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Seasonal impacts of climate change on electricity production

JRC PESETA IV project – Task 4

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Foreword

This report is part of the PESETA IV project analysing the impacts of climate change. It focuses on energy and more specifically on power production. Extreme meteorological events are considered in other PESETA IV tasks, such as floods, droughts or wind storms. This report rather focuses on the impacts of monthly or seasonal climate tendencies on electricity production.

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Executive summary

PESETA IV assesses the impacts of climate change on electricity production by hydro, wind, solar, nuclear and other thermal power plants, including biomass, coal, gas and oil. We assess these impacts in the present power system and in 2050 for a dynamic scenario in line with 2°C mitigation efforts. Both scenarios show that, at EU-level, the production of hydropower plants increases with global warming thanks to higher water availability (although this does not imply substantial development of new hydro plants), while nuclear power decreases. However, there are regional differences in the impacts, such as increased hydro production in the North, and a decline in hydro- and nuclear power production in southern Europe due to lower water availability for direct production or for cooling river-based plants. In northern Europe, the increasing availability of cheaper hydro results in substitution effects and lower production costs, while in southern Europe production costs could increase. Based on the modelling methodology used and the latest available climate simulations, the direct impacts of climate change on wind and solar production are not significant at EU-level. However, in the 2050 power system their capacity would increase in southern regions to compensate for the lost hydro and nuclear production. Climate change impacts on energy in the rest of the world show a negligible spill-over effect on Europe. Improved cooling technologies have the potential to reduce strongly the negative effects of water scarcity, particularly for nuclear plants in southern Europe.

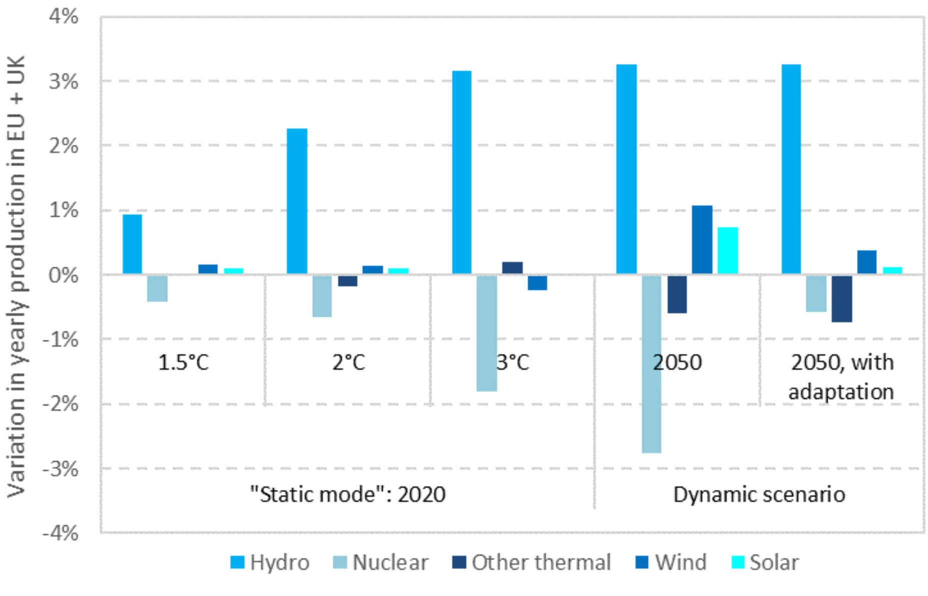
Energy production, transport and demand are impacted by climate change in several forms: temperatures, winds, precipitations, water discharge and extreme events (European Environment Agency, 2019). While PESETA III focused on climate change impacts on energy demand, in this PESETA IV report we estimate the effects of climate change on electricity production, at the seasonal time-scale and national or regional geographical aggregation. Of course, extreme events like floods, droughts or windstorms can lead to temporal disruption of electricity production, transmission or demand, but they are out of the scope of this report.

Impacts on electricity production

Global warming results in an overall increase in hydropower production from the EU + UK plants, especially in northern regions that rely heavily on hydropower plants. On the contrary, nuclear power reduces significantly, while other energy sources are only moderately impacted (see Figure 1).

Figure 1: Climate change impact on power production in Europe

Median values of climate ensembles. Impacts of 1.5, 2 and 3°C global warming imposed on today's power system (static mode), and impacts in the 2050 power system in line with a 2°C mitigation scenario (dynamic scenario, including socioeconomic and energy sector evolution), with and without adaptation of water cooling. Note: "other thermal" designates biomass, coal, gas and oil plants.



When assuming a static 2020 power system, hydropower production in the EU is expected to increase by 0.9% with 1.5°C global warming (median value) and by 2.3% and 3.2% with 2 and 3°C warming respectively. Nuclear production would decrease by 0.5% with 1.5°C warming and by 1.8% in a 3°C warming static scenario. Other thermal, wind and solar plants are barely impacted in the 2020 static study and at EU + UK level.

In a separate analysis with dynamic scenarios, climate mitigation is assumed in line with a 2°C scenario (see the Approach section below). Therefore, the 2050 power system is modified and progressively impacted by climate change. When comparing results in 2050 with and without climate impacts, hydropower production increases by 3.3%, pushing out nuclear (-2.8%) and other thermal production (-0.6%). Wind and solar develop more (+1.1% for wind and +0.7% for solar at EU + UK level), mainly in response to the lack of hydro and nuclear production in southern Europe. The evolution of the mix is in itself an adaptation of the system to climate change.

The overall increase in hydropower is dominated by northern European countries that rely heavily on hydropower and benefit from an increasing water availability. Since hydro has a lower marginal cost, it undercuts the demand in these regions for power from other energy sources. Depending on the local electricity production mix, the substitution effect is different. In the static scenarios, hydro mainly replaces biomass in Sweden, coal in Finland, oil in Lithuania and gas in Latvia. This leads to annual economic benefits in northern Europe of around 1.3 €billion (2015 values) with 3°C warming.

In southern regions of Europe, and particularly the Iberian Peninsula, the projected reduction in water availability negatively affects hydro and nuclear production, especially in summer. Thermal plants act as a substitute to hydro and nuclear in the Iberian Peninsula: in order to meet demand in periods of reduced hydro and nuclear power, the thermal power capacities in reserve (e.g. combined cycle gas with CCS) have to increase production. This is more expensive than hydro and nuclear power generation, which means that production costs in southern Europe increase by around 0.9 €billion per year (2015 values) with 3°C warming assuming a static 2020 power system. In the dynamic scenarios, this effect is less pronounced because the increased development of wind and solar contributes to filling the gap left by hydro and nuclear.

Based on the 11 climate runs, the uncertainty on water availability is important in Central Europe South, resulting in important variations in electricity production of all sources. Southern and northern Europe also have significant uncertainties but with consistent directions of change. Central Europe North, UK and Ireland show overall limited climate change impacts.

Adaptation

In the dynamic scenarios, the mix evolves in response to climate change impacts (e.g. increased wind and solar installations). Allowing adaptation of nuclear and other thermal plants leads to a different evolution of the mix. Nuclear production is particularly reactive and climate change impacts can be almost completely avoided with a switch to less water-intensive cooling technologies (reduction of -0.6% instead of -2.8%, see Figure 1). This mostly takes place in Central South Europe and Southern Europe, allowing a drastic reduction of water-constrained periods. Other thermal plants do not show a similar benefit from these adaptation measures, either because they do not operate at full capacity (reserve capacities can compensate for local constraints) or because they are already using efficient cooling technologies.

Spill-over effects

The spill-over effects from the rest of the world on EU + UK are also quantified (in “static mode”) and appear negligible (less than 0.1%). The main impact at global level is a decrease in fuel consumption and fuel prices because of lower heating demand in buildings. Lower fuel prices could potentially create a slight increase of demand in Europe, supplied by reserve capacities of thermal plants as well as some additional decentralised solar capacities.

Implications

Results of this study suggest that energy policies should consider climate change impacts in their electric capacity planning. With global warming, hydropower plants will become even more valuable assets in central and northern Europe thanks to increased water availability in these regions. On the other hand, in the south of Europe (especially the Iberian Peninsula and Greece), reduced water availability will reduce the available capacity of hydropower as well as nuclear and thermal plants. Adaptation, through the upgrade to less water-intensive cooling technologies, could avoid most of the loss in capacity, especially for nuclear plants currently based on once-through river cooling. In northern Europe, nuclear and thermal production could be undermined by an increase in lower-cost hydropower production. Finally, wind and solar do not appear to be constrained directly by climate impacts and could benefit from the negative effects on other technologies, especially during summer periods in southern regions. Expanding inter-regional electricity interconnections is a way to balance the evolving production patterns across Europe and their associated costs. For example, with 2°C global warming applied to the current power system, electricity production costs could decrease by 2.5% in northern Europe and increase by 0.6% in southern Europe as a consequence of the changes in water resources and hydropower production, if no additional trade occurs.

Limitations

Impacts on individual technologies are not assessed separately but as a system. Smaller impacts on some technologies (for example, wind and solar) can then be dominated by other impacts (demand and prices evolution, variations of other technology).

The energy supply assessment does not incorporate the effects of climate extremes due to the temporal (seasonal) and spatial (country) resolution of the energy analysis. The drought analysis in PESETA IV shows that increasing drought conditions with global warming in southern and western regions of Europe will result in growing economic losses in the energy sector. Further, increased river and coastal flooding could result in higher direct damages to energy infrastructures in flood-prone areas.

This study assumes that hydropower plants are not saturated most of the year and that they can benefit linearly from increasing water resources. Similarly, the average wind speeds used here impact linearly wind power production. Although a single turbine has a typical (non-linear) power curve, the relation is more difficult to characterize once the plants of a country are aggregated. The temperature effect on solar PV panels does not reflect the (non-linear) heat accumulation effect, which could result in higher efficiency losses than when considering the ambient temperature. Finally, the water temperature estimation is based on a linear relation with air temperature and lacks a more detailed spatial and temporal modelling.

