)^{-t}$	=	Discount factor for year t;
r	=	Discount rate (3%).
GJ	=	Energy production in year t.

This result of the LCOE formula can be interpreted as the costs, excluding energy incomes, for a measure over the lifetime of a project (measured in €/GJ).

We have calculated the net costs for the technologies by subtracting the energy incomes from the costs. For the current prices, we have assumed that incomes measured in terms of € per GJ are equal to the current gas prices (heat market) and electricity prices (electricity market).[15] For the 2030 cost curve, market prices for 2030 have been selected as proxy for the average incomes of the technologies for the lifetime of the project.[16] We have assumed that respectively gas prices and electricity prices are representative for the heat and electricity market. For the transport market, a weighted average of the diesel and gasoline price has been used.[17] Both current and future gas and electricity prices are obtained from the Word Energy Outlook (2015).[18]

15 For technologies generating both electricity and heat we have calculated the weighted energy income.

16 These prices might be underestimation of the real income, as prices are expected to increase over the lifetime of a technology.

17 For the transport market, prices have been specified on member state level. For electricity and gas prices however, this has not been possible, as price projections for 2030 have not been specified on member state level in the World Energy Outlook 2015.

18 2030 gas and electricity prices are based upon the New Policies scenario in the World Energy Outlook 2015 (central scenario).

The data source for current gasoline and diesel prices is oil bulletin of the European Commission (2016). Future prices have been predicted based on oil price developments in World Bank (2016). The prices assumed and the sources used are presented in Table 3.

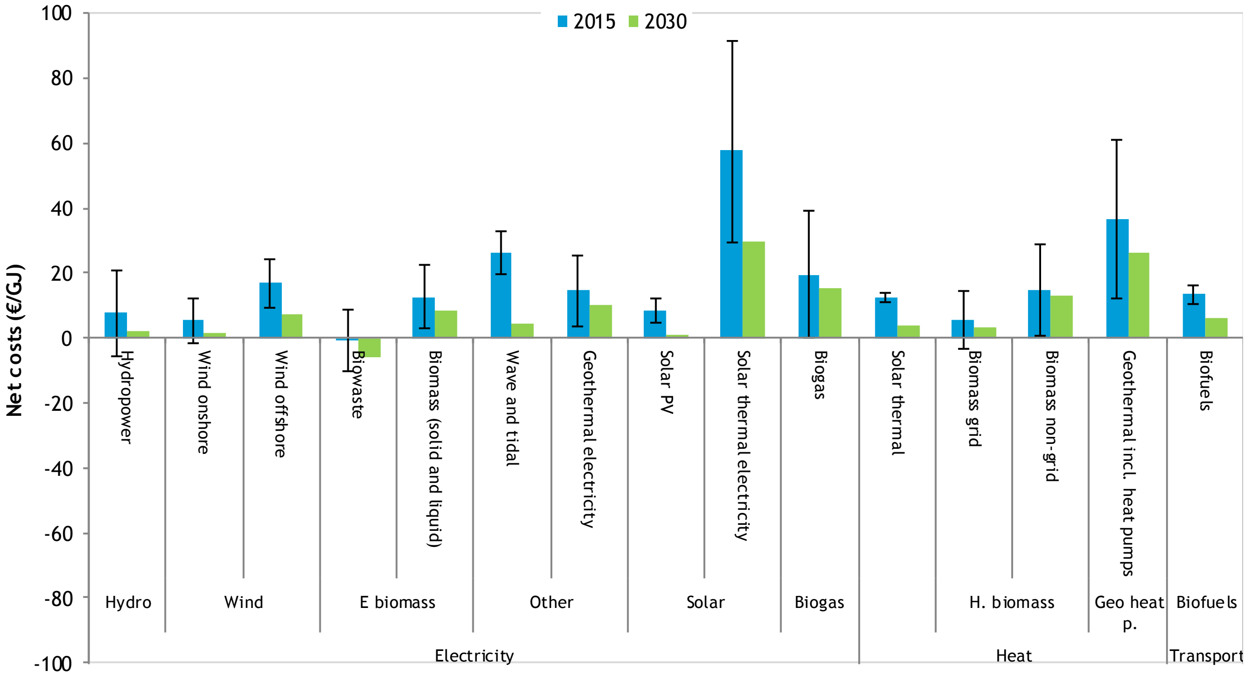
Table 3 Prices of energy sales (€/GJ)

	2015	2030	Source[19]:
Import gas Europe	7	8	IEA (2015a)
Electricity price Europe	11	16	IEA (2015a)
Fossil gasoline and diesel	12	15	European Commission(2016), World Bank (2016)[20]

Cost in the EU-28

The results for net current and 2030 costs for the EU-28 are presented in Figure 8. The bandwidth presents the uncertainty margin (for the current costs, for the year 2030 it has not been possible to estimate uncertainty margins).[21]

Figure 8 Net costs in 2015 and 2030 (€/GJ), EU average



19 In these report data are presented for 2014. Prices have been translated to 2015 values by correcting for inflation.

20 http://pubdocs.worldbank.org/en/328921469543025388/CMO-July-2016-Full-Report.pdf

21 The margin should not be interpreted as the variation of costs across the EU-28. For instance, there are hydropower plants which are commercially viable and can play break even without subsidies, the same holds for onshore wind energy at attractive locations. The bandwidth presents the uncertainty range for the EU average. The uncertainty margins for the costs have been based upon Ecofys 2014.

The blue bars in the figure show that current net costs vary widely between the technologies. Solar thermal electricity[22] (CSP), wave and tidal energy and geothermal heat are the most expensive technologies, while bio-waste[23] has the lowest costs, as the additional costs (compared to incinerating without electricity production) are relatively limited.

In the electricity market, bio-waste is followed by onshore wind and solar PV in terms of costs. Hydropower, biomass, geothermal electricity and offshore wind, are the next technologies in the ranking, while wave and tidal, biogas and solar thermal electricity are the most expensive options.

In the heat market, biomass that is connected to the grid (heat networks), is on average the cheapest option, followed by solar thermal and biomass non grid. Heat pumps are on average the most expensive technologies in the heat market.

However, the cost ranges are very considerable for most technologies. For instance, hydro plants on favourable locations are among the most cost-effective options of all renewable technologies, while the upper bound is among the highest costs. Wind offshore is more expensive than onshore wind, although the results show that costs are overlapping: the cheapest offshore wind farms, such as the one recently developed in the Netherlands, are cheaper than the onshore wind farms at unfavourable locations.

In the heat market, cost ranges are comparable or larger. Prices for bioenergy for instance vary considerably per conversion technology and sources and types of biomass. A major factor that determines the costs for bioenergy is the price of biomass. This price varies per country, type of biomass and scale of application. Owners of industrial applications and large scale (often grid connected) heat boilers have considerably lower costs for purchasing biomass than domestic users, as bulk prices are higher than unit prices.

For instance, for the Dutch subsidy scheme, fuel prices are assumed to be € 5.4 for residuals and € 9.4/GJ for wood pellets.[24] These prices are for large scale heat operations and have been reviewed and agreed by the industry. However, biomass prices for domestic purposes are significantly higher. The Biomass Trade Centre (BTC, 2014) [25] report shows that prices of wood pellets for domestic purposes (excluding VAT) range from € 12/GJ in Romania to over € 17/GJ in countries like Greece, Germany and Ireland. The Sustainable Energy Authority of Ireland (SEAI, 2016), recommended a similar price (€ 18/GJ, excluding VAT) for domestic wood pellets in Ireland for 2016.

