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COMPARISON OF THE FUTURE RESIDUAL LOAD IN FIFTEEN COUNTRIES AND REQUIREMENTS TO GRID-SUPPORTIVE BUILDING OPERATION

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Abstract

Many countries in the world plan to increase their share of wind and solar power. In order to efficiently utilize large amounts intermittent renewable power, flexible consumers such as buildings with heat pumps and chillers may play a crucial role. However, it is not clear how heat pumps and chillers should be operated in order to make the best use of the volatile renewable energy. For this purpose, the residual loads of 13 European countries, Great Britain, and Alberta in the year 2030 were simulated and analyzed. The term "residual load" refers to the electricity demand that is not covered with intermittent renewable systems and that, therefore, must be met by dispatchable electricity generation units. It was calculated as the difference of the wind and PV generation simulated as part of this study, and the electric load of 2011.

The results show a high relative variability in the residual load in almost all analyzed countries. In winter, the lowest residual loads (i.e. the most favorable times for electricity consumption) occur either around noon (particularly in the countries with the highest amount of wind and solar power), or at night. In summer, the residual loads are usually lowest around noon, which coincides well with the typical cooling load profile of a building. PV-dominated countries show stronger daily variations in the residual load, which can be managed even with relatively small storage capacities as typically found in buildings. In contrast, in wind-dominated countries, the residual load fluctuates on longer time scales, which requires larger storages.

Keywords: *energy system, residual load, energy scenario, demand response, heat pumps*

1. Introduction

In an effort to reduce the emissions of greenhouse gases and combat climate change, intermittent renewable energy sources such as wind and photovoltaics (PV) are gaining in importance in many countries of Europe and throughout the world. A large share of intermittent renewable energy in the electricity mix presents serious challenges to power systems, as load and generation must match at any time. However, the generation of intermittent renewables depends on the current weather conditions and, unlike in conventional plants, cannot be dispatched and controlled at will.

In order to promote an efficient integration of a large share of intermittent renewables into the electric energy system, a part of the electric consumers can be made flexible such that their consumption follows the renewable generation. This concept is known as 'demand response'. Demand response has been identified by (IEA, 2003) as a viable alternative to traditional supply side remedies and the most cost effective solution to integrate large amounts of renewable in the energy mix.

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Presently, many international research activities (e.g. as part of IEA EBC Annex 67) study how buildings can be used for demand response purposes by implementing special control strategies for heat pumps, chillers, CHP units and other technical systems in order to support the electric energy system.

Efforts in the recent years have been made to understand the interaction between buildings and grid, particularly with buildings that incorporates on-site renewable energy systems. Thus Salom et al. (2014) analyzed several indicators to study grid interaction of prosumer buildings, particularly Net Zero Energy Buildings and Cubí et al. (2015) proposed a method to incorporate GHG emissions intensity changes due to grid variability into building environmental assessment with the objective to encourage building systems that reduce electricity use during peak periods. Several solutions have already been investigated how buildings can be providers of flexibility in the grid and demand response agents. Hedegaard et al. (2012) studied the potential of individual heat pumps, using heat accumulation tanks or passive heat storage in the construction, for increasing wind power utilisation and providing cost-effective fuel savings in the Danish energy system. Results show that by displacing less efficient heating technologies and increasing electricity demand, the installation of heat pumps alone can contribute to the integration of wind power, providing significant reductions in excess electricity production and fuel consumption.

However, the load profiles that ideal flexible buildings should follow are unique for each country, because each country or region has a different combination of amount of wind and solar power to be integrated in the energy system, electric load profile, as well as weather conditions. Furthermore, the amount of energy that can be stored and shifted by buildings depends on the dynamics of the thermal load, which is influenced by the ambient temperature and irradiation and thus changes with the geographical location. It is thus relevant to analyze and compare the availability of renewable energy generation as well as thermal demand and deduce requirements to grid-friendly heating and cooling strategies in buildings for each location.

In the current paper, 15 geographies (more accurately: 13 European countries, Great Britain (i.e. UK sans Northern Ireland, which is part of the Irish power grid), as well as the Canadian province of Alberta, which is similar in population to the smaller European countries), are compared in terms of the projected residual load in the year 2030. The residual load is here defined as the electric load minus the generation of intermittent renewable plants (wind and PV). Therefore, it is the electric power that needs to be provided by conventional dispatchable plants in order to balance generation and demand, and can be used as an indication of the relative demand for conventionally-produced electricity.

2. Methodology

The methodological procedure and structure of this paper is illustrated in Fig. 1.

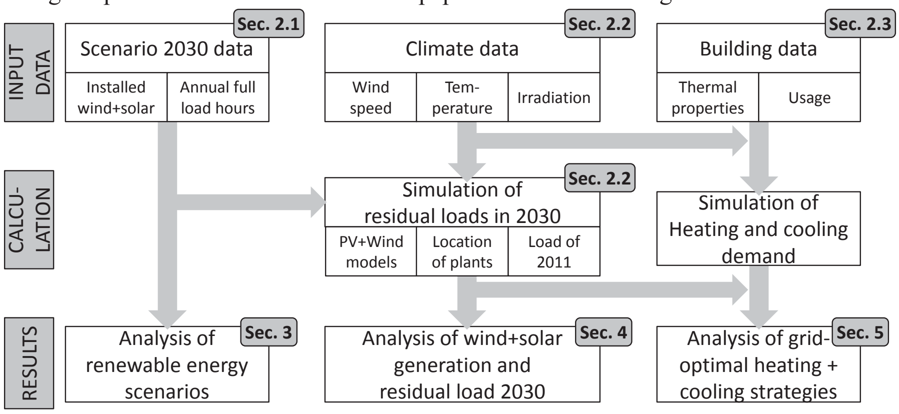


Fig. 1: Process flow, data and models used for this study.