Approach

PESETA IV estimates the effects of climate change on electricity production by hydro, wind, solar, nuclear and other thermal power plants (biomass, coal, gas and oil). Extreme events such as floods, droughts or windstorms can lead to a temporal disruption of electricity production, transmission or demand. Impacts of drought on energy production have been quantified in the drought analysis of PESETA IV. However, the required temporal and geographical detail is not compatible with the long-term system-wide analysis performed here with the energy model POLES (Prospective Outlook on Long-term Energy Systems). Climate change projections (RCP4.5 and RCP8.5 pathways) and hydrological simulations are identical to those used in the PESETA IV tasks on water resources, droughts and river floods. The impacts assessed relate to changes in water resources availability for hydropower and cooling nuclear and other thermal plants, changes in wind resources for wind energy and changes in temperature for the efficiency of solar panels[1]. Results are obtained by comparing scenarios with and without the climate impacts on electricity production, so that other factors are neutralized (e.g. climate impacts on energy demand are modelled but not shown here).

A number of different scenarios have been considered. A first analysis looks at the impacts of 1.5, 2 and 3°C global warming on the 2020 power system (energy model used in "static mode"), in order to neutralize other effects such as climate policy or natural power mix evolution. In this "static mode" we further quantified spill-over effects on the EU caused by climate change impacts on energy production in the rest of the world. The energy model was also run in dynamic scenarios until 2050 corresponding to 2°C compatible mitigation efforts and emission pathway (RCP4.5, with stabilized radiative forcing at 4.5 Watts per square metre in 2100, without ever exceeding that value) and a changing technical and socioeconomic context according to the ECFIN 2015 Ageing Report. In this dynamic setting we then quantified the potential of open recirculating cooling (evaporating towers) and dry cooling to reduce the negative effects of climate change on thermal plants cooling.

[1] Other climate change impacts cannot be studied by lack of data or unclear dynamics. For example, cloud cover influences solar production but the climate science of clouds is still too uncertain.

1 Introduction

The energy sector faces climate change impacts in the production, transformation, transport and consumption of energy. Studying these impacts is crucial for evaluating and designing adequate mitigation and adaptation policies in order to minimize the negative consequences of climate change. Ciscar and Dowling (2014) looked at how impact assessment models represent these impacts. The PESETA IV project builds on the literature by bringing together different sectoral analyses of the impacts of climate change in Europe.

On the energy supply aspects, a change in water availability can change hydro production patterns or cause decreased thermal production efficiency (van Vliet, 2016). Other indirect impacts, such as agricultural yields can influence bioenergy prices and development throughout the world. The report of the European Environment Agency on the topic (EEA, 2019) included coverage of biofuel supply as well as the impacts of some extreme weather and climate-related events on infrastructure: coastal and inland flooding, ice, snow and maritime storms, hail and lightning, wildfire events, thawing permafrost. Indeed, extreme events represent a disruption risk for critical infrastructures such as energy (Forzieri et al., 2018). They can experience strong impacts linked to gradual shifts in climatic conditions: oil and gas refineries (potentially facing extreme heat or water scarcity), pipelines (with risks of damage in areas of thawing permafrost such as Russia or Alaska) or maritime routes (e.g. the Northern Sea route could open in the Arctic Sea) are examples. Electricity networks can also lose part of their rating capacity due to increased temperatures. Heavy precipitations are projected to increase (including in regions with lower precipitations on average, like southern Europe) and entail flooding risks (COACCH 2019). The PESETA IV report on river and coastal floods in a warming world identify a massive increase of damages that also concern energy infrastructures. According to the PESETA IV report on droughts, the energy sector bears 23% of drought damages inflicted under present climate conditions (1981-2010). The PESETA IV report on wind and windstorms does not indicate a consistent increase in risks linked with global warming. The latest climate models used in PESETA IV do not show a link between global warming and extreme winds across Europe (some regions see more windstorms while others would face less of them). Accordingly, the current risk on the energy sector would not increase (besides the evolution of the energy sector exposure). Energy demand will evolve in response to a warming climate, with less heating and more cooling energy demand. This will result in less demand for heating fuels such as oil and gas and more demand for electricity, as shown in the PESETA III energy report (Kitous and Després, 2018).

Climate change impacts will affect the existing system, especially if no adaptation measures are adopted. New infrastructure could be designed more resilient and located at more favourable places than current assets. However, given the longevity of energy infrastructures, a reinforcement against climate extremes could be necessary. For example, water retention areas could reduce flood peaks and dykes could protect particular assets. Increasing windstorm forecast accuracy and wind-proofing the relevant infrastructures (mainly electricity grid) could enhance the asset protection and resilience. More generally, the risk management of extreme events require emergency communication and action plans in disaster situations. For power plants, the adoption of less water-intensive cooling technologies, such as open-recirculating cooling or dry cooling, can reduce risks of forced outage. Seawater cooling can also be an option for adequately situated plants.

While the focus of the PESETA III energy report was on residential demand for heating and cooling energy, this report considers instead the impacts on electricity production and the corresponding adaptation options. Like in the PESETA III project, the study is based on multiple climate models from the EURO-CORDEX dataset (11 instead of 5 in PESETA III, see annex 1). In this study, the climate-forcing scenario RCP (Representative Concentration Pathway) 4.5 is added to the previously studied RCP 8.5 (stabilized radiative forcing at maximum values of 4.5 or 8.5 Watts per square metre in 2100). This addition allows studying a more diverse range of climate change possibilities and further illustrating the uncertainty and diversity in modelling results.

The modelling tool used, POLES (Prospective Outlook on Long-term Energy Systems, see Annex 2), allows evaluating impacts on yearly energy demand, and has been substantially modified to include impacts on electricity production. Already in the PESETA II project, Dowling (2013) studied the impact of several climate change scenarios from different Global Climate Models (GCM) at the European scale. The focus of this study was on residential and service energy needs for heating and cooling, as well as the thermal power plants efficiency loss linked to increased temperatures and the changes in renewable production (hydro, wind and solar). Mima and Criqui (2015) looked at the European impacts of climate change within the ClimateCost project, country by country. It included an evaluation not only of the increase of cooling needs and decrease of heating needs, but also of the variations in water resource availability for hydropower and the decreased thermal production availability and efficiency due to increased temperatures. The energy-water nexus is examined in the USA and Europe (van Vliet et al., 2012). Some integrated management of water reservoirs and energy system were carried out for Greece with the LISFLOOD and DISPA-SET models to evaluate the power and water inter-linkages in dry, average or wet years (Fernández-Blanco et al., 2017). The "Water – Energy nexus in Europe" report (Magagna et al., 2019) used the same hydrological data as our study with different indicators, focusing on the future water needs of several energy sectors including the power sector. It also showed the water availability at hydro and thermal plants with the evolution of low river flow and an index of water stress at the power plant level across Europe.

The new POLES developments in the context of PESETA IV allow studying the impacts of climate change on power plant availability and production, for hydro, thermal (including nuclear), wind and solar photovoltaic (PV) plants. Adaptation of thermal plants is also considered. The climate data used as input to POLES, identical to other PESETA IV sectoral studies, are air temperatures (Dosio, 2018), wind speeds and water runoff in rivers, which are produced in the PESETA IV water task with the hydrological model LISFLOOD (Bisselink et al., 2018). This new energy-water linkage relies on current power plant locations for calibration, instead of considering national averages as in the previous PESETA studies. This study takes into account non-linear environmental constraints on river temperatures and runoff, instead of a linear approximation (Mima and Criqui, 2015). Besides, the POLES model ensures a system-wide analysis of the energy sector: the balance between supply, prices and demand is ensured in the whole energy sector. All electricity-producing technologies are inter-linked. The electricity mix can evolve in POLES dynamic scenarios, which can be seen as a way of adapting to evolving conditions such as climate change. Global effects on Europe are tested in a “spill-over” analysis using the global climate change ISIMIP Fast-track database.

All results are presented for Europe as well as its five reporting regions; thus lessens the weight of small-scale effects.

2 Methodology

While PESETA III studied the climate change impacts on energy demand only, PESETA IV looks at (some of) the impacts on power supply (van Vliet et al., 2016, Tobin et al., 2018) – cf. annex 3.

The climate impacts considered are chosen based on their relevance and compatibility with a system-wide, dynamic analysis. Solar panels are affected by the outside temperatures (affine function) because a warmer weather reduces their efficiency (Dowling, 2013). Wind and hydro power production are linearly dependent on respectively wind speeds and river water discharge at hydro plants[2], averaged at the seasonal scale. Nuclear and other thermal plants (coal, gas, oil and biomass) can be constrained by reduced water availability for cooling when they use river cooling (non-linear relation with an approximated threshold effect). River runoffs and water temperatures (see Mima and Criqui, 2015) are compared with cooling needs, which depend on the technology and energy source. In hot and/or dry conditions, the thermal plants may have to reduce output or shut down completely, as recent examples show (Reuters, 2019). Other climate drivers may be relevant (e.g. cloud cover for solar power) but are too uncertainty or unavailable, so they cannot be quantified here.

The 11 climate models of the EURO-CORDEX database (described in Annex 1) are used, combined with two sets of climate projections (RCP 4.5 and 8.5). They provide temperature[3], wind speeds and water availability in gridded maps. The LISFLOOD model (Van Der Knijff et al., 2010) computes the river runoffs in the PESETA IV water task, with evolving land use and water demand throughout the century (Bisselink et al., 2018). For the analysis of global spill-over effects we use the ISIMIP Fast-track data, with five climate models, combined with RCP 4.5 and 8.5 and with five hydrological models (see annex 1 and 3).

