Potential of prosumer technologies in the EU

PROSEU results

CE Delft

Committed to the Environment

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Content

Summary

Introduction

Increasingly, households and enterprises are getting involved in their own energy generation and storage. They not only consume energy, but are also actively engaged in producing energy from renewable sources, for example by installing solar PV on their rooftops. These so-called prosumers can act individually or as part of a broader collective. Either way, their actions are found to contribute to national and EU energy and climate goals, empower citizens and enhance their awareness of the ongoing transition from fossil to renewable energy.

The number of prosumers is increasing in many countries of the EU but an overall picture of the extent to which EU-citizens could contribute to the future energy system is lacking. To increase the understanding of the overall potential of prosumerism throughout the EU + UK, CE Delft developed the CEPROM model. This model aims to answer the question: To what extent can EU citizens and enterprises in the tertiary sector (service providers) contribute to the energy transition in the role of prosumer?

The CEPROM model is an update of the model used in the 2016-study of CE Delft *'The potential of energy citizens in the European Union'* (CE Delft, 2016). It was developed in the PROSEU project, an EU-funded research project that brought together eleven project partners from seven European countries and aimed to enable the mainstreaming of the renewable energy prosumer phenomenon into the European Energy Union. Much of what is presented in this report is also reported in Deliverable D5.2 of PROSEU, the *Report on local, national and EU scenarios*. This additional report was drafted to enhance the accessibility of the EU-wide scenarios and compare the results with those of the 2016 study.

Prosumer scenarios

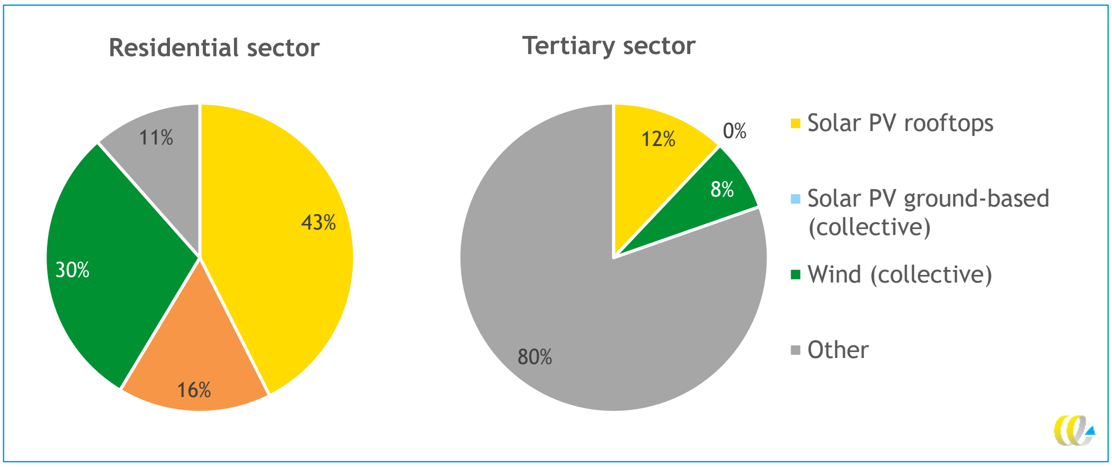
CEPROM calculates for each EU member state and the UK the future electricity and heat demand, the potential for prosumer production capacities and energy production and the potential degree of self-sufficiency of prosumers. Prosumers considered are individual households, collectives and the tertiary sector. The model includes a broad range of technologies and takes three different scenarios into account:
- Reference scenario, which represents 'business as usual'. This scenario provides results for 2015, 2030 and 2050.
- Maximum Renewables scenario, in which prosumers generate as much renewable energy themselves as possible, without storing this energy. Results are calculated for 2030 and 2050. The calculated production of the prosumers corresponds to the technical potential. Social and financial constraints are not taken into account.
- Maximum Self-sufficiency scenario, which uses the same assumptions as the Maximum Renewables scenario, but also includes energy storage. Results are also calculated for 2030 and 2050.

Compared to the 2016-study of CE Delft, heat technologies are added, data have been updated and several changes have been made to the modelling methodology and scope.

Results

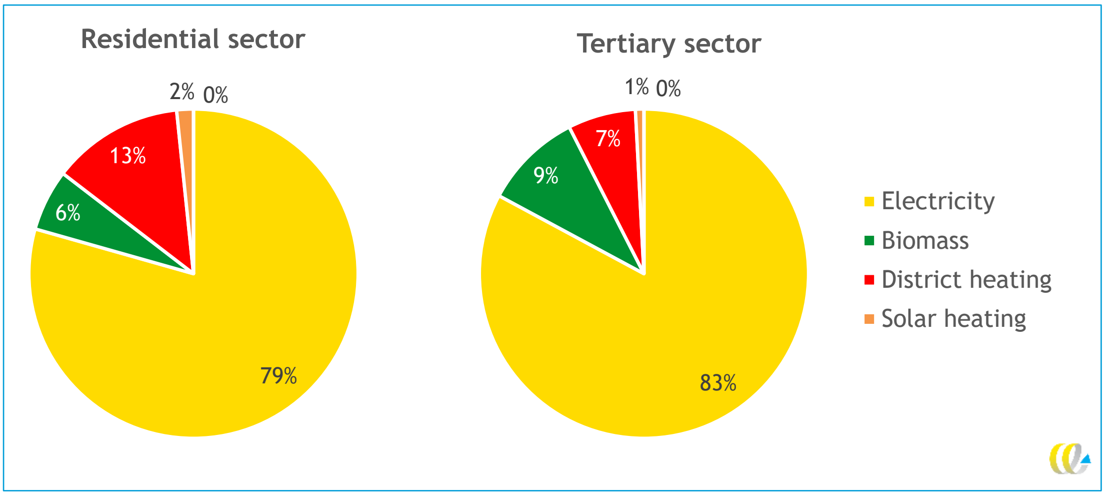
The model shows that in 2050, up to 89% of electricity demand of households can be generated by the households themselves. Electricity production from solar PV has the highest potential for growth, especially in Southern Europe. More than 70% of this solar PV potential is on rooftops (often owned by individuals), the rest is ground-based (owned by collectives). Wind turbines owned by prosumer collectives have a high potential in countries with enough available space around cities and towns and enough wind power density.
The results for the EU + UK are shown in Figure 1.

Figure 1 - Share of technologies used for generation of electricity in 2050 Maximum Renewables/Maximum Self-sufficiency scenario (EU + UK)



The total electricity demand for households and residential buildings will increase significantly in the two prosumer scenarios (Maximum Renewables scenario and Maximum Self-sufficiency scenario). This is due to the increased use of heat technologies that operate on electricity (mostly heat pumps) and electric vehicles. Heating and cooling demand stays fairly constant over time in the different scenarios, and is mainly provided by heat pumps, especially in southern countries that also have a significant cooling demand. In countries with biomass availability, biomass boilers and CHP are applied as well. District heating is mainly applied in northern countries, where heat demand is high and cooling demand is low.

Figure 2 - Share of energy sources used for heating in 2050 Maximum Renewables/Maximum Self-sufficiency scenario



Recommendations for further research

The CEPROM model aims to determine the maximal potential of prosumerism, implicitly assuming that supportive legislation and financial schemes are present. Social and financial constraints are not taken into account. These should be included to make a more realistic estimation of the potential of prosumers. Furthermore, a top-down approach is used in the model based on datasets on a national level. This allows us to model the whole EU + UK and provide comparable national results, based on a transparent set of data and assumptions. To assess the local and regional opportunities in more detail, more detailed modelling is recommended with regional or even local data.

1 Introduction

1.1 Background

Increasingly, households and enterprises are getting involved in their own energy generation and storage. Solar PV is installed on rooftops, households collectively invest in wind turbines, alternative technologies like heat pumps are used to provide heat. Furthermore, batteries are developed which enable prosumers to store electricity in times of oversupply instead of feeding electricity back into the grid. Some prosumers participate in pilots to further explore how to create demand side flexibility.

These new technologies contribute to EU climate goals and enhance the energy transition. Also on a local level various cities and communities are pursuing the goal of becoming self-sufficient and reliant on renewable energy only, encouraging their inhabitants to be actively involved. The growth of prosumers challenges existing market structures and institutions. Currently, the impact of prosumers might seem small. This could however change in the near future.

Global and EU-wide decarbonisation scenarios typically model increasing renewable energy production capacities, but do not go into detail on how this is achieved and who will be involved. To fill this knowledge gap, a previous study of CE Delft provided first insights into the potential of prosumers in the EU. This new study, performed within the PROSEU project, aims to answer this question more accurately:
To what extent can EU citizens and enterprises (tertiary sector) contribute to the energy transition in the role of prosumer?

To answer this question and further explore the prosumer potential in the EU, a model was developed within the PROSEU project: CEPROM (CE Delft Prosumers Model). The CEPROM-model calculates the technical potential of energy citizens (households and the tertiary sector) for a broad range of energy technologies. This is done per member state and for the EU as a whole, for 2015 (base year), 2030 and 2050[1].

The CEPROM-model calculates the technical potential for prosumers in the EU, it's goal is to determine the maximal potential for a future with supportive legislation and financial schemes. Therefore, social and financial constraints are not taken into account.
These should be included to make a more realistic estimation of the potential of prosumers.

CEPROM is an update of the model used in the study 'The potential of energy citizens in the European Union' (CE Delft, 2016)[2]. Compared to the calculations for that study, multiple improvements have been made:
- Heat technologies are now taken into account. The 2016 study is limited to electricity generation and storage.
- The definition of energy citizens is somewhat different compared to the previous study. The current study includes individual households and the tertiary sector while the previous study includes households, public entities and small enterprises.
- Input data and assumptions are updated.

[1] The project scope was the EU28, all results in this report are therefore for the EU + UK (EU28).
[2] https://www.cedelft.eu/en/publications/1845/the-potential-of-energy-citizens-in-the-european-union

- The technical potential of electricity generation by prosumers is determined without taking into account financial capabilities or interest in investing in renewable energy of the citizens. The 2016 study took into account the investment potential and willingness to invest in renewable energy. This was not included in this update, since more research is needed to determine this accurately. Also, these factors could be overcome by cost reductions of the technologies, effective policies and innovative business models.

1.2 The PROSEU project

CEPROM is developed within the PROSEU research project, a project that received funding from the European Union's Horizon 2020 research and innovation programme. PROSEU aims to enable the mainstreaming of the renewable energy prosumer phenomenon into the European Energy Union. PROSEU's research focuses on collectives of RES Prosumers and investigates new business models, market regulations, infrastructural integration, technology scenarios and energy policies across Europe. Through work in different work packages, PROSEU has built an integrated knowledge framework for a broad understanding of RES Prosumerism. More information on the PROSEU project and it's various deliverables can be found on proseu.eu.

The work reported on in this report contributes to one of the objectives of the PROSEU project: "to *develop scenarios for 2030 and 2050 based on in-depth analysis of technological solutions for RES Prosumers under different geographical, climatic and socio-political conditions*". While other partners within the PROSEU project researched and developed models to describe impact on a local level (individual, neighbourhood, city), CEPROM was developed to give more insight on the overall potential and possible impact on member state and EU level. The complete results of this modelling work can be found in deliverable D5.2 of the PROSEU project, the 'Report on local, national and EU scenarios'[3].

1.3 This report

This report describes the EU-wide modelling, scenarios and results that were also included in deliverable D5.2. In addition, we included a comparison of these results with that of the CE Delft 2016 study on energy citizens mentioned above.

First, the main in- and outputs of the CEPROM model are described in Chapter 2. Subsequently assumptions and the modelling methodology are explained in Chapter 3. Chapter 4 discusses the results, and compares these to the 2016 study. Chapter 5 then describes the main conclusions and our recommendations for further research and improvements to the CEPROM-model.

[3] https://proseu.eu/sites/default/files/Resources/PROSEU_D5.2%20Report%20on%20local%2C%20national%20and%20EU%20scenarios.pdf

2 Model

To determine the technical potential of prosumers in the EU, CE Delft developed the Prosumers Model CEPROM. CEPROM calculates the maximum potential of energy generation with prosumer technologies and the use of this energy in households and tertiary buildings. The model calculates the technical potential of prosumer technologies in all member states and in the EU in total. The technical potential is the potential that can maximally be reached if all households and buildings in the tertiary sector will make maximum use of the available prosumer technologies to heat or cool their buildings and generate the renewable energy that is needed to cover their own demand, given certain practical boundary conditions and provided that it is technically possible.

Costs and emissions are not taken into account in CEPROM. It should also be noted that CEPROM is not a detailed optimization model. In reality, using the maximum share of renewable energy generated by consumers, is not necessarily always the situation that is most desirable. The social and technical consequences of going fully for an energy system driven by prosumers is not taken into account in the model. The outcome of the model shows the technical potential that could be achieved, but the costs of such a change in energy system and the effort in organizing this change are not taken into account.

This chapter describes the main outputs and inputs of the model. Furthermore, differences compared to the previous CE-model (CE Delft, 2016) are discussed. In the next chapter the methodology and assumptions per technology will be discussed in detail.

2.1 Output variables

The model generates the following output:
- electricity demand;
- heating and cooling demand[4];
- installed capacity both for renewable energy technologies and storage;
- energy production;
- percentage of self-sufficiency[5].

These outputs are calculated for the EU and member states; distinguishing three scenarios; considering households and the tertiary sector as prosumers; including a broad range of technologies. This is explained below.

Geographical scope

All Member states and the United Kingdom[6] are considered. The model calculates the output variables for each Member State separately. The EU-results are the sum of the results on country level.

4 Based on the PRIMES-scenario.

5 The share of self-sufficiency is expressed as a percentage of self-produced energy that is directly used or used via storage in battery or ATES, against the total use of energy.

6 At the start of the project, the United Kingdom was still a member of the EU, therefore, they are also taken into account in this analysis.

Time horizon

The base year is chosen to be 2015. The model calculates the output variables for 2030 and 2050. For two scenario's, the Maximum Renewables and Maximum Self-sufficiency scenario, the technical potential of all prosumer technologies is calculated for 2050. A linear interpolation between 2015 and 2050 is used to determine values for 2030.

Scenarios

Three scenarios were developed:
1. Reference scenario: 2015, 2030, 2050.
2. Maximum Renewables scenario: 2030, 2050.
3. Maximum Self-sufficiency scenario: 2030, 2050.

The *Reference scenario* ensures comparability with business as usual. The Reference scenario provides only business-as-usual changes in demands, technological parameters, etc. but does not incorporate any changes in technology mix being used to produce energy, i.e. no additional uptake of prosumers is expected. The Reference scenario was modelled for 2015, 2030 and 2050.

The Maximum *Renewables scenario* shows the impact of maximizing the energy production with renewable prosumer technologies. This scenario does not take into account the implementation of energy storage. It examines the full exploitation of renewable energy generation in the existing system, with excess production being fed into the grid.
The Maximum Renewables scenario was modelled for 2030 and 2050.

The *Maximum Self-sufficiency* scenario shows how storage technologies can improve self-sufficiency. this scenario analyses the possibility of achieving high shares of self-sufficiency of the prosumers, taking into account energy storage technologies, additional to the Maximum Renewables scenario. In this scenario, electric battery storage and thermal energy storage have been added. The amount of battery storage is linked to the capacity of the solar panels and wind turbines, while thermal energy storage is only applied on specific locations, see Chapter 3. The Maximum Renewables scenario was modelled for 2030 and 2050.

Technologies

A wide range of prosumer technologies is included in the model, as it includes technologies that generate electricity or heat (or both) and technologies that can store energy.
In Table 1 the types of technologies included in the model are listed.

Table 1 - Technologies used in CEPROM

Technology	Type
Solar PV	Generation of electricity
Wind turbines	Generation of electricity
Hydro power (small scale)	Generation of electricity
Solar thermal	Generation of heat
Heat pump	Generation of heat and cooling
Biomass boiler	Generation of heat
District heating	Generation of heat
CHP	Generation of heat and electricity

Technology	Type
Thermal energy storage	Heat storage
Batteries	Electricity storage
Electric vehicles	Electricity storage

Energy citizens

Three different types of citizens are distinguished:

1. *Individual households:* These are households which invest in renewable energy technologies for own use.
2. *Collectives:* These are households which collectively invest in renewable energy technologies. They can be residents of an apartment block investing together in solar PV on their shared rooftop or a group of citizens participating in an energy collective that invests in a wind turbine or ground-bases solar panels.
3. *Tertiary sector:* the model considers the tertiary sector, focussing on the suitability of the building stock (the tertiary buildings[7]) for renewable energy technologies.

In case of the tertiary sector and individual households only the technologies which can be realised on site (on private property) are considered. In case of collectives also the surroundings of where the citizens live are taken into account to realize renewable energy technologies.

2.2 Key input data/variables

Which technology is suitable for which household, collective or tertiary building depends on different factors. In the model the following key factors are taken into account to determine the technology that can be used:

- **Current numbers of heating technologies and energy production of prosumers**: Used for the Reference scenario.
- **Population and number of households:** Used to determine the potential of heating technologies.
- **Energy demand:** This affects the potential amount of energy production with prosumer technologies, since the total potential production is limited to the energy demand in a region (urban, suburban, rural). Individual households can produce more than their energy demand.
- **Degree of urbanization:** Each of the degrees of urbanization (urban, suburban, rural) is considered separately. This categorization is used to determine preference heating technologies.
- **Land use:** Used to determine potential *biomass availability* for heating (amount of woodland) and potential for ground-based solar PV and wind turbines (available bare land area).
- **Building stock:** Used to determine the potential production of solar PV.
- **Climate conditions:** Used to determine preference heating technologies and potential for solar and wind energy.

Details regarding the methodology and assumptions can be found in Chapter 3.

[7] Tertiary buildings are buildings of organizations or companies active in the service sector. A full list of sub-sectors that part of this sector can be found on https://stats.oecd.org/glossary/detail.asp?ID=2432. A large part of tertiary buildings are used by SMEs. SMEs are defined by the European Commission as having less than 250 persons employed and having an annual turnover of up to EUR 50 million.

2.3 Main differences compared to the 2016-study

In the following paragraphs, the main differences between the 2016-study and the PROSEU study are explained.

Energy citizen types

The 2016-study focused on three energy citizen types: households, public entities and small enterprises. The scope of the PROSEU study is somewhat broader; the study looks at households and the tertiary sector, under which the public entities and the small enterprises, but also larger enterprises. It looks at the building stock of all residential and tertiary buildings to determine the technical potential of rooftop solar PV and heating and cooling technologies.

Electricity and/or heating and cooling

The biggest difference between the 2016-study and the PROSEU study is that in the latter also heating and cooling are taken into account. In the 2016-study, only electricity generation and storage are taken into account. In the PROSEU study, heating and cooling, and the storage of those two are added. This not only leads to a broader range of results, but also different results. The use of heat pumps has an effect on the electricity demand and the use of solar thermal has an effect on the available area of solar panels.

Different methodology

Concerning the generation of electricity, two different methods are used. In the 2016-study, the potential of electricity production and storage is determined based on the current installed capacity of solar and wind by prosumers, either by individual households or collectives. An estimation of the increase in installation capacity in solar and wind is determined with the Energy Revolution Scenarios of OECD. Apart from this technical potential, the investment potential is determined. This is based on the willingness to invest and the annual savings rate of a member state. The investment potential is used to determine the capacity that can be installed in solar and wind energy. This installed capacity cannot be larger than the technical potential.

In the PROSEU study, only the technical potential of electricity generation by prosumers is determined. It is assumed that all households could have solar panels on their rooftops, either individual or in a collective in case of multifamily buildings. The technical potential of ground-based solar and wind turbines is based on the available area around where people live, or utility buildings are situated, and the total technical potential of the member state. It is assumed that to use energy from wind turbines or ground-based solar as a prosumer, the wind turbines or solar panels need to be situated within 5 km from the area you live in. No social or financial aspects are taken into account in this technical potential.

Data

For the PROSEU study, the parameters used in the 2016-study were updated. A lot of new references are used, which leads to results that are more based on actual data as compared to assumptions. For some results this leads to a large difference. The average battery size of electric vehicles, for example, is in the 2016-study estimated on 100 kWh, while in the PROSEU study, it is assumed to be 60 kWh. Furthermore, the data used in the 2016-study are in some cases based on data for one country, while in the PROSEU study, more country specific data are used.

3 Methodology and assumptions

The model determines the technical potential of different prosumer technologies.
When necessary, the model makes a decision between competing technologies based on the type of building, the population density and the characteristics of the country. The main starting point is to use as much as possible renewable energy generated by prosumers.
In the following paragraphs, the general assumptions are presented and for each technology, the conditions and assumptions for the use of that technology are elaborated. An overview of the key parameters, the used data and the choice of technologies can be found in the appendix.

3.1 General assumptions

In Table 2 and Table 3 general data of each country are presented for the Reference scenario. These are based on the results of the PRIMES model. These data are also used as input for the Maximum Renewables scenario and Maximum Self-sufficiency scenario.
The number of households is linked to the development of the population, as given in the PRIMES model. The number of utility buildings remains equal. The heating and cooling demand is based on the PRIMES model and is equal for all scenarios. The electricity demand, however, will increase in the Maximum Renewables and Maximum Self-sufficiency scenario, due to extra use of electric vehicles and heat pumps. Energy savings are incorporated in the electricity demand of the Reference scenario.

Table 2 - Number of households and utility buildings and energy demand 2015

Member state	Households	Utility buildings	Heating & cooling demand (TWh)	Electricity demand (TWh)
Austria	3,816,000	650,000	65	32
Belgium	4,699,000	1,170,000	90	32
Bulgaria	2,940,000	590,000	20	32
Croatia	1,487,000	510,000	20	32
Cyprus	298,000	309,000	8	32
Czech Republic	4,644,000	700,000	66	32
Denmark	2,373,000	760,000	46	32
Estonia	572,000	816,000	9	32
Finland	2,623,000	1,523,000	62	32
France	28,931,000	6,130,000	429	32
Germany	40,258,000	11,890,000	666	32
Greece	4,376,000	1,190,000	52	32
Hungary	4,152,000	410,000	59	32
Ireland	1,731,000	430,000	29	32
Italy	25,789,000	2,990,000	410	32
Latvia	833,000	140,000	13	32
Lithuania	1,332,000	200,000	13	32
Luxembourg	229,000	39,000	7	32
Malta	173,000	39,000	2	32
Netherlands	7,622,000	1,128,000	117	32

Member state	Households	Utility buildings	Heating & cooling demand (TWh)	Electricity demand (TWh)
Poland	14,110,000	2,650,000	182	32
Portugal	4,083,000	940,000	22	32
Romania	7,470,000	880,000	53	32
Slovakia	1,847,000	90,000	26	32
Slovenia	883,000	945,000	11	32
Spain	18,376,000	2,980,000	173	32
Sweden	5,100,000	460,000	82	32
United Kingdom	28,269,000	7,110,000	375	32
Total	**219,016,000**	**47,669,000**	**3,109**	**885**

Table 3 - Number of households and utitlity buildings and energy demand 2050 (PRIMES)

Member state	Number of households	Number of utility buildings	Heating demand 2050 (TWh)	Cooling demand 2050 (TWh)	Electricity demand 2050 (TWh)
Austria	4,230,000	720,000	52	2	49
Belgium	5,866,000	1,460,000	73	3	89
Bulgaria	2,437,000	489,000	15	4	22
Croatia	1,356,000	465,000	16	2	16
Cyprus	346,000	359,000	2	19	11
Czech Republic	4,831,000	728,000	53	1	53
Denmark	2,637,000	845,000	37	1	41
Estonia	503,000	719,000	8	0	7
Finland	2,876,000	1,670,000	51	1	46
France	31,769,000	6,731,000	343	33	419
Germany	37,304,000	11,018,000	537	11	526
Greece	3,734,000	1,016,000	28	53	52
Hungary	3,961,000	391,000	47	3	47
Ireland	1,864,000	463,000	24	0	23
Italy	27,910,000	3,236,000	291	153	385
Latvia	644,000	108,000	10	0	9
Lithuania	952,000	143,000	10	0	9
Luxembourg	381,000	65,000	6	0	9
Malta	185,000	42,000	1	5	4
Netherlands	7,740,000	1,146,000	95	3	115
Poland	12,806,000	2,405,000	150	4	158
Portugal	3,568,000	822,000	13	13	35
Romania	6,820,000	803,000	42	6	51
Slovakia	1,661,000	81,000	21	0	23
Slovenia	876,000	937,000	9	1	10
Spain	18,275,000	2,964,000	103	104	196
Sweden	6,261,000	565,000	66	2	66
United Kingdom	32,713,000	8,228,000	306	9	325
Total	**224,506,000**	**48,619,000**	**2,408**	**434**	**2,797**

3.2 Heating/cooling generation

To fulfil the heat demand of households and the tertiary sector five technologies are taken into account: CHP, biomass boiler, district heating, heat pump and solar thermal. In the Maximum Renewables and the Maximum Self-sufficiency scenario it is assumed that all buildings make use of one of these technologies in 2050. In the Reference scenario, it is assumed that the used heating technologies remain equal after 2015.