Biomass prices for large scale bio-heat options have been obtained from JRC et al. (2015). In this study, prices have been presented on member state level for the years 2010, 2020 and 2030. As there are various types of feedstock, prices have been averaged.

22 Spain is the only of the six included countries with potential for solar thermal electricity.

23 According to the renewable energy directive, bio-waste includes the biodegradable fraction of both industrial and municipal waste.

24 Differences between regions in Europe (Western Europe, Eastern Europe, Scandinavian countries) are assumed to be relatively limited in this study.

25 Biomass Trade Centre, 2014, Monitoring of Wood Fuel Prices in Slovenia, Austria, Italy, Croatia, Romania, Spain and Ireland.

Table 4 Prices for large scale biomass (€/GJ)

	France	Germany	Poland	Spain	Sweden	UK	EU-28*
Primary agricultural residues**	3,0	4,7	3,1	3,8	5,1	5,4	3,9
Roundwood fuelwood	4,7	5,0	4,7	5,3	6,0	6,4	4,9
Roundwood Chips & Pellets	9,9	9,9	4,7	11,1	12,5	13,4	10,0
Forest residues (chips and pellets, energy residues)	5,6	6,2	3,5	6,4	7,4	7,4	5,9
Secondary woodchips	3,1	3,5	3,0	3,0	2,8	2,3	3,0
Secondary sawdust	2,4	2,5	1,7	2,7	2,0	2,2	2,4
Landscape care wood and road side verge grass	3,3	3,5	3,3	3,7	4,1	3,2	3,5
Average* **	**6,2**	**6,4**	**4,0**	**6,8**	**8,1**	**7,7**	**6,5**

Source: JRC et al. (2015)

* In JRC et al. (2015) no figures for the EU-28 have been presented, we have averaged the costs for the six countries as a proxy for the EU-28.

** Stubbles, OSR and sunflower, cereal straw, rice straw, sugar beet, cherries and other soft fruits, apples and pears, citrus, olives and olives pits, vineyards, grass and maize.

*** Prices have been averaged based on the availability per stream. Biomass streams with larger availability have therefore a larger weight factor in the average price. Figures on availability data are based on JRC et al. (2015).

For domestic applications, we have averaged domestic prices of wood pellets, wood chips, wood briquettes and firewood. Prices are based on BTC (2014).[26] In this report prices have been determined for Austria, Germany, Italy, Romania, Croatia, Spain Slovenia, Greece and Ireland. For these countries, prices in Germany, Greece and Ireland are relatively high, while prices in Croatia and Romania are the lowest. As only Spain (lower end prices) and Germany (upper end prices) overlap with the member states in our study, we have assumed that average prices of Spain and Germany are representative for the other four member states and the EU-28. As prices in reality might differ, results have to be interpreted taking into account an uncertainty boundary.

26 Corrected for VAT.

Table 5 Average prices domestic biomass (€/GJ)

	Germany	Spain	Other member states and EU-28
Wood chips	7	6	6
Fire wood	16	17	17
Wood briquettes	15	N.a.	N.a.
Wood pellets	16	14	15
Average	**14**	**12**	**13**

Source: BTC (2014).

We have assumed that grid connected options require mainly bulk purchase of biomass, while non-grid options are most dominantly domestic applications. The briefing of the European Parliamentary service showed that 15% of the heat was produced in industrial units (8.8 Mtoe), while the lion's share (63.5 Mtoe) was produced by domestic users (EPRS, 2015). Based on this information, we assume that the majority of non-grid biomass will be used for domestic purposes.

Future costs

The green bars show the expected average net costs in 2030. All technologies show lower costs compared to 2015 due to technological developments and assumptions on energy price paths, but the size of the cost reductions differs per technology. Assumptions on technology learning rates are based on IEA Technology roadmaps (IEA, 2011; 2011a; 2012; 2015) and additional literature by DECC (2016) and IEA-ETSAP and IRENA (2013). Hydropower and biomass technologies are expected to be relatively mature, which results in modest cost reductions over time.

The price for primary biomass is determined by supply (technically achievable biomass supply volume with associated cost) and demand. These factors are dynamically interlinked and require economic models for detailed assessment. As modelling is complex and depends on many factors, some studies assume that prices remain constant (in real terms) up to 2030 (Irena, 2014; ECN et al., 2015). International biomass traders for wood pellets assume constant prices in real terms for future developments as well (personal communication).

In more sophisticated models, such as JRC et al. (2015) and Forest Research (2015), current and future prices are determined based on supply and demand curves, taking into account the current and future cost of biomass production, harvesting for biomass at the place of origin, transport, pre-treatment cost up-to the conversion gate (including the cost made after harvesting for pre-processing), and forwarding and transport to the place of collection. In JRC et al. (2015) predicts equal prices or relatively small decreases between 2015 and 2030. The prices are often based on a sample of few countries extrapolated to all EU countries, thus the prices are considered estimates. Forest Research (2015) presents predictions for 2030, ranging from € 2/GJ for traditional firewood to approximately € 11/GJ for stem wood. Price differences between different regions within the EU are relatively limited according to the study.

Overall, we can conclude that **there are large uncertainty boundaries for future biomass prices**. For large scale bio-heat and biogas (manure) feedstocks, we have used the JRC-times model results for current and future costs. For domestic bio-heat sources, we have assumed that prices remain constant given the lack of model predictions (see Table 6). However, uncertainty boundaries are significant.

Table 6 **Price developments biomass (€/GJ)**

	Average bulk price		Average domestic price		Average price manure (biogas)	
	2015	**2030**	**2015**	**2030**	**2015**	**2030**
France	6	5	13	13	7	7
Germany	6	6	14	14	6	7
Poland	4	4	13	13	4	4
Spain	7	6	13	13	5	5
Sweden	8	8	13	13	7	7
UK	8	6	13	13	7	7
EU-28	6	6	13	13	6	6
Source	JRC (2015)	JRC (2015)	BTC (2014)	Assumption	JRC (2015)	JRC (2015)

For biofuels, we have based the price predictions on IEA Etsap and Irena (2013). The study shows that advanced biofuels are currently more expensive than conventional biofuels, but the potential for cost reductions is higher. The average price of advanced biofuels decreases from € 28/GJ in 2010 to € 21 per GJ in 2030, while the cost price of land based biofuels is assumed to remain more or less constant in this study.

Table 7 **Price developments biofuels (€/GJ)***

		2010	2020	2030
Land based (excluded from our study)	Sugarcane ethanol	15	15	15
	Corn ethanol	19	18	18
Advanced (included in our study)	Cell ethanol	28	23	21
	BTL Biodiesel	29	23	21
	Average advanced	**28**	**23**	**21**

Source: IEA Etsap and Irena (2013).