The assumed scenario data are introduced in sec. 2.1, the climate data and models used for the simulation of renewable wind and PV generation in 2030 and calculation of the residual load are discussed in sec. 2.2. Building data and assumptions used for the simulation of thermal demand are given in sec. 2.3. The evaluation is done in three steps: First, the assumed energy systems of 2030 in the individual countries are characterized in terms of the installed capacity of solar and wind plants, as well as the share of renewable energy generation in the energy mix (sec. 3). Following this, the residual loads for the year 2030 are analyzed in terms of their daily and seasonal characteristic (sec. 4). Finally, requirements to grid-supportive heat pump operation (in heating mode and in cooling mode) in the respective countries are deduced (sec. 5)

2.1 Scenario data for wind and PV energy in 2030

The assumed installed capacities of wind and PV plants in 2030 are mostly based on (Agora, 2016). For nearly all of the countries considered as part of the current paper, the assumed values from said study match (closely, if not exactly) with the "Vision 3" assumptions of (ENTSO-E, 2014). Some differing figures were used for the following countries. The complete data are given in Table 1 in the Appendix.

- For Germany installed capacities of 73.5 GW wind power and 66.3 GW PV power in 2030 were chosen according to the latest Grid Development Plan (Bundesnetzagentur, 2016; scen. B2030).
- For Denmark, there was a big mismatch between the assumed solar generation capacity in (Agora 2016) and (ENTSO-E, 2014). After consultation with Danish researchers which are familiar with the latest status in Danish energy policies, a third source was chosen (Energienet.tk, 2016).
- For Greece, assumptions from (ENTSO-E, 2014) were used as the country was not included in (Agora, 2016).
- For Alberta, a wind generation capacity of 5.5 GW was assumed in accordance with (Canadian Wind Energy Association, 2016). The province neither has nor plans to acquire significant amounts of solar generation power.

2.2 Simulation of wind and PV generation

The renewable energy generation is simulated using historic weather data of the numeric weather model COSMO-EU, run by the German Weather Service (DWD). COSMO-EU has a high spatial (average distance 7 km) and temporal (hourly) resolution and predicts the area of Europe. The meteorological values of irradiance, wind speed and temperature are allocated to a NUTS3 level, which covers different national counties. The processed weather data forms the basis of a PV and wind turbine power production estimation by additionally including their technical characteristics. In the case of PV, the simulation differs between azimuth and inclination angles as well as installation and module types. To represent the wide variety of wind turbines in reality, different power curves and hub heights are used and result in 61 individual specifications. Furthermore the roughness length of the ground is used to transform the wind speed to the individual hub height. The simulation procedure has already been employed with the COSMO-DE model on a national scale by (Killinger et al. 2015).

In order to simulate the total renewable energy generation of a country, it is assumed that the total installed capacity is evenly distributed over the NUTS3 regions, meaning that the regions are weighted by their area. The installed capacities of wind and PV plants assumed according to sec. 2.1.

Figure 2, left and right, show the simulated full load hours of wind and PV power in the examined European countries, respectively. Although these values are further aggregated and processed in order to derive the residual load within a country, the figures show clearly the large fluctuation within Europe. The full load hours of PV range between 700 in the North and 1489 in the South. In terms of wind power, this variability between the NUTS3 regions is even increased and differs between 174 and 4080 full load hours per year with the best locations close to the sea in the northern parts of Europe.

As becomes evident from Fig 2, the annual full load hours of wind and PV plants are highly inhomogeneous even within the respective countries. Since it is not known how the future installed capacity of wind and PV plants will be allocated to the individual NUTS3 areas, the following assumptions are made: First, it is assumed that the renewable generation units are distributed homogeneously throughout the country (i.e. proportional to the size of the NUTS 3 area).

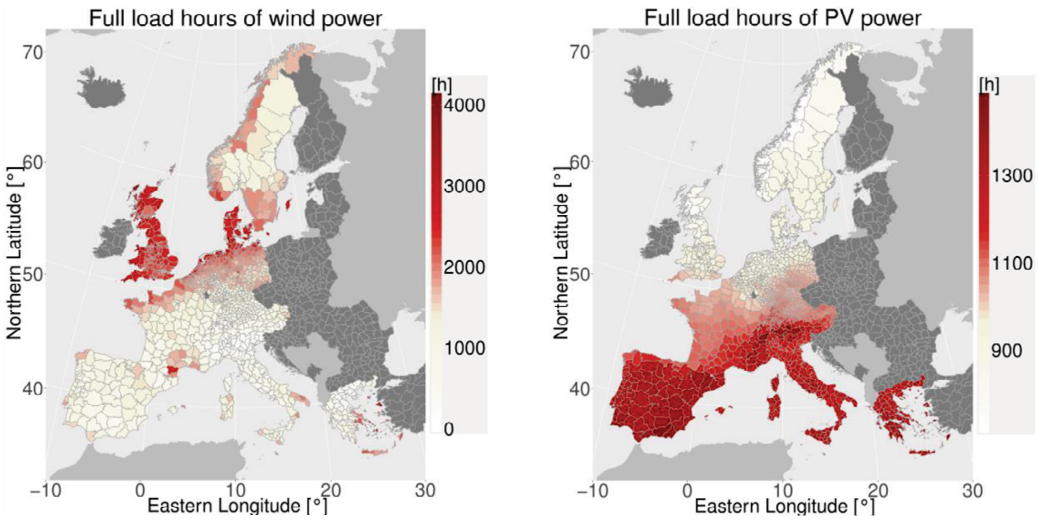


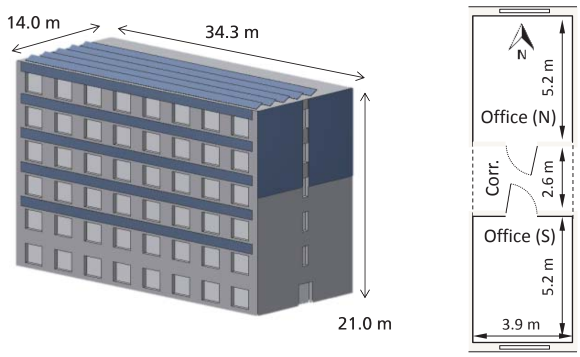
Fig. 2: Full load hours on NUTS3-level of PV (left) and wind power (right) based on the numeric weather model COSMO-EU and a power simulation with different technical specifications.