Households making use of CHP, biomass boilers, heat pumps or solar heating are considered to be prosumers. District heating can be a collective prosumer technology, if the connected households or utility buildings are part of an energy collective that is the owner of the heat grid and heat source. The heat source should in this case be renewable and local, for example a geothermal plant or a biomass CHP plant with local biomass. However, it hard to determine in general that a certain heat grid can meet these conditions. Therefore, in the model district heating is seen as non-prosumer technology. Households making use of district heating are not considered prosumers.

The building stock is categorized in single family homes (individual prosumers), multifamily homes (collectives) and utility buildings (tertiary sector). In the Maximum Renewables and Maximum Self-sufficiency scenario, the heating technologies are spread over the building stock based on several parameters. The choice for heat technology depends on population density, the availability of woodland (biomass), type of building and the cooling demand. The figures below display a geographical overview of the type of area, availability of woodland and cooling demand in Europe. In the appendix, the decision matrix for the heating technologies is given which indicates which technology is chosen in which situation. These assumptions are further detailed in this paragraph.

Figure 3 - Biomass availability and cooling degree days

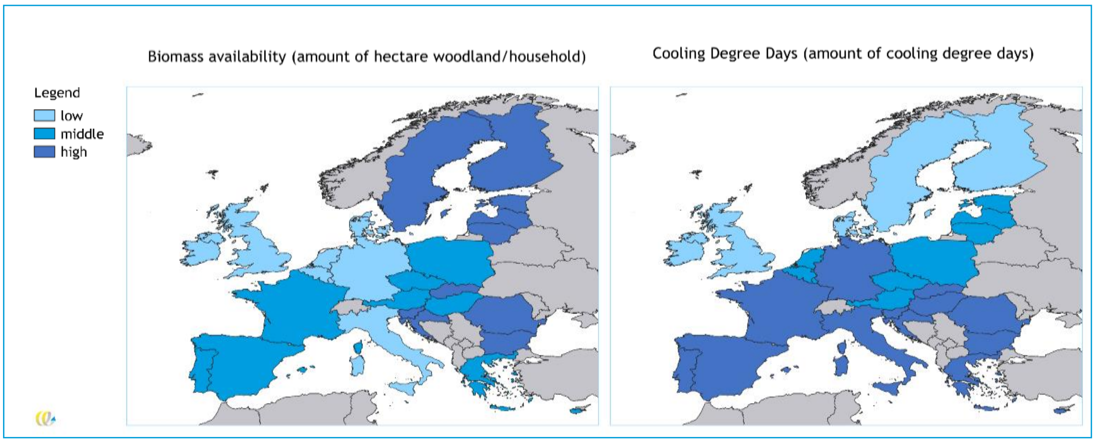
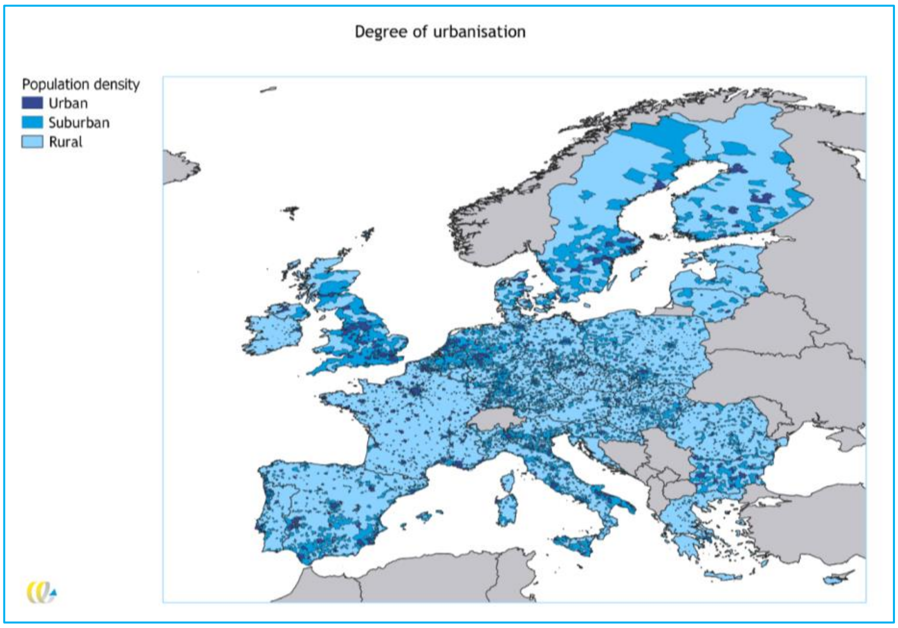


Figure 4 - Degree of urbanisation



Buildings, especially in warmer climates, also have a cooling demand. Heat pumps are able to provide both heating and cooling. Therefore, in most situations where cooling is required, heat pumps are applied. In the other cases, air conditioning is applied.
The electricity consumption for air conditioning is included in the calculations of the total electricity demand.

CHP

In CEPROM, cogeneration or combined heat and power (CHP) is seen as a prosumer technology if the energy carrier that is used, is produced by the user itself. For CHP, this is only the case if biomass is used which is grown on the property of the user itself. With this definition, you need a certain amount of woodland[8] in the country to be able to say in general that there is enough biomass to feed the CHP. Furthermore, it is likely that only households or utility buildings in rural areas have enough biomass of their own to meet the heat demand. Finally, a CHP is not likely to be used by individual households, since the technology asks for a fairly stable energy demand and is rather expensive for an individual household.

We therefore assume that CHP can be used by prosumers in a certain region under the following conditions:
- average of at least 0.5 hectare of woodland per household;
- only in rural area;
- only in combination with multifamily households and utility buildings;
- both in Maximum Renewables scenario and Maximum self-sufficiency scenario.

[8] Other types of biomass and locally produced biogas can also be used for a CHP, but these are not taken into account.

Biomass boiler

Similar to CHP, the biomass boiler can be seen as a prosumer technology if the biomass that is used, is produced by the prosumer itself. This means that the prosumer should have enough biomass on his own property to meet the heat demand. With this definition, you need a certain amount of woodland in the country to be able to say in general that there is enough biomass to feed the biomass boiler. Furthermore, it is likely that only households or utility buildings in rural area have enough biomass of their own to meet the heat demand. In the model. the biomass boiler is only used by individual users.

Conditions and assumptions:
- Average of at least 0.5 hectare of woodland per household.
- Only in rural area.
- Only in combination with single family households. Multifamily households or tertiary buildings will use a CHP in case they have enough biomass.
- Cooling demand of less than 50 cooling degree days. In case there is a significant cooling demand. the heat pump is preferred over the biomass boiler, because the heat pump can also cool the building with a high energy efficiency.
- 50% of single-family households, under the above conditions, with an average between 0.5- and 1.0-hectare woodland per household.
- 100% of single-family households, under the above conditions, with an average of more than 1.0 hectare woodland per household.
- Both in Maximum Renewables scenario and Maximum Self-sufficiency scenario.

Heat pump

A heat pump is a technology that uses the heat from surroundings (air/ground/water) and is driven by electricity. This technology can be seen as a prosumer technology when the heat pump is installed next to a residential building or utility building which uses the heat itself. An advantage of the heat pump is that it can also produce cooling with energy from the surroundings. Heat pumps could be used in both areas with a low and a high population density. Heat pumps are more efficient in buildings with a low, continuous heat demand. For buildings with a high heat demand, this may imply that they need extra insulation and another heat transfer system, such as low temperature radiators or floor heating.[9]

Conditions and assumptions:
- residential buildings in urban area with a cooling demand of more than 50 cooling degree days;
- utility buildings in urban area with a cooling demand of more than 20 cooling degree days;
- all buildings in suburban area;
- all buildings in rural area in member states with an average of less than 0.5 hectare woodland per household (otherwise buildings use a biomass boiler or a CHP);
- 50% of single-family households, under the above conditions, with an average between 0.5- and 1.0-hectare woodland per household;
- both in Maximum Renewables scenario and Maximum Self-sufficiency scenario.

[9] This is not taken into account within this research.

Solar thermal

Solar thermal energy can be used to capture the heat from the sun. In our model, this technology is combined with other technologies, since solar thermal on itself will not produce enough heat to cover the heat demand of a building, especially not in winter when the demand is the highest. If it is used by a prosumer, it will be placed on the rooftop of a building. In our model, it is only used as an option for individual households or utility buildings to produce (part of) the heat for tap water. A small buffer tank is also applied to store the heat for a few days. Solar thermal competes with PV panels in terms of needed rooftop area. Under the conditions and assumption mentioned below, all solar thermal panels are applied to cover the demand. The remaining roof area is available for solar PV panels.

Conditions and assumptions:
- It is only used to generate heat for hot tap water.
- In case it is applied, it could only generate 50% of the energy demand for hot tap water.
- It is applied in combination with district heating. It is only used to cover 50% of the demand for tap water. But the heat could also be inserted into the heat network.
- It is applied in combination with CHP and biomass boilers. Less biomass is needed when part of the heat is produced by solar thermal.
- It is not applied in combination with heat pumps, since heat pumps need a lot of electricity that can be generated with PV-panels.
- Both in Maximum Renewables scenario and Maximum Self-sufficiency scenario.

3.3 Electricity generation

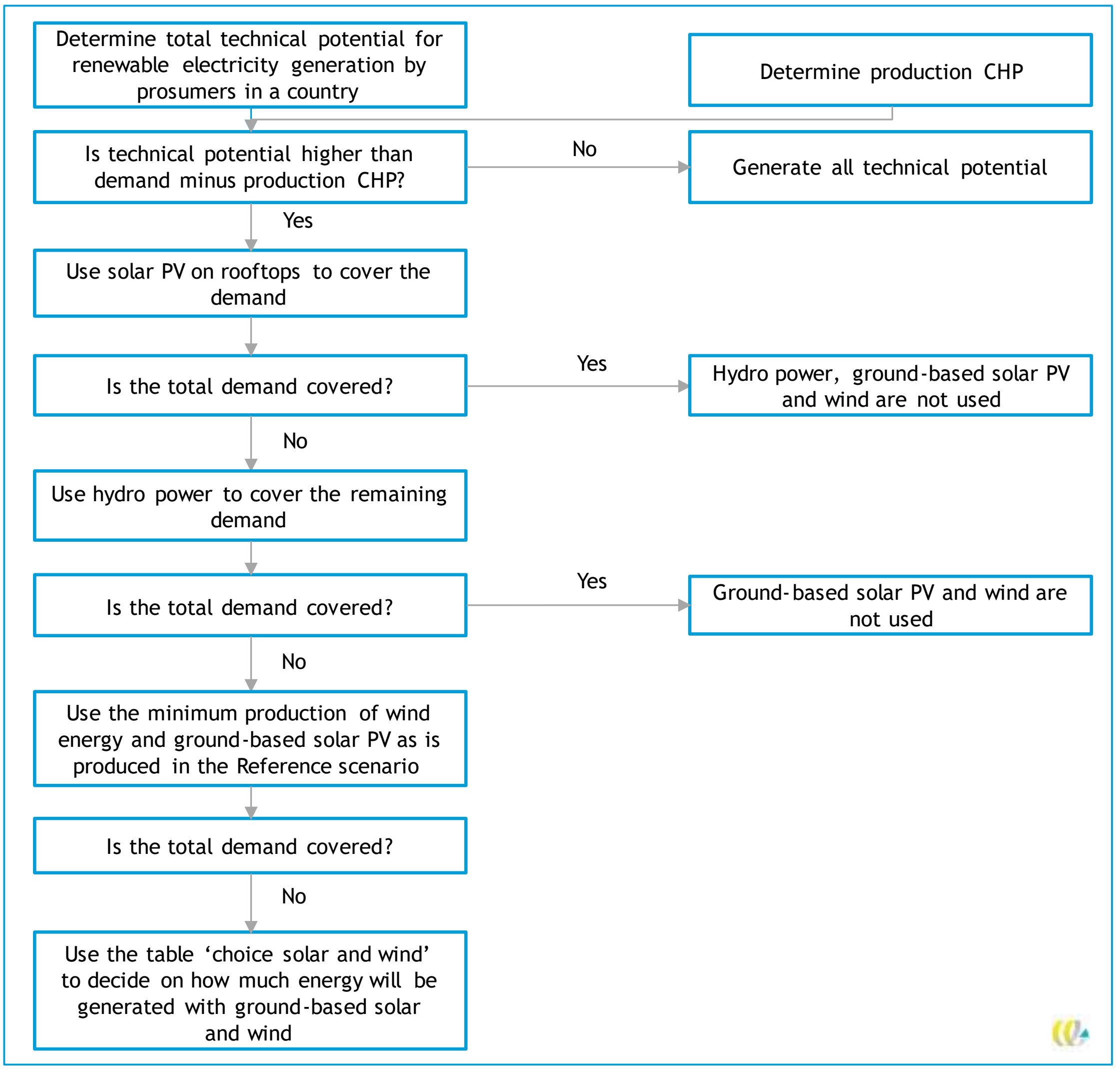
In the model four technologies are taken into account to generate electricity: solar PV (rooftop, on land); wind turbines; hydro power (small scale) and CHP.

To determine the amount of electricity generated by prosumers per technology first the technical potential of each technology is determined. It should however be noted that not the entire technical potential can and will be realised by prosumers. Therefore, additional conditions are applied. For example only the electricity generated from wind turbines and solar parks within 5 km around a city or town is assigned to prosumers. For hydropower, only small projects are taken into account. The potential of electricity generated with CHP, is based on the amount of CHP's applied for heating purposes with the assumptions explained in Section 3.2.

Secondly, the model calculates the prosumer demand by adding up all electricity that is needed for electric devices, heat technologies and electric vehicles and aims to cover that in the Maximum Renewables scenario and the Maximum Self-sufficiency scenario with as much generation of electricity by prosumers as possible. If the technical potential is smaller than the demand of electricity, it is assumed that the entire technical potential is realised by prosumers. When the technical potential exceeds the prosumer electricity demand, only part of the potential is realised, because it is assumed that prosumers do not generate more electricity than what they need for consumption themselves.

In case the technical potential exceeds prosumer consumption, the model has to decide which technologies are implemented. Some technologies are preferred over others.
The methodology to decide on which technology will generate the electricity demand of the prosumers, is illustrated in Figure 5.

Figure 5 - Decision tree on how to decide which technology is used to fill the electricity demand



As can be seen in Figure 5, in case the potential exceeds demand, technologies are implemented in the following order:
1. CHP.
2. Rooftop solar PV.
3. Hydropower.
4. Ground-based solar PV and wind.

It is assumed that solar panels on roofs are preferred over collective options like hydro, solar parks and wind farms. In case CHP is used as a heating technology, it is assumed that all electricity that is generated is used. To determine if prosumers invest in wind and/or ground-based solar energy, climate conditions of the member state are taken into account.

Finally, it is assumed that small scale hydro power, ground-based solar PV and wind are technologies that can only be invested in by energy collectives. Collectives consist of groups of individual and/or multifamily households. The tertiary sector can generate energy by solar PV on rooftops and, if they have enough space around their building, by using small wind turbines.

CHP

The CHP generates both heat and electricity. The conditions under which the CHP is applied in the model are described in Section 3.2. It is assumed that all electricity produced by the CHP is used when a CHP is placed to cover for heating demand.

Solar PV (rooftop)

PV panels can be placed on rooftops or in ground-based solar parks. The current electricity generation of solar PV and the forecast for 2030 and 2050 per member state as calculated by PRIMES for the EU Reference scenario are used in the model for the Reference scenario. The current distribution of solar PV over residential roofs, commercial roofs and ground-based parks is taken from the EU market Outlook (SolarPower Europe, 2019)

Solar PV can be placed on rooftops of residential and utility buildings. The technical potential depends on the solar irradiation and the available rooftop area. It is assumed that 40% of the available rooftop area can be used for solar energy (Defaix, et al., 2012).
Solar PV competes with solar thermal for available rooftop area. In the paragraph on solar heat, assumptions for applying solar heat are stated. The rest of the available roof area is utilized by solar PV.

Conditions and assumptions:
- all types of energy citizens can use solar PV on rooftops;
- multifamily houses can place solar PV on their rooftops in the form of collectives;
- in all climate conditions, solar PV on rooftops can be applied;
- in all types of population densities, solar PV on rooftops can be applied.

Hydro power (small scale)

Hydro power is also a technology to generate electricity. The current electricity generation of hydro power and the forecast for 2030 and 2050 per member state from PRIMES are used for the Reference scenario. For the Maximum Renewables and Maximum Self-sufficiency scenario, the technical potential mentioned in a study of EC is used (EC, SETIS, 2011).
For the Reference scenario, predictions from the PRIMES model are used. To determine the share of hydro power of prosumers, only small hydro power projects are taken into account. At this moment, only a very small part of the hydro power projects are owned by collectives. In the model it is assumed that in 2030 and 2050, 20% of the new small hydro power projects can be owned by prosumer collectives.

Conditions and assumptions:
- technical potential in Reference scenario is used for Maximum Renewables and Maximum Self-sufficiency scenario;
- only collectives can generate electricity with hydro power.

Wind turbines and ground-based solar PV

Both wind turbines and ground-based solar PV are included as technologies that can be used by prosumers to generate electricity. Because wind turbines and ground-based solar PV interfere in land use these are discussed jointly.

For the Reference scenario, predictions from the PRIMES model are used. For the maximum RES and maximum Self-sufficiency scenario, the technical potential of wind energy is based on the article ‘Wind potentials for EU and neighbouring countries’ (Dalla Longa, et al., 2018). For ground-based solar, it is assumed that 3% of bare land is available for solar parks (Ruiz, et al., 2019); (JRC, ongoing). It is assumed that around cities, the percentage of bare land is the same as elsewhere in the country.

Because not all electricity generated with these five technologies can be assigned to prosumers, for wind turbines and ground-based solar PV, it is assumed that only the electricity generated from wind turbines and solar parks within 5 km around a city or town (each type of population density area) is assigned to prosumers that live or are situated in that area, see Figure 6 and Figure 7. Overlapping areas are filtered out, to determine the available area that can be used for wind and ground-based solar. Another assumption is that wind turbines and ground-based solar are not placed in urban or suburban areas. because in general there is not enough space left for energy generation. Not the whole 5 km zone is assumed to be suited for electricity generation: specific criteria are used for both solar and wind within the boundaries of the area. Only areas which are not used for other purposes, bare land, can be used for solar and wind.

Figure 6 – Degree of urbanisation with location to zoom in for buffer zone maps

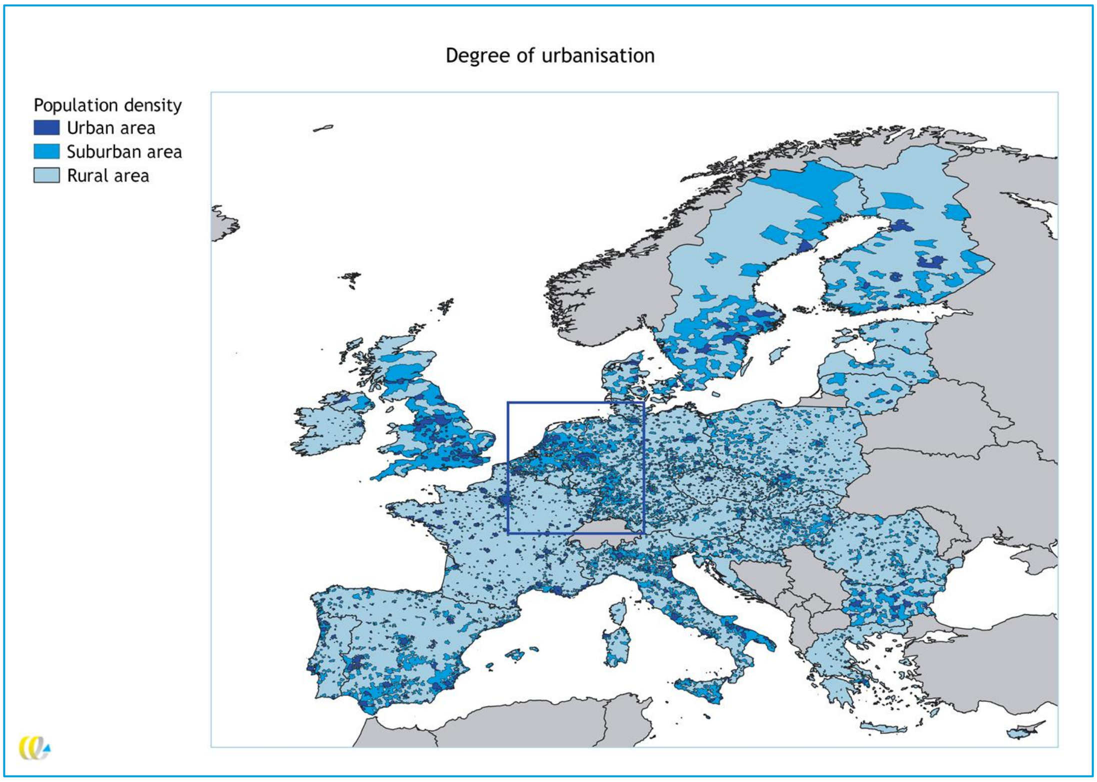
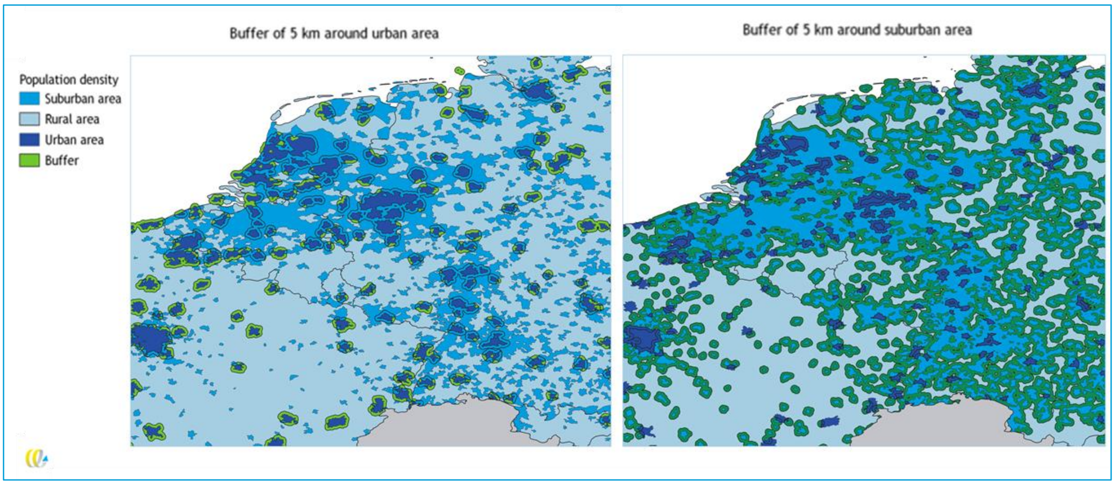
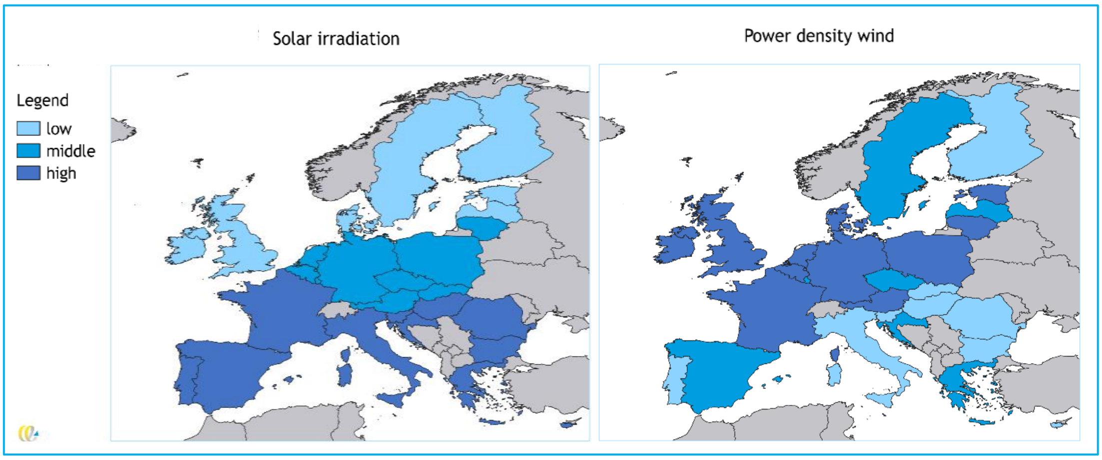


Figure 7 - Impression of buffer zones



In case the technical potential of energy generated by solar parks and wind energy is higher than the demand, a choice between the two is made by the model. This choice depends on the average solar irradiation and power density in the country. This choice is based on the yield of each technology. In countries with high solar irradiation. Solar PV is financially and spatially a good option. For countries with high wind power density, wind turbines give good revenues. CE Delft has categorized the solar irradiation and power density of wind in three categories. that indicate a low, middle or high solar irradiation or wind power density, see Figure 8.