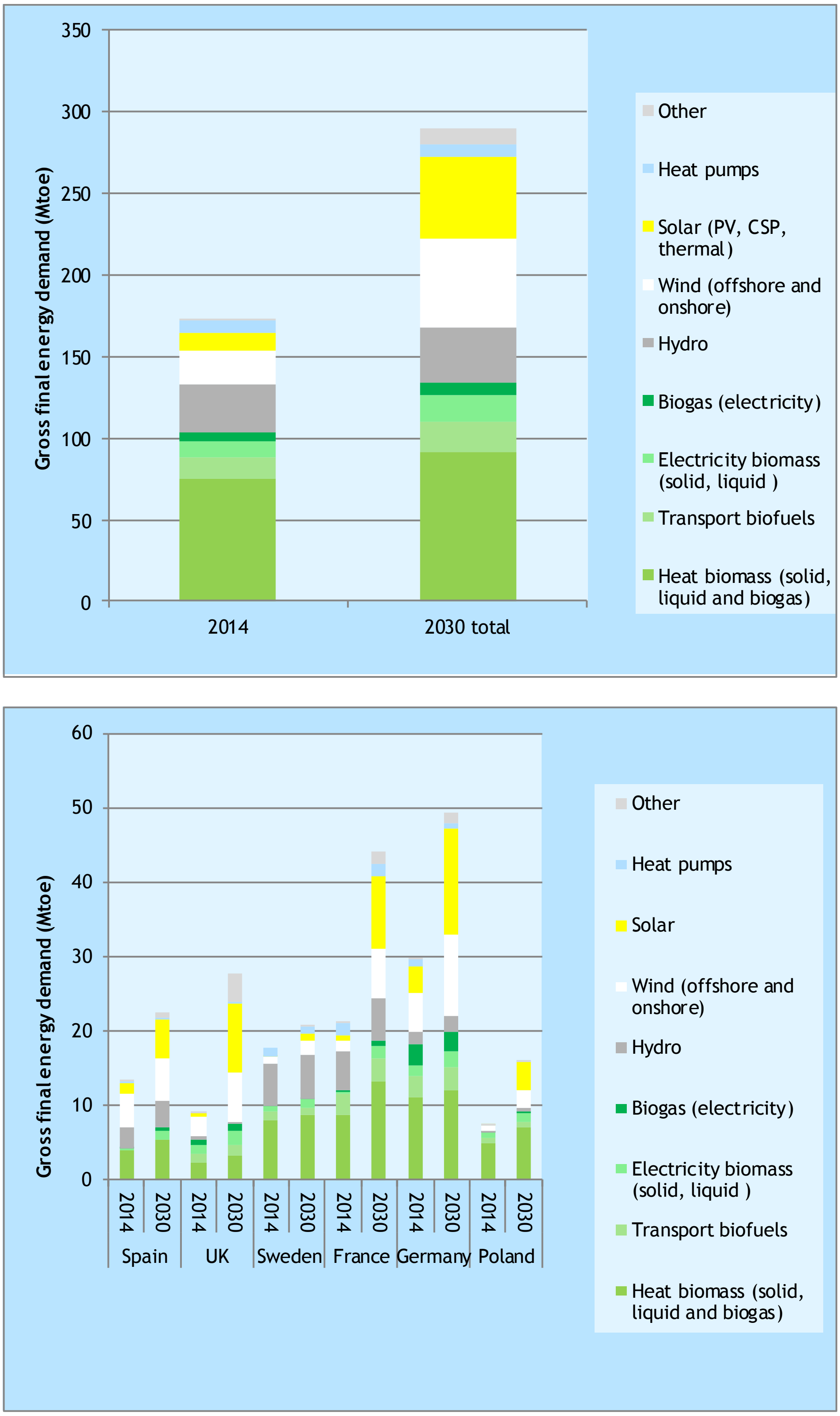
* As no data are presented for the year 2015, we have calculated 2015 price based on the average of the 2010 and 2020 prices. The average costs are € 26/GJ for advanced biofuels. The additional costs compared to fossil gasoline/diesel are respectively € 13/GJ (2015) and € 6/GJ (2030, see Figure 8).

Wind, solar, and wave and tidal energy are still in the growth phase of the product life cycle and robust cost reductions are expected due to learning and scale effects. However, on the other hand balancing costs will increase up to 2030 as deployment increases. This is expected to have a downward effect on the market value of wind and solar energy (which is corrected for in our analysis). For geothermal heat medium costs reductions are expected.

3.4 Results on most optimal mix

The results representing the 2030 optimal mix for the EU-28 (upper diagram) and six member states (lower diagram) are presented in Figure 9. Final energy demand has been determined by multiplying the renewable target with projected final demand in the EU reference scenario 2016.

Figure 9 Gross final energy demand RES 2014 (actual demand) and 2030 optimal 2030 mix RES to meet the 27% EU renewables target (upper diagram) and six member states (lower diagram)



The figures show that in particular solar energy and wind energy will increase up to 2030 in the most cost-effective mix.[27] Wind energy will increase by more than a factor 2.5, while solar energy increases by nearly a factor 5 between 2014 and 2030. Although the potential for heat pumps is large, final demand is limited in the most cost optimal mix due to relatively high costs. Hydropower increases only slightly. For this technology the largest share of the potential is already exploited. The category 'other' includes wave and tidal energy. Demand for these technologies will mainly increase in the UK, due to a high potential and strong potential for cost reductions.

The final demand of bioenergy increases from just over 100 Mtoe in 2014 to approximately 135 Mtoe in 2030. As other renewables increase more up to 2030, total share of bioenergy will decrease from 60% in 2014 to 46% in 2030. The highest relative growth within the bioenergy categories will come from biomass for electricity production, increasing by a factor 1.7 between 2014 and 2030.

For the individual member states results differ, although the trends are more or less comparable. Wind and solar energy have the largest growth of demand, while the increase of bioenergy options is relatively more limited. Typical country specific developments are:
- Only Spain shows an increase in the relative share of bioenergy. Currently the biomass share is relatively low (about one third) and this will increase slightly to 37%. In Spain the increase of wind energy is lower than in other member states. One of the reasons is that the amount of full load hours in lower than in the other member states.
- In the UK the relative share of biomass will more than halve.
  This is explained by the current high share and growth potential for non-bioenergy options. Current deployment of solar, wave and tidal energy is low, but can increase if prices drop. Potential for wind energy is high because of the amount of full load hours. The largest additional potential for solar energy (in particular solar thermal).
- In Sweden, the current renewable energy share is already over 50%, mainly because of high deployment of biomass heat and hydropower. Highest (relative) growth is expected from solar and wind energy.
- In France, the share of bioenergy options will decrease from 56% in 2014 to 45% in 2030.
- Germany will face a significant growth of solar and wind energy. The share of biomass energy in the energy mix will drop by one third.
- In Poland the current renewable energy mix is dominated by biomass options, but the largest growth is expected from wind and solar energy.

The total share of bioenergy in the optimal mix decreases from 60% in 2014 to 46% in 2030. The notion that other renewables technologies will increase more than bioenergy, is in line with the 2020 prediction in the renewables progress report, but in contrast with the EU reference scenario 2013, and the GHG40 and GHG40EE scenario in the impact assessment for the 2030 framework for climate and energy policies (predicting an increasing share of bioenergy).