The energy impacts are derived with the energy system model POLES, which has the advantage of covering the world and offers the possibility to look at dynamic scenarios throughout the century. The spatial disaggregation is at country level and the temporal detail allows a seasonal approach. This limits the scope of results compared to more specialised but shorter-term, local models. POLES cannot study well weekly or sub-national (extreme) weather events but rather focuses on climate tendencies with monthly or seasonal patterns and on national and international energy balances between supply and demand. However, the impacts of drought are quantified in the dedicated PESETA IV report based on the relative economical weight of the energy sector. The floods and wind reports also quantify impacts, for example showing that wind extremes are not expected to increase consistently, which is relevant for the safety of future wind turbines.

The available data has to be adapted by aggregating spatially and temporally. Spatial matrixes of weighting coefficients (rasters) represent population (for the aggregation of temperatures), current and potential future wind plants (for wind speeds) and current hydro and thermal plants (for river runoffs at hydro, nuclear, coal, oil, gas and biomass plants respectively). The weighting factor uncertainty is assumed to be negligible. The temporal description of the POLES model distinguishes summer, winter or swing seasons within six representative days per annual time-step. The seasonal variations of the climate data impacts the infra-annual availability of power plants. Extreme and short events (sub-monthly dynamics) like droughts, floods or windstorms can imply short-term disruptions of energy production but are not considered under this analysis.

First we present static scenarios of the 1.5, 2 and 3 degree warming levels, everything else maintained equal (2020's power system and socio-economic conditions, no climate change mitigation nor adaptation, constant water use). We apply this to Europe only and to the whole world in order to see the magnitude of spill-over effects. Then we present a 2-degree scenario (mitigation effort consistent with 2 degree warming at global level, RCP 4.5 climate scenario in Europe) in a dynamic context, where electricity demand and supply evolve along the century[4]. An adaptation option is then added, consisting of a technology switch of thermal plant cooling system, going from once-through systems to recirculating towers or dry cooling.

In order to neutralize other effects (e.g. energy demand, mitigation or adaptation efforts, evolution of the production mix), the impacts shown are from a scenario comparison with and without climate change impacts on electricity production.

[2] This assumes a simplification of the wind power curve at national scale and that water spillage in flooding periods comes in the same proportion as today.

[3] Temperatures are bias-adjusted (Dosio and Paruolo, 2011, Dosio et al., 2012, Dosio, 2016, Dosio, 2018, Dosio and Fischer 2018).

[4] The geographical distribution of plants within each country is assumed constant across the century by lack of better assumptions. Note that this reduces the adaptation potential.

3 Findings

First we present scenarios of climate change impacts on today's electricity production, with potential rest-of-the-world spill-over effects. Then we present scenarios of climate change impacts in a dynamic scenario, for the year 2050. Finally, the adaptation of the cooling technology is allowed in the simulation.

3.1 Impacts of climate change on today's electricity production

The climate change impacts on (2020) electricity production are diverse across the continent. We analyse the main results below, from North to South, as shown in Figure 2 (for Europe as a whole and by region).

In **Northern Europe** (Denmark, Estonia, Finland, Latvia, Lithuania, Sweden) we note a strong increase in water availability (especially in winter and swing seasons) that is correlated with hydro power production. Since most nuclear plants are located on sea-shores (Sweden, Finland) with abundant supplies of water, we do not observe any simulated impact on the nuclear production in POLES, despite the presence of hotter days that could still lead to some cooling limitations. On the other hand, thermal plants are indirectly affected because the lower marginal costs of hydro power undercut the demand for electricity from thermal electricity sources. The local electricity mix determines what energy source production is replaced by hydropower: biomass in Sweden, coal in Finland, oil in Lithuania, gas in Latvia. Coal plants in Estonia are affected by the higher water temperatures but being the main electricity source, they use their spare capacity to compensate.

UK and Ireland face no major impact. The general higher water availability does not impact the power system substantially since the installed hydropower capacity is small. Besides, the temperature and wind speeds effects are negligible.

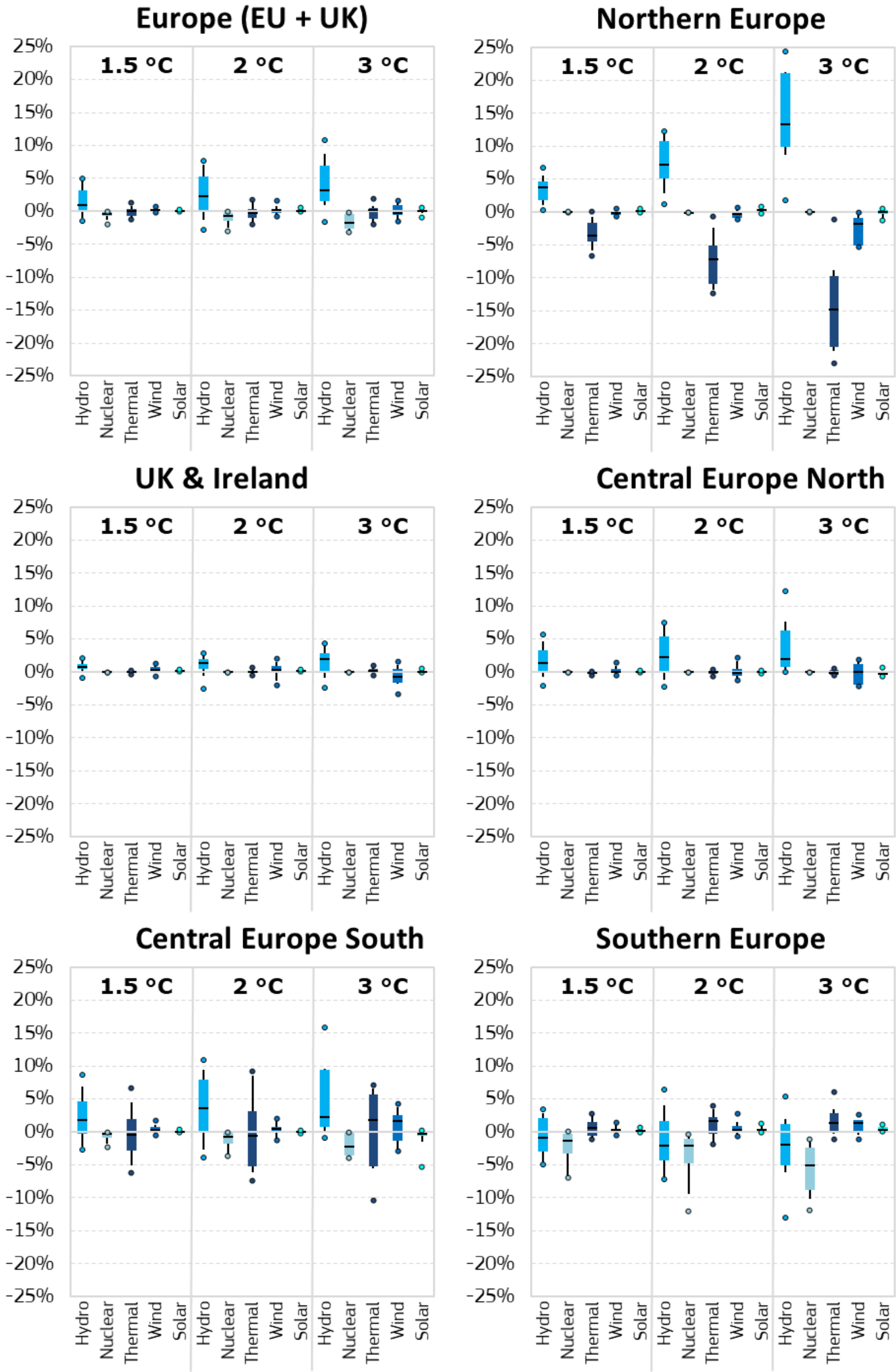
In **Central Europe North** (Belgium, Germany, Netherlands, Poland, Luxembourg), there is also an increase of hydro production linked to the projected increase in water availability in all seasons and especially winter and swing seasons. However, the impact on the power system is small since hydropower only represents 3.6% of the regional electricity mix. The other electricity sources are marginally impacted (around 0.5% or less at 2 degree warming), mainly due to increased temperatures (effects on solar efficiency) or lower summer river runoff in some scenarios (impact on availability of German coal).

In **Central Europe South** (Austria, Czechia, France, Hungary, Slovakia, Romania) the water availability is on average projected to increase, although there are large variations across the different climate models' projections. Hydropower production is strongly correlated with water availability and follows this pattern. Nuclear power plants are also affected and characterized by a reduction in their summer production in some scenarios. This is mainly due to the adverse effect of reduced streamflow on cooling water demand (e.g. in France, Romania and Czechia) or to impact of higher water temperatures (e.g. in Hungary). While thermal plants face the same cooling constraints, they can still replace the missing hydro and nuclear production due to their excess electric generation capacity.

Southern Europe (Bulgaria, Croatia, Cyprus, Greece, Italy, Malta, Portugal, Slovenia, Spain) are projected to experience an overall decrease of water availability. While the Iberian Peninsula faces across-the-board decreases in water availability, these losses are scenario-dependant in Greece and Bulgaria. Spanish nuclear plants and Greek lignite plants are projected to reduce their production due to reductions in river runoff, particularly in summer. Water temperatures also limit the availability of thermal plants in the hottest summer days because of environmental regulations. The consequence of these reduced productions is that other (more expensive) thermal plants increase their production in order to meet the electricity demand. These plants also have to face the reduced water availability for cooling, but they compensate by using their existing excess capacity (e.g. in Spain, Portugal and Greece). On the other hand, water availability, and thus hydro production, is projected to increase in Italy, Slovenia and Croatia. Gas plants are not needed as much to meet demand and decrease their production. Finally, Cyprus, Malta and Croatia face hotter summers with higher water temperatures but no impact on the rest of the system is projected since abundant cooling water is available from the sea.