Figure 8 – Solar irradiation and power density of wind



In Table 4 the choice on what percentage of prosumers will potentially invest in which technology is presented.

Table 4 - Choice between solar parks and wind turbines

Combination	Power density of wind (W/m²)	Solar irradiation (kWh/m²/year)	Choice
1	< 275	< 1,000	Both (50% wind/50% solar PV)
2	< 275	1,000-1,250	Both (25% wind/75% solar PV)
3	< 275	> 1,250	100% solar PV
4	275-350	< 1,000	Both (75% wind/25% solar PV)
5	275-350	1,000-1,250	Both (50% wind/50% solar PV)
6	275-350	> 1,250	Both (25% wind/75% solar PV)
7	> 350	< 1,000	100% wind
8	> 350	1,000-1,250	Both (75% wind/25% solar PV)
9	> 350	> 1,250	Both (50% wind/50% solar PV)

Conditions and assumptions:
- Wind turbines are not placed by individual households. Collectives (which could include individual households) and the tertiary sector invest in wind. Utility buildings need enough space around their building to place a wind turbine. It is assumed that only utility buildings in rural area potentially have their own wind turbine.
- Only collectives invest in ground-based solar PV. The tertiary sector does not invest in ground-based solar PV.
- Collectives in all types of population density areas can participate.
- The choice between wind turbines and solar parks is represented in Table 4.

3.4 Energy storage

In the Maximum Self-sufficiency scenario, prosumers are likely to use options to store heat or electricity. The aim is that prosumers will use, as much as possible, the energy that they have generated directly or from heat storage or battery storage. The share of energy needed from the grid is in this scenario as small as possible. If we look at electricity, it is technically possible to store all energy produced by prosumers in batteries so that they can use energy from the battery all year long. This, however, leads to really large batteries, which is not desirable from a practical point of view taking into account economic, sustainability and spatial aspects. The same can be argued for heat: self-produced heat can also be stored in very large buffer tanks, but this is costly and not desirable if we take into accounts the costs and spatial aspects. In the model we optimize the size of energy storage economically. Only if an increase in battery size leads to a significant increase in share of self-sufficiency, it is applied.

3.4.1 Heat storage

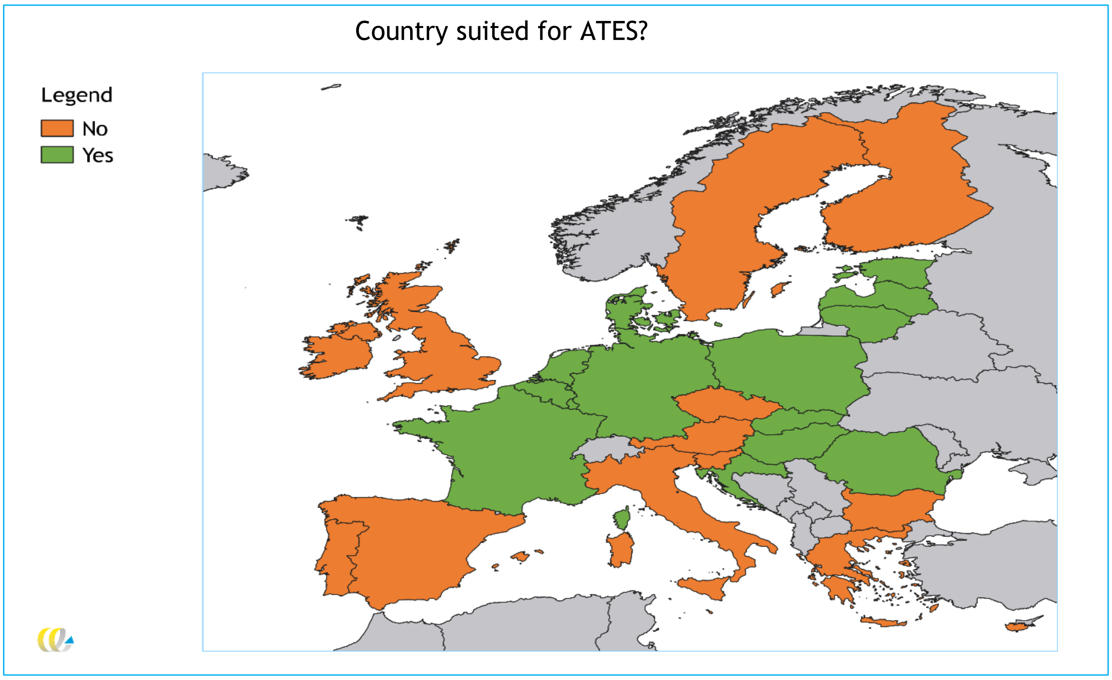
Two technologies are considered for heat storage. Aquifer thermal energy storage (ATES) and a small buffer tank. Under which conditions these technologies are applied is explained in this paragraph. It depends on the heat technology that a prosumer uses whether storage of heat is desirable. It is assumed that only buildings with a heat pump can make use of thermal energy storage, with the exception of small buffer tanks for the water heating demand which are used in combination with all heating technologies.

ATES

Aquifer thermal energy storage can be applied to store heat and cold for the heating and cooling of buildings. The advantage is that less energy is needed to heat and cool the building, because the energy is already stored in the ground. This way, a higher degree of self-sufficiency can be reached. The construction of an ATES has a large impact on the surroundings, therefore it is assumed that it will, under the conditions and assumptions mentioned below, only be placed in combination with newly build residential and utility buildings. It is assumed that an ATES is only in countries with a balanced heating and cooling demand[10] (see Figure 9).

Conditions and assumptions:
- always in combination with a heat pump;
- only in combination with multifamily households or utility buildings;
- only in newly build buildings;
- in combination with utility buildings when the amount of cooling degree days is higher than 20;
- in combination with multifamily households when the amount of cooling degree days is higher than 50;
- the subsurface conditions of the member state need to be suitable (see Figure 9).

Figure 9 - Country suited for ATES, based on energy demand



[10] It is assumed that the ATES installations that have already been installed will not be removed and that the Maximum Self-sufficiency scenario will have at least the same amount of energy stored in ATES as the Reference scenario. Because of that, Sweden does have ATES installed, even though the heating demand is much higher than the cooling demand.

Small buffer tank

Heat can also be stored in small hot water buffer tanks inside buildings. This is useful to store generated energy for a couple of days when not used right away, for example with solar thermal energy. In the model it is assumed that the heat pump, the biomass boiler, the CHP and solar thermal are all combined with a small buffer tank to store heat for tap water. In the model, no calculation is made of the amount of heat that is stored in small buffer tanks, but it is taken into account in the efficiencies of heating tap water.

3.4.2 Electricity storage

To obtain maximum self-sufficiency, generated energy that cannot be used directly by prosumers can be stored in batteries instead of supplied to the electricity grid. For the calculation of the share of self-sufficiency, the results from our model are used in a separate tool. This tool calculates the energy demand and the generation of electricity day by day. It also calculates the percentage of generated electricity that can be used directly, the percentage that is stored in the battery and the percentage that is needed from the grid.

To calculate how much energy can directly be used by prosumers, the following assumptions are made:
- The electricity demand for electric devices of households and tertiary building is on average equal each day of the year.
- The heat pump needs most of its energy for heating in winter (except for heating of tap water) (see Table 5).
- Cooling with a heat pump or air-conditioning is only needed in summer (see Table 5).
- The demand for electricity for electric vehicles is on average equal each day of the year.
- The generation of wind is higher in winter and is on average equal throughout the day. For het generation of wind an average daily wind profile of a country in the EU is used.
- The generation of solar energy is higher in summertime and has a peak around noon. For het generation of solar an average daily solar profile of a country in the EU is used.
- The generation of electricity from a CHP is in line with the heat demand profile of a heat pump.
- The generation of electricity of hydro power is on average equal each day of the year.

Table 5 - Monthly share of electricity demand for heat pumps

Month	Electricity demand heat pump: heating[11]	Electricity demand heat pump: heating: cooling[12]
January	17%	0%
February	15%	0%
March	13%	0%
April	7%	0%
May	4%	9%
June	2%	15%
July	2%	21%
August	2%	35%
September	3%	15%
October	7%	6%
November	12%	0%
December	16%	0%

[11] Based on average gas use of households in the Netherlands.

[12] Source: (Luca Cirillo, 2016).

During the day, there are also differences in generation and demand. This is taken into account to calculate how much of the generated energy can directly be used in households or tertiary buildings, see Table 6. This indicates the average percentage of generated energy that can directly be used for different appliances for one day. For example, solar energy is all generated during the day, electric vehicles are charged at night, so there is only an overlap of about 10% in the supply and demand.

For the calculation of the percentage self-sufficiency, it is assumed that the energy that is generated in one day, can all be used for the demand of that day. In reality, it is possible that either:
- The battery is full and there is no energy demand at a certain time, while there is energy generation. In that case, the generated energy should be inserted into the grid.
- The battery is empty and the energy generated at a certain moment is not enough to fulfil the demand at that moment. In that case, electricity from the grid is needed.

It is also assumed that the part of the energy that is generated during a day which is not needed for the demand of that day, is stored in the battery, with a maximum of the capacity of the battery. The energy stored in the battery can be used for the demand of the following day, or any day after, in case the daily demand is lower than the daily generation.

Table 6 - Direct use of generated energy in one day[13]

	Wind	Hydro	CHP	Solar
Electric devices	40%	40%	50%	34%[14]
Electric vehicles	40%	40%	50%	10%
Heat pump heating	50%	50%	0%	40%
Heat pump cooling	50%	50%	0%	60%

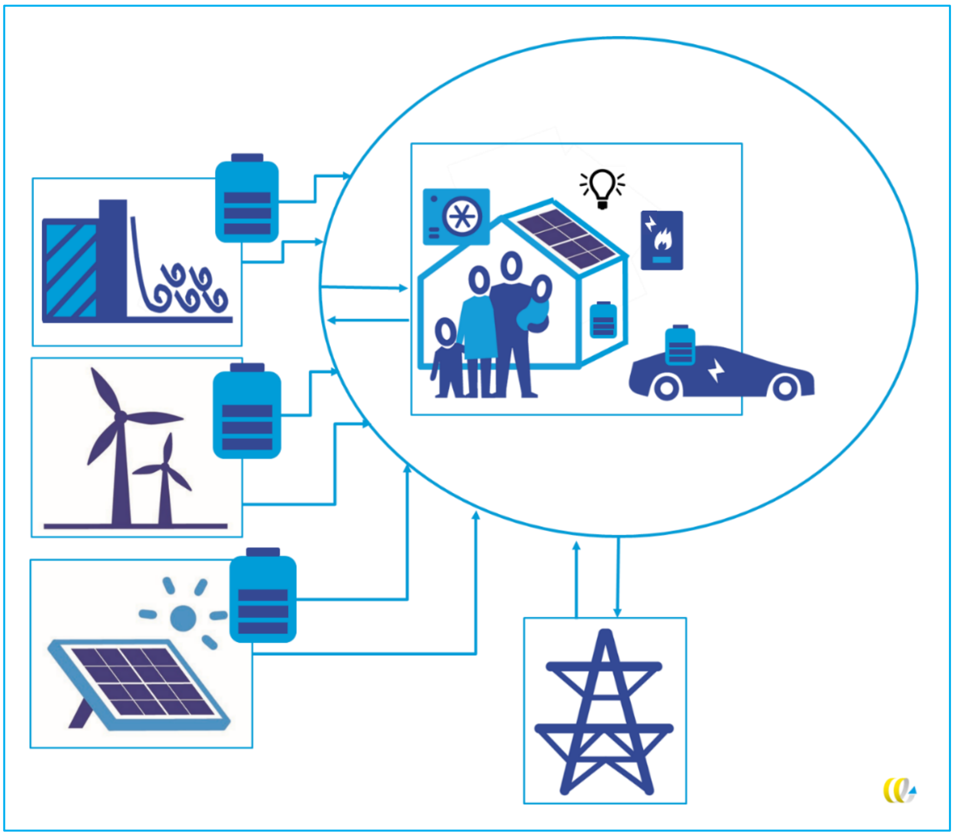
Batteries

Batteries are applied in the model in the Maximum Self-sufficiency scenario at locations where electricity is generated. The amount of storage capacity in the Reference scenario is assumed to be negligible compared to the total electricity generation. For the collective options: ground-based solar PV, wind turbines and hydro power, large batteries are placed at the site where the energy is generated. The excess electricity generated with solar PV on roofs is stored in a home-battery. The excess electricity that is generated with the CHP is stored in the battery of the building, and that battery will also be used to store electricity from solar PV on rooftops. Figure 10 gives a schematized overview of the use of battery in the calculation tool. It is assumed in this scenario that in 2050 all locations with generation of electricity have batteries and that in 2030 43% of locations with electricity generation have batteries (linear increase from 2015 to 2050). The size of the batteries are chosen in such a way, that the batteries can cover the daily demand as much as possible, but without making it too costly:
- for solar PV 60% of the maximum generation in one day can be stored in the battery;
- for wind 80% of the maximum generation in one day can be stored in the battery;
- for hydro power the average daily energy generation can be stored in the battery;
- for CHP the maximum daily generation can be stored in the battery.

[13] Estimations made by CE Delft.

[14] Source: Luthander et al., 2015, Photovoltaicself-consumption in buildings: A review.

Figure 10 - Schematized image of battery use in calculation tool



Electric vehicles

Electric vehicles can use electricity from the grid but also electricity generated by prosumers. The amount of kWh that electric vehicles use is input for the calculation of the amount of renewable energy needed. Electric vehicles can also be used for storage of electricity. This is not taken into account in the calculation of the percentage of self-sufficiency, though. It is difficult to determine how much the electric vehicle can add to the share of self-sufficiency of a household. For electricity generated with solar PV on rooftops or with CHP, the battery of the EV cannot be used much, as it is assumed that the car is used during the day, at the moment that most energy is generated by solar PV and CHP. When the electric vehicle is parked in front of the residential building during the night, it could help, especially in wintertime when there is not much solar energy, to increase the share in self-sufficiency.

Conditions and assumptions:
- electric vehicles are only assigned to households;
- electric vehicles are applied in all scenarios;
- the battery of the electric vehicles is charged at night at residential buildings;
- the battery of the electric vehicles could be used for households during night time, but this is not taken into account in the calculation.

4 Results

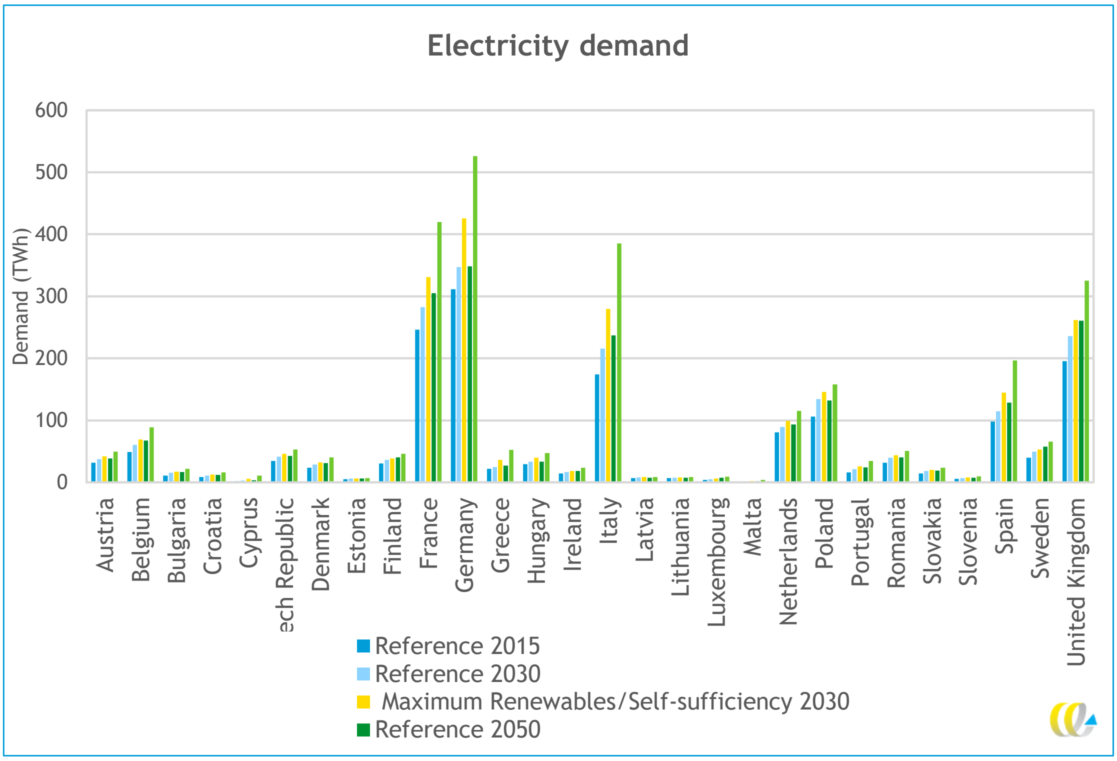
4.1 Results by country

Based on the methodology and assumptions elaborated in the previous chapter, in this section the results on the country level are presented. The model has generated a lot of output, which is too much to show in the report. Data behind the figures presented in this chapter are placed the appendix.

Electricity

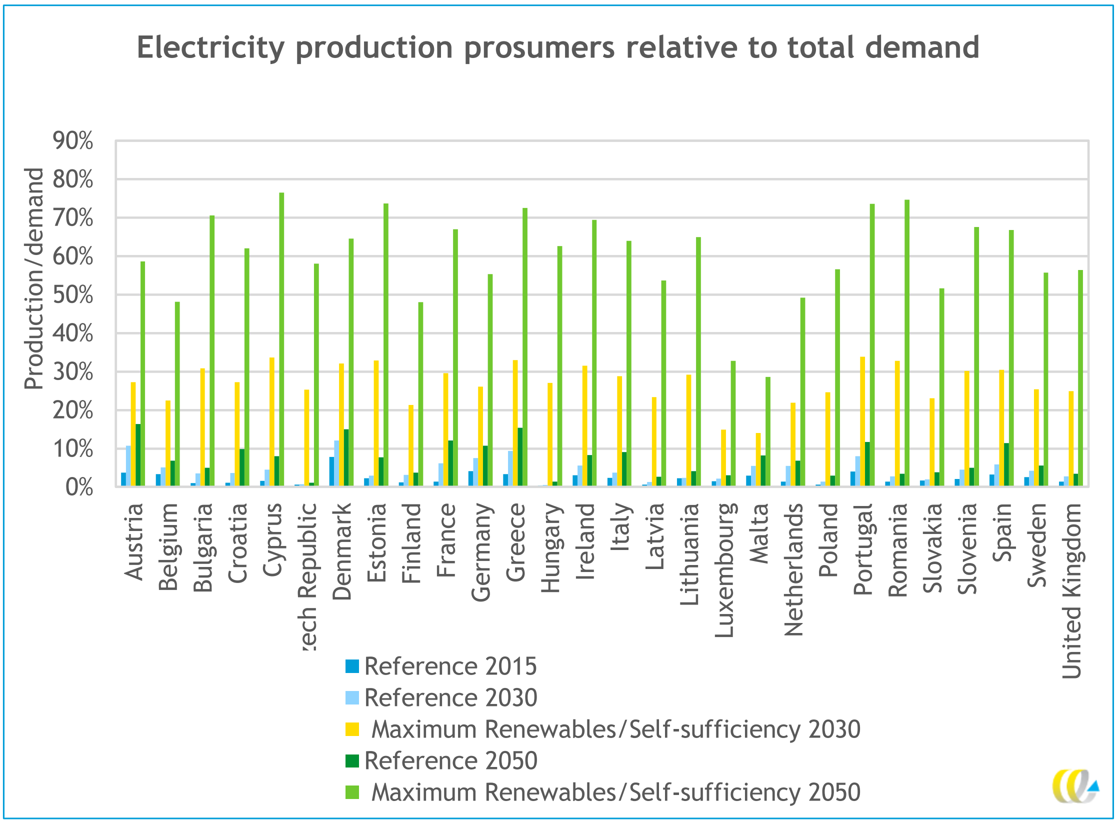
In Figure 11, the electricity demand in the different scenarios and reference years is presented. The electricity demand for the Maximum Renewables and Maximum Self-sufficiency scenario is the same, since in the Maximum Self-sufficiency scenario only storage is added. What becomes clear from the figure is that the increase in electricity demand is significant in all countries. Also, there is a very large difference in electricity demand per country. In Figure 12 the relative change in electricity demand is presented. For most countries the difference between Reference 2050 and Maximum Renewables/Maximum Self-sufficiency 2050 lies around 50%, due to an increase in the use of electric vehicles and heat pumps in the latter two scenarios. In Cyprus and Malta, the relative increase in electricity demand is very high. The current use of electricity is relatively low and therefore the increase in electricity due to electric vehicles is significant.