This procedure will in tendency underestimate the wind and PV yield potential, because in reality, the locations with the best conditions (i.e. most sunshine hours, most steady wind) will be preferred. In order to account for this, the generation curve is in a second step corrected by a factor such that the full load hours of wind and PV plants match those assumed by the national renewable energy plants of 2020 (European Commission, 2008).

For the load, data of the year 2011 from the European Network of Transmission System Operators for Electricity (ENTSO-E, 2016) are used, assuming that the oppositional effects of economic growth and advances in energy efficiency will lead to a similar electricity demand in 2030 as today. The ENTSO-E load data are corrected by a factor such that the official electricity consumption according to Eurostat is matched. For Alberta, which is not contained in ENTSO-E, the load data are obtained from the Alberta Electric System Operator (AESO, 2016).

2.2 Simulation of heating and cooling demand for an office building in each country

In order to analyze how a buildings should be heated or cooled in order to promote the integration intermittent renewable energy, the thermal energy demand must be known. Evidently, the heating and cooling demand differs between the studied countries depending on the ambient temperature and irradiation.



	value	unit
U-value walls	0.24	W/m2·K
U-value baseplate	0.3	W/m2·K
U-value roof	0.2	W/m2·K
U-value window	1.0	W/m2·K
g-value window	0.58	(-)
shading factor	0.4	(-)

a) **b)** **c)**

Fig. 3: Bulding model used for determination of thermal demand in each country. a) outside view of the building, b) geometry of the internal space usage, c) thermal properties of the building

The heating and cooling demand in the considered geographies is quantified using a simple single-zone model of a generic office building with a useful area of approximately 2430 m^2, which was described in

(Klein et al, 2015). It is assumed that the building is composed of two-person offices on the Northern and Southern façade with a connecting corridor in between. The building is modeled as a resistor-capacitor network in compliance with the ISO 13790 modeling standard. The insulation standard is based on the German building code EnEV 2014. The assumptions for usage (occupancy on weekdays from 7 a.m. to 6 p.m., six full-occupancy hours per day), the control of the external shading devices (activated above 200 W/m^2 irradiation onto the façade, deactivated below 150 W/m^2), the heat gains by human occupancy and appliances (100 W/pers. and 7 W/m^2, respectively), as well as the mechanical ventilation (30 m^3/hr·pers. during occupancy, heat recovery factor 0.75) are based on the DIN-V 18599 standard (DIN-V 18599, 2011). The interior temperature of the building is controlled using an ideal heater, such that the interior temperature does not fall below 20°C in heating operation and does not exceed 26°C in cooling operation. If the interior temperature assumes a value between these two limits (e.g. in the intermediate periods, spring and autumn), the building is neither heated nor cooled.

3. Characteristics of energy systems in 2030

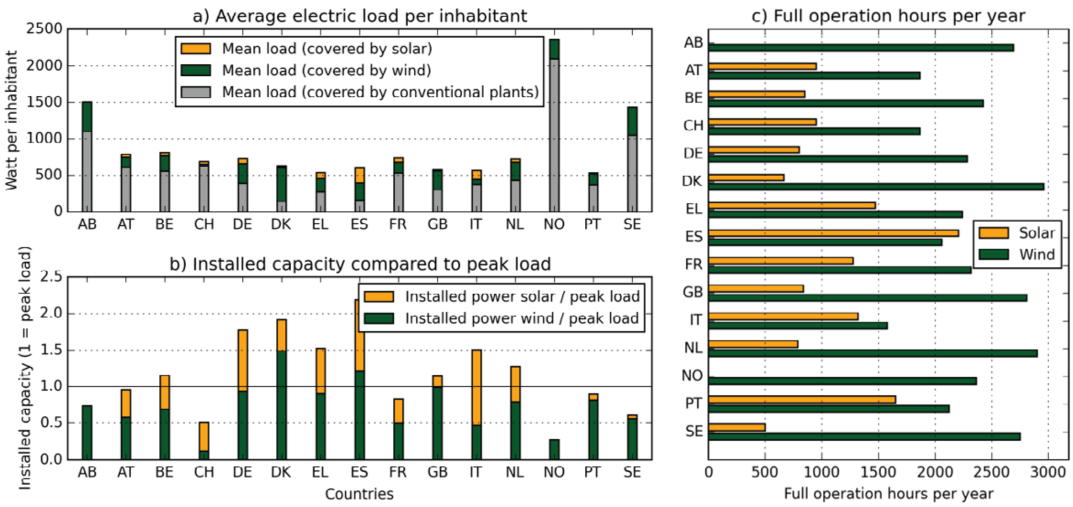


Fig. 4: Characteristics of the energy systems under evaluation. a) Mean electric load and share of solar and wind power in energy mix. b) installed power of solar and wind plants compared to peak load, c) annual full operation hours of solar and wind plants (from (European Commission, 2008)).

Fig. 4 a) shows the average electric power used by each inhabitant, which can be interpreted as an indication of how much a society relies on electricity. A glossary of the country codes is provided in Table 1 in the appendix. It becomes evident that Norway has the highest per capita electricity load, followed by Sweden and Alberta. The reasons for this are on the one hand the electricity-intensive heavy industries (notably the steel and aluminum production in Norway and Sweden, oil and gas industries in Alberta), and on the other hand the high share of electricity-based heating. Most other countries have a significantly lower mean load per inhabitant in the order of 500-700 W/person because they rely more on fossil fuels. Fig 4 a) also illustrates that Denmark and Spain are the countries with the highest share of intermittent renewable electricity, followed by Germany, Great Britain, the Netherlands and Sweden. Norway has a relatively large share of conventional electricity, however, is shall be noted that the renewable, but non-intermittent hydroelectric power accounts for nearly all of the conventional generation.