The common characteristics across Europe are that wind and solar plants are not projected to experience large impacts of climate change. Climate models project only small changes in wind speeds (Tobin et al., 2015, Tobin et al., 2016). This result should be viewed with some caution due to the complexity of modelling wind speeds in climate models, for example considering their rather coarse spatial resolution. Projected temperature increases have a limited impact on solar production that is compensated for by the energy mix effect, in that all energy sources of the electricity mix need to add up to the demand and some other electricity sources (hydro, nuclear) face much stronger impacts that dwarf the wind or solar impacts. Other studies (Jerez et al., 2015), which examine all drivers of PV productivity (including irradiation linked to cloud cover) do not project consistent change either in any direction.

Figure 2: Climate change impacts on 2020’s electricity production by energy source in Europe, by region
To read the figure, note that "thermal" designates biomass, coal, gas and oil plants' production. The scenarios represented are based on 11 climate models, with RCP 4.5 (compatible with 1.5 and 2 degree warming levels) and RCP 8.5 (used for 1.5, 2 and 3 degree warming levels). Dots indicate the extreme scenarios; vertical lines indicate the spread of all other points; coloured areas indicate the two middle quartiles separated by the median line. All effects other than climate impact on electricity supply are neutralized; only the relative differences of production of each electricity source are shown.



To summarize Figure 2, we observe an increase of EU hydro production, particularly in Northern Europe, where thermal plants have to reduce their production. Central Europe and the British Isles see a slight increase of hydro but no other sizeable impact. Inter-model variations of projections are important for hydro production in Central South and Southern Europe. In the former, thermal plant production is also quite uncertain. In the later, nuclear plants are somewhat impacted by water scarcity and thermal plants make up for the lost production by using their existing reserve capacities. Wind and solar productions face moderate and uncertain impacts.

Total electricity production costs with today's power mix are not significantly impacted by climate change if the whole of Europe is considered (respectively +0.0%, +0.0% and -0.1% for 1.5, 2 and 3 degree scenarios, equivalent to +0.2, +0.2 and -0.3 €billion (2015 values), but there are regional variations. The annual economic benefits are concentrated in Northern Europe (respectively -0.2, -0.7 and -1.2 €billion annually (2015 values), i.e. -0.8%, -2.5% and -3.8% for 1.5, 2 and 3 degree scenarios) due to the increased hydropower resource. On the other hand, Southern Europe faces additional costs due to the need to replace some of its hydro and nuclear power with more expensive thermal production (respectively +0.3, +0.7 and +0.8 €billion annually (2015 values), i.e. +0.3%, +0.6% and +0.7% for 1.5, 2 and 3 degree scenarios).

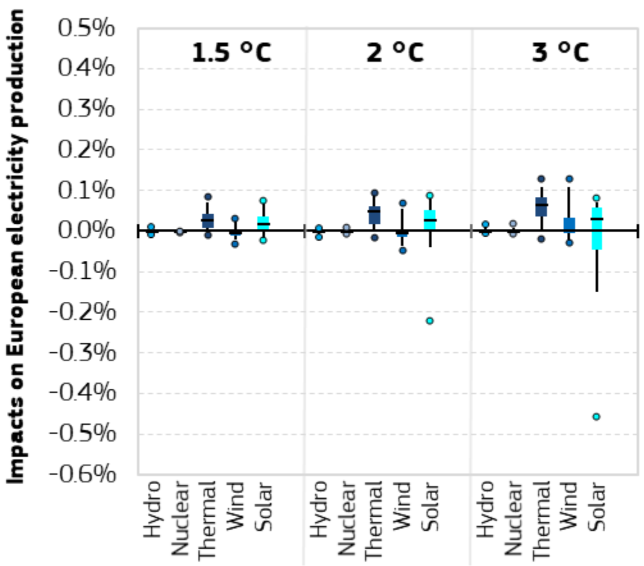
3.2 Rest-of-the-world spill-over effects on Europe

In this section, we study the additional impacts caused on the EU power production because of climate change impacts in the rest of the world. The range of climate impacts considered is the same as in the previous section. Therefore, some important impacts are out of scope, such as impacts on energy infrastructure (e.g. permafrost thawing on pipeline routes, impacts of extreme events on energy supply disruptions). International impacts on agriculture are not assessed either, despite their potential impact on the price of biomass for EU imports and use in biomass power plants (for example, UK has imported some USA biomass for its power plants by lack of local resource).

We compare European power production (by source) with European-only climate impacts and with global climate impacts. We carry out two sets of scenarios with the same climate simulations (ISIMIP fast-track, see Annex 1), where the only difference is that climate change is applied to Europe only or to the whole world. We show below the differential effects, so that the differences in the European power supply (see Figure 3) are purely due to the spill-over effects of non-EU climate change impacts.

Figure 3: Indirect impacts on European electricity production from climate change in the rest of the world, by energy source

To read the figure, note that "thermal" designates biomass, coal, gas and oil plants' production. The scenarios represented are based on 42 climate models, 17 with RCP 4.5 (compatible with 1.5 and 2 degree warming levels) and 25 with RCP 8.5 (used for 1.5, 2 and 3 degree warming levels). Dots indicate the extreme scenarios; vertical lines indicate the spread of all other scenarios; coloured areas indicate the two middle quartiles. All effects other than climate change impacts on non-EU regions are cancelled out; only the relative differences of production of each electricity source in the EU are shown.



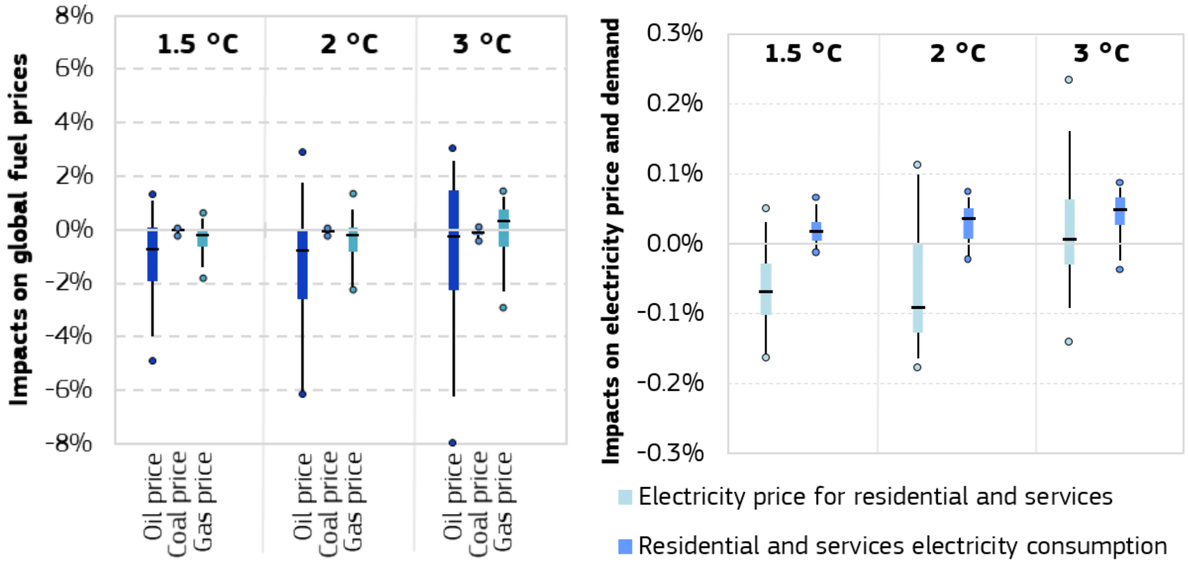
In Figure 3 we see how non-EU climate impacts cause a slight increase of thermal and solar electricity production in EU, less than 0.1%. Other sources of electricity are not substantially impacted.

The interactions between EU and the rest of the world are multiple. We focus here on the fuel prices (see Figure 4, left) to try explaining the small variations of electricity production in Europe (other factors could be biomass and biofuel prices and supply to Europe).

Non-EU climate change reduces energy demand and fuel prices. This is due to lower heating demand in countries like China or the USA that have less cold winters. This effect prevails over the increase of cooling demand in other regions, in part because the cooling technologies (air conditioning) are not yet widely developed. The lower prices lead to higher industrial, residential and services demand in Europe (see Figure 4 right).

Figure 4: Indirect impacts on global fossil fuel prices (left) and European electricity price and demand in the residential and service sectors (right) from climate change in the rest of the world

To read the figure, note that "thermal" designates biomass, coal, gas and oil plants' production. The scenarios represented are based on 42 climate models, 17 with RCP 4.5 (compatible with 1.5 and 2 degree warming levels) and 25 with RCP 8.5 (used for 1.5, 2 and 3 degree warming levels). Dots indicate the extreme scenarios; vertical lines indicate the spread of all other scenarios; coloured areas indicate the two middle quartiles. All effects other than climate change impacts on non-EU regions are cancelled out; only the relative differences of prices and electricity consumption in the EU are shown.