Figure 11 - Annual electricity demand in different scenarios and different reference years



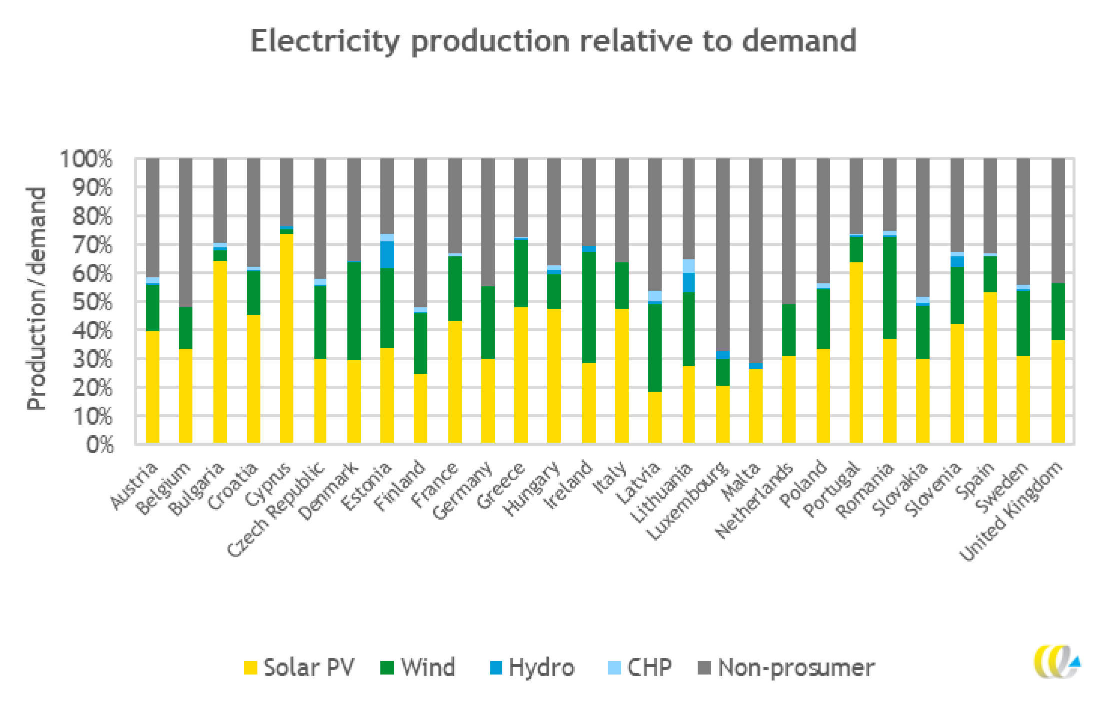
The electricity demand can partly be filled with electricity generated with prosumer technologies. In Figure 12 the total generated electricity with prosumer technologies is presented. This figure shows that the current electricity production by prosumers is only a fraction of what they could produce in 2030 and 2050 in the Maximum Renewables and Maximum Self-sufficiency scenario. Currently, in all member states the electricity generated by prosumers is between 0 and 10% of the electricity demand of the residential and tertiary sector. Only in Denmark, Portugal and Germany this share is over 4%. However the production of prosumers can increase to over 50% of the demand in 2050 for most member states.

Figure 12 - Annual electricity production with prosumer technologies relative to total demand in the residential and tertiary sector



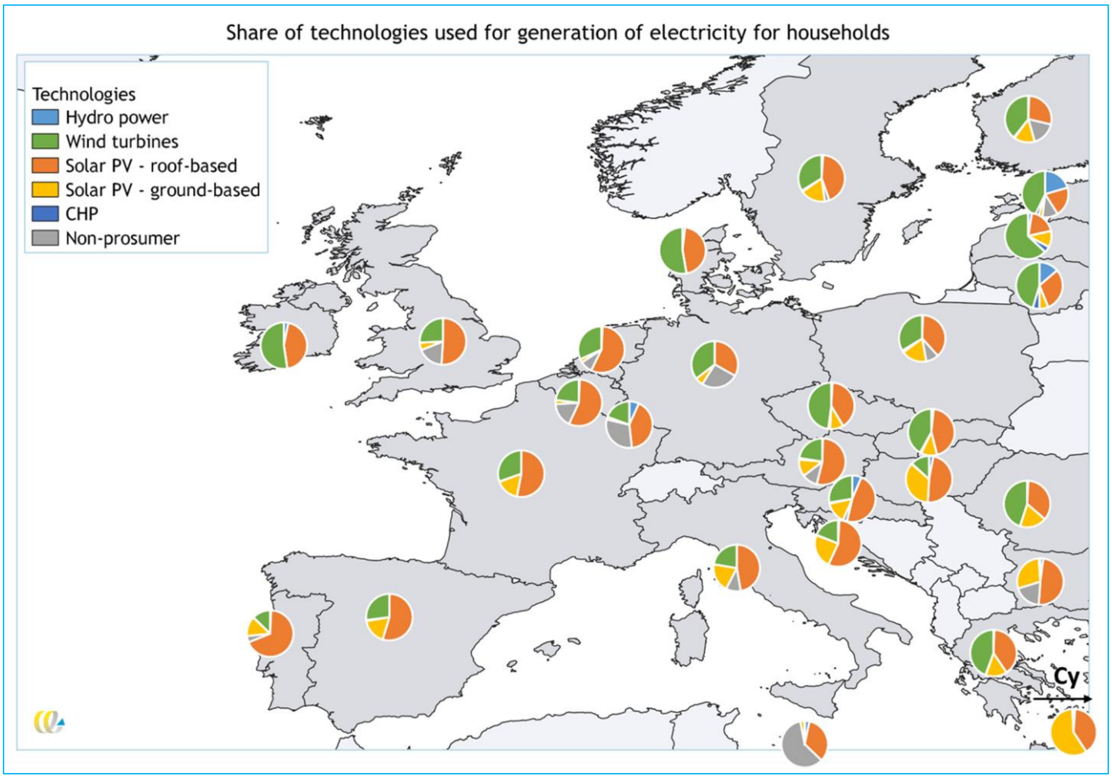
In Figure 13 the electricity production of different technologies relative to the total demand of the residential and tertiary sector is presented for each country. The potential percentage of energy generated by prosumers varies widely between the different member states, with Luxembourg and Malta having the least potential and Cyprus, Estonia, Greece, Potugal and Romania having the most potential.

Figure 13 - Annual electricity production of prosumer technology relative to total demand residential and tertiary sector in Maximum Renewables/Maximum Self-sufficiency scenario in 2050



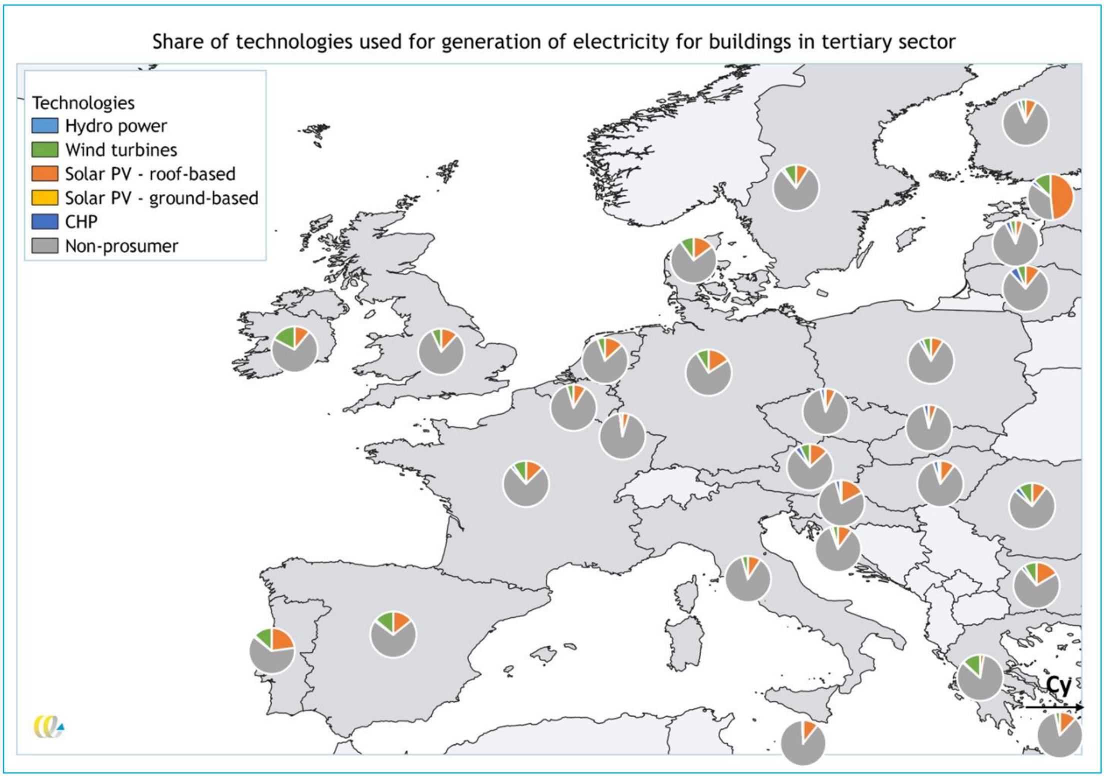
In CEPROM, results for households (residential buildings) and the tertiary sector (utility buildings) are separately calculated. In Figure 14 results of technologies used for generation of electricity in households are shown geographically for the Maximum Renewables/Maximum Self-sufficiency scenario in 2050. All technologies, except for the category 'non-prosumer' are prosumer technologies. The figure shows that most countries, except for Malta, can cover the largest part of their electricity demand for households with prosumer technologies. The technologies wind and solar PV roof-based and ground-based can all contribute significantly. Hydro power is applied in very few countries. CHP does not attribute much to the total generation of electricity.

Figure 14 - Share of technologies used for generation of electricity for residential buildings in the Maximum Renewables/Maximum Self-sufficiency scenario in 2050



In Figure 15 the results of technologies used for generation of electricity in utility buildings are shown. For utility buildings, other than residential buildings, the largest share in generation of electricity is by non-prosumer technologies. For a large part this can be explained by the assumption in our scenarios that the tertiary sector does not participate in collectives. They will generate their electricity with roof-based solar and small wind turbines on own property. This is not enough to cover their electricity demand.

Figure 15 - Share of technologies used for generation of electricity for utility buildings in the Maximum Renewables/Maximum Self-sufficiency scenario in 2050



Heating and cooling

The heating demand, contrary to the electricity demand, slightly decreases over the different reference years. However, the cooling demand will increase significantly from 2015 to 2050. It is assumed that at this moment many households and tertiary buildings with a small cooling demand do not have a device to cool, so they do not fill the cooling demand. Therefore, in the current numbers of energy use, cooling is only a very small share compared to heating. In case households and utility buildings will have a heat pump in 2030 or 2050, it is assumed that they will also start using it for cooling, which increases the electricity use for cooling. For some countries, the decrease in heating demand and increase in cooling demand, lead to a small increase in the combined demand for heating and cooling in 2030 and 2050, for some countries in a small decrease.

Figure 16 - Annual combined heating and cooling demand in the residential and tertiary sector

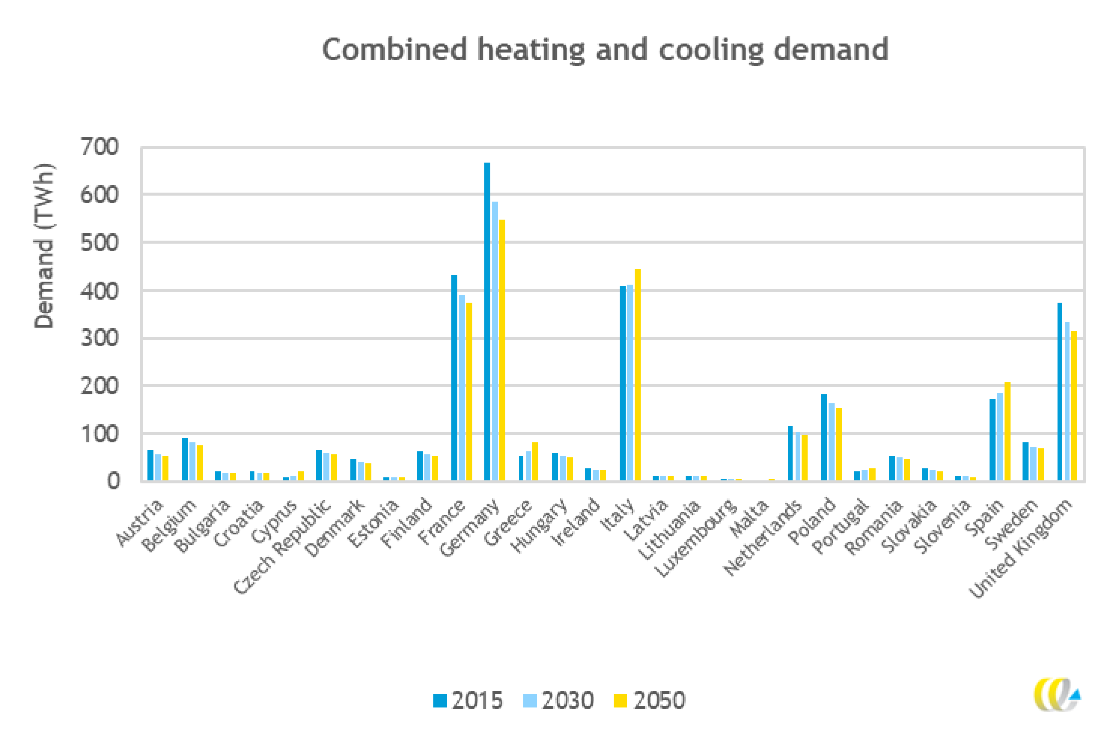


Figure 17 and Figure 18 show the share of energy carriers that can be used by prosumers to cover the energy demand for heating and cooling in residential buildings in the Maximum Renewables/Maximum Self-sufficiency scenario. The overall picture is that the heat pump is the technology that fills in the largest part of the heating and cooling demand. In the countries with biomass availability, biomass can also cover a significant part of the heat demand. District heating is only applied in countries with a smaller cooling demand, because it cannot cover cooling demand. Solar heat is applied is all countries, but only contributes for a small part to the demand of heating and cooling.

Figure 17 - Share of energy carriers used to cover the energy demand for heating and cooling in residential buildings in the Maximum Renewables/Maximum Self-sufficiency scenario in 2050

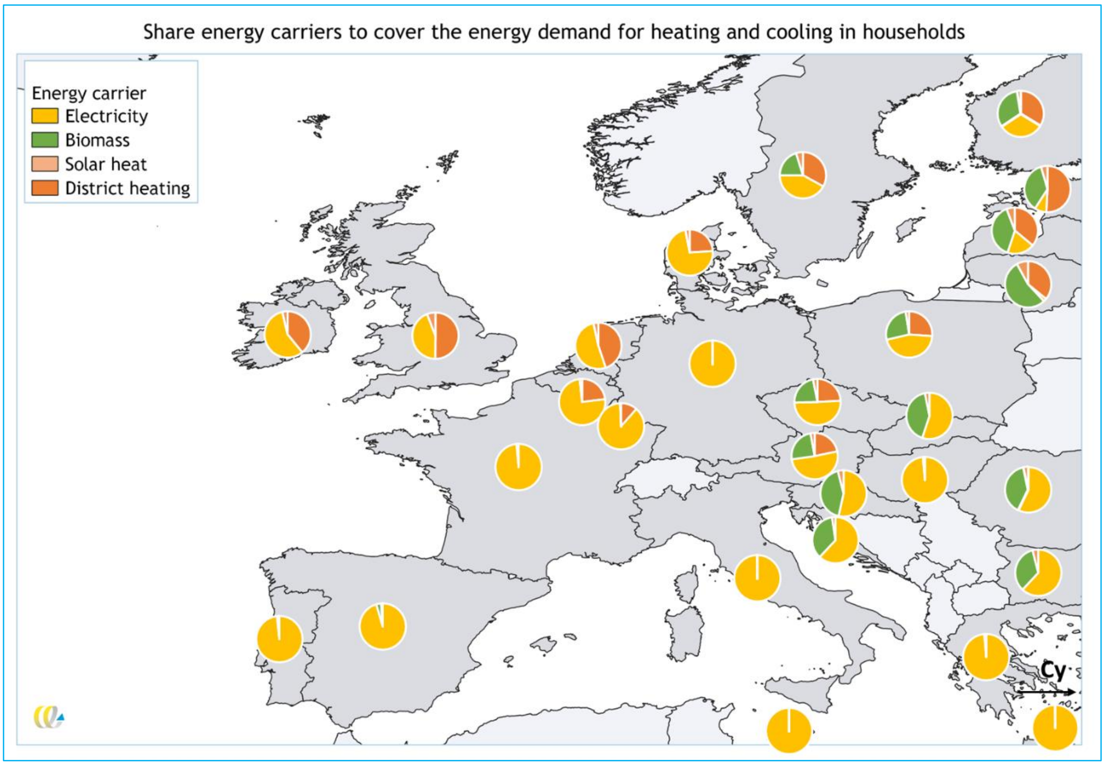
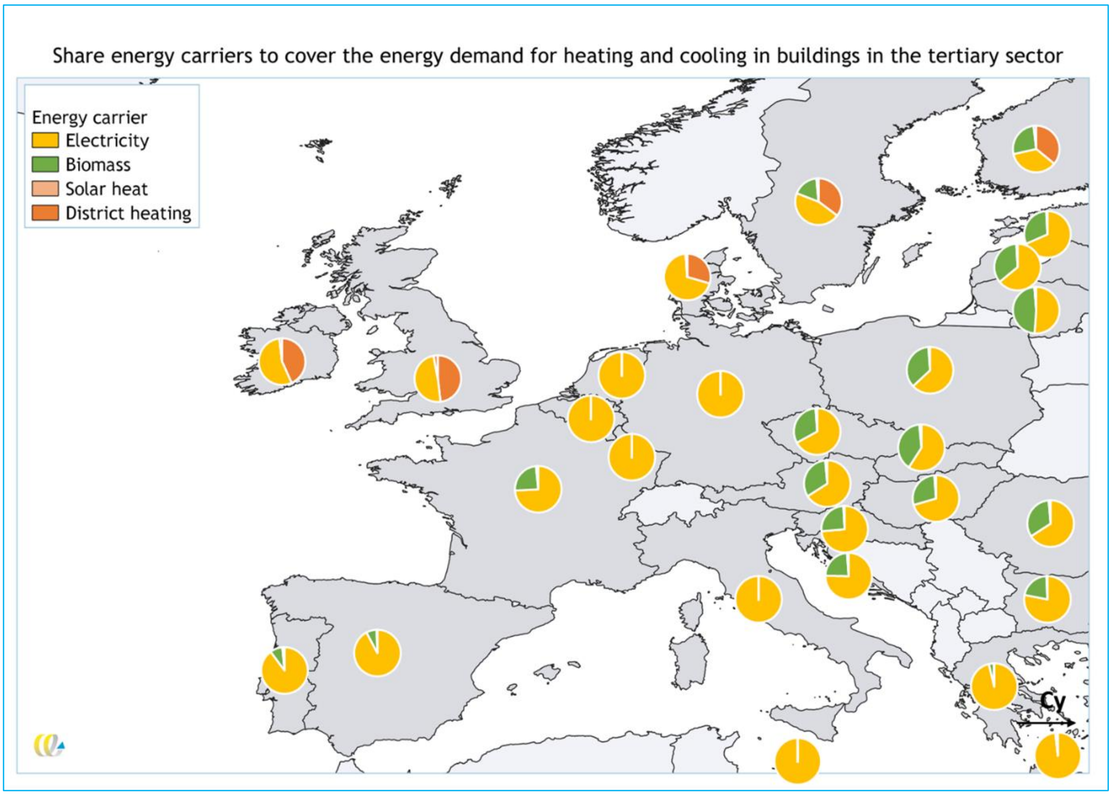


Figure 18 presents the share of energy carriers used to cover the energy demand for heating and cooling in buildings in the tertiary sector in the Maximum Renewables/Maximum Self-sufficiency scenario in 2050. The difference with residential buildings, is that an even larger part of the heating and cooling demand is filled with heat pumps. The reason for this is the extra cooling demand that utility buildings have compared to households. The application of biomass is also somewhat higher for utility buildings than for households. It is assumed that for utility buildings in urban areas, biomass-fired CHP is a good option.

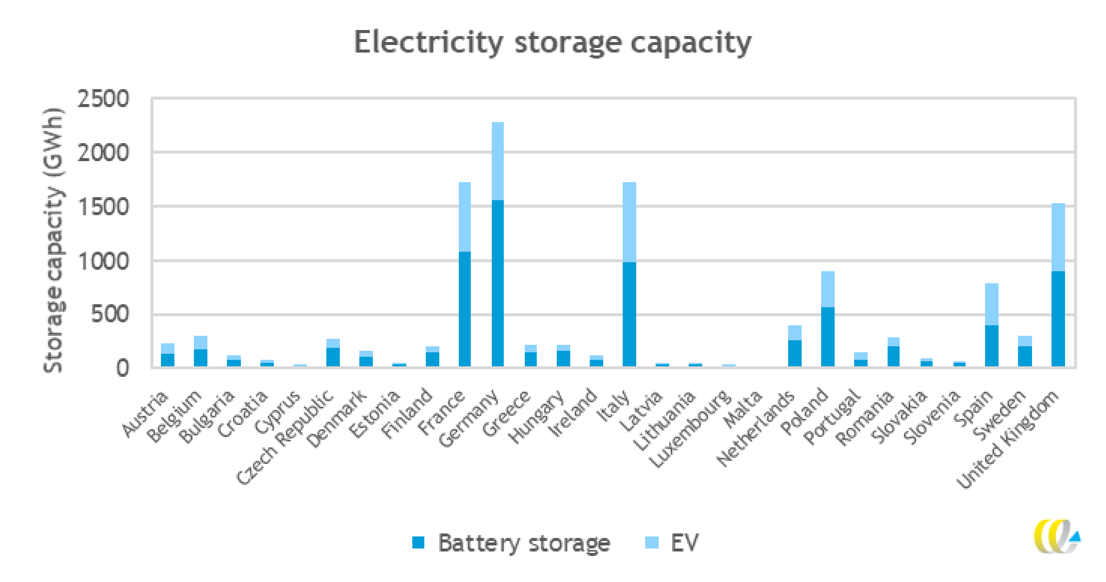
Figure 18 - Share of energy carriers used to cover the energy demand for heating and cooling in buildings in the tertiary sector in the Maximum Renewables/Maximum Self-sufficiency scenario in 2050



Energy storage

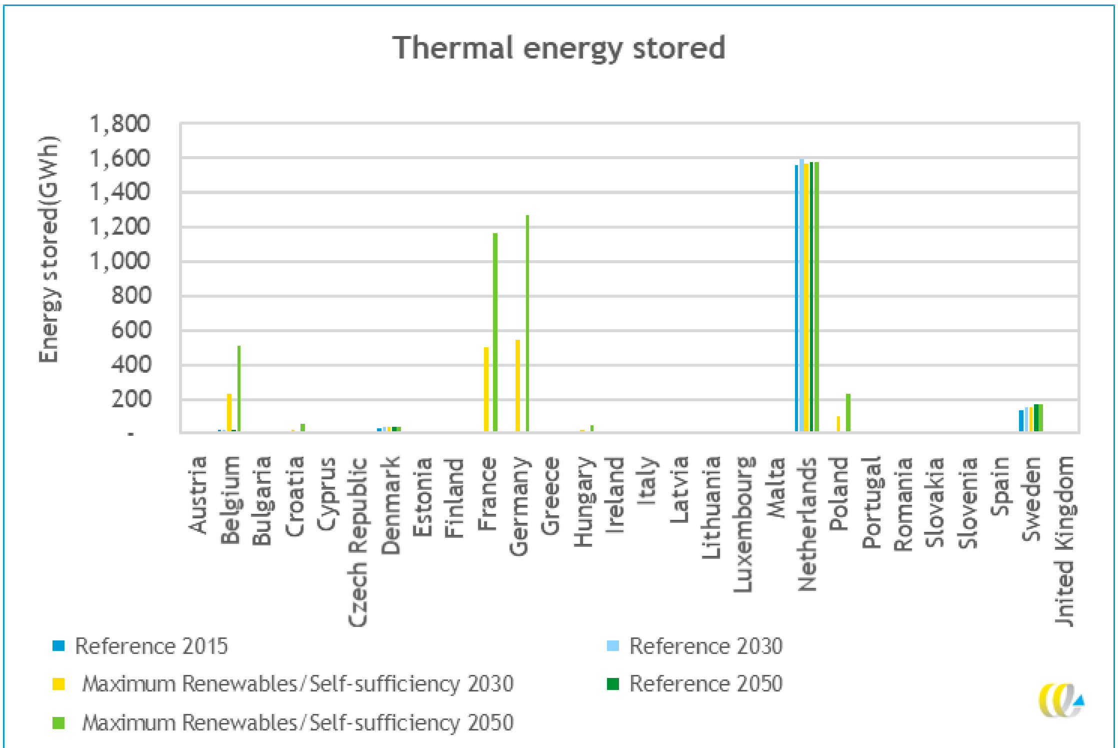
In the Maximum Self-sufficiency scenario, energy storage is taken into account. In Figure 19 the total electricity storage capacity of prosumers is presented in each country in the Maximum Self-sufficiency scenario in 2050. This storage consists of separate battery storage and storage in batteries of electric vehicles. The amount of storage is linked to the amount of installed capacity of solar PV, wind turbines, hydro power, CHP and electric vehicles.