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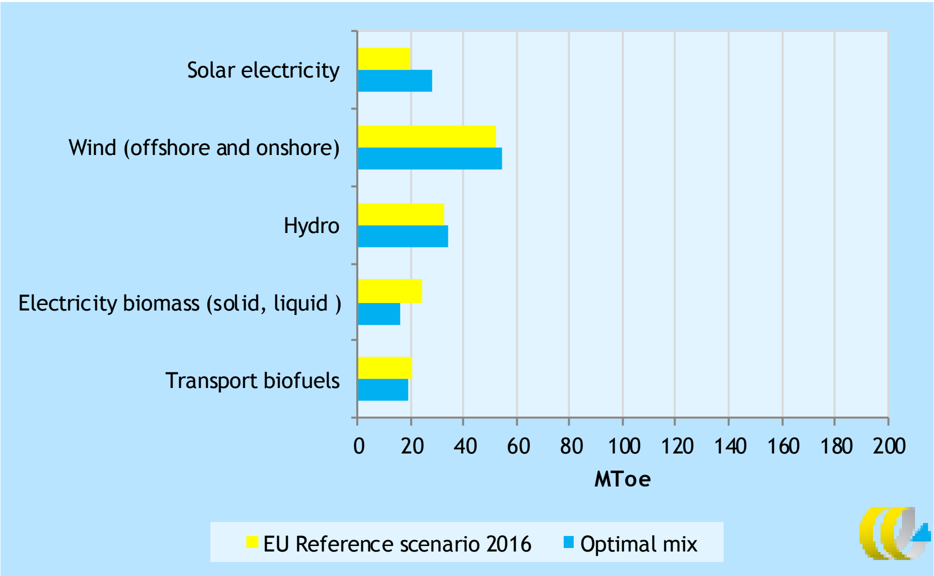
[27] Total demand of renewables to meet the 27% target is assumed to be 292 Mtoe, based on total final demand of 1081 Mtoe in the EU reference scenario 2016.

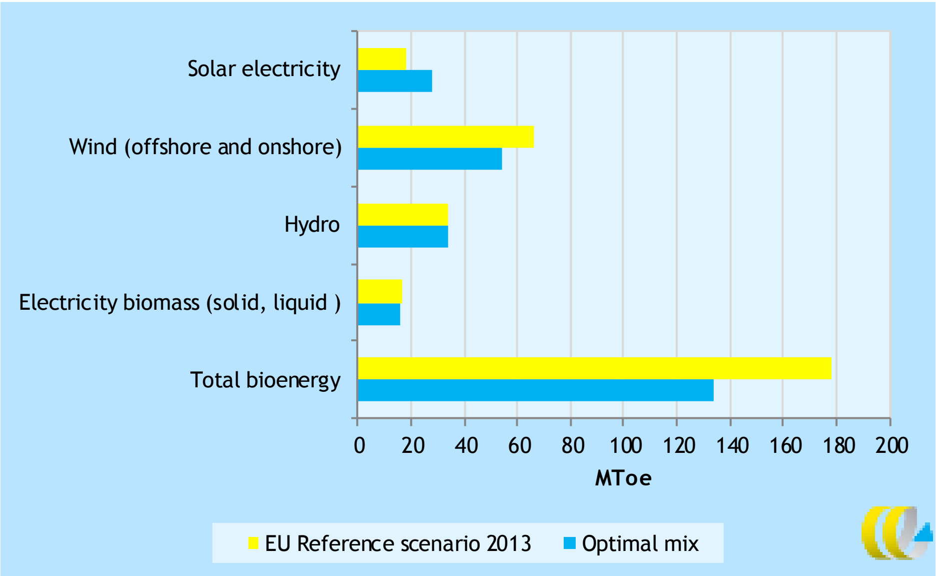
3.5 Comparison 2030 results with EU Reference Scenarios 2013 and 2016

It would be interesting to compare our results in more detail with the most recent EU reference scenario 2016 (that has been published in July 2016). However, unfortunately, no information is presented on total gross final energy demand of bioenergy nor information on renewables demand split up by category in the heat market. It is possible to compare our results with the information that is publically available. (Final demand of wind energy, solar PV, hydro energy, biomass for electricity production and transport biofuels).

In addition, we compare our results to the final energy demand in the EU reference scenario 2013. This study presents specific results on final demand of wind energy, solar PV, hydro energy and in addition the reference scenario 2016, total demand for bioenergy.

Figure 10 **Comparison 2030 results with EU reference scenario 2016 (upper diagram) and EU reference scenario 2013 (lower diagram)**





The comparison shows that for many technologies, demand in the optimal mix is more or less comparable to the EU reference scenarios. This is the case for hydropower, wind energy (EU reference scenario 2016) and transport biofuels. Demand for solar electricity is higher in the optimal mix, while demand for biomass in electricity production is lower compared to the EU reference scenario 2016. Demand for wind energy is somewhat lower in the optimal mix compared to the reference scenario 2013.

The main difference in results is the total demand for bioenergy. Demand in the optimal mix is approximately 45 Mtoe lower than in the EU reference scenario 2013. The most probable explanation is a different demand of bioenergy in the heat sector, where our results indicate a large increase in solar thermal energy demand in the most cost-effective mix. However, as we do not have information on demand of all categories in the EU reference scenario 2013, it has not been possible to determine where these differences arise.

For the EU reference scenario 2016, the total final demand of bioenergy is not presented. If the share of bioenergy in the EU reference scenario 2016 is still over 60%, it will implicate that an increase of bioenergy demand is particularly modelled in the heat sector. However, more detailed results are required for the EU reference scenario 2016 as well to make this comparison possible.

3.6 What explains the differences?

The optimal mix differs from the EU reference scenarios 2013 in terms of total bioenergy demand. Although we do not have insight in all the underlying assumptions of PRIMES, the differences in discount rate might be an important factor explaining the differences.

The PRIMES model reflects decisions from a private perspective, subject to uncertainties, risk taking behaviours and limited access to funding. Discount rate that have been applied vary from 7,5% for energy intensive industries, 9% for non-energy intensive industries, 11% for service sectors and 14,75% for public households.
In our study, we have been using a social discount rate of 3% for all technologies. This rate of 3% is prescribed for EU member states; for Cohesion countries the discount rate is 5% (EC, 2014). The discount rate represents the optimum mix from a social perspective, and is for instance often used in social cost benefit analyses. Clearly, higher discount rates may reflect reality, but it does not mean that it results in the most feasible mix from a social perspective.

Other major differences may result from differences in other assumptions, such as cost prices, potentials per technology, trajectories up to 2030 etc. However, as we do not have full insight in the PRIMES modelling and all the underlying assumptions, it has not been possible to compare our assumptions with the PRIMES model.

3.7 Conclusion

In this chapter we estimated the most cost optimal mix for the EU and six member states by constructing a (high level) cost curve ranking the technologies (additional potential) in terms of cost-effectiveness. For all renewable energy technologies marginal costs will drop. Due to differences in learning rates, fuel costs and other factors the order of the cost curve will change. In an optimal situation, in terms of costs effectiveness, the EU biomass share will drop from 60% now to 46% in 2030. Solar and wind energy will show the highest growth potential. Results per technology differ per country, but the overall conclusion holds more or less for each of the six countries.

4 Conclusions

In this study, the most cost optimal mix has been determined to meet the 2030 EU renewables target from a social perspective based on a high level cost curve. The most important conclusions of our study are:

In the EU reference scenario 2013 over 90% of realisable bioenergy potentials are exploited and only 35% of other renewables
An important conclusion is that EU reference scenario 2013 predicts that over 90% of the realisable bioenergy potentials are exploited. This is also the case for the GHG40 and GHG40 EE scenario in for the impact assessment for the 2030 framework for climate and energy policies. While the demand for bioenergy is close to the maximum, there is still a huge growth potential for other sources, most notably wind energy, solar, and geothermal energy including heat pumps. Of the other renewables, s smaller share of 35% of the realisable potential will be exploited in the scenarios for the impact assessment.