Fig 4 b) indicates the installed capacity of wind and solar plants in comparison to the peak load (determined here as the 98th percentile of the electric load). Interestingly, 10 out of the 15 countries have installed capacities close to or larger than the peak load. In Denmark, Spain and Germany, the installed wind power alone exceeds the peak load, closely followed by Great Britain and Greece.

In all countries except Spain, wind power provides more full operation hours per year than solar power, which is why it produces more electricity in proportion to the installed capacity than solar power. That said, the number of full load hours of both solar and wind varies greatly between the considered countries. The countries along the North Sea reach close to 3000 full load hours per year, whereas Italy reaches just over half that number. Sweden gets around 500 full load hours for solar plants, while Spain, Portugal and Greece get nearly three times as many. Spain's exceptionally high solar full load hours are partly due to the fact that Spain plans to build concentrated solar power plants with storages which operate during part of the night.

4. Wind and solar generation and residual load in 2030 in 15 countries

4.1 Wind and PV generation in 2030

The aggregated daily profiles of the electric load are given in Fig. 5. The daily aggregation has been performed for the sample months January, April, July and October illustrating seasonal variations: the generation curve for January is most representative of the heating season, while July is most representative of the cooling season. April and October represent the intermediate seasons, spring and autumn.

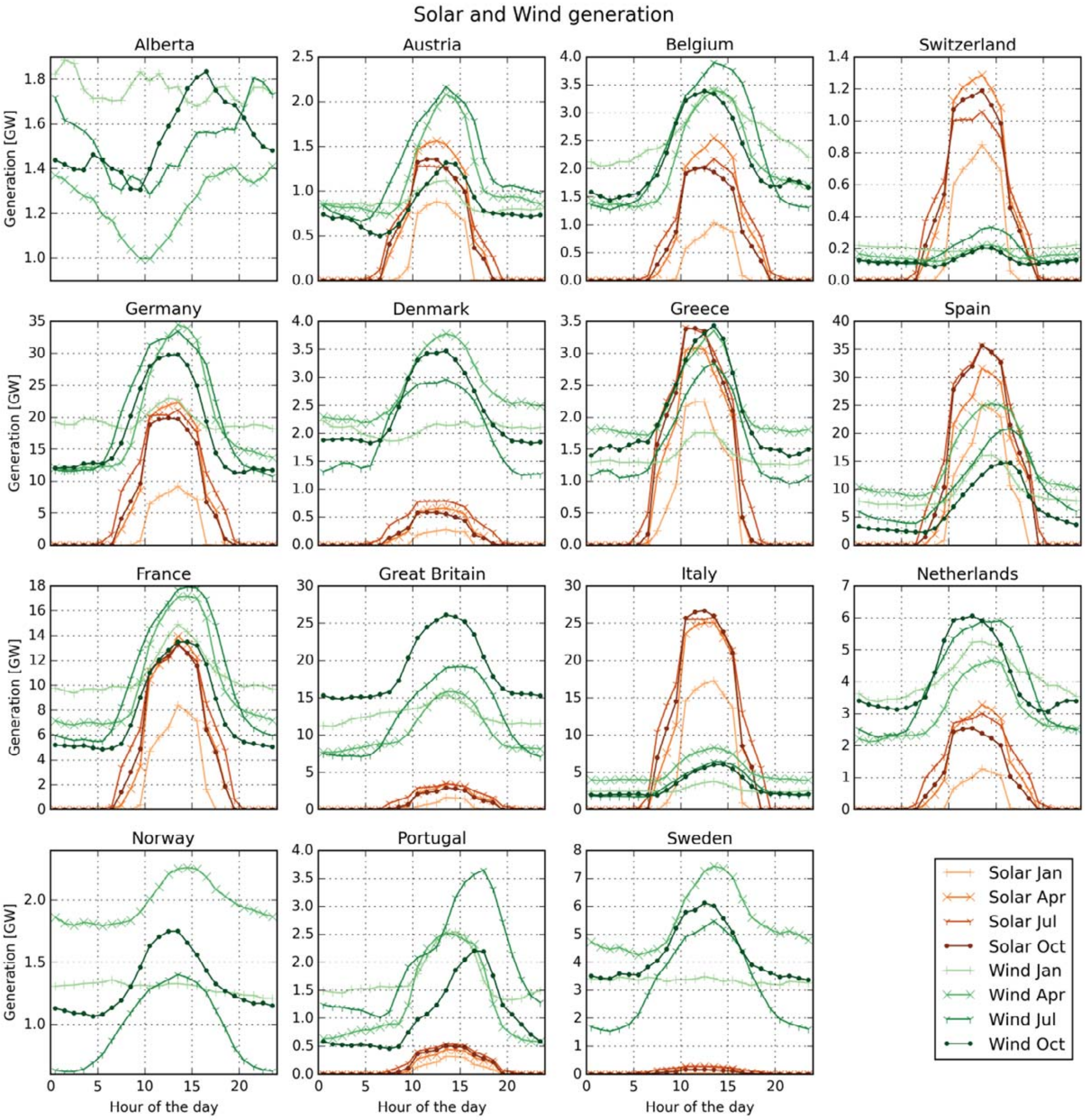


Fig. 5: Aggregated daily profiles of solar and wind generation 2030 for the months January, April, July and October.

As expected, solar generation peaks around noon and is highest in quantity in July, with April and October close behind. The Solar generation in January typically amounts to 50-70% of the generation in July. The time delay between the solar noons of Austria and Portugal due to their different longitudes is visible in the solar generation peaks. Note that Alberta and Norway have no solar plants and thus no generation.

Wind generation also peaks in the day and thus shows a high coincidence with solar generation, although a base generation usually occurs throughout the night. The daily generation peak is more pronounced in the summer than in the winter due to the larger share of solar irradiation in summer. Wind power seems to be partly overestimated during day in the summer. The explanation can be found in the methodology itself for two reasons. The wind speed is provided by COSMO-EU for a height of 10m, which is interpolated to the hub height by only including the roughness length of the ground. Nightly inversions in summer will strongly affect this ground layer and lead to almost no wind, although in reality there is significant wind potential close to hub height. Furthermore the stability of the atmosphere is unknown, but influences the growth of the wind speed with an increasing height. Unstable atmospherical conditions, which are likely to occur in the summer, will lead to an overestimation of the wind speed at hub height and the generated power as well (Focken and Heinemann, 2003).