Figure 19 - Electricity storage capacity in the Maximum Self-sufficiency scenario in 2050



Apart from the electricity storage, thermal energy is also stored. This is energy stored in an ATES. In the Netherlands, Sweden and Denmark this is already a common technology to store thermal energy. ATES is most suited in countries with both heating and cooling demand, therefore it is mainly applicable in countries in North- and Western-Europe, like the Netherlands, Germany and France.

Figure 20 - Annual amount of thermal energy stored



Share of Maximum Self-sufficiency

With a separate calculation tool, the self-sufficiency percentage per scenario is calculated. For the Maximum Renewables scenario the self-sufficiency percentage is the percentage energy that is generated with prosumer technologies that can be used directly, as no energy storage is assumed in that scenario. For the Maximum Self-sufficiency scenario, it is the sum of the direct energy use from prosumer generation and the use of energy from battery storage and thermal energy storage. The results are separately calculated for residential buildings and utility buildings and for electricity, and heating and cooling.

Figure 21 shows the results of the share of self-sufficiency in residential buildings in 2050. The highest percentage is reached for electricity use in the Maximum Self-sufficiency scenario, where between 50 and 95% of electricity demand of electric devices, lighting and electric vehicles can be covered by the prosumer generated electricity. Lithuania and Finland can almost reach 100% self-sufficiency of their electricity use, while Malta only reaches just over 50%. For heating and cooling the Maximum Renewables and Maximum Self-sufficiency scenario do not show very big differences. This is mainly because the difference in the share of self-sufficiency is only caused by the electricity storage for heat pumps and ATES in combination with heat pumps. Individual technologies on biomass are assumed to be 100% self-sufficient in both scenarios, just as the use of solar heat. For solar heat, it is assumed that a small buffer tank is also applied in the Maximum Renewables scenario. District heating is assumed not to be a self-sufficient technology.

Figure 21 - Percentage Maximum Self-sufficiency in residential buildings for electricity and heating and cooling in the scenarios Maximum Renewables and Maximum Self-sufficiency in 2050

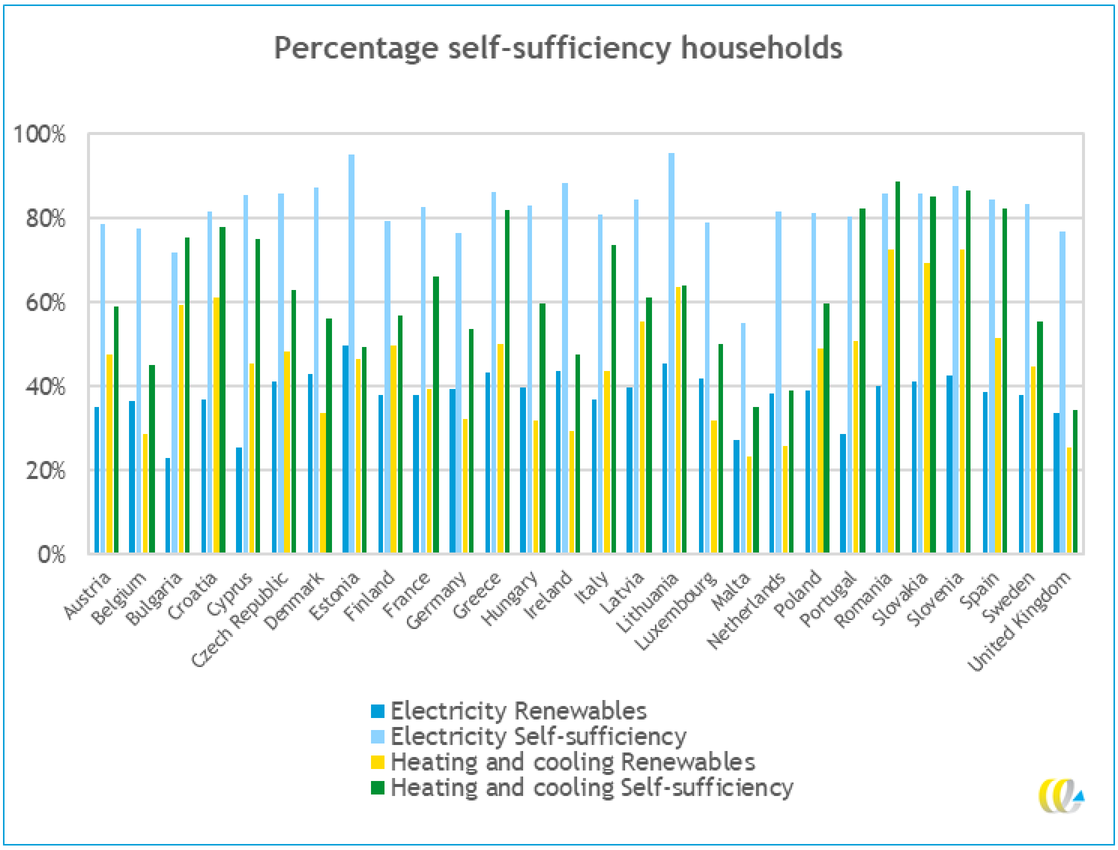
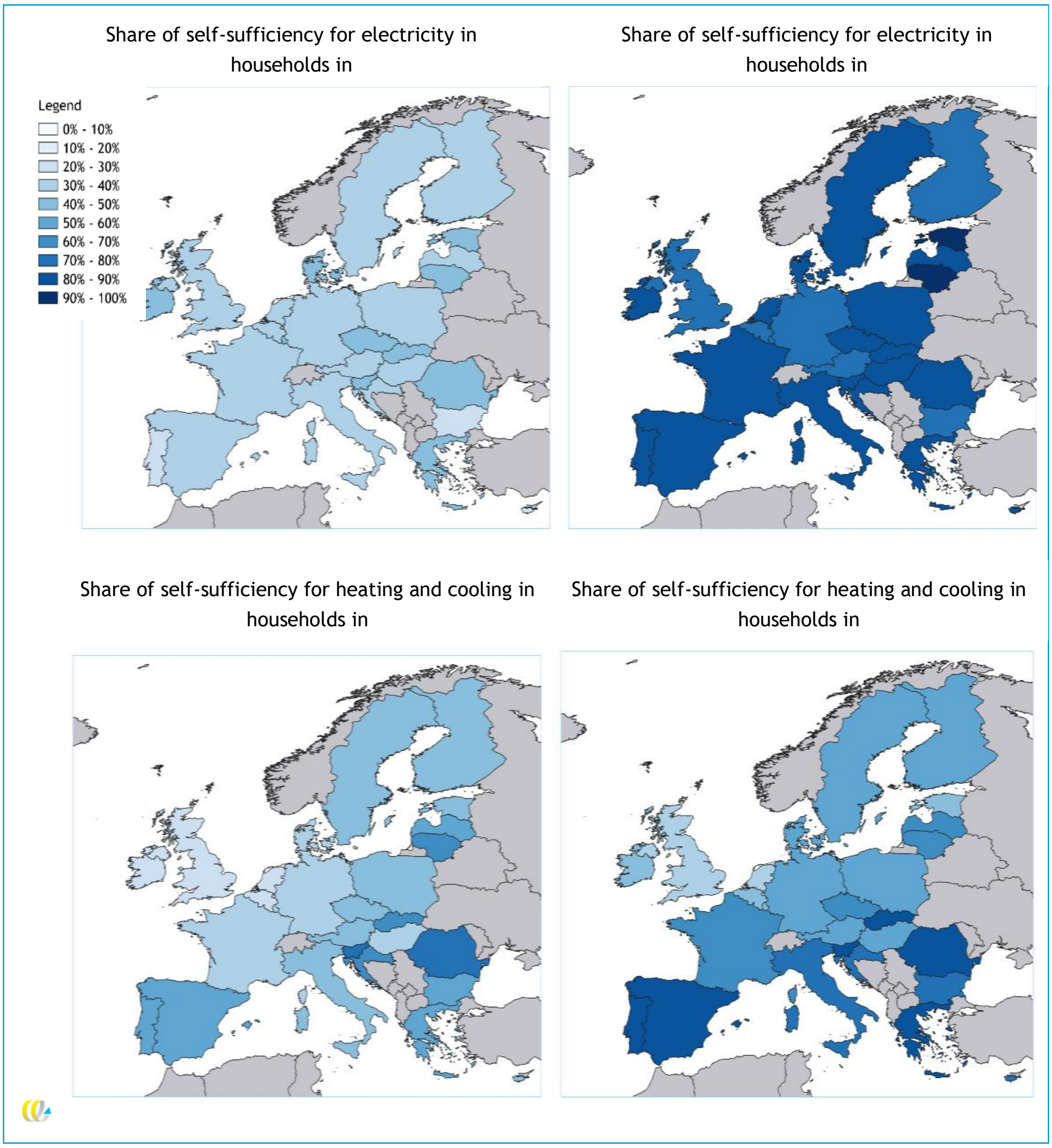
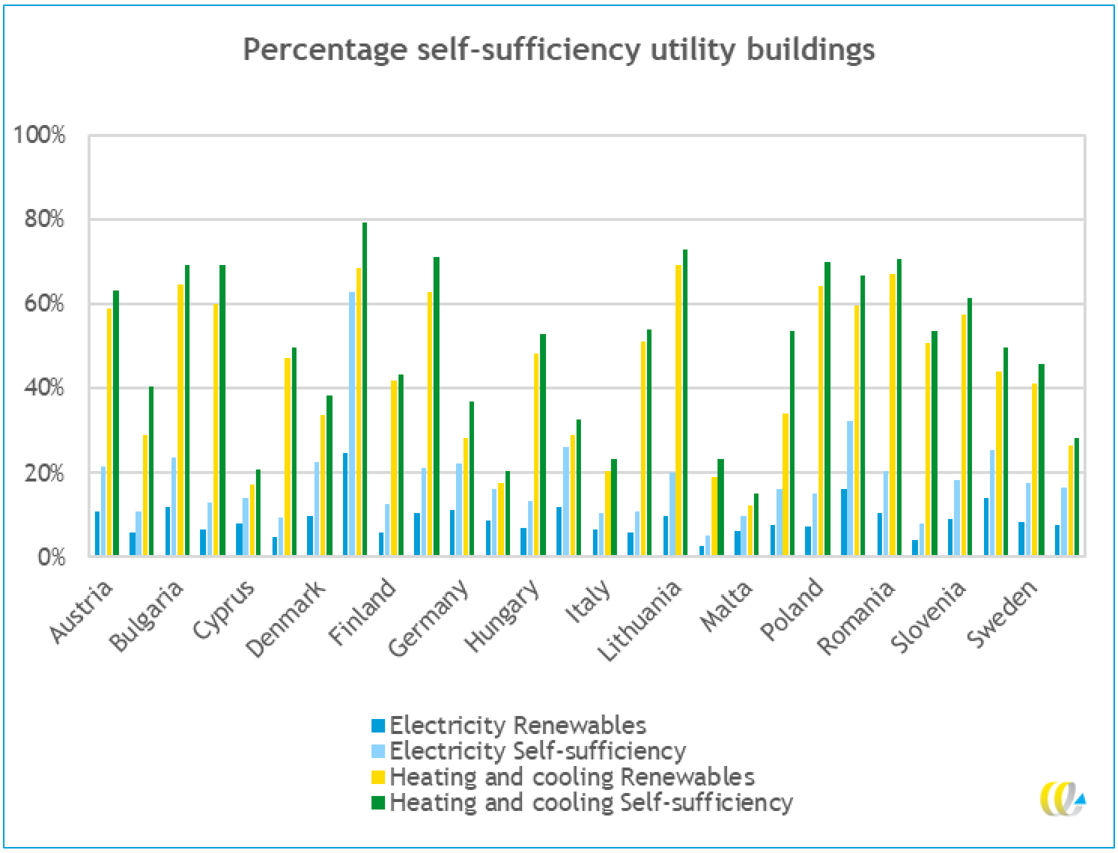


Figure 22 - Share of self-sufficiency in households in different scenarios in 2050



For utility buildings the results are presented in Figure 23. This figure shows that the share of the demand that is covered by self-generated electricity, either directly used or used through a battery, is lower compared to residential buildings. This has to do with, as earlier described, the assumption that the tertiary sector only generates their own energy by PV on their own rooftops or by small wind turbines on own property. For the heating and cooling demand the results are quite similar to those of residential buildings. The percentage self-sufficiency is a little bit lower, also because of the lower share in electricity generation, which has consequences for the percentage self-sufficiency of buildings with heat pumps.

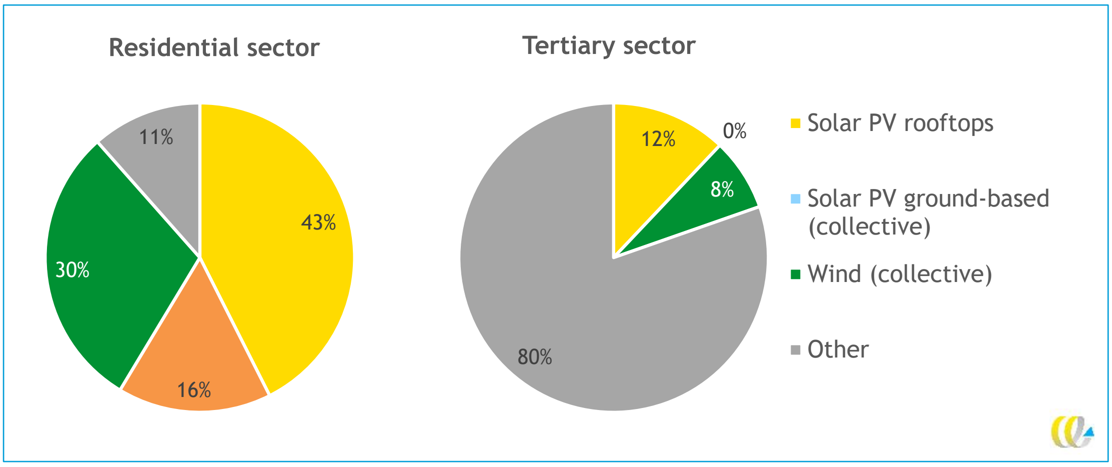
Figure 23 - Percentage Maximum Self-sufficiency in utility buildings for electricity and heating and cooling in the scenarios Maximum Renewables and Maximum Self-sufficiency in 2050



4.2 Results on European level

The following graphs show the results on EU-level. As mentioned before, the EU-results are the sum of the results on country level. Figure 24 presents the share of technologies used for the generation of electricity by prosumers in 2050 in the Maximum Renewables/Maximum Self-sufficiency scenario. For residential buildings, the share of ground-based solar PV is the largest in the total generation of electricity. Wind turbines also have a large share. The generation of electricity with hydro power and CHP, however, is very small. The share of electricity from non-prosumer technologies is 11%. For the tertiary sector, the largest part of electricity comes from non-prosumer technologies. Roof-based solar PV and wind turbines have a share of 12% and 8% in the electricity demand of this sector, CHP contributes less than 0.5%.

Figure 24 - Share of technologies used for generation of electricity in 2050. Maximum Renewables/Maximum Self-sufficiency scenario



Electricity

Figure 25 and Figure 26 present the total electricity production with prosumer technologies for each scenario and for each type of building. In the 2050 Maximum Renewables/Maximum Self-sufficiency scenario the electricity production of prosumers corresponds to 60% of the total electricity demand of the residential sector and tertiary sector.

Figure 25 - Electricity production prosumers, divided by technology

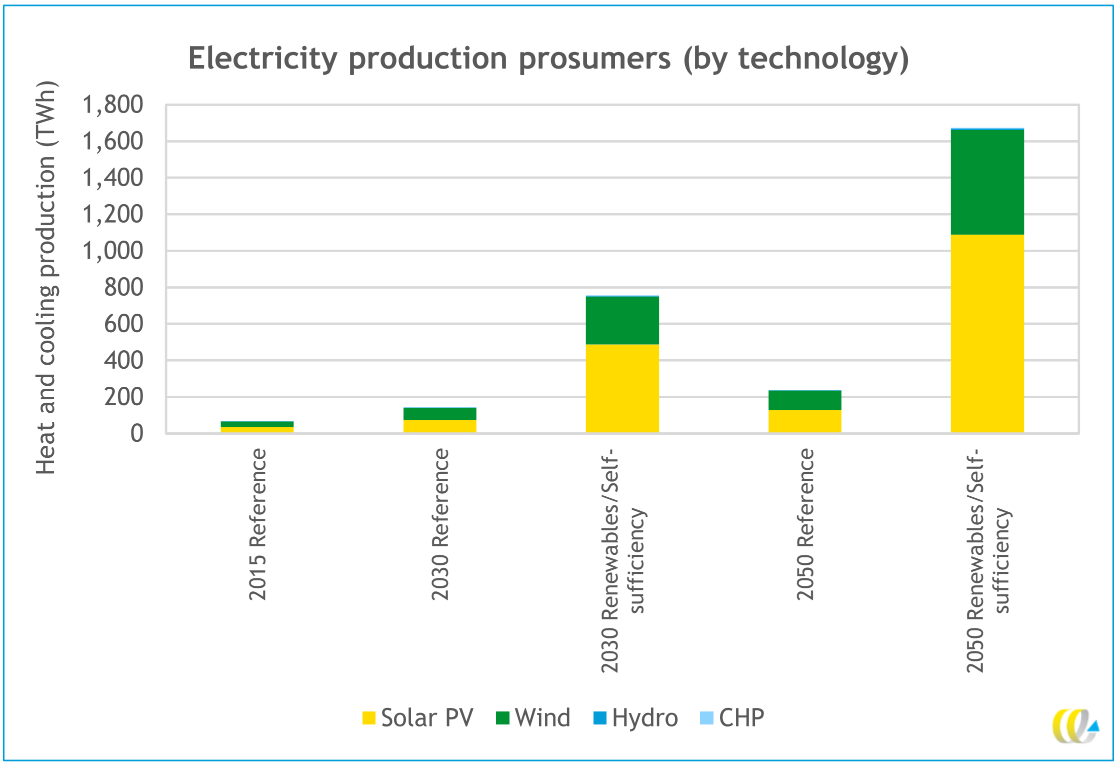
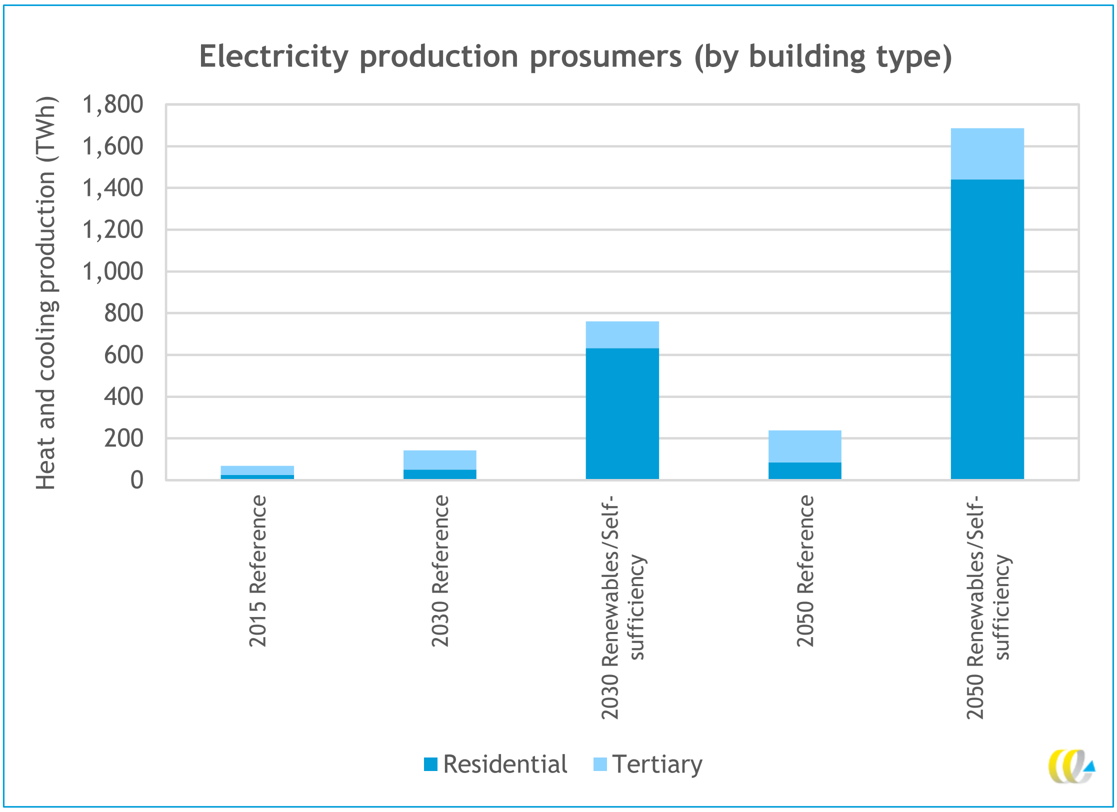


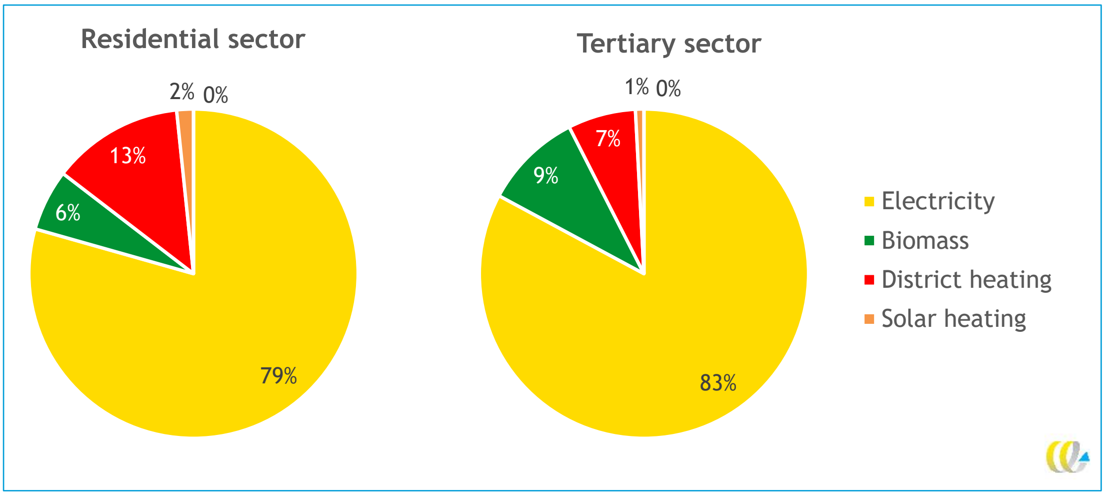
Figure 26 - Electricity production by prosumers, divided by residential and tertiary sector



Heating and cooling

Figure 27 presents the share of energy sources used for heating in 2050 in the Maximum Renewables/Maximum Self-sufficiency scenario. For both residential and utility buildings, electricity has by far the largest share. For residential buildings, also district heating has a significant share, followed by biomass, for tertiary buildings this is the other way around. The share of solar heat in the total heating demand of buildings is fairly small in both type of buildings.