The most cost-effective RES mix in 2030 has a significantly lower share of bioenergy than the EU reference scenario 2013 and the GHG 40 and GHG40EE scenarios in the IA 2030
In this project the most cost optimal mix has been determined based on a high level cost curve. The results show, just like the modelling exercises in the renewables progress report 2015, a decreasing share of bioenergy. The share of bioenergy will drop to 46% in 2030 in the most cost optimal mix. Although we do not have all the underlying assumptions in the models used for the EU reference 2013 and GHG 40 scenario, a major explanatory factor could be the lower discount rate that has been applied in this study.

Governmental interventions are required to meet the most cost optimal mix
The social optimum will not materialize under normal market conditions, as economic actors require higher discount rates than the social discount rate. With higher discount rates, technologies requiring large upfront investments (such as wind, solar) are less favourable. In order to achieve the social optimum in 2030, interventions from the government are required.

In most of the six selected member states trends are similar, although there are location and country specific features.
In this study the optimal mix has been determined on EU-28 level and for six selected member states. For the individual member states results differ, although the trends are more or less comparable. In all countries, except Spain, the share of bioenergy will decrease in the mix if renewables are deployed in a cost-effective manner. Renewables increasing most sharply are wind and solar energy.

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Annex A Cost curves

This annex presents the cost curves for the EU-28 and the six member states. The vertical axis presents the net costs per GJ production. The horizontal axis gives the total additional potential gross final demand of renewable energy (in Mtoe). The additional demand is defined as the realisable potential minus actual current demand.

The blue line indicates the required additional renewable energy demand to meet the EU target or indicative target (member state level). The optimal mix is calculated by adding op additional demand (technologies on the left of the blue line) with current demand. The colours of the bars refer to the main renewable energy category such as been presented in the results (for instance wind energy, see Figure 9 in Chapter 3). The descriptions in the images refer to the sub-categories for which cost levels have been determined, for instance onshore and offshore wind, see Figure 8 in Chapter 3). For the readability of the cost curves not all sub-categories are mentioned separately in the curves.

Solar (thermal, CSP, PV)	
Wind (offshore and onshore)	
Biofuels for transport	
Bio heat (solid, liquid and biogas)	
Bio electricity (solid, liquid)	
Biogas electricity	
Hydropower	
Geothermal incl. heat pumps	
Others	

Figure 11 Cost curve additional demand EU-28, (2030)

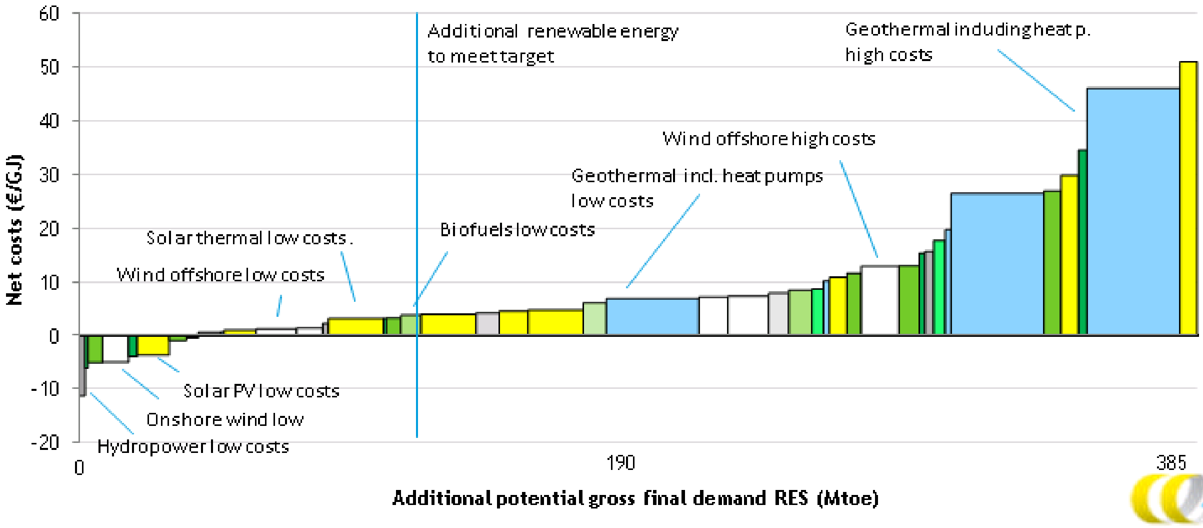


Figure 12 Cost curve additional demand UNITED KINGDOM (2030)

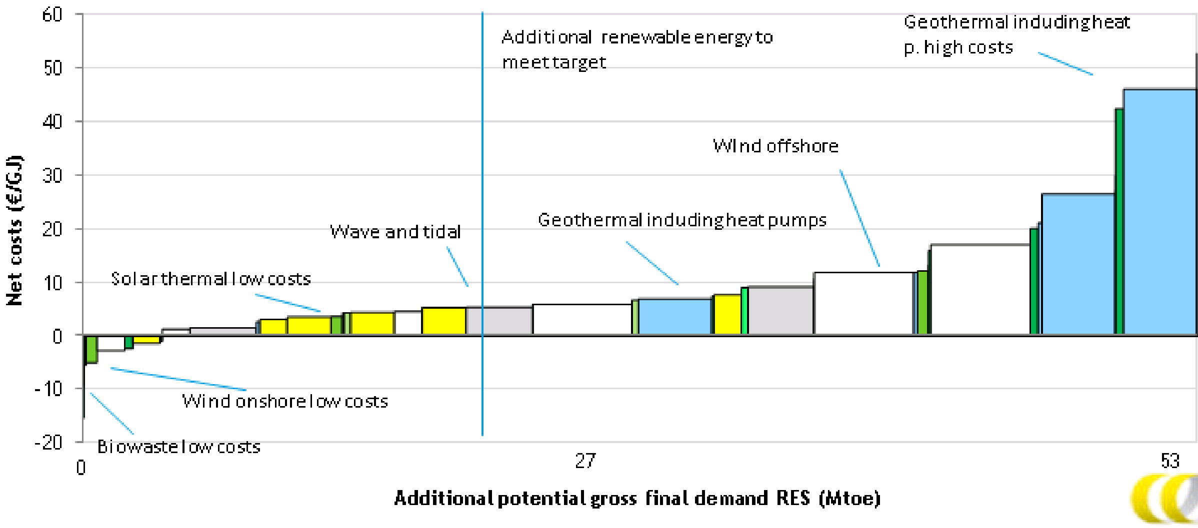


Figure 13 Cost curve additional demand SPAIN (2030)