4.2 Electric load

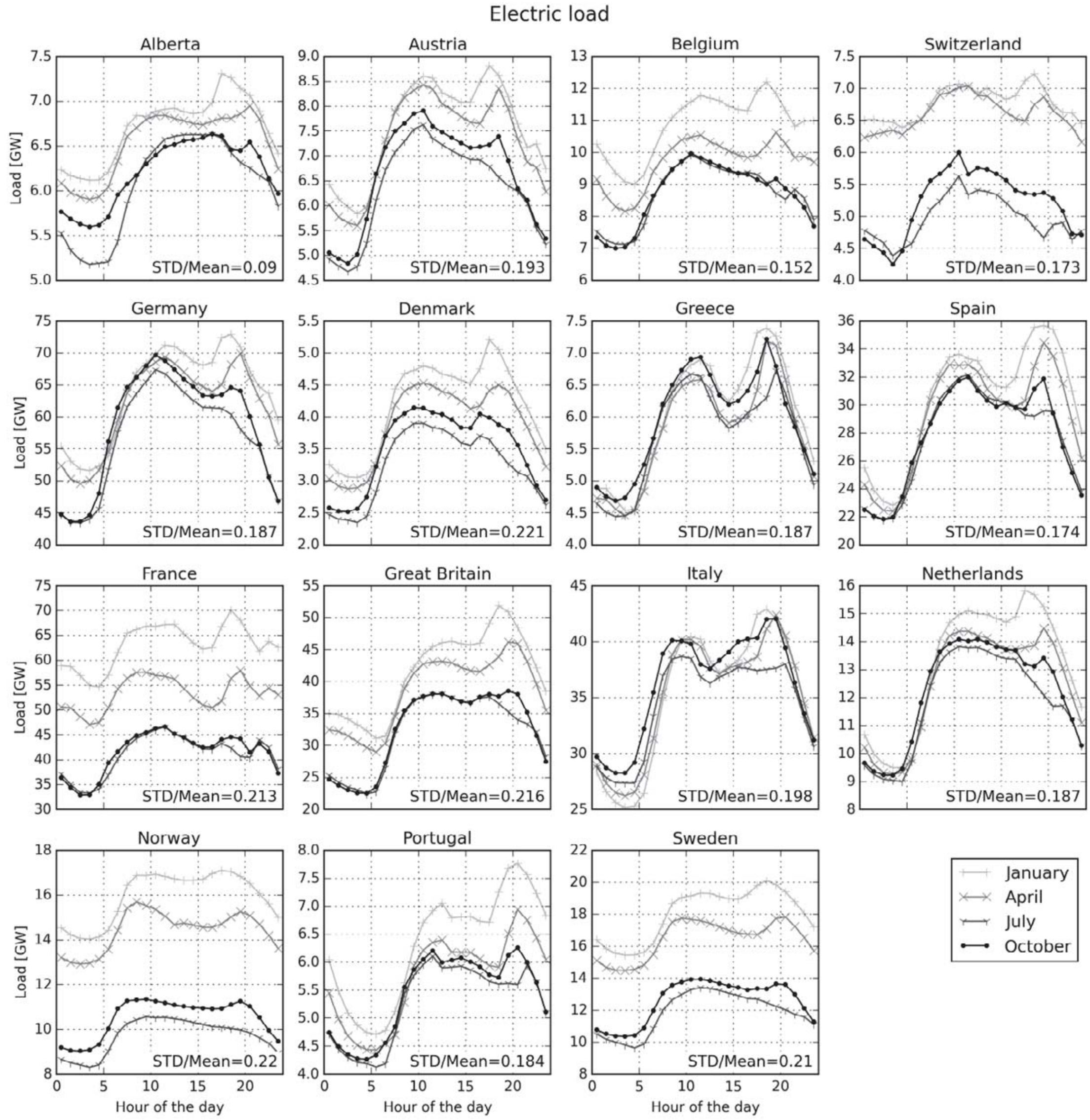


Fig. 6: Aggregated daily profiles of the electric load in 2011 for the months January, April, July and October.

The aggregated daily profiles of the electric load of 2011 are given in Fig. 6 for the same sample months as previously. The load of 2011 is used for the calculation of the residual load of 2030. In all considered countries, the electric load is significantly higher during the day than in the night. Typically, two demand peaks occur in the morning and in the evening. In some countries (Norway, Sweden, Switzerland, France, Belgium) a notable seasonal difference in the electric load is observed, which is mainly attributable to a high share of electricity-based space heating using heat pumps or direct-electric heaters and a larger lighting demand due to longer nights in winter, while other countries (Greece, Italy) have a nearly identical load profile in the evaluated months. The relative fluctuation of the load, quantified here by the standard deviation (STD) of the load in relation to its mean value, assumes relatively similar values between 0.09 (Alberta) and 0.22 (Denmark, Norway). In absence of significant renewable energy capacities in a traditional energy system, the load is equal to the residual load. The relative fluctuation of the load is thus similar to the level of variability that most energy systems (and markets) were designed to deal with.

4.3 Residual load

The daily curve of the projected residual load 2030 for the four sample months is given in Fig. 7.