Figure 27 - Share of energy sources used for heating in 2050. Maximum Renewables/Maximum Self-sufficiency scenario



These shares correspond to the number of households and utility building presented in Table 7[15].

Table 7 - Number of household/utility buildings per energy source used for heating in 2050 Maximum Renewables/Maximum Self-sufficiency scenario

Energy source	Number of households	Number of utility buildings
Electricity	169,634,000	35,029,000
Biomass	16,450,000	7,417,000
Solar heat	51,330,000	13,589,000
District heating	38,421,000	6,172,000

Figure 28 and Figure 29 present the total heating and cooling production by energy source and by type of building.

[15] The total number of technologies used is higher than the total number of households and utility buildings, since multiple technologies can be used in one building.

Figure 28 - Heating and cooling consumption, divided by energy source

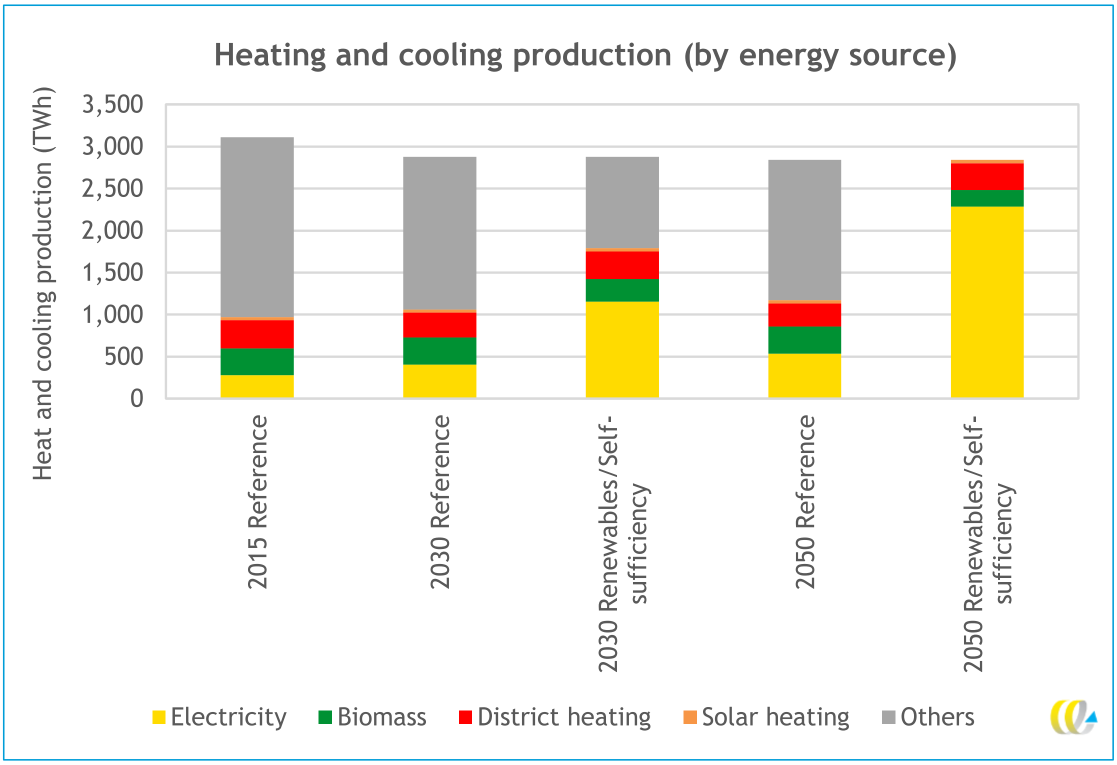
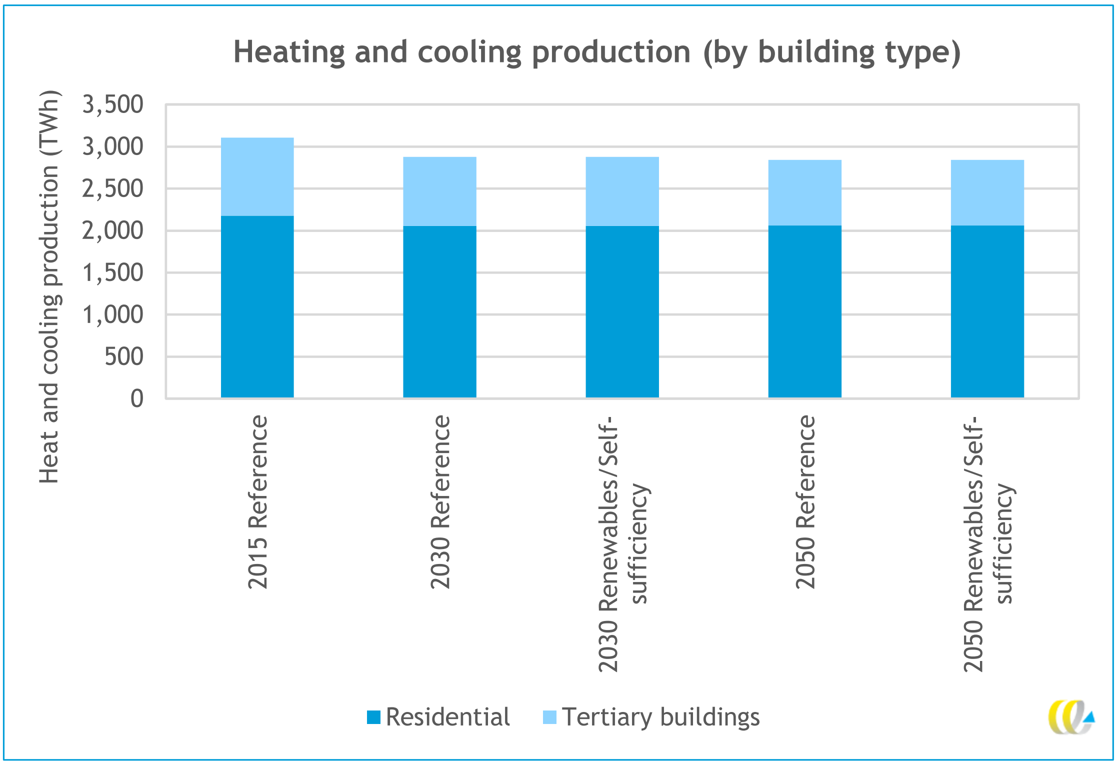


Figure 29 - Heating and cooling consumption, divided by residential and tertiary sector



Storage

In Figure 30 the contribution of each member state to the total amount of electricity storage capacity in the Maximum Self-sufficiency scenario in 2050 is presented. France, Germany, Italy and the United Kingdom have the largest share.

Figure 30 - Contribution electricity storage capacity member states to EU-28 total in 2050 Maximum Self-sufficiency scenario

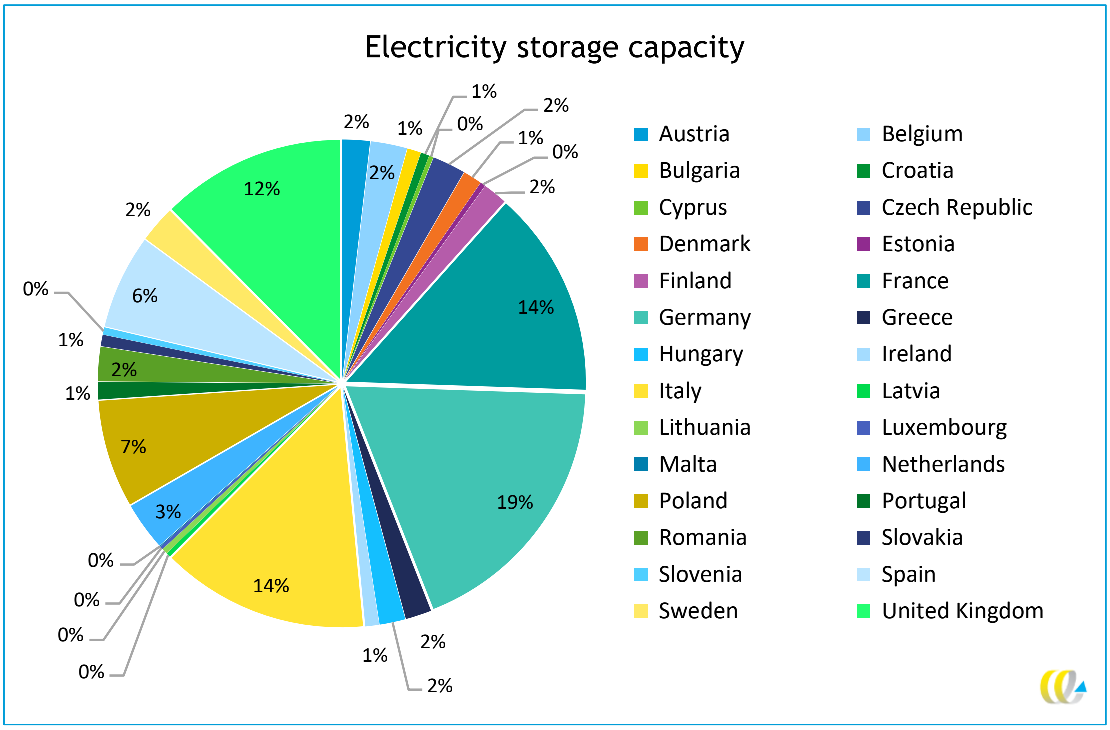
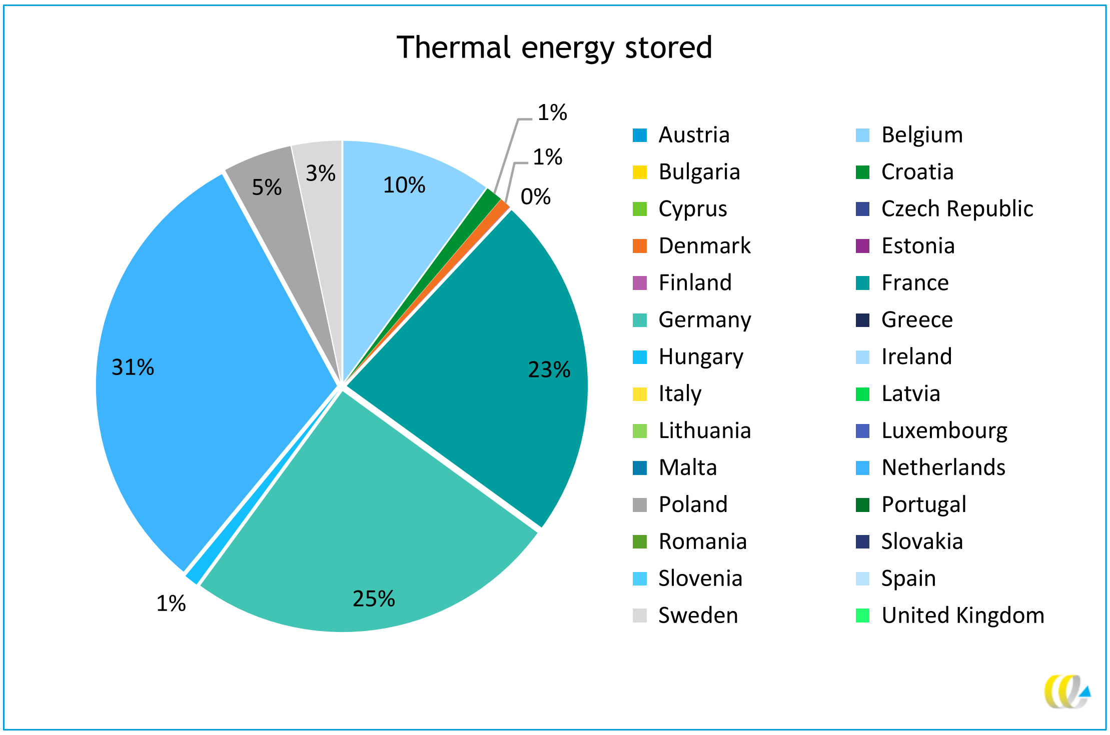


Figure 31 presents the contribution of the countries to the total amount of thermal energy storage in ATES in the Maximum Self-sufficiency scenario in 2050. Belgium, France, Germany, and the Netherlands have the largest share of ATES in this scenario.

Figure 31 - Contribution thermal energy storage member states to EU-28 total in 2050 Maximum Self-sufficiency scenario



Maximum Self-sufficiency

Table 8 presents the output of the model of the total share of Maximum Self-sufficiency in the EU in the Maximum Renewables and Maximum Self-sufficiency scenarios in 2050. The share of sufficiency is the highest for the residential buildings in the Maximum Self-sufficiency scenario. The share of self-sufficiency of electricity use can go up to 76%, while the share of self-sufficiency in heating and cooling reaches 61%.

Table 8 - Total share of Maximum Self-sufficiency for the EU in Maximum Renewables and Maximum Self-sufficiency scenario in 2050

Type of building	Scenario	Type of energy	Percentage Maximum Self-sufficiency
Residential	Maximum Renewables	Electricity	38%
		Heating and cooling	40%
	Maximum Self-sufficiency	Electricity	76%
		Heating and cooling	61%
Tertiary	Maximum Renewables	Electricity	12%
		Heating and cooling	37%
	Maximum Self-sufficiency	Electricity	21%
		Heating and cooling	43%

4.3 Comparison of results previous study

In this paragraph some of the main results of the 2016 CE Delft study and the PROSEU study are compared. In this new study, changes were made to the calculation methodologies and scope and both the input data and the scenario assumptions were updated. These changes reflect our increased understanding of prosumerism, recent trends, data and studies, and also the somewhat different focus of the two studies. To illustrate how the various changes have impacted the results, the results of the two studies are assessed for two key topics: electricity production and electricity storage on the EU28-level.

Electricity generation

If we look at results for the electricity generation potential by prosumers (Figure 32), we see that in the 2016 study the total calculated potential of wind energy is 950 TWh and the total production of solar energy is 560 TWh in 2050. The total production of both could potentially be 1,510 TWh in 2050 according to the 2016 study. In the PROSEU study, the total calculated potential of solar and wind energy is 1,660 TWh, of which 1,090 TWh solar energy and 570 TWh wind energy. We therefore find that the total difference in electricity production by prosumers between the two studies is fairly small, but the share of solar and wind energy in the production is very different.

Figure 33 again displays the potential electricity production of prosumers, but now distinguishing the contributions of the residential and tertiary sector. In the 2016 study, SMEs have a large share in the potential electricity production, while in the PROSEU study, by far the largest part of the electricity is produced by individual households or households that participate in collectives.

The differences in results are mainly due to the following modelling changes:
- Assumptions on the location of wind turbines for prosumers. In the 2016 study, there are no limitations on the distance between the prosumer and the wind turbine, except that the wind turbine has to be situated in the same country. In the PROSEU study, the wind turbines have to be within a distance of 5 km from the area in which the building of the prosumer is situated. This boundary condition was included to take into account the community and social aspects of prosumption and of energy communities, one of the key drivers for prosumerism and also a key research topic of the PROSEU project.
- A large part of the potential of wind energy in the 2016 study is based on wind turbines placed by farmers. In the PROSEU study, farmers were not within the scope, since they are not part of the tertiary sector. This resulted in a significantly lower total potential for wind energy generation in this study.
- Solar energy, on the other hand, has a higher potential in the PROSEU study, because it is assumed that all households could have solar PV on their rooftops in 2050. Only the available rooftop area is taken as a limitation to the potential. In the 2016 study, the potential is based on a certain annual growth rate, starting with the current solar capacity on rooftops. The growth rate was assumed to increase with a certain S-curve to arrive at to the potential in 2050.
- In the PROSEU study, solar PV on rooftops is chosen over wind turbines and ground-based solar. In the 2016 study, the available investment potential is determined, and then split into 50% for solar on rooftops, 25% for wind turbines and 25% for ground-based solar.
- In the PROSEU scenarios, financial restrictions are not taken into account, since these may be overcome by effective policies, loans or business models.

Figure 32 - Comparison between the 2016 study and PROSEU results: estimated potential for electricity production in 2050 for the EU28, divided by technology

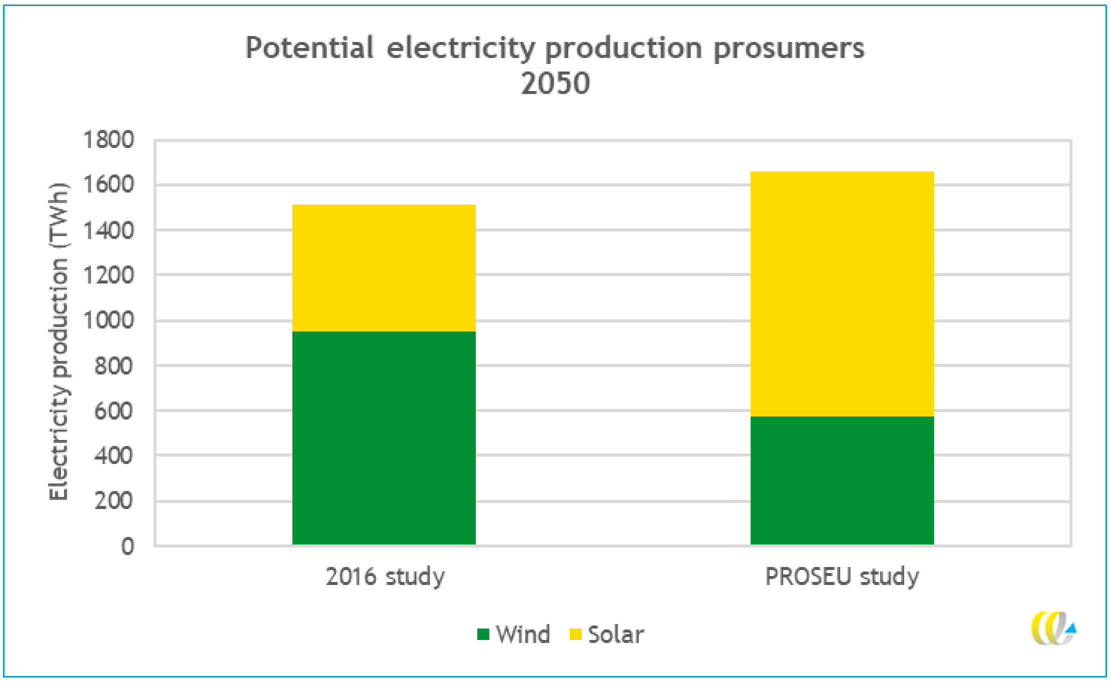
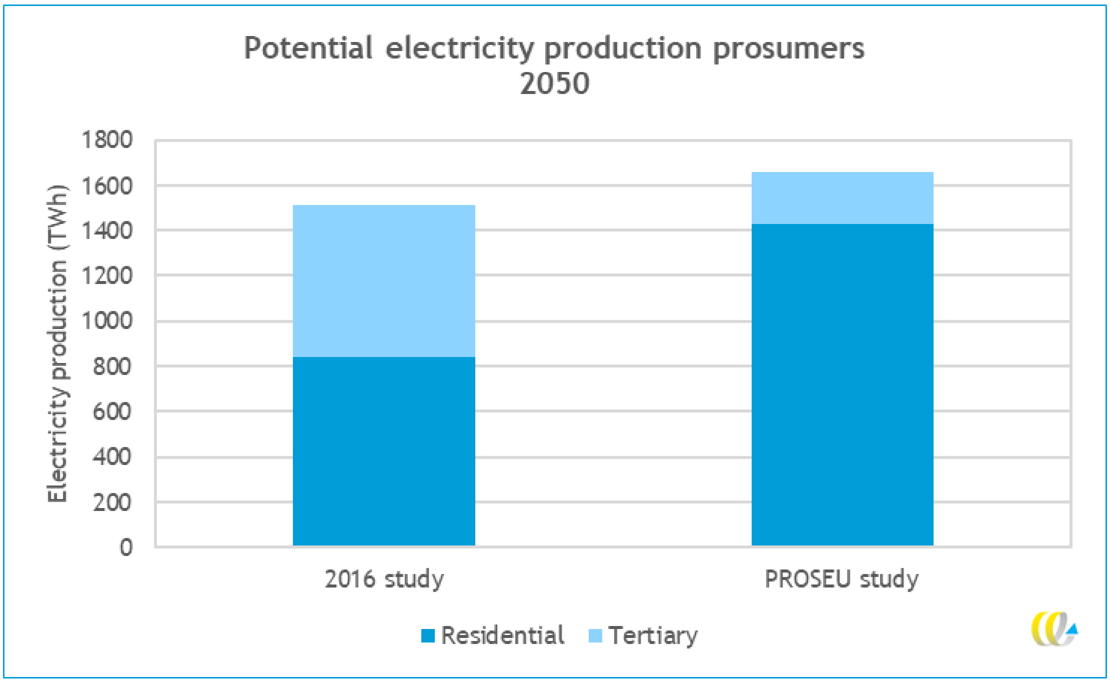


Figure 33 - Comparison between the 2016 study and PROSEU results: estimated potential for electricity production in 2050 for the EU28, divided by residential and tertiary sector

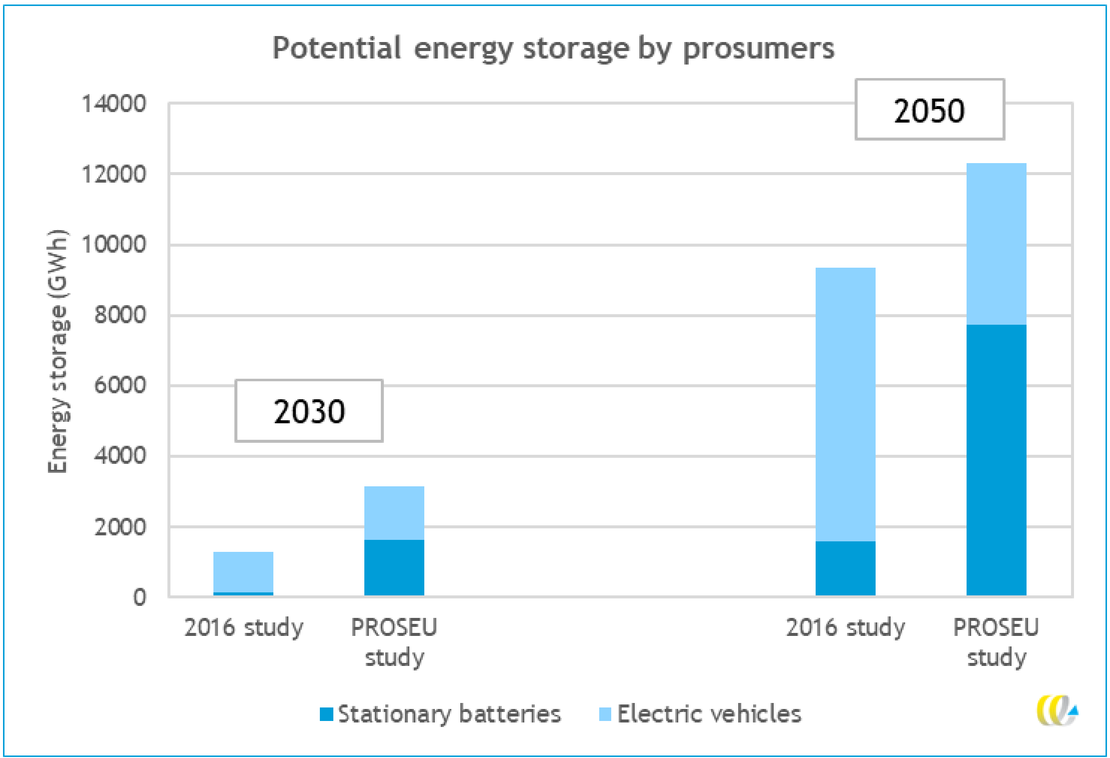


Electricity storage

Looking at potential for electricity storage by prosumers in the EU28 in 2050, we see in Figure 34 that the energy storage potential in the 2016 study is almost 10,000 GWh. The largest part is achieved by storage in electric vehicles. Stationary batteries account for about 1,500 GWh of storage capacity In the PROSEU study, the total potential storage in 2050 of electric vehicles is 4,600 GWh and the total storage of batteries is 7,700 GWh. This adds up to a total storage capacity of just over 12,000 GWh. We see, just as with electricity production, that the total storage capacity for electricity is in the same order of magnitude, but the different technologies have a very different share in this total number.