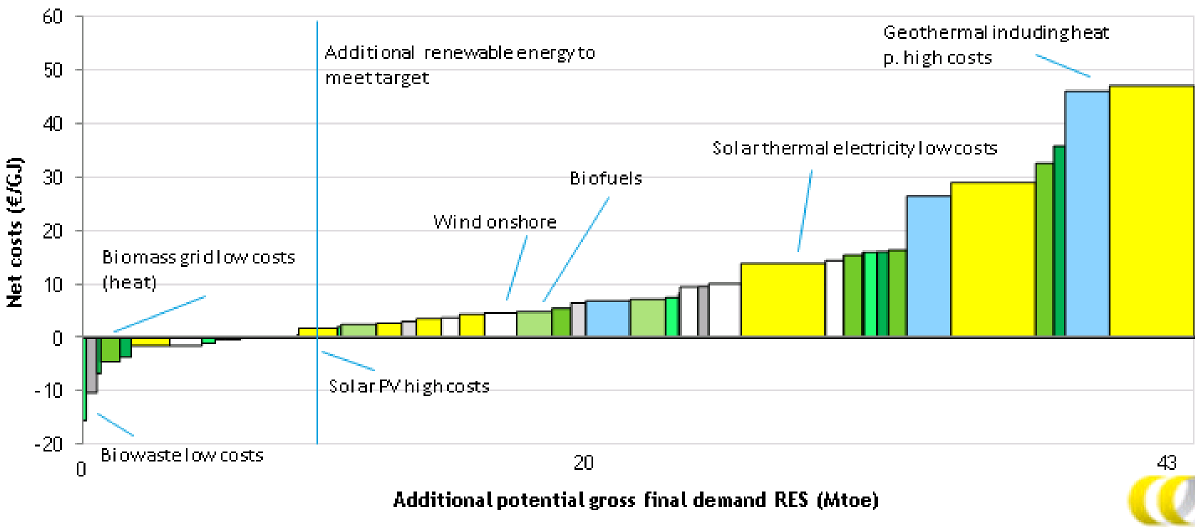


Figure 14 Cost curve additional demand POLAND (2030)

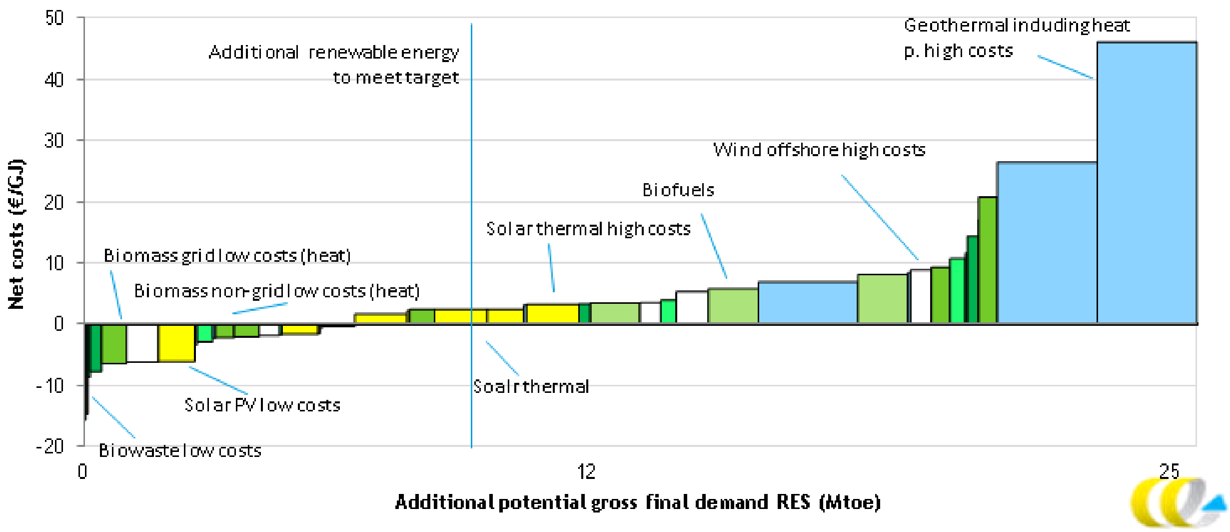


Figure 15 Cost curve additional demand SWEDEN (2030)

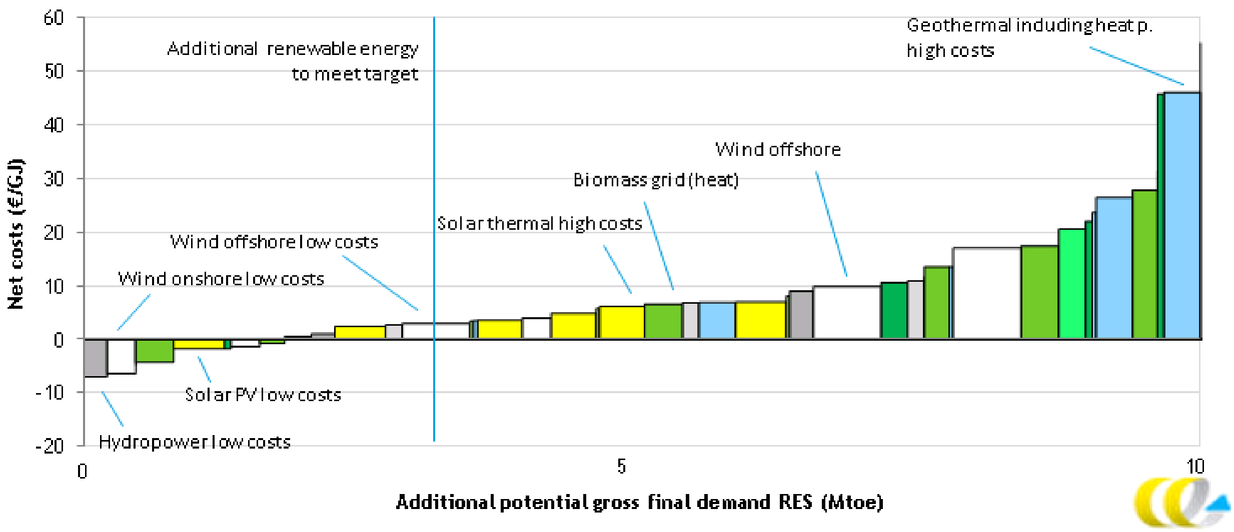


Figure 16 Cost curve additional demand FRANCE (2030)