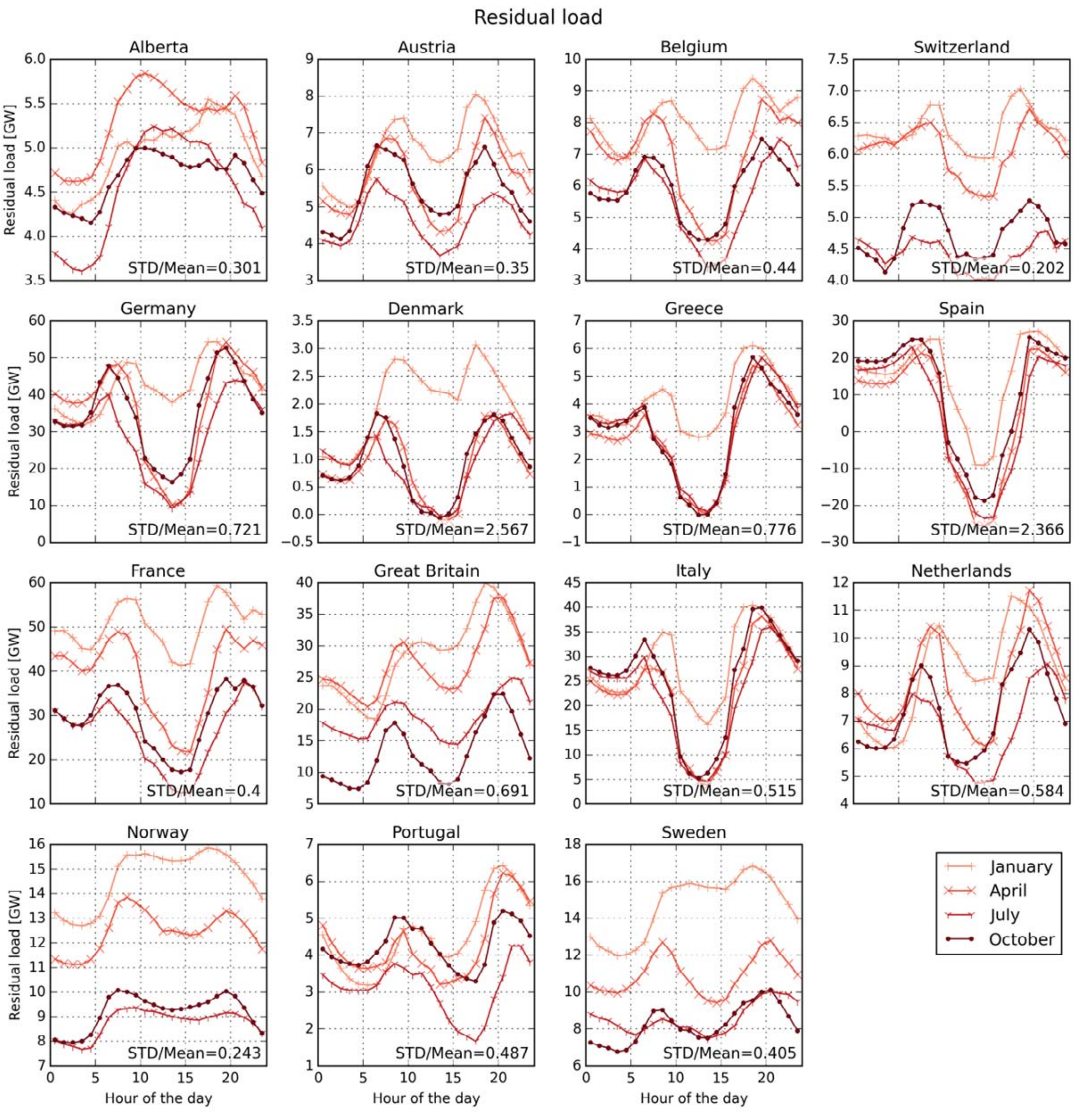


Fig. 7: Aggregated daily profiles of the residual load 2030 for the months January, April, July and October.

In most countries, the residual load shows its lowest values around noon as a consequence of peak solar and (on average) wind generation, as well as lower loads compared to the morning and evening. Even in the aggregated form shown in Fig. 7, residual loads close or below zero occur in Spain, Denmark, Greece and

Italy. This means that during especially sunny and/or windy days, extreme surpluses of renewable electricity (emission-free and at zero marginal cost) are expected. Storing this surplus or making it useful by demand response will be a major challenge and builds a strong case for considering variable grid conditions in heat pump and chiller control strategies.

Moreover, the residual loads in the analyzed countries show significant seasonal differences: they are typically lower and more volatile in summer than in winter. This is largely due to higher solar and wind generation and lower electric loads in summer. This means that daily variations in the availability of electricity, which justify grid-supportive building operation, are most prevalent during the cooling season.

Finally, it is noteworthy that the residual loads of 2030 of most of the analyzed countries have a much higher relative fluctuation (standard deviation/mean value) than the respective loads (Fig. 6). Particularly in the countries with the highest share of intermittent renewable energy, Denmark and Spain, the standard deviation of the residual load is over twice as large as its mean value, indicating rapid and substantial changes in the relative demand for electric energy – and thus the value of electricity. The relative fluctuations in residual load are up to ten times larger than those for the electric load – which underlines the necessity of demand response and other new measures to integrate intermittent renewables.

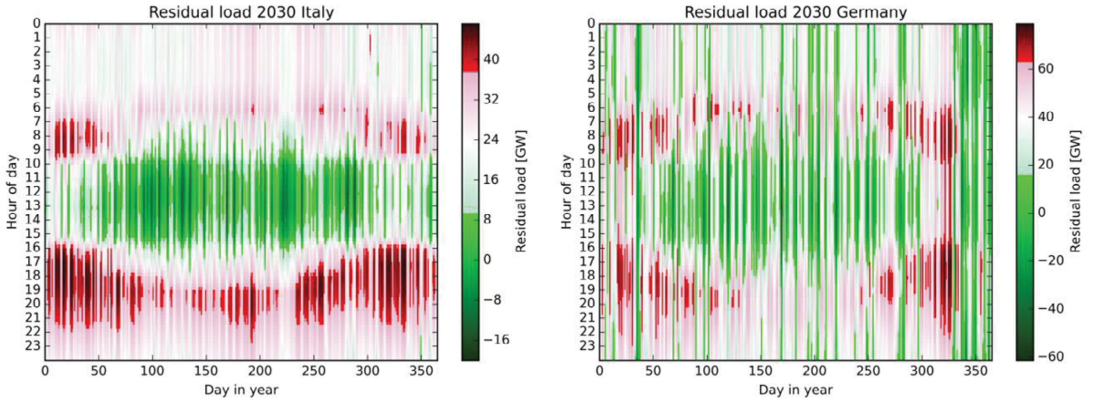


Fig. 9: Carpet plot diagrams of the residual load 2030 in Italy and Germany. For visual reference, highlighted areas residual loads above 80% of the peak load (red) and below 20% of the peak load (green).