We found that the difference in battery storage of electric vehicles is mainly caused by the difference in assumption of the average battery capacity of an electric vehicle in 2050. Also, a different number of electric vehicles is assumed in both studies. The difference in battery storage for solar PV and wind turbines is caused by a number of other factors:
- In the 2016 study, it is assumed that battery storage is only applied in combination with solar PV and not in combination with wind turbines.
- We used different assumptions for the percentage of wind and solar installations that have batteries associated with them in 2050. In the 2016 study, it is assumed that 70% of the solar installations have battery storage, while in the PROSEU study, all wind turbines and solar PV installations are combined with battery storage.
- The amount of battery storage is based on the amount of installed solar PV, which is different in both studies.

Figure 34 - Comparison between the 2016 study and PROSEU results: energy storage by prosumers in EU28



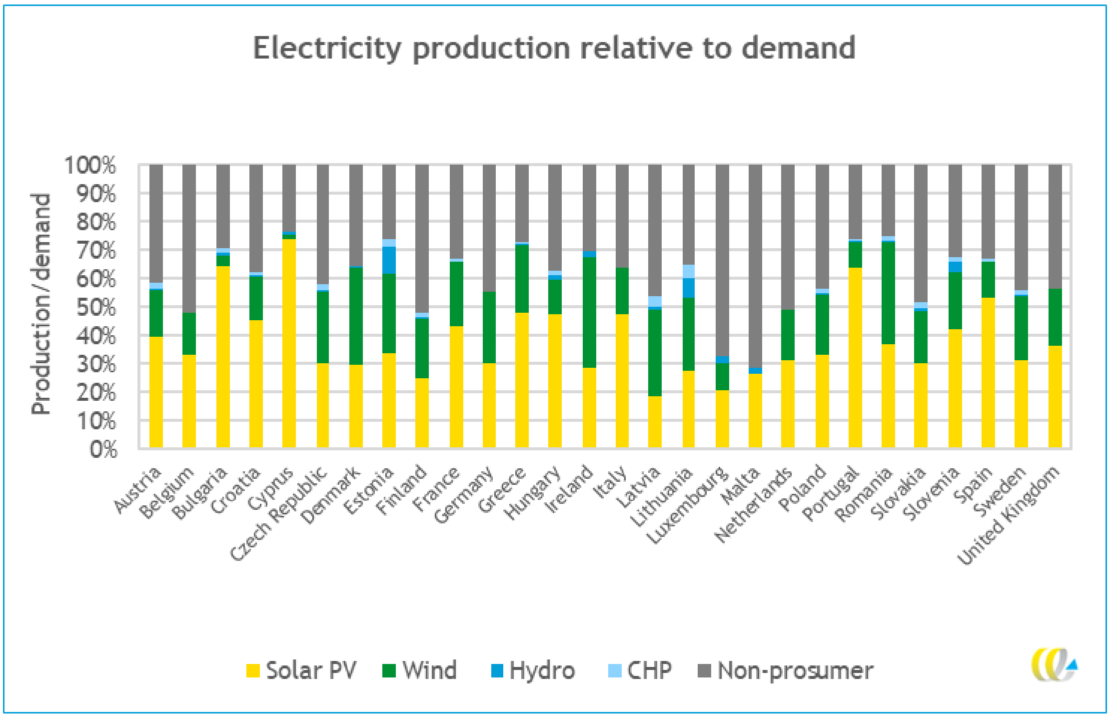
5 Conclusions and recommendations

5.1 Conclusions

The results from the CEPROM-model on country level show that with the use of different heat technologies (mostly heat pumps) and electric vehicles, the total electricity demand for households and residential buildings increase significantly in the Maximum Renewables and Maximum Self-sufficiency scenario.

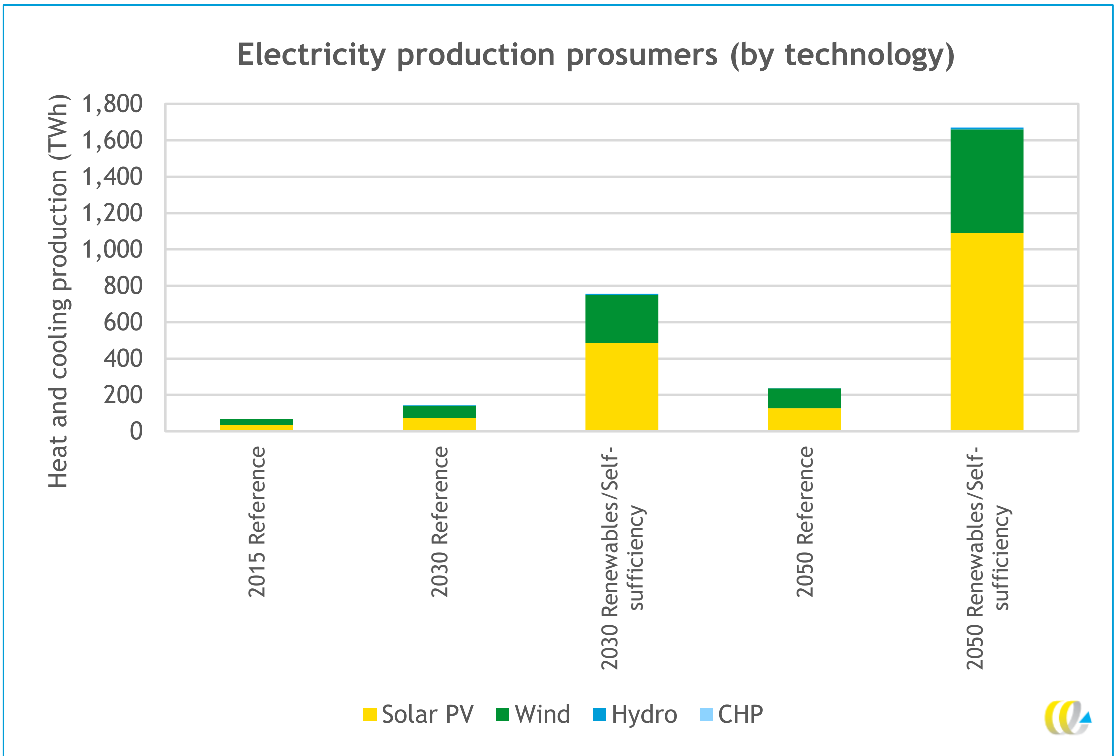
There are large differences in the share of electricity that can be produced by prosumer technologies throughout the EU. This production potential mostly depends on the available area for solar PV and wind turbines and on the climate conditions in the different countries. Figure 35 shows the share for each country in the Maximum Renewables/Maximum Self-sufficiency scenario in 2050. It can be concluded that solar PV, both on roof-tops (often owned by individuals) and ground-based (owned by collectives), has the highest potential, especially in countries in southern Europe. Generation of electricity with wind turbines owned by prosumer collectives also have a high potential in countries with enough available space around cities and towns and with enough wind power density.

Figure 35 - Annual electricity production of prosumer technologies relative to the total demand in the Maximum Renewables and Maximum Self-sufficiency scenario in 2050



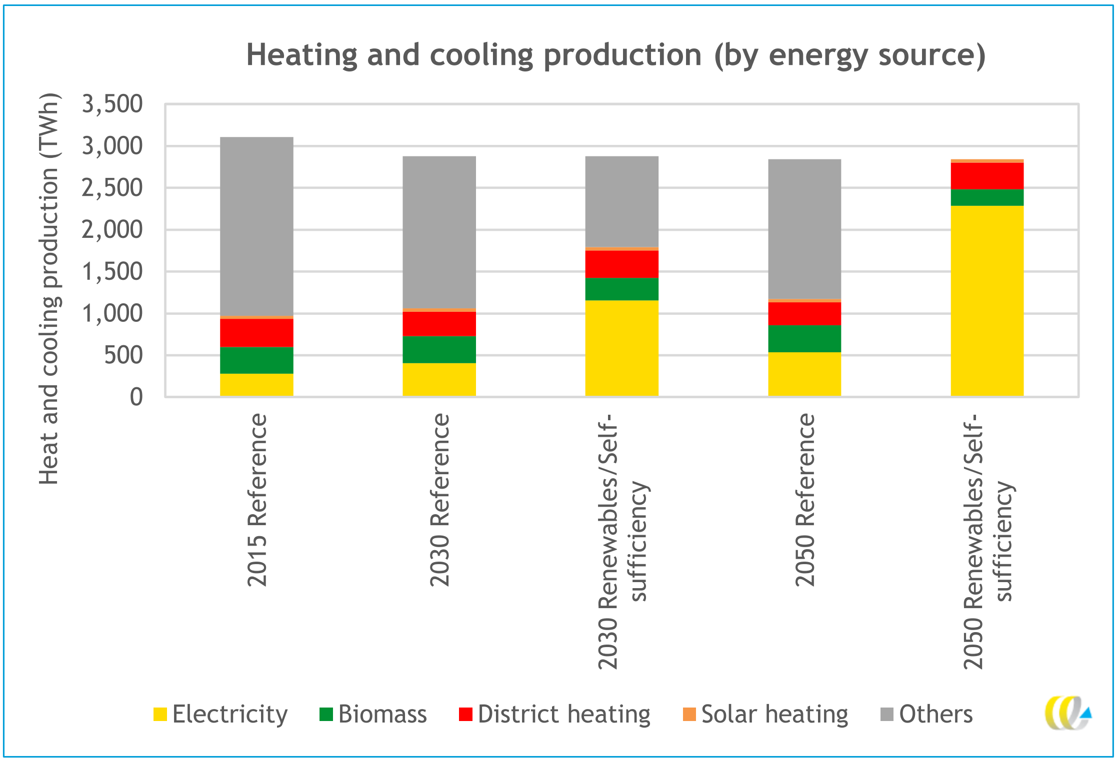
The CEPROM results for the EU as a whole and all scenarios are shown in Figure 36. From this figure it becomes even clearer that hydro power and CHP have very minimal contribution to the total potential of generated electricity by prosumers. It can also be noticed that to reach the outcome of the Maximum Renewables/Maximum Self-sufficiency scenario, the current generation of electricity by prosumers has to increase by a very large amount.

Figure 36 - Electricity production prosumers (by technology)



Whereas electricity demand increases significantly in these scenarios, the heating and cooling demand stays fairly constant over the different scenarios and reference years. The share of technologies that are applied to fill this demand vary between the Reference scenario and the Maximum Renewables/Maximum Self-sufficiency scenario. In the latter two scenarios, a large part of the heating and cooling consumption is filled with heat pumps, especially in southern countries that also have a significant cooling demand. In countries with biomass availability, biomass boilers and CHP are also applied. District heating is mainly applied in northern countries, where the heat demand is high and the cooling demand is low. In our model, households or companies that make use of district heating are not considered prosumers.

Figure 37 - Heating and cooling production, divided by energy source



We can furthermore conclude that a high level of self-sufficiency can be reached for residential buildings, especially for the electricity production. The share of self-sufficiency is expressed as a percentage of the self-produced energy that is directly used, compared to energy demand of the specific sector (residential or tertiary buildings). In the Maximum Self-sufficiency scenario, the electricity used from battery storage is also included and considered to be self-consumption. The percentage is mainly based on the amount of electricity production and the percentage of direct energy use and the electricity demand. Tertiary buildings do not reach a high level of self-sufficiency, due to the assumption that they only generate electricity by solar PV on their own roof and small wind turbines in case they have enough space around their building.

Table 9 - Total share of Maximum Self-sufficiency for the EU in Maximum Renewables and Maximum Self-sufficiency scenario in 2050

Type of building	Scenario	Type of energy	Percentage Maximum Self-sufficiency
Residential	Maximum Renewables	Electricity	38%
		Heating and cooling	40%
	Maximum Self-sufficiency	Electricity	76%
		Heating and cooling	61%
Tertiary	Maximum Renewables	Electricity	12%
		Heating and cooling	37%
	Maximum Self-sufficiency	Electricity	21%
		Heating and cooling	43%

5.2 Recommendations for further research

The CEPROM model calculates the technical potential per country based on general indicators such as type and amount of buildings and climate. These indicators might not in all cases sufficiently reflect the specific circumstances in each country. For example, some technologies, like district heating, might be less suited in mountainous regions. The existing energy grid and heating technologies could also ask for another favourable solution. Taking more country-specific circumstances into account could therefore lead to more accurate calculations of the technical potential.

CEPROM has a top-down approach based on datasets on a national level. Another option would be to do the same exercise using a bottom-up approach based on regional data. This would be useful to assess whether a top-down approach gives realistic results, and enable an assessment of how accurate the applied indicators estimate the technical potential.

Another recommended line of further research could be to get more insights in the non-technical aspects of the future prosumer potential. What are the costs associated with realizing the technical potential? What social constraints and opportunities should be taken account? This would give some more insight into the extent to which it is desirable to fully realize the technical potential. Taking other than technical constraints into account will also result in a more realistic estimation of the potential of prosumers.

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A Appendix

A.1 Parameters

Table 10 - Parameters country archetypes and building stock

	Reference			Renewables		Self-sufficiency		Unit	Reference
	2015	2030	2050	2030	2050	2030	2050		
Country archetypes									
Boundary cooling degree days									
Lower boundary	20	20	20	20	20	20	20	Degree days	Assumption CE Delft
Upper boundary	50	50	50	50	50	50	50	Degree days	Assumption CE Delft
Boundary biomass availability degree days									
Lower boundary	0.5	0.5	0.5	0.5	0.5	0.5	0.5	Ha/ household	Assumption CE Delft
Upper boundary	1	1	1	1	1	1	1	Ha/ household	Assumption CE Delft
Dwellings									
Number of floors									
Single family dwelling	2	2	2	2	2	2	2	#	(Defaix, et al., 2012)
Multifamily, high rise	5.75	5.75	5.75	5.75	5.75	5.75	5.75	#	(Defaix, et al., 2012)
Tertiary	4	4	4	4	4	4	4	#	(Defaix, et al., 2012)
Ratio floor area flat/ floor area per house	0.58	0.58	0.58	0.58	0.58	0.58	0.58		Data Netherlands (CBS, 2018)

Table 11 - Parameters solar energy (solar PV and solar thermal) per scenario

Solar energy	Reference			Renewables		Self-sufficiency		Unit	Reference
	2015	2030	2050	2030	2050	2030	2050		
Solar suitable area on rooftops	40%	40%	40%	40%	40%	40%	40%		(Defaix, et al., 2012)
Solar suitable area bare land	3%	3%	3%	3%	3%	3%	3%		(JRC, ongoing), (Ruiz, et al., 2019)
Solar PV									
Efficiency solar PV	15%	19%	23%	19%	23%	19%	23%		(ProsEU, ongoing a)
Performance ratio	80%	80%	80%	80%	80%	80%	80%		(Defaix, et al., 2012)
Fraction commercial PV tertiary prosumer	60%	60%	60%						Estimation CE Delft
Solar Thermal									
Efficiency solar heat north Europe	44%	49%	55%	49%	55%	49%	55%		(ProsEU, ongoing a)
Efficiency solar heat south Europe	40%	45%	50%	45%	50%	45%	50%		(ProsEU, ongoing a)
Irradiance boundary north/south	1,250	1,250	1,250	1,250	1,250	1,250	1,250	kWh/m^2/ year	Assumption CE Delft
Fraction water heating demand covered by solar heating	50%	50%	50%	50%	50%	50%	50%		Assumption CE Delft

Table 12 - Parameters electricity production (except solar PV) per scenario

Electricity	Reference			Renewables		Self-sufficiency		Unit	Reference
	2015	2030	2050	2030	2050	2030	2050		
Wind									
Fraction Tertiary wind on land Reference	10%	10%	10%						Estimation CE Delft
Hydro (small scale)									
Fraction small hydro cooperatives	3%	3%	3%						Estimation CE Delft (Wirling, et al., 2018)
Fraction new small hydro collectives				20%	20%	20%	20%		Assumption CE Delft
Electricity production total									
Boundary solar irradiation									
High	1,250	1,250	1,250	1,250	1,250	1,250	1,250	$kWh/m^2/year$	Assumption CE Delft
Low	1,000	1,000	1,000	1,000	1,000	1,000	1,000	$kWh/m^2/year$	Assumption CE Delft
Boundary power density wind									
High	350	350	350	350	350	350	350	W/m^2	Assumption CE Delft
Low	275	275	275	275	275	275	275	W/m^2	Assumption CE Delft

Table 13 - Parameters energy storage (thermal storage, batteries and electric vehicles) per scenario

Energy storage	Reference			Renewables		Self-sufficiency		Unit	Reference
	2015	2030	2050	2030	2050	2030	2050		
Thermal energy storage									
Efficiency storage (full cycle of storing and extracting from storage)	50%	50%	50%	50%	50%	50%	50%		(ProsEU, ongoing a)
Share ATES Reference collectives	30%	30%	30%	30%	30%	30%	30%		(Fleuchaus, et al., 2018)(results Netherlands)
Fraction ATES Reference Tertiary	70%	70%	70%	70%	70%	70%	70%		(Fleuchaus, et al., 2018) (results Netherlands)
Electric vehicles									
Average battery capacity	46	60	60	60	60	60	60	kWh	Current capacity NL (2019), 2030, 2050 (Element Energy, 2019)
Share EV in total fleet passenger cars		15%	46%	23%	69%	23%	69%	%	CE Delft scenarios based on (EC, 2018)
share households	100%	100%	100%	100%	100%	100%	100%	%	Assumption CE Delft
share Tertiary	0%	0%	0%	0%	0%	0%	0%	%	Assumption CE Delft
Charging capacity	3	5	11	5	11	5	11	kW	Estimation CE Delft based on Element Energy (2019)
time plugged in	50%	50%	50%	50%	50%	50%	50%	%	Estimation CE Delft
availability for flex	85%	85%	85%	85%	85%	85%	85%	%	Estimation CE Delft
Percentage electricity from battery	25%	25%	25%	25%	25%	25%	25%	%	Estimation CE Delft
Change in driven km	100%	114%	126%	114%	126%	114%	126%	%	(E3M Lab ; National Technical University of Athens, 2016))
Electricity consumption electric vehicle	0,16	0,15	0,13	0,15	0,13	0,15	0,13	kWh/km	Estimation CE Delft
Stationary Batteries									
Adoption batteries	0%	0%	0%	0%	0%	43%	100%	%	Assumption CE Delft
Charging/discharging	0.4	0.4	0.4	0.4	0.4	0.4	0.4	kW/kWh	Estimation CE Delft
Storage per unit capacity PV									
Solar PV	4	4	4	4	4	4	4	kWh/kWp	Estimation CE Delft
Wind	15.0	15.0	15.0	15.0	15.0	15.0	15.0	kWh/kWp	Estimation CE Delft
Hydro (small scale)	9	9	9	9	9	9	9	kWh/kWp	Estimation CE Delft
CHP	2.0	2.0	2.0	2.0	2.0	2.0	2.0	kWh/kWp	Estimation CE Delft

Table 14 - Parameters heating technologies (CHP, district heating, biomass boiler and heat pump) per scenario

Heating technologies	Reference			Renewables		Self-sufficiency		Unit	Reference
	2015	2030	2050	2030	2050	2030	2050		
CHP									
Efficiency CHP total	97.3%	97.3%	97.6%	97.3%	97.6%	97.3%	97.6%		(ProsEU, ongoing a)
Efficiency CHP heat	83.0%	83.0%	83.6%	83.0%	83.6%	83.0%	83.6%		(ProsEU, ongoing a)
Efficiency CHP electricity	14.3%	14.3%	14.0%	14.3%	14.0%	14.3%	14.0%		(ProsEU, ongoing a)
Number of CHP (Reference)	0	0	0						Assumption CE Delft, Data unknown
District heating									
Share district heating individual/multifamily households Reference									
Individual households	25%	25%	25%					% in terms of #	Estimation CE Delft
Multifamily households	75%	75%	75%					% in terms of #	Estimation CE Delft
Capacity households: single family	0.09	0.09	0.09	0.09	0.09	0.09	0.09	kW/m^2	CE Delft (CEGOIA model)
Capacity collective: multifamily	0.075	0.075	0.075	0.075	0.075	0.075	0.075	kW/m^2	CE Delft (CEGOIA model)
Capacity Tertiary	0.075	0.075	0.075	0.075	0.075	0.075	0.075	kW/m^2	CE Delft (CEGOIA model)
Biomass boiler									
Share biomass boiler individual/multifamily households Reference									
Individual households	50%	50%	50%					% in terms of #	Estimation CE Delft
Multifamily households	50%	50%	50%					% in terms of #	Estimation CE Delft
Biomass boiler fraction of equivalent full load hours compared to Heatpump	75%	75%	75%	75%	75%	75%	75%	%	Assumption CE Delft
Heat pump									
Share heat pumps individual/multifamily households Reference									
Individual households	75%	75%	75%					% in terms of #	Estimation CE Delft
Multifamily households	25%	25%	25%					% in terms of #	Estimation CE Delft
COP heat pump for space heating	3.5	3.9	4.0	3.9	4.0	3.9	4.0	#	(ProsEU, ongoing a)
COP heat pump for hot water/tap water	2.0	2.3	2.6	2.3	2.6	2.3	2.6	#	(CE Delft, 2017)
COP heat pump for space cooling	2.5	2.9	3.0	2.9	3.0	2.9	3.0	#	COP_c=COP_h - 1 (Wikipedia.org, 2020)