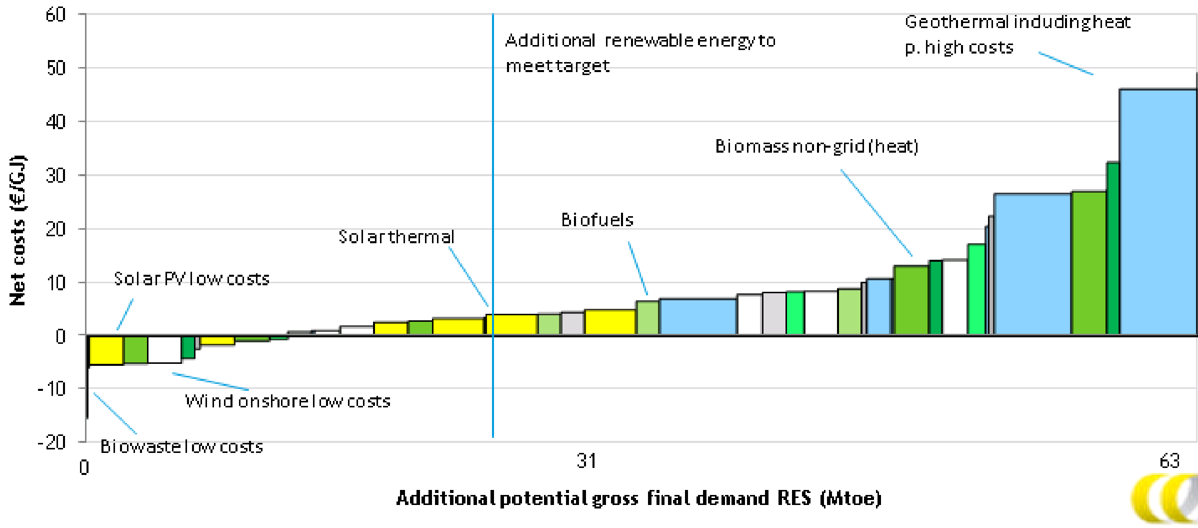
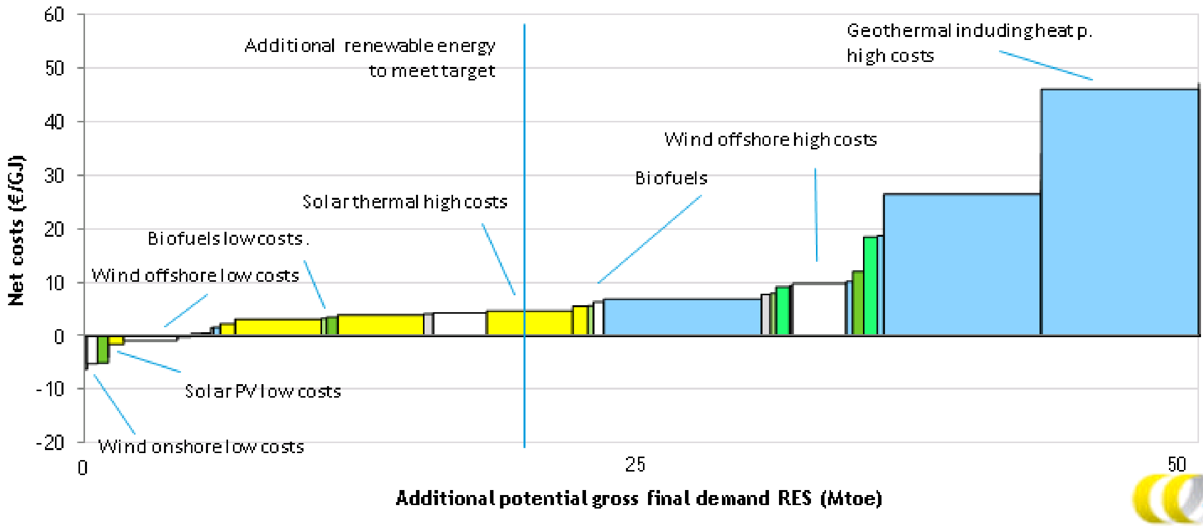


Figure 17 Cost curve additional demand GERMANY, (2030)

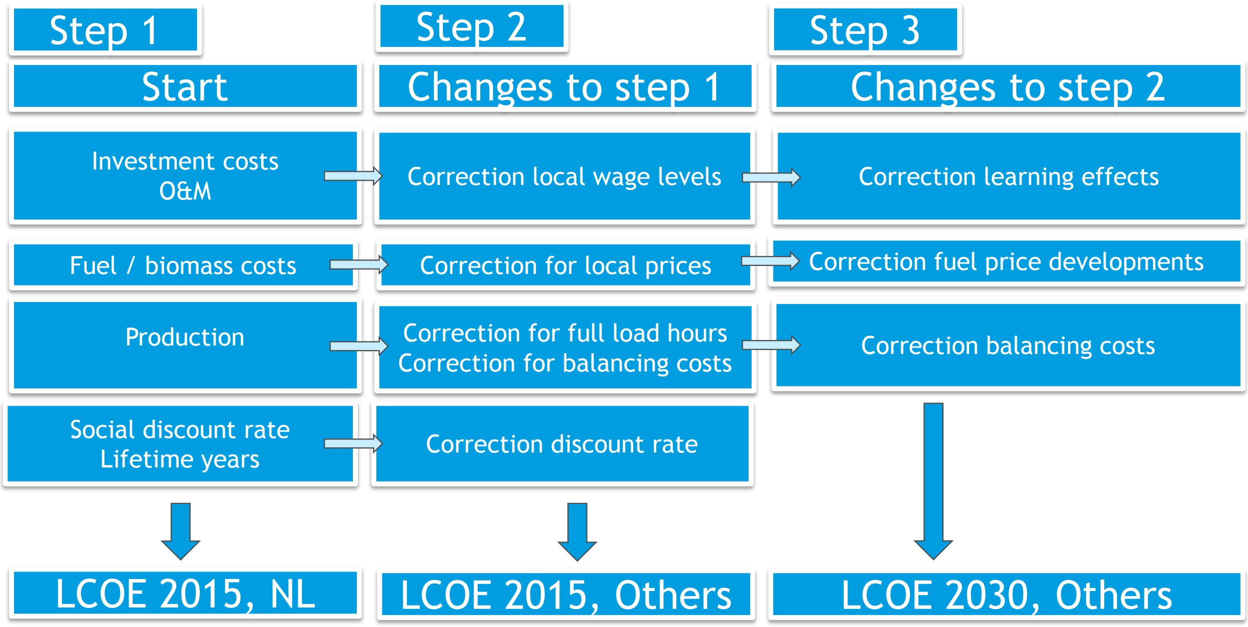


Annex B Costs calculations

B.1 Overview model

In Figure 18 the model for calculating the costs is schematically presented. In Step 1, the LCOE has been calculated for the year 2015 in the Netherlands. In Step 2, we have calculated costs for the other member states and the EU-28. In the third step the LCOE has been calculated for the year 2030. As described earlier, the results have been intensively cross checked with international literature studies comparing costs of renewable technologies.

Figure 18 Overview costs estimation model



B.2 Cost estimation Netherlands

Table 8 presents the parameters for the cost calculation for the Netherlands. The column in the right represents the LCOE for the technologies in €/GJ (not corrected for energy incomes).

Table 8 Cost estimation Netherlands 2015 (€/GJ)

		Investment corrected for lead time	Lifetime	O&M costs	Fuel and carbon costs	TOTEX	Production	LCOE
		Mio €	years	Mio €/y	Mio €/y	Mio €	GJ	€/GJ
Electricity	Hydropower	8.6	30	0.05	-	9.6	402,201	24
Electricity	Wind onshore	1.3	20	0.05	-	2.0	141,396	14
Electricity	Wind offshore	3.7	20	0.13	-	5.6	201,746	28
Electricity	Solar PV	1.0	20	0.02	-	1.3	50,881	25
Electricity	Solar thermal	7.6	25	0.2	-	11.7	170,235	69
Electricity	Wave and tidal	5.2	20	0.2	-	7.5	198,168	38
Electricity	Geothermal electricity	28.1	25	1.5	0.5	62.8	2,820,930	22
Electricity	Biogas	2.8	20	0.2	0.8	16.8	706,978	24
Electricity	Bio-waste	2.9	20	0.1	-	4.5	432,756	10
Electricity	Biomass (solid and liquid)	8.1	20	0.5	1.2	32.9	1,606,767	20
Transport	Biofuels	-		-	-	-	-	26
Heat	Biomass grid	0.5	20	0.09	0.1	3.9	374,912	10
Heat	Biomass non-grid	0.5	20	0.03	0.5	8.0	374,912	21
Heat	Solar thermal	0.8	25	0.002	-	0.8	43,881	19
Heat	Geothermal incl. heat pumps	2.4	25	0.04	0.01	3.4	79,488	43

B.3 Conversion to other coutries

Costs have been converted to other countries by among others, correcting for labour costs and labour productivity. For the correction Eurostat labour cost data (total labour costs) and labour productivity (labour productivity per hour worked) data are used. Index numbers are used (Netherlands = 1).