Fig. 9 shows the residual loads of Italy and Germany in carpet plot diagrams For visual reference, the periods with very high demand (residual load > 80% of the peak load) and low relative demand (residual load < 20% of the peak load) are highlighted in red and green, respectively. It becomes clear that in Italy, which is characterized by a high amount of solar power, the relative demand for electricity varies very strongly and regularly within one day, between peak demands in the morning and evening and generation surplus around noon. This provides a strong incentive for intraday storage and load shifting. Germany, in contrast, has both a high amount of solar generation, which produces a similar pattern as in Italy, and additionally a significant amount of wind power generation, which causes sequences of entire operating days with surplus electricity. In addition, Germany has a stronger seasonal load variation than Italy, which leads to fewer peak load situations in summer. In such a situation, electricity needs to be stored for longer time periods, which is more challenging for conventionally designed building energy systems.

5. Requirements to grid-supportive heating and cooling

The annual heating and cooling energy consumption as well as the thermal peak loads (based on the 98^{th} percentile) for are given in Fig. 10. Alberta, Norway and Sweden have both the highest heating energy consumption and the highest heating load. Greece has the highest highest cooling energy consumption and cooling load, followed by Italy and Spain. Portugal is the country with the lowest combined annual thermal demand of about 18 $W/m^2{\cdot}a$, as well as the lowest combined heating and cooling load.

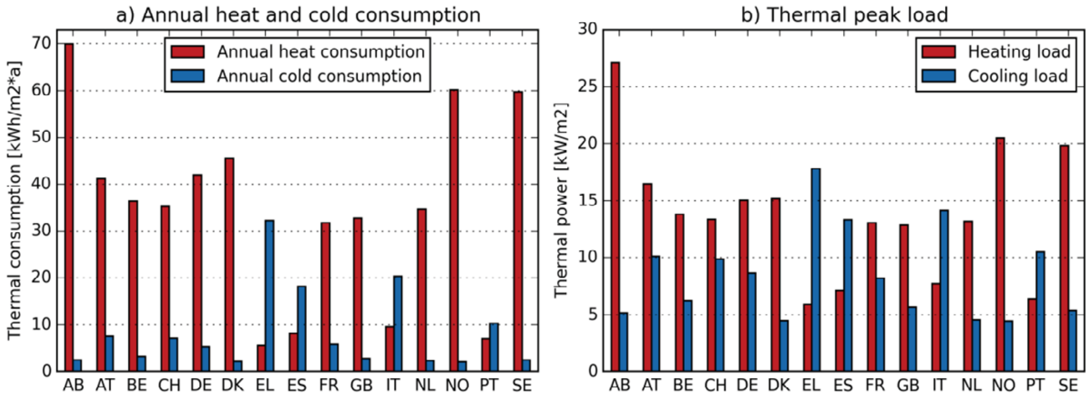


Fig. 10: Annual thermal consumption and peak heating and cooling loads

Figure 11 shows the aggregated thermal loads and the grid-optimized thermal generation trajectories for January (heating, red) and July (cooling, blue), i.e. the operation periods during the hours of the day with the lowest residual load. For calculation of the latter, 25% overdimensioned heating and cooling systems (according to Fig. 10 b)) and sufficient thermal storage capacity for intraday load shifting were assumed.