A.2 Data

Table 15 - Overview used data including references

Description data	Reference
Population member states (2015, 2030, 2050)	(E3M Lab ; National Technical University of Athens, 2016)
Number of households (2015)	(E3M Lab ; National Technical University of Athens, 2016)
Heating and cooling degree days	(Eurostat, 2019)
Land cover (woodland and bare land)	(Eurostat, 2020a) Reference year 2012
Distribution population by housing type and living area	(Eurostat, 2020b) Reference year 2018
Floor area per dwelling	(Eurostat, 2020e) Reference year
Floor area Tertiary	(EC, ongoing) Building Stock Characteristics
New residential buildings per year	(EC, ongoing) Building stock characteristics
Buildings tertiary sector	(Eurostat, 2020c) Reference year 2017
Electricity demand (2015, 2030, 2050)	(E3M Lab ; National Technical University of Athens, 2016)
Installed capacity off-shore and onshore wind	(Eurobserv'er, 2016)
Installed capacity wind and solar PV collectives	(RESCoop, 2015)
Electricity generation wind/solar PV/hydro Reference (2015, 2030, 2050)	(E3M Lab ; National Technical University of Athens, 2016)
Full-load hours generation wind/solar PV/hydro Reference (2015, 2030, 2050)	(E3M Lab ; National Technical University of Athens, 2016)
Mean power density wind power @100m	(Global wind atlas, ongoing)
Technical potential wind	(Dalla Longa, et al., 2018)
Solar irradiation	(Beták, et al., 2012)
Market segmentation solar PV Reference	(SolarPower Europe, 2019)
Solar heat production (2015)	(Eurostat, 2020d) Reference year 2015
Production small hydro	(ESHA, 2012)
Technical potential hydropower	(EC, SETIS, 2011)
Subsurface suitability ATES	(Bloemendal, et al., 2015)
Energy stored ATES	(Fleuchaus, et al., 2018)(Based on results of the Netherlands)
Passenger cars per 1000 inhabitants	(Eurostat, 2020) Reference year 2016
Full electric vehicles	(Eurostat, 2091b)
Households without a car	(ACEA, 2017) (year data between 2010 and 2015)
Delivered energy demand heat (total heat produced)	(Fraunhofer ISI ; TEP Energy GmbH; University Utrecht; ARMINES, 2017)
Equivalent full load hours heat pumps	(EU, 2013)

A.3 Matrix technologies

Table 16 - Matrix choice heating technologies individual prosumers

Climate zone	Woodland	Population density	Heat pump	Thermal energy storage	District heating	Biomass boiler	Solar thermal	CHP
CDD <20	>1ha/hh	Rural				1	1	
CDD <20	>1ha/hh	Suburban	1					
CDD <20	>1ha/hh	Urban			1		1	
CDD <20	0.5<ha/hh<1	Rural	0.5			0.5		
CDD <20	0.5<ha/hh<1	Suburban	1					
CDD <20	0.5<ha/hh<1	Urban			1		1	
CDD <20	ha/hh<0.5	Rural	1					
CDD <20	ha/hh<0.5	Suburban	1					
CDD <20	ha/hh<0.5	Urban			1		1	
20<CDD<50	>1ha/hh	Rural				1	1	
20<CDD<50	>1ha/hh	Suburban	1					
20<CDD<50	>1ha/hh	Urban			1		1	
20<CDD<50	0.5<ha/hh<1	Rural	0.5			0.5		
20<CDD<50	0.5<ha/hh<1	Suburban	1					
20<CDD<50	0.5<ha/hh<1	Urban			1		1	
20<CDD<50	ha/hh<0.5	Rural	1					
20<CDD<50	ha/hh<0.5	Suburban	1					
20<CDD<50	ha/hh<0.5	Urban			1		1	
CDD>50	>1ha/hh	Rural				1	1	
CDD>50	>1ha/hh	Suburban	1					
CDD>50	>1ha/hh	Urban	1					
CDD>50	0.5<ha/hh<1	Rural	1					
CDD>50	0.5<ha/hh<1	Suburban	1					
CDD>50	0.5<ha/hh<1	Urban	1					
CDD>50	ha/hh<0.5	Rural	1					
CDD>50	ha/hh<0.5	Suburban	1					
CDD>50	ha/hh<0.5	Urban	1					

Table 17 - Matrix choice heating technologies collective prosumers

Climate zone	Woodland	Population density	Heat pump	Thermal energy storage	District heating	Biomass boiler	Solar thermal	CHP
CDD <20	>1ha/hh	Rural					1	1
CDD <20	>1ha/hh	Suburban	1					
CDD <20	>1ha/hh	Urban			1		1	
CDD <20	0.5<ha/hh<1	Rural					1	1
CDD <20	0.5<ha/hh<1	Suburban	1					
CDD <20	0.5<ha/hh<1	Urban			1		1	
CDD <20	ha/hh<0.5	Rural	1					
CDD <20	ha/hh<0.5	Suburban	1					
CDD <20	ha/hh<0.5	Urban			1		1	
20<CDD<50	>1ha/hh	Rural					1	1
20<CDD<50	>1ha/hh	Suburban	1					
20<CDD<50	>1ha/hh	Urban			1		1	
20<CDD<50	0.5<ha/hh<1	Rural					1	1
20<CDD<50	0.5<ha/hh<1	Suburban	1					
20<CDD<50	0.5<ha/hh<1	Urban			1		1	
20<CDD<50	ha/hh<0.5	Rural	1					
20<CDD<50	ha/hh<0.5	Suburban	1					
20<CDD<50	ha/hh<0.5	Urban			1		1	
CDD>50	>1ha/hh	Rural					1	1
CDD>50	>1ha/hh	Suburban	1	1				
CDD>50	>1ha/hh	Urban	1					
CDD>50	0.5<ha/hh<1	Rural					1	1
CDD>50	0.5<ha/hh<1	Suburban	1	1				
CDD>50	0.5<ha/hh<1	Urban	1					
CDD>50	ha/hh<0.5	Rural	1					
CDD>50	ha/hh<0.5	Suburban	1	1				
CDD>50	ha/hh<0.5	Urban	1					

Table 18 - Matrix choice heating technologies tertiary sector

Climate zone	Woodland	Population density	Heat pump	Thermal energy storage	District heating	Biomass boiler	Solar thermal	CHP
CDD <20	>1ha/hh	Rural					1	1
CDD <20	>1ha/hh	Suburban	1					
CDD <20	>1ha/hh	Urban			1		1	
CDD <20	0.5<ha/hh<1	Rural					1	1
CDD <20	0.5<ha/hh<1	Suburban	1					
CDD <20	0.5<ha/hh<1	Urban			1		1	
CDD <20	ha/hh<0.5	Rural	1					
CDD <20	ha/hh<0.5	Suburban	1					
CDD <20	ha/hh<0.5	Urban			1		1	
20<CDD<50	>1ha/hh	Rural					1	1
20<CDD<50	>1ha/hh	Suburban	1	1				
20<CDD<50	>1ha/hh	Urban	1					
20<CDD<50	0.5<ha/hh<1	Rural					1	1
20<CDD<50	0.5<ha/hh<1	Suburban	1	1				
20<CDD<50	0.5<ha/hh<1	Urban	1					
20<CDD<50	ha/hh<0.5	Rural	1					
20<CDD<50	ha/hh<0.5	Suburban	1	1				
20<CDD<50	ha/hh<0.5	Urban	1					
CDD>50	>1ha/hh	Rural					1	1
CDD>50	>1ha/hh	Suburban	1	1				
CDD>50	>1ha/hh	Urban	1					
CDD>50	0.5<ha/hh<1	Rural					1	1
CDD>50	0.5<ha/hh<1	Suburban	1	1				
CDD>50	0.5<ha/hh<1	Urban	1					
CDD>50	ha/hh<0.5	Rural	1					
CDD>50	ha/hh<0.5	Suburban	1	1				
CDD>50	ha/hh<0.5	Urban	1					

A.4 Overview results

A.4.1 Results graphs

Table 19 - Annual electricity demand in different scenarios and different reference years (in TWh)

Member state	Reference 2015	Reference 2030	Renewables/ Self-sufficiency 2030	Reference 2050	Renewables/ Self-sufficiency 2050
Austria	32	38	42	39	49
Belgium	49	60	69	67	89
Bulgaria	11	15	17	17	22
Croatia	9	11	13	12	16
Cyprus	2	3	6	4	11
Czech Republic	34	41	46	43	53
Denmark	24	29	33	31	41
Estonia	5	6	6	6	7
Finland	30	36	39	40	46
France	246	282	331	305	420
Germany	312	347	426	348	526
Greece	22	25	36	27	52
Hungary	29	34	40	33	47
Ireland	14	17	19	19	23
Italy	174	216	280	237	385
Latvia	7	8	8	8	9
Lithuania	7	8	8	7	9
Luxembourg	4	5	6	7	9
Malta	1	1	2	2	4
Netherlands	81	90	99	93	115
Poland	106	134	146	132	158
Portugal	16	21	26	24	35
Romania	32	40	44	40	51
Slovakia	14	18	20	19	23
Slovenia	6	7	8	8	10
Spain	98	115	145	129	196
Sweden	40	50	53	57	66
United Kingdom	196	236	262	261	325
Total	**1,601**	**1,892**	**2,230**	**2,016**	**2,798**

Table 20 - Electricity production with prosumer technologies relative to total demand residential and tertiary sector (in TWh)

Member state	Reference 2015	Reference 2030	Renewables/ Self-sufficiency 2030	Reference 2050	Renewables/ Self-sufficiency 2050	Demand 2050 Self-sufficiency
Austria	2	5	13	8	29	49
Belgium	3	5	20	6	43	89
Bulgaria	0	1	7	1	15	22
Croatia	0	1	4	2	10	16
Cyprus	0	0	4	1	8	11
Czech Republic	0	0	13	1	31	53
Denmark	3	5	13	6	26	41
Estonia	0	0	2	1	5	7
Finland	1	1	10	2	22	46
France	6	26	124	51	281	419
Germany	22	40	137	56	291	526
Greece	2	5	17	8	38	52
Hungary	0	0	13	1	29	47
Ireland	1	1	7	2	16	23
Italy	9	15	111	35	247	385
Latvia	0	0	2	0	5	9
Lithuania	0	0	2	0	6	9
Luxembourg	0	0	1	0	3	9
Malta	0	0	1	0	1	4
Netherlands	2	6	25	8	57	115
Poland	1	2	39	5	89	158
Portugal	1	3	12	4	25	35
Romania	1	1	17	2	38	51
Slovakia	0	0	5	1	12	23
Slovenia	0	0	3	0	7	10
Spain	6	12	60	22	131	196
Sweden	2	3	17	4	37	66
United Kingdom	4	9	81	11	183	325
Total	**68**	**143**	**761**	**238**	**1,686**	**2,797**

Table 21 - Electricity production of prosumer technologies relative to total demand residential and tertiary sector in Renewables/Self-sufficiency scenario in 2050 (in TWh)

Member state	Solar PV	Wind	Hydro (small scale)	CHP	Demand
Austria	20	8	0	1	49
Belgium	30	13	0	0	89
Bulgaria	14	1	0	0	22
Croatia	7	2	0	0	16
Cyprus	8	0	0	0	11
Czech Republic	16	14	0	1	53
Denmark	12	14	0	0	41
Estonia	2	2	1	0	7
Finland	11	10	0	1	46
France	182	95	0	5	419
Germany	159	132	0	0	526
Greece	25	12	0	0	52
Hungary	22	6	1	1	47
Ireland	7	9	0	0	23
Italy	183	63	0	0	385
Latvia	2	3	0	0	9
Lithuania	2	2	1	0	9
Luxembourg	2	1	0	0	9
Malta	1	0	0	0	4
Netherlands	36	20	0	0	115
Poland	52	33	0	3	158
Portugal	22	3	0	0	35
Romania	19	18	0	1	51
Slovakia	7	4	0	0	23
Slovenia	4	2	0	0	10
Spain	105	25	0	2	196
Sweden	20	15	0	1	66
United Kingdom	119	64	0	0	325
Total	**1,090**	**572**	**8**	**17**	**2,797**

Table 22 - Heating and cooling demand residential and tertiary sector (in TWh)

Member state	Heating demand			Cooling demand		
	2015	2030	2050	2015	2030	2050
Austria	64	56	52	1	2	2
Belgium	89	78	73	2	3	3
Bulgaria	19	16	15	2	3	4
Croatia	19	17	16	1	1	2
Cyprus	2	2	2	6	11	19
Czech Republic	65	57	53	1	1	1
Denmark	45	40	37	0	0	1
Estonia	9	8	8	0	0	0
Finland	62	55	51	0	1	1
France	414	366	343	16	26	33
Germany	660	574	537	6	10	11
Greece	32	29	28	19	34	53
Hungary	58	51	47	1	2	3
Ireland	29	25	24	0	0	0
Italy	349	310	291	61	104	153
Latvia	13	11	10	0	0	0
Lithuania	12	11	10	0	0	0
Luxembourg	7	6	6	0	0	0
Malta	1	1	1	2	3	5
Netherlands	116	101	95	2	3	3
Poland	180	160	150	2	3	4
Portugal	16	14	13	6	9	13
Romania	51	45	42	2	4	6
Slovakia	26	23	21	0	0	0
Slovenia	11	9	9	1	1	1
Spain	126	110	103	46	77	104
Sweden	81	70	66	1	2	2
United Kingdom	369	325	306	6	9	9
Total	**2,924**	**2,570**	**2,408**	**185**	**310**	**434**

Table 23 - Energy carriers used to cover the energy demand for heating and cooling in residential buildings in the Renewables/Self-sufficiency scenario in 2050

Member state	Electricity	Derived heat	Biomass	Solar heat
Austria	30	8	14	1
Belgium	62	12	0	1
Bulgaria	13	0	6	1
Croatia	12	0	6	0
Cyprus	21	0	0	0
Czech Republic	30	10	13	1
Denmark	27	10	0	1
Estonia	2	3	3	0
Finland	17	18	16	1
France	346	0	28	2
Germany	548	0	0	0
Greece	79	0	1	0
Hungary	46	0	5	0
Ireland	14	10	0	1
Italy	444	0	0	0
Latvia	3	3	4	0
Lithuania	2	3	6	1
Luxembourg	5	0	0	0
Malta	6	0	0	0
Netherlands	64	31	0	2
Poland	75	32	43	3
Portugal	25	0	1	0
Romania	28	0	18	1
Slovakia	12	0	9	1
Slovenia	6	0	4	0
Spain	196	0	10	2
Sweden	29	23	13	3
United Kingdom	142	157	0	16
Total	**2,284**	**319**	**200**	**40**

Table 24 - Electricity storage capacity in the Self-sufficiency scenario in 2050 (in GWh)

Member state	Electricity storage capacity	
	Battery storage	EV
Austria	136	94
Belgium	174	129
Bulgaria	69	45
Croatia	46	24
Cyprus	26	10
Czech Republic	181	94
Denmark	110	47
Estonia	33	10
Finland	139	64
France	1,085	633
Germany	1,561	720
Greece	141	76
Hungary	162	53
Ireland	77	38
Italy	985	737
Latvia	27	9
Lithuania	34	14
Luxembourg	15	12
Malta	2	5
Netherlands	256	146
Poland	562	335
Portugal	75	71
Romania	204	83
Slovakia	63	32
Slovenia	42	19
Spain	402	385
Sweden	201	104
United Kingdom	905	629
Total	**7,712**	**4,621**

Table 25 - Annual amount of thermal energy stored (in GWh)

Member state	Heat/cold stored				
	2015 Reference	2030 Reference	2030 Self-sufficiency	2050 Reference	2050 Self-sufficiency
Austria	-	-	-	-	-
Belgium	19	20	229	23	511
Bulgaria	-	-	-	-	-
Croatia	-	-	25	-	58
Cyprus	-	-	-	-	-
Czech Republic	-	-	-	-	-
Denmark	34	36	36	38	38
Estonia	-	-	1	-	1
Finland	-	-	-	-	-
France	-	-	500	-	1,167
Germany	2	2	546	2	1,270
Greece	-	-	-	-	-
Hungary	-	-	20	-	47
Ireland	-	-	-	-	-
Italy	-	-	-	-	-
Latvia	-	-	1	-	2
Lithuania	-	-	0	-	1
Luxembourg	-	-	6	-	14
Malta	-	-	-	-	-
Netherlands	1,553	1,591	1,563	1,577	1,577
Poland	-	-	100	-	234
Portugal	-	-	-	-	-
Romania	-	-	-	-	-
Slovakia	-	-	6	-	14
Slovenia	-	-	-	-	-
Spain	-	-	-	-	-
Sweden	137	148	150	168	168
United Kingdom	7	8	8	9	9
Total	**1,752**	**1,806**	**3,190**	**1,816**	**5,108**

A.5 Other results

Table 26 - Distribution electricity demand different application in Renewables/Self-sufficiency 2050 scenario (in TWh)

Member state	Electricity demand lightning and devices		Electricity demand EV	Electricity demand heating and cooling		Total electricity demand	
	Residential	Tertiary	Residential	Residential	Tertiary	Residential	Tertiary
Austria	13	19	10	5	3	28	22
Belgium	21	36	15	11	6	48	41
Bulgaria	5	7	6	2	1	13	8
Croatia	4	6	3	2	1	9	7
Cyprus	1	2	1	6	1	8	3
Czech Republic	14	23	8	6	2	28	25
Denmark	9	17	7	6	2	22	19
Estonia	2	3	1	0	0	4	4
Finland	11	22	8	3	1	23	24
France	76	164	89	72	18	237	182
Germany	116	164	97	106	43	319	207
Greece	7	13	10	18	5	35	17
Hungary	11	18	6	9	3	26	21
Ireland	7	9	4	3	1	13	10
Italy	65	109	82	92	36	240	145
Latvia	3	4	1	0	0	4	5
Lithuania	3	4	2	0	0	5	4
Luxembourg	2	5	2	1	1	4	5
Malta	0	1	1	2	0	2	1
Netherlands	23	58	19	9	7	51	65
Poland	47	71	21	14	5	82	76
Portugal	6	12	9	5	2	20	14
Romania	18	15	11	5	2	34	17
Slovakia	5	12	4	2	1	11	12
Slovenia	2	3	3	1	0	6	4
Spain	31	73	36	37	19	104	92
Sweden	14	30	14	5	2	33	32
United Kingdom	91	112	85	58	16	235	128
Total	**607**	**1,013**	**554**	**483**	**177**	**1,644**	**1,190**

Table 27 - Installed capacity electricity generation Renewables/Self-sufficiency 2050 scenario (in GW)

Member state	Installed capacity				
	Solar PV	Wind	Hydro (small scale)	CHP	Total
Austria	16	4	0	8	27
Belgium	27	4	0	-	32
Bulgaria	10	0	0	4	14
Croatia	5	1	0	2	8
Cyprus	4	0	0	0	4
Czech Republic	17	6	0	5	28
Denmark	13	4	0	-	17
Estonia	3	1	0	5	8
Finland	14	4	0	6	23
France	106	32	0	53	191
Germany	165	58	0	-	223
Greece	14	4	0	1	19
Hungary	21	3	0	5	29
Ireland	8	3	0	-	11
Italy	118	26	0	-	145
Latvia	2	1	0	1	4
Lithuania	3	1	0	2	6
Luxembourg	2	0	0	-	2
Malta	1	0	0	-	1
Netherlands	39	7	0	-	46
Poland	60	14	0	23	98
Portugal	11	1	0	5	16
Romania	14	8	0	5	27
Slovakia	6	2	0	2	10
Slovenia	4	1	0	2	7
Spain	48	9	0	20	78
Sweden	23	6	0	6	35
United Kingdom	142	20	0	-	162
Total	**893**	**222**	**3**	**156**	**1,274**

Table 28 - Potential production prosumers without cap by technology in Renewables/Self-sufficiency 2050 scenario (in TWh)

Member state	Potential production prosumers (TWh)				
	Solar PV	Wind	Hydro (small scale)	CHP	Total
Austria	51	24	0	1	76
Belgium	30	15	0	0	45
Bulgaria	24	62	0	0	86
Croatia	11	43	0	0	55
Cyprus	20	1	0	0	21
Czech Republic	18	141	0	1	160
Denmark	15	120	0	0	135
Estonia	5	59	1	0	65
Finland	20	57	0	1	78
France	283	1,757	0	5	2,045
Germany	159	176	0	0	335
Greece	55	396	0	0	452
Hungary	35	79	1	1	116
Ireland	10	549	0	0	559
Italy	228	240	0	0	468
Latvia	5	170	0	0	175
Lithuania	5	268	1	0	274
Luxembourg	2	1	0	0	3
Malta	1	0	0	0	1
Netherlands	36	50	0	0	86
Poland	69	199	0	3	272
Portugal	61	67	0	0	128
Romania	29	294	0	1	324
Slovakia	9	52	0	0	62
Slovenia	5	4	0	0	9
Spain	499	1,150	0	2	1,651
Sweden	87	245	0	1	333
United Kingdom	121	325	0	0	446
Total	**1,893**	**6,542**	**8**	**17**	**8,459**

Table 29 - Potential production prosumers without cap compared to demand in Renewables/Self-sufficiency 2050 scenario (in TWh)

Member state	Residential			Tertiary		
	Potential production	Demand	Production relative to demand	Potential production	Demand	Production relative to demand
Austria	71	28	255%	5	22	24%
Belgium	40	48	83%	6	41	13%
Bulgaria	84	13	632%	2	8	28%
Croatia	53	9	597%	1	7	16%
Cyprus	21	8	267%	0	3	15%
Czech Republic	157	28	557%	3	25	11%
Denmark	130	22	599%	5	19	25%
Estonia	63	4	1,751%	2	4	64%
Finland	74	23	330%	3	24	14%
France	2,000	237	844%	44	182	24%
Germany	284	319	89%	51	207	25%
Greece	449	35	1,274%	3	17	16%
Hungary	112	26	427%	3	21	15%
Ireland	556	13	4,159%	3	10	28%
Italy	449	240	187%	19	145	13%
Latvia	175	4	4,183%	1	5	12%
Lithuania	273	5	5,836%	1	4	22%
Luxembourg	3	4	64%	0	5	7%
Malta	1	2	40%	0	1	11%
Netherlands	74	51	146%	12	65	19%
Poland	259	82	316%	13	76	17%
Portugal	123	20	613%	5	14	37%
Romania	320	34	941%	4	17	24%
Slovakia	61	11	550%	1	12	9%
Slovenia	8	6	132%	1	4	22%
Spain	1,624	104	1,556%	27	92	29%
Sweden	327	33	976%	6	32	20%
United Kingdom	848	235	361%	45	128	35%
Total	8,638	1,644	525%	268	1,190	22%