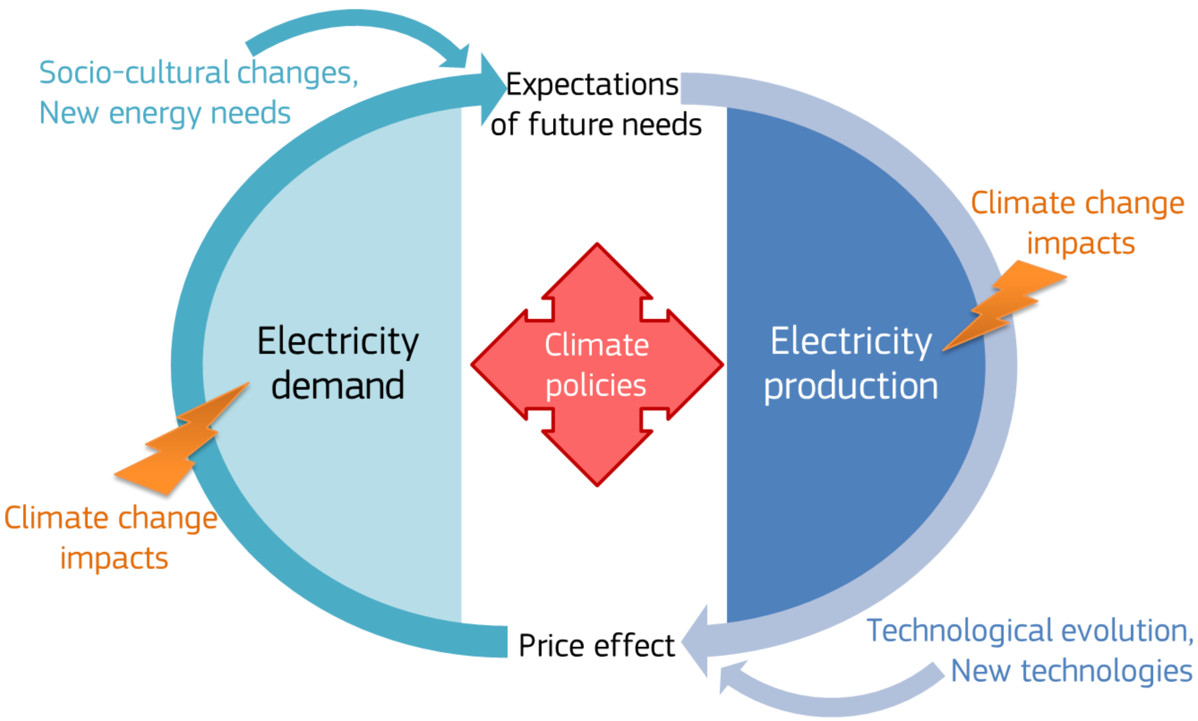
The left panel of Figure 4 shows that most climate models lead to lower global fuel prices, with large variations across scenarios. This is due to decreased oil and gas demand for heating. (Oil is more sensitive than gas because it does not benefit from the increase of electricity demand for cooling.) Coal prices are not impacted. The overall decrease of global fuel prices, particularly gas, leads to a slight decrease of electricity prices in EU of about 0.1% (Figure 4, right panel).

This leads to a slight increase of consumption in EU (around 0.05%) that is in priority covered with existing reserve capacities (non-nuclear thermal plants). Indeed, thermal plants have higher variable costs than hydro or nuclear plants. Therefore they are the adjustment variable. Decentralised solar plants also develop slightly more because the additional demand is favourable to new installations of decentralised solar.

3.3 Impacts of climate change in 2050 under a 2-degree scenario

This section presents the dynamic results of POLES. The climate change impacts now have retroactive effects on the demand and supply of electricity. During the scenario evolution, climate change affects energy demand directly through an evolving heating technology mix and installation of cooling equipment (air conditioning), but also indirectly through changing energy prices in response to climate effects on supply. Climate change also influences electricity capacity investments, directly through different resource availabilities (as in the previous section) and indirectly through different expectations of future energy demand (changing electricity needs and load profile). On top of the climate impacts, the scenarios follow the ECFIN 2015 Ageing Report[5] (Ciscar et al. 2017) for population and economic growth. Some technologies develop (decentralised photovoltaics) or appear (carbon capture and sequestration), while climate policies are applied. Climate change impacts the relative value of electric plants and thus their development. All these interactions, visualised in Figure 5, modify the energy mix and make it challenging to interpret precisely what impacts are caused specifically by climate change.

Figure 5: Multiple interactions in the dynamic model POLES



As in the previous section on the theoretical impacts of climate change on today's system, counter-factual scenarios where climate does not affect electricity production are used as comparison points. Here are the results detailed by energy source (see also Figure 7).

We observe an overall increase of water resource and hydro production in EU + UK (median value of +3.3% i.e. +14 TWh), counterbalanced by a decreasing nuclear production (-2.8%; -18 TWh). Other thermal plants are little affected over Europe (-0.6%; -4 TWh). Wind and solar power production increases slightly with climate impacts at EU + UK level (respectively +1.1%; +13 TWh and +0.7%; +7 TWh).

If we decompose by region, we see the same patterns than in the static scenarios with higher variability of results in the dynamic scenarios. This is attributable to the higher degree of interactions of energy supply sources between themselves and with the level of demand. This illustrates different ways the electricity system can respond to the climate change impacts once multiple other aspects are factored in.

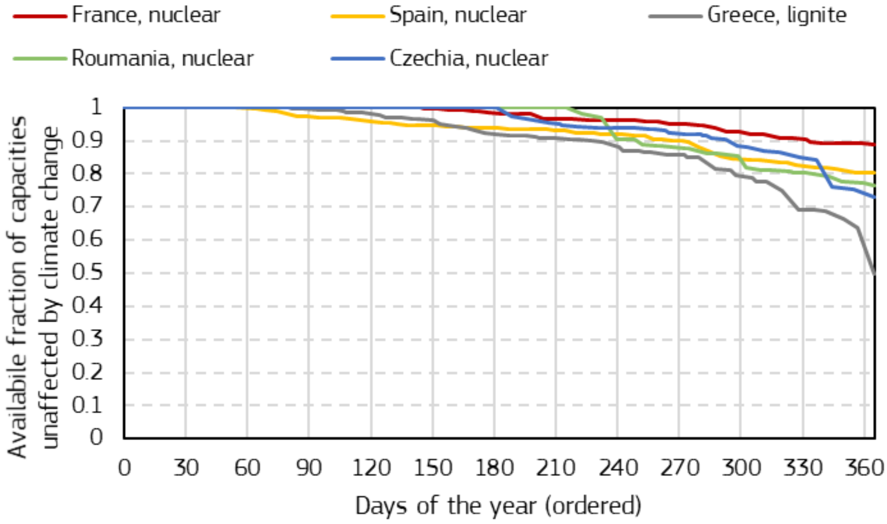
Most of the hydro production increase is concentrated in Northern Europe (+9.6 TWh), thanks to an increased water availability. Central Europe North, UK and Ireland see little change in the hydro production. Central Europe South hydro production increase (+4.3 TWh) but is compensated by a decrease in Southern Europe (-5.4 TWh). These two regions have a high variability of results across scenarios, around +/-10%.

[5] The population and growth projections were updated during PESETA IV project but were not incorporated by lack of time. These updated projections do not affect the main conclusions of this report.

Nuclear production decreases in Northern Europe (-4.6 TWh), penalized by the higher hydro production, and in Central Europe South (-4.0 TWh) and Southern Europe (-5.8 TWh), where, on the contrary, the drier conditions create water availability constraints (in France this happens mainly in summer but in Spain it happens throughout the year, see Figure 6). Nuclear in Central Europe North, UK and Ireland is little impacted.

Figure 6: Fraction of electric capacities unaffected by climate change for a few affected countries in 2050

Reading note: for 60 days of 2050, nuclear capacities are not affected by climate change, while for the most affected 60 days, their capacity is reduced by 16 to 20% in Spain.



The situation for other thermal productions (coal, gas, oil and biomass) is the contrary of the hydropower situation. Northern Europe sees a decreased production (-3.0 TWh) caused by the higher role of hydro. Central Europe North, UK and Ireland face negligible impacts from climate change. Central Europe South thermal production decreases (-3.8 TWh), linked to the higher year-round hydro and wind production. On the contrary, Southern Europe thermal plants make up for the lost hydro and nuclear production (+3.9 TWh).

The relative variations of wind and solar are relatively small (median values between -2.2% and +1.9% depending on the region). However, due to their increasing importance in the climate mitigation scenario, in absolute terms the production changes in 2050 are comparable to other electricity sources. In particular, wind and solar increase in Central Europe South (respectively +4.2 TWh and +1.5 TWh) and Southern Europe (respectively +4.0 TWh and +3.6 TWh), boosted by the restrictions on nuclear production due to a lack of cooling water. These two regions have variable results across scenarios, around +/-5%. This is due to many factors, including uncertainty on future wind speeds. In Northern Europe, Central Europe North, UK and Ireland the wind and solar production are almost not affected (less than 1 TWh of difference on average).

Results for the year 2050[6] are presented in Figure 7.

[6] We note that some results are also sensitive to the year chosen (only 2050 is shown here). The POLES model is simulating possible trajectories (simulation model) with reactions delayed in time. Since, in the meantime, market and demand conditions have evolved, electricity production keeps adapting to imperfect future anticipations and never reach a stable state. Therefore, individual results are more difficult to interpret in a dynamic scenario.

Figure 7: Climate change impacts in 2050 production by energy source in a dynamic scenario, in Europe, by region, in relative (%) and absolute (TWh) terms

Reading note: "thermal" designates biomass, coal, gas and oil plants' production. The scenarios represented are based on 11 climate models, with RCP 4.5 and climate mitigation action consistent with a global warming of 2 degrees. Dots indicate the four extreme scenarios; coloured areas indicate the other seven scenarios and the line is the median scenario. All effects other than climate impacts on electricity supply are neutralized; only the relative differences of production of each electricity source are shown.