Table 9 Correction for labour costs and labour productivity

Member state	Index
Germany	0,95
Spain	0,84
France	0,98
Netherlands	1,00
Poland	0,52
UK	1,08
Sweden	1,24
EU-28	0,96

Another important factor determining LCOE is the capacity factor. For hydro, wind, solar, biomass heat and geothermal energy full load hours differ per country due to local circumstances (e.g. weather, soil characteristics). We based our full load hours conversion on information by Ecofys (2014), Hoefnagels et al. (2011) and IEA/OECD (2015). For the other technologies, we assumed no differences in full load hours.

Table 10 Correction for capacity factor

	NL	DE	PO	ES	FR	SE	UK	EU
Hydropower	1,00	1,33	1,35	1,43	0,91	1,49	1,15	1,28
Wind onshore	1,00	0,88	0,72	0,73	0,81	1,12	1,12	0,90
Wind offshore	1,00	1,12	0,91	0,91	0,93	0,91	0,91	1
Solar	1,00	1,00	1,09	1,73	1,36	1,00	1,00	1,36
Geothermal incl. heat pumps	1,00	1,00	1,05	0,63	0,63	1,24	1,00	0,63
Biomass grid	1,00	1,00	1,00	0,80	1,00	0,99	1,00	1,00
Biomass non-grid	1,00	1,00	1,00	0,80	1,00	0,99	1,00	1,00

B.4 Conversion to 2030

B.4.1 Technology developments

For future costs, technology developments play a crucial role.
Table 11 shows the assumed cost reduction per technology in this study.

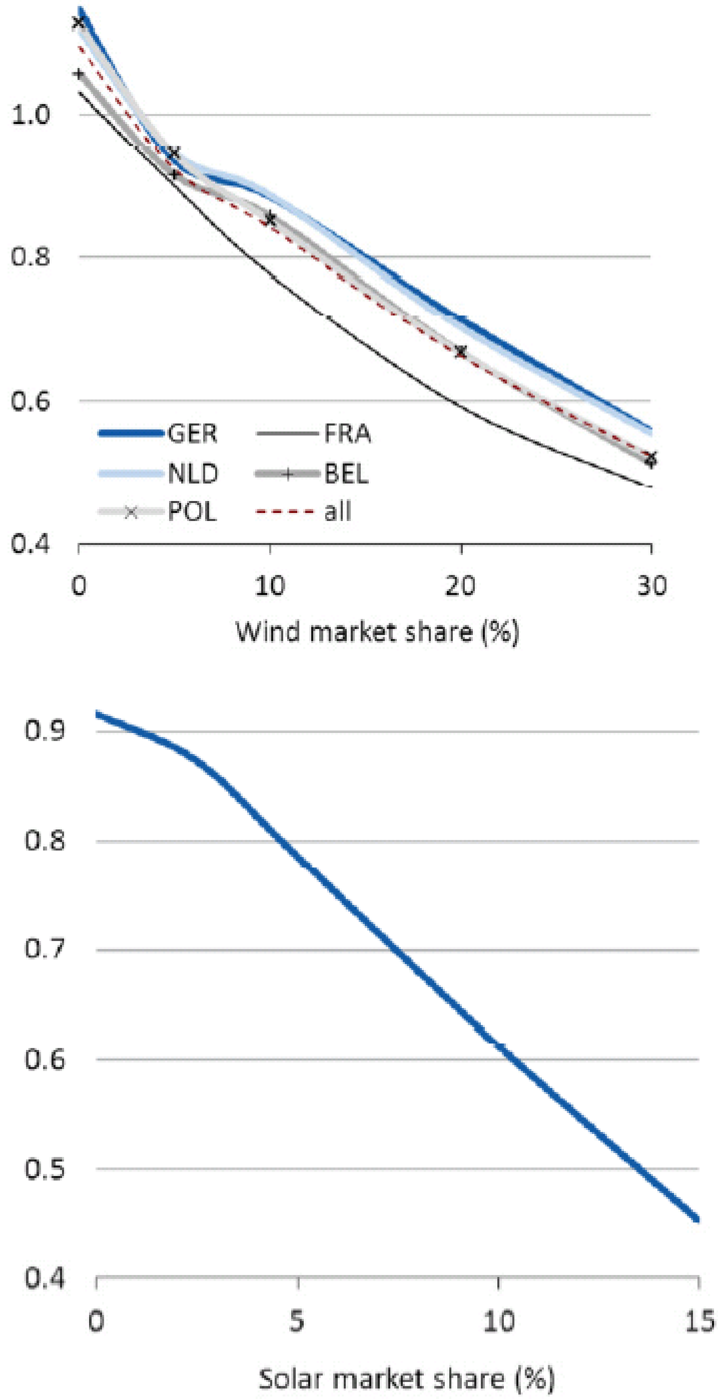
Table 11 Cost reductions per technology

Technology	Reduction in 2030	Base for reduction	Source
Hydropower	No reduction		IEA (2012b)
Wind onshore	25%	LCOE	IEA (2015b)
Wind offshore	35%	LCOE	IEA (2015b)
Solar PV	45%	LCOE	IEA (2015d)
Solar thermal	42%	LCOE	IEA (2015c)
Wave and tidal	45%	LCOE	IEA & NEA (2015)
Geothermal electricity	15%	Investment, O&M, Fuel and Carbon	IEA, 2010
Biogas	20%	Investment costs	Irena, 2014
Bio-waste	No reduction		OECD tech roadmap
Biomass (solid and liquid)	17%	Investment costs	IEA (2012)
Biofuels	18%	LCOE	Irena and IEA Etsap (2013)
Biomass grid	21%	Investment costs	IEA (2012a)
Biomass non-grid	21%	Investment costs	IEA (2012a)
Solar thermal	38%	LCOE	IEA, 2015
Geothermal incl. heat pumps	20%	LCOE	DECC, 2016

B.4.1 Variability costs

Costs for variable sources will increase with demand, due to balancing costs and profile effects. In this study, the costs of variability have been modelled by decreasing the electricity incomes of wind and solar when market shares increase. The relation between demand and the market price is based upon Hirth (2013)

Figure 19 Relationship between market share wind and solar (horizontal axis) and market value (vertical axis)



Source: Hirth (2013).

B.5 Cost estimation 2030, EU-28, average costs

The average costs per technology for the EU-28 are presented in Table 12.

Table 12 Net costs EU-28

	LCOE	Market price	Net costs
	€/GJ	€/GJ	€/GJ
Hydropower	18	16	2
Wind onshore	12	11*	1
Wind offshore	18	11*	7
Solar PV	10	9*	1
Solar thermal	39	9*	30
Wave and tidal	20	16	4
Geothermal electricity	19	9**	10
Biogas	28	13**	15
Bio-waste	10	16	-6
Biomass (solid and liquid)	19	10* *	9
Biofuels	21	15	6
Biomass grid	11	8	3
Biomass non-grid	21	8	13
Solar thermal	12	8	4
Geothermal incl. heat p	34	8	26

* The market price for wind and solar energy is lower than for hydropower, because of variability impacts (profile effects, balancing costs).

** Weighted average incomes of heat and electricity.