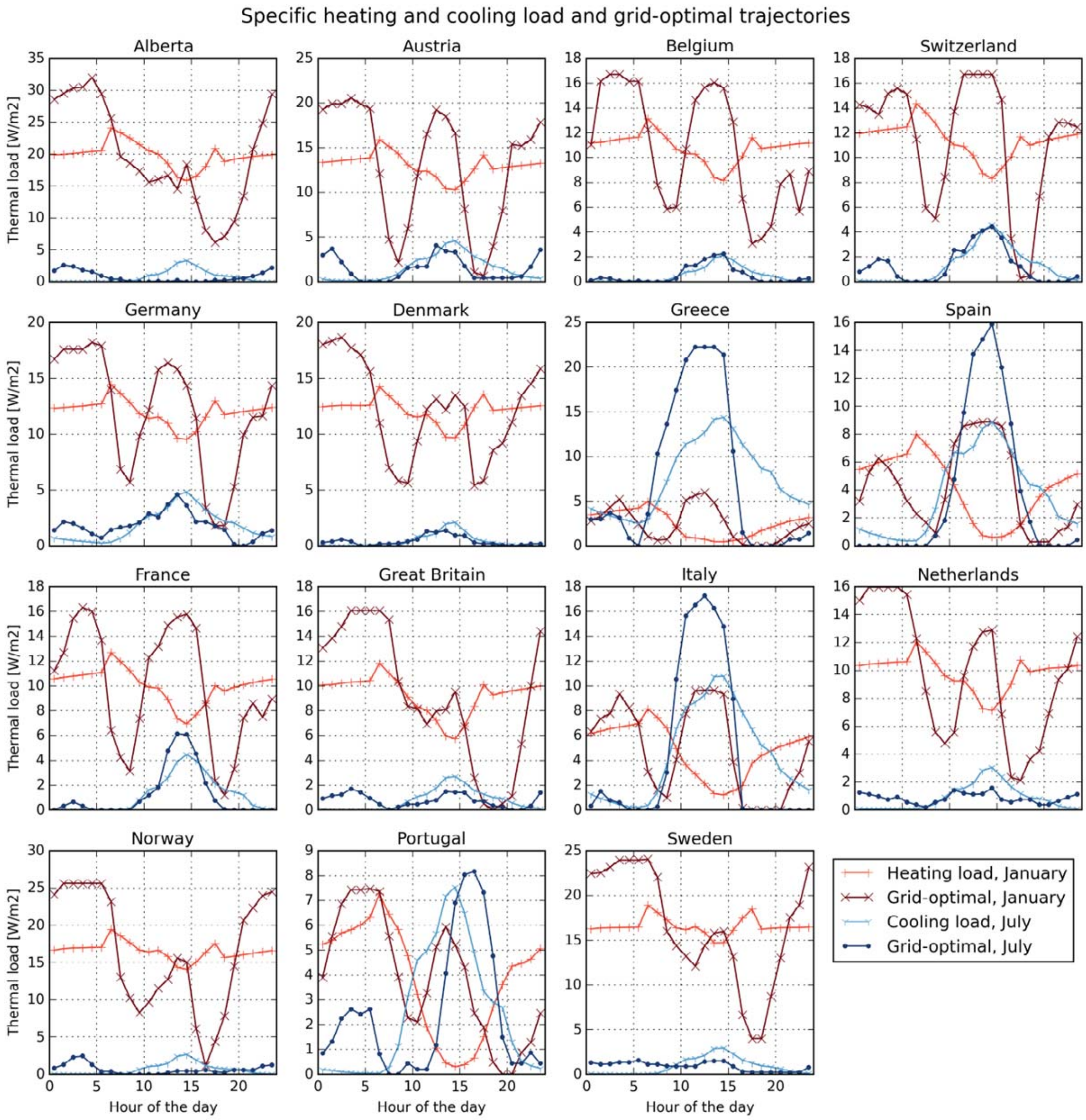


Fig. 11: Specific thermal loads and grid-optimal heating and cooling trajectories for January and July

As expected, the cooling loads assume their highest values around noon due to the high ambient temperatures and irradiation intensity. In nearly all countries, this coincides well with the generation and wind and PV and thus the residual load, which is why the grid-optimized cooling trajectory is similar to the load profile. Notable exceptions are Norway and Alberta, which lack solar generation and whose grid-optimal operation is scheduled at night when the load and residual load are lowest.

The heating load profile of the considered reference building is nearly constant throughout the day in the colder countries (e.g. Alberta, Norway, Denmark, Germany) and is more variable in warmer countries (Portugal, Spain), with the highest heating load occurirng in the morning (due to an increase in ventilation rate at the beginning of occupancy in the morning, when ambient temperatures are low) and the lowest heating loads occurring in the afternoon. The grid-optimal heating trajectory depends on the renewable energies mix: in wind-dominated regions such as Alberta, Norway and Sweden, it peaks in the night hours, whereas in PV-dominated countries such as Spain, it peaks around noon. Most countries, however, have a combination of wind and PV power, leading to two peaks in the grid-optimal heating profile at night and in the middle of the day. Their relative size depends on the mix of wind and PV in the energy system and the weather conditions of the individual day, which affects the thermal demand as well as wind and PV generation. This makes it difficult to derive general rules for grid-optimal scheduling of heat pump operation only based on the hour of the day. Note that for CHP units, which unlike heat pumps are electric generators rather than loads, the conclusions for grid-optimal scheduling of heating must be reversed: the most favorable times of the day for heating with CHP units are usually in the morning and evening.

6. Conclusions

This paper analyzes the dynamics of future renewable electricity generation and electricity demand profiles in a range of 15 geographies. The future scenarios (2030) are forecasted based on the current dynamics of the systems in combination with claims or commitments on PV and wind power installed capacities stated in the corresponding energy plans. At the core of this analysis, the "residual load" is defined as the electricity demand that must be met by conventional dispatchable electricity generation systems. This study explores short term and long term variability in the residual load, as a first step towards assessing the role that demand response systems (such as controls of heat pumps in buildings) might have in mitigating such variability and maximizing use of renewable generation.

Results show that, if the energy plans materialize, residual loads will be highly variable in 2030. The magnitude and variability of residual load varies across countries. However, some general trends can still be identified:

- Residual loads are lower and more variable in summer than in winter. In summer, electricity demand is generally lower (which helps lower residual load), and renewable generation is larger (which also contributes to reducing residual load, but adds variability)
- In summer, the lowest residual loads are seen around noon. This is good news, as the use of electricity in space conditioning devices (chillers, heat pumps) during the hottest periods of the day coincide in time with the lowest residual loads (i.e., when electricity use is the least disturbing for the electricity system)
- In winter, the lowest residual loads are either around noon or at night, none of which coincides well with the typical peak heating demand of a building. If heat pumps were to be used as a demand response system to accommodate variability in the grid, they would likely have to be accompanied by a thermal storage system.

It is interesting to note that one of the factors that make a difference in the dynamics of the residual load is the relative capacities of solar and wind power. In the European geographies, wind power peaks during daytime. However, unlike solar, generation does not necessarily drop to zero at night. Large solar generation capacities lead to strong daily variations in residual load, which can be more easily managed with short term storage systems. In contrast, variability of wind power is often in a longer time scale (days or even weeks). Managing variability in a longer time scale would require storage systems of higher capacity. The relative share of solar vs. wind power can, to some extent, be determined by the local jurisdictions. Electricity management and the opportunities for demand response could (and arguably, should) be among the criteria in defining renewable energy policies.

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Appendix

Table 1: Country codes and installed wind and PV generation capacities in 2030 assumed in this study

	Alber-ta	Aus-tria	Bel-gium	Switz-erland	Ger-many	Den-mark	Gree-ce	Spain	Frane	Great Britain	Italy	Nether-lands	Nor-way	Portu-gal	Swe-den
Abbreviation	AB	AT	BE	CH	DE	DK	EL	ES	FR	GB	IT	NL	NO	PT	SE
Wind capacity [GW]	5.5	5.5	8.54	0.9	73.5	7.79	7.8	46.1	36.6	51.0	22.1	13.0	5.0	6.34	12.1
PV capacity [GW]	0	3.5	5.74	3.0	66.3	2.24	5.3	37.0	24.1	8.27	48.9	8.0	0	0.72	1.0