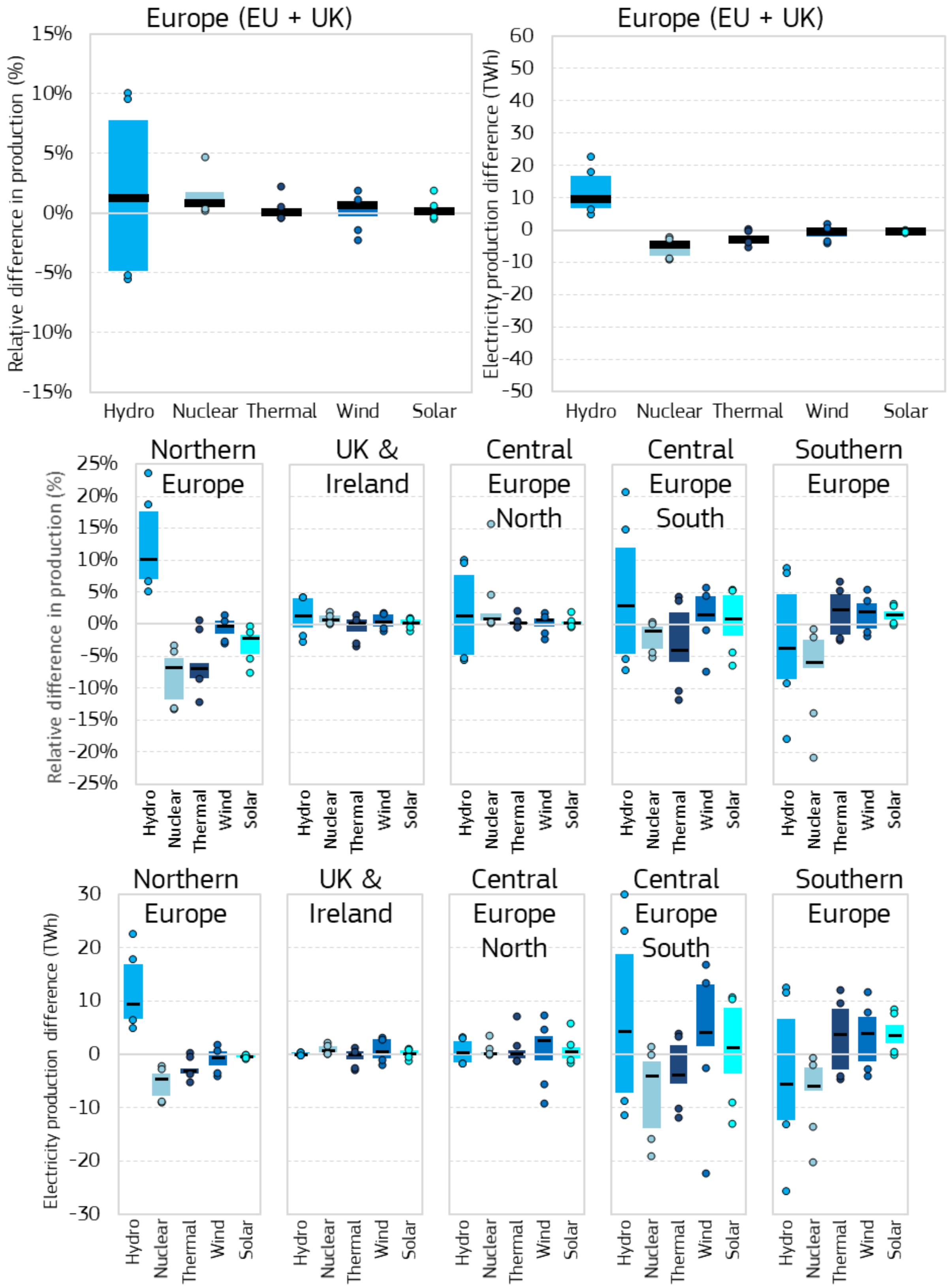
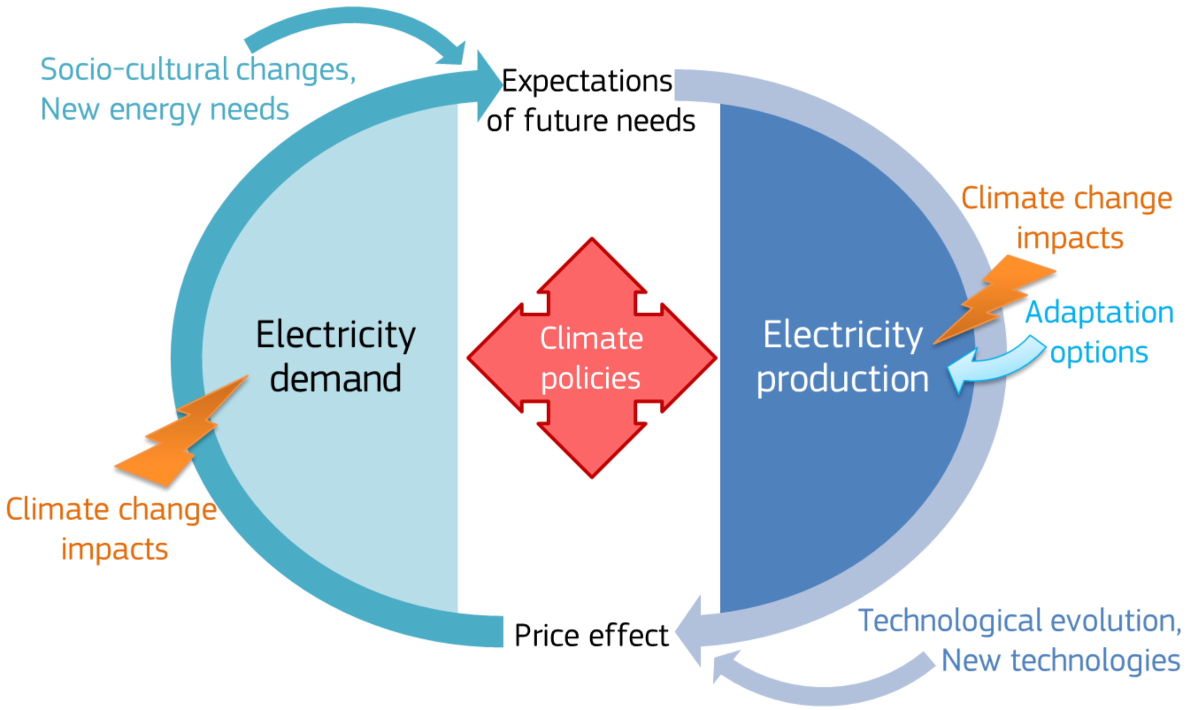


Figure 7 shows overall similar climate change impacts in Europe (EU + UK) compared to the static scenarios of 2 or 3 degrees warming levels (see Figure 2). Hydro production is boosted at European level thanks to favourable climatic conditions in Northern Europe. Nuclear plants are constrained, either by too much water availability, because hydro power replaces them, or by too little water availability, as cooling needs are not covered and nuclear plants have to shut down. Other thermal plants are also pushed out in Northern Europe but make up for the lost hydro and nuclear production in Southern Europe. Wind and solar are developed faster because of climate impacts, mainly in Southern Europe.

3.4 Adaptation of thermal plants to climate change, in 2050 under a 2-degree scenario

The same dynamic scenario as in the previous section can include adaptation options. These reduce the observable climate change impacts while adding a variable in the mix (Figure 8).

Figure 8: Interactions between demand, supply, climate and adaptation in the dynamic model POLES

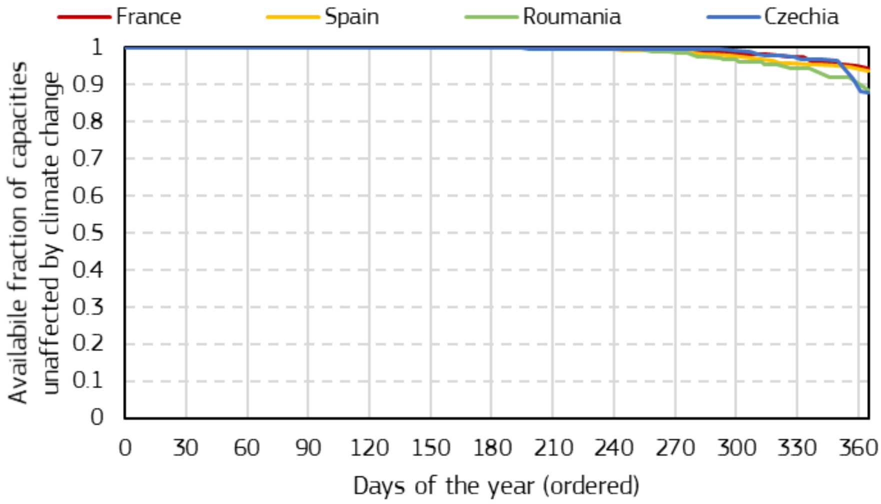


The adaptation options considered only apply to nuclear and other thermal plants. The climate change impacts on these plants are linked to the cooling technology used. The main technologies, which are represented in POLES, are once-through cooling (water is pumped in and out with a small temperature difference), open recirculating cooling (water is sprayed in cooling towers and the part not evaporated is reused), sea-water cooling and dry cooling (air is moved by fans). In order to adapt to climate change and lack of cooling water, electric plants can move from once-through to open recirculating cooling, which reduces the water consumed, or to dry cooling that make the plants independent on the water availability at the expense of a reduced efficiency (linked to the electric consumption of the fans). Sea-water cooling can also be pushed slightly in countries which already have this possibility. Another possibility (not represented in POLES) is to combine technologies in a single plant, which brings more operational flexibility.

The adaptation options of thermal plants reduces significantly the climate impacts, as shown in Figure 9. For example, the availability of nuclear reactors is improved by 2.8% in France, 4.8% in Czechia, 5.5% in Romania and 7.5% in Spain.

Figure 9: Fraction of unaffected nuclear capacities with adaptation options, in 2050 for some countries

Reading note: for around 270 days of 2050, nuclear capacities are not affected by climate change, while for the most affected 60 days, their capacity is reduced by 3 to 6% in Spain. Greek lignite is not shown since capacities drop to near-zero by 2050 in the climate mitigation scenario.



Hydro plants are not impacted by the adaptation options considered here. Nuclear electricity production is benefiting from adaptation options the most, with a median increase of production of 16 TWh (2.4%) at European scale. This leads to a different development of the electricity mix. Indeed, the increased nuclear production is balanced by a slight reduction of production from wind (-0.6%; -7.3 TWh) and solar (-0.3%; -2.7 TWh) plants.

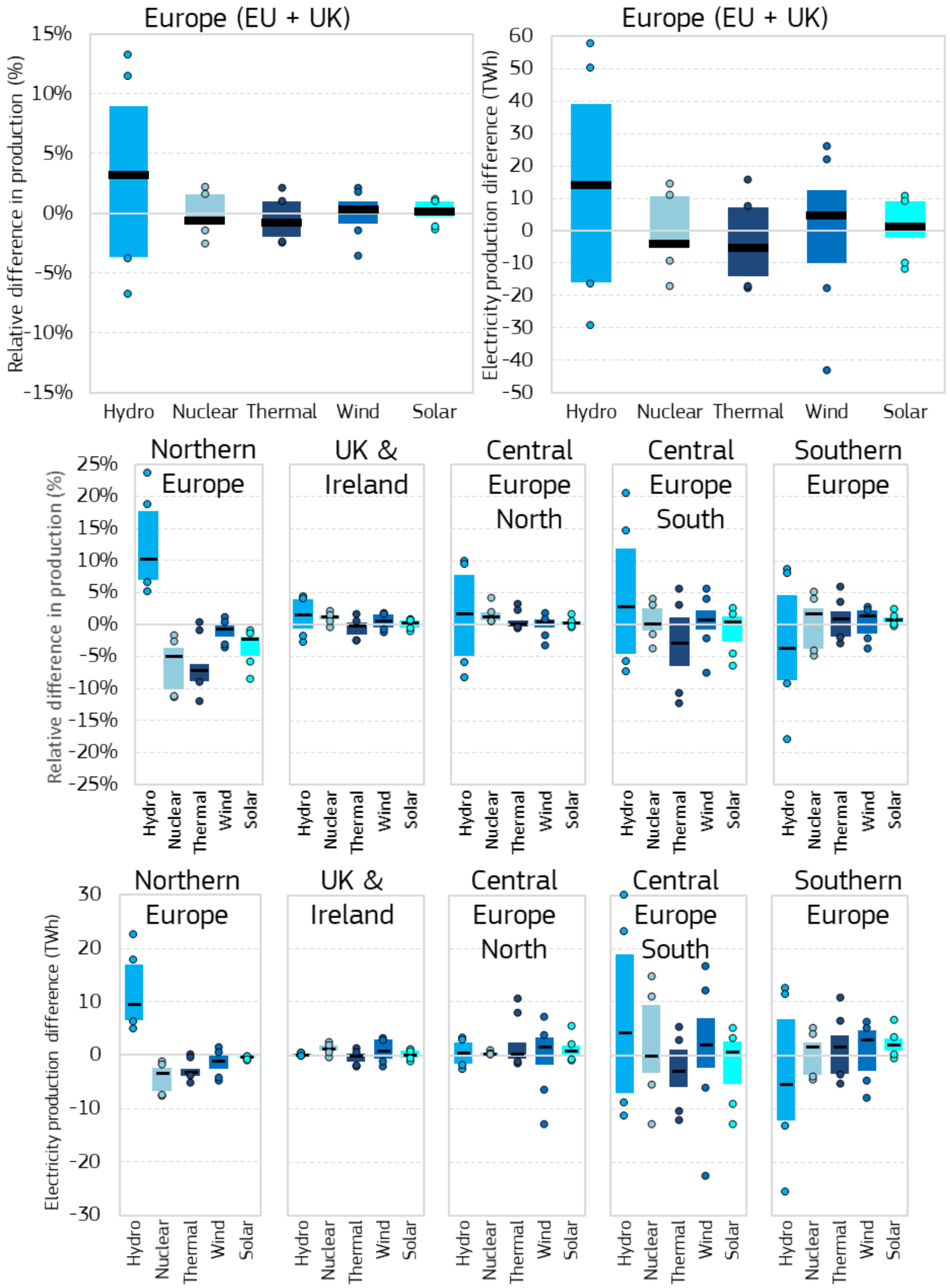
The adaptation options have negligible impacts in Northern Europe, Central Europe North, UK & Ireland. The biggest changes due to adaptation are nuclear production in Central Europe South (+0.8%; +3.0 TWh) and Southern Europe (+4.8%; +4.6 TWh). The scenarios show variable results: adaptation allows nuclear production to increase by up to +29 TWh (+8%) in Central Europe South in the R5-G5 scenario and +22 TWh (+23%) in Southern Europe in the R5-G4 scenario.

Water constraints leading to adaptation of other thermal production are less frequent than for nuclear plants. Most thermal plants already use open recirculating cooling, which consume small amounts of river water. However, the adaptation of nuclear plants influences negatively the production of other thermal plants, wind and solar, in particular in Southern Europe. Therefore, the variability between scenarios is also seen for other thermal (up to -6.5 TWh in Southern Europe), wind (up to -12 TWh in Central Europe South and -8.3 TWh in Southern Europe) and solar (up to -8.2 TWh in Central Europe South and -5.8 TWh in Southern Europe).

All results combining climate change impacts and adaptation are shown by energy source and by region in Figure 10.

Figure 10: Impacts of climate change with adaptation in 2050, by energy source in a dynamic scenario, by region, in relative (%) and absolute (TWh) terms

Reading note: "thermal" designates biomass, coal, gas and oil plants' production. The scenarios represented are based on 11 climate models, with RCP 4.5 and climate mitigation action consistent with a global warming of 2 degrees. Dots indicate the four extreme scenarios; coloured areas indicate the other seven scenarios and the line is the median scenario. All effects other than climate impacts on electricity supply are neutralized; only the relative differences of production of each electricity source are shown.



When combining all aspects of climate impacts and adaptation in POLES scenarios, the main impact at European level is the increase in hydropower production (+3.3%; +14 TWh). This mainly comes from Northern Europe (+10%; +9.6 TWh) and shows a high variability in Central Europe South (from -7.2% to +21%; -11 to +32 TWh) and Southern Europe (from -18% to +9%; -26 to +12 TWh).

Nuclear plants avoid excessive negative climate impacts by adapting their cooling technology. At European level the nuclear production is slightly reduced (-0.6%; -4.0 TWh), which can be linked to the Northern Europe situation (-5.0%; -3.4 TWh) where nuclear is pushed out by additional hydro production. In other regions, the impact of climate change is either negligible or compensated by changes in the mix of cooling technologies. The variability observed in EU + UK (-2.5% to +2.2%; -17 to +15 TWh) is mainly due to the diversity of climate scenario projections for France (where the difference between scenarios reaches a spread of 28 TWh), Czechia (4.3 TWh of spread) and Spain (spread of 7.9 TWh).

Other thermal plants come out with moderate negative impacts (-0.7%; -5.4 TWh), driven by Northern Europe (-7.3%; +3.2 TWh) and Central Europe South (-3.0%; -2.8 TWh), impacted by the increased hydro production. Southern Europe, on the contrary, increases slightly its thermal production (+0.9%; +1.6 TWh), compensating for the loss of hydro production due to drier conditions. Other regions show little differences.

Very moderate positive impacts are faced over EU + UK by wind (+0.4%; +4.6 TWh) and solar plants (+0.1%; +1.2 TWh). The variability of results can be highlighted (at EU + UK level, spread of 69 TWh for wind and 22 TWh for solar), mainly in Central and Southern Europe.

4 Conclusions

The study quantifies the impacts of climate change on electricity production, at the seasonal resolution, given the temporal and spatial detail of the analysis. The main message is that the electricity supply impacts are strongly linked to the evolution of water availability for hydro power and for thermal plant cooling. This is a clear example of the water-energy nexus.

The higher hydro production (based on almost unaffected installed capacities) in the Northern countries reduces the need for nuclear and other thermal plants there, while lower water availability in Southern countries reduces production from hydro and nuclear plants. The power system then needs to fill the gap with other capacities: thermal plants in a static power system, complemented by higher wind and solar capacities in a dynamic scenario up to 2050. Adaptation of the cooling technology can reduce water scarcity impacts on nuclear plants in southern regions. This reduces the negative impacts on nuclear and thus the additional production of other capacities. The UK, Ireland and the northern central Europe (e.g. Germany) are not particularly affected due to their low sensitivity to hydro power.

The direct impacts of climate change on wind and solar production seem small. The decreased PV panel efficiency due to higher temperatures is absorbed in the balancing of the power system mix, while wind speeds are not consistently changing. However, the dynamic scenario show higher installed capacities to make up for the lost production of other electricity sources in southern regions of Europe.

The analysis overall suggests that national and local electricity planners should consider climate change impacts. With global warming, an increased water availability in centre and northern Europe will make hydropower plants even more valuable. At the same time, nuclear and thermal production could be undermined by an increase in lower-cost hydropower production. On the other hand, in the Iberian Peninsula and Greece, water availability decreases and droughts affect hydro plants as well as nuclear and thermal plants, by lack of cooling water. The water scarcity issues can be eliminated by adaptation, through the upgrade to less water-intensive cooling technologies, especially for nuclear plants currently based on once-through river cooling. Wind and solar face small direct climate impacts; actually, in dynamic scenarios up to 2050, they can increase capacities to compensate for the losses of hydro and nuclear in southern regions with water scarcity. The contrasted geographical patterns of climate change impacts across Europe reinforce the value of electricity interconnections. Indeed, the projected impacts with today's power system represent important benefits in terms of power production costs for Northern Europe (-2.5% under a 2°C warming scenario), while climate change brings a small additional cost to Southern European power production costs (+0.6% for 2°C).

The spill-over effects from the rest of the world on Europe are negligible. A close look points to lower fuel consumption in the rest of the world due to warmer winter and lower heating demand. This leads to slightly lower fuel prices, which marginally increase European power demand and the solar and thermal power production.

The scope of this work had to be limited and has a number of limits. Despite integrating detailed water, temperature and wind speed data as inputs, the spatial and temporal resolution of the energy system model POLES reduces the analysis to seasonal tendencies. The effects of extreme events on power supply cannot be properly accounted within the POLES analysis. The links between infrastructures could lead to domino effects where one meteorological event affects the energy supply, which has rippling effects on other sectors like telecommunications. Global warming can lead to increased river and coastal flooding, resulting in higher direct damage to energy infrastructures in flood prone areas. The drought analysis of PESETA IV provides some estimates. Under the current climate (1981-2010), the expected annual losses to energy production due to drought damages in the EU reach around 2.2 €billion/year, and would rise to 3.3 €billion/year for 3°C global warming, assuming static economic conditions. When including dynamic projections of the economic importance of the energy sector, based on the 2015 Ageing Report and a reference scenario without mitigation, the annual losses amount to 8.7 €billion/year for 3°C global warming in 2100. There is a strong geographical imbalance in these projections. Drought losses in the energy sector will rise strongest in southern and western regions of the EU. In northern countries, droughts would be less frequent with global warming and drought impacts would decrease. According to the PESETA IV report on windstorms, there is no consensus on any climate-induced trend in windstorms over Europe (despite increasing windstorm frequencies over the last decades). Regionally, though, the slight tendencies indicate that wind extremes increase in 17% of the area of southern Europe at 3°C warming (region with the most impacted area). This could lead to disruption of electricity lines due to falling trees. Areas affected by wind extremes decrease by 24% in central western Europe (region most preserved). In parallel, the frequency of calm days (daily maximum wind speed below 3.5 m/s) increases in central Europe (West and East) for more than two thirds of the climate models.

However, the impacts of resources on electricity production also depend on the turbine locations. In this study, with limited spatial and temporal resolution, the impacts on the wind power production are considered negligible and too uncertain, compared to other electricity production impacts. Another limitation of this work is the modelling implementation, with some necessary linear approximations (see annex 3). Finally, the adaptation measures tested are limited. Some technical improvements in efficiency may also mitigate the adverse effects identified. For example, mixed cooling technologies including dry cooling offer more flexibility and avoid losing too much efficiency. Future works could include other adaptation options like geographical optimisation within countries to reduce the water scarcity impacts on thermal plants.

List of abbreviations

CDD: Cooling Degree Days

CORDEX: Coordinated Regional Climate Downscaling Experiment

GCM: Global Climate Model

HDD: Heating Degree Days

POLES: Prospective Outlook on Long-term Energy Systems

PV: Photovoltaic

RCM: Regional Climate Model

RCP: Representative Concentration Pathway

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Annexes

Annex 1: Scenario acronyms and time-windows around specific warming levels

The EURO-CORDEX scenario characteristics are described in the table below.

Table 1: EURO-CORDEX scenario used in PESETA IV with their years of specific warming levels

Institute	RCM (R)	Driving GCM (G)	CORDEX full name	Acronym (R-G)	1.5 C		2 C		3 C
					RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 8.5
CLMcom	CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	CNRM-CERFACS-CNRM-CM5_r1i1p1_CLMcom-CCLM4-8-17	R1-G1	2035	2029	2057	2044	2067
		ICHEC-EC-EARTH	ICHEC-EC-EARTH_r12i1p1_CLMcom-CCLM4-8-17	R1-G2	2033	2026	2056	2041	2066
		MPI-M-MPI-ESM-LR	MPI-M-MPI-ESM-LR_r1i1p1_CLMcom-CCLM4-8-17	R1-G3	2034	2028	2064	2044	2067
DMI	HIRHAM5	ICHEC-EC-EARTH	ICHEC-EC-EARTH_r3i1p1_DMI-HIRHAM5	R2-G2	2032	2028	2054	2043	2065
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR	IPSL-IPSL-CM5A-MR_r1i1p1_IPSL-INERIS-WRF331F	R3-G4	2023	2021	2042	2035	2054
KNMI	RACMO22E	ICHEC-EC-EARTH	ICHEC-EC-EARTH_r1i1p1_KNMI-RACMO22E	R4-G2	2032	2026	2056	2042	2065
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5	CNRM-CERFACS-CNRM-CM5_r1i1p1_SMHI-RCA4	R5-G1	2035	2029	2057	2044	2067
		ICHEC-EC-EARTH	ICHEC-EC-EARTH_r12i1p1_SMHI-RCA4	R5-G2	2033	2026	2056	2041	2066
		IPSL-IPSL-CM5A-MR	IPSL-IPSL-CM5A-MR_r1i1p1_SMHI-RCA4	R5-G4	2023	2021	2042	2035	2054
		MOHC-HadGEM2-ES	MOHC-HadGEM2-ES_r1i1p1_SMHI-RCA4	R5-G5	2021	2018	2037	2030	2051
		MPI-M-MPI-ESM-LR	MPI-M-MPI-ESM-LR_r1i1p1_SMHI-RCA4	R5-G3	2034	2028	2064	2044	2067

Source: JRC, 2019.

The ISIMIP Fast-track scenarios are described below.

Table 2: ISI-MIP scenarios used in the spill-over analysis and their years of specific warming levels

GCM	1.5C		2C		3C
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 8.5
GFDL-ESM2M	2055	2040	2144	2055	2085
HADGEM2-ES	2033	2027	2048	2039	2057
IPSL-CM5A-LR	2018	2015	2034	2030	2050
MIROC-ESM-CHEM	2027	2023	2042	2035	2053
NORESM1-M	2044	2035	2081	2052	2075

Source: JRC, 2019.

For each scenario, three to five hydrological models from the ISIMIP project were applied (dbh, h08, matsiro, mpihm, pcrglobwb). Some hydrological models were not run in all climate scenarios with RCP 4.5, so in total 42 scenarios are run.

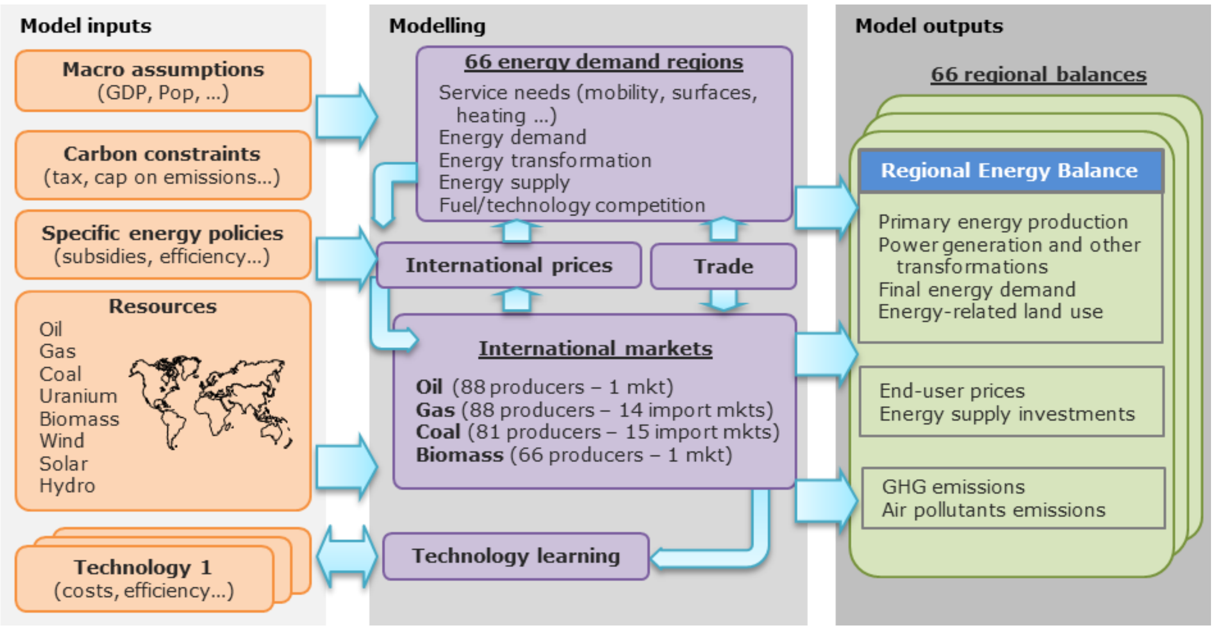
Annex 2: POLES-JRC description

POLES (Prospective Outlook on Long-term Energy Systems) is a global energy model covering the entire energy system, from primary supply (fossil fuels, renewables, ..) to transformation (power, biofuels, hydrogen) and final sectoral demand. International market and prices of energy fuels are simulated endogenously. Its relatively high level of regional detail (66 countries or regions) and sectoral description (see Figure 11) allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES usually operates on a yearly basis up to 2050 or 2100 and is updated yearly with recent information (2015 data for most series). Differences with other exercises done with the POLES model by JRC in other projects, or by other entities (namely the University of Grenoble and Enerdata) can come from different model version, historical data sets, parameterisation, or policies considered.

The JRC POLES version developed and used in the Global Energy and Climate Outlook 2018 has been used for this exercise and is described in (Després et al., 2018). It includes climate change impacts on energy demand in residential and services buildings. For this study, impacts on electricity production have been added (see Annex 3). The model has been used in a "static" mode, i.e. scenarios were run only until 2020 with future climate situations applied with a linear transition from 2015 (historical climate) to 2020 (future climate). This is supposed to isolate the climate change impacts from the socio-economical changes that occur along the century, the mitigation policies, the adaptation measures or the impact of gradual development of air conditioning in many countries. Climate models are compared based on their specific warming levels (1.5, 2 and 3 degree) even if they do not happen at the same 30-year period. In a separate analysis, the model is run in dynamic scenarios along the century. This includes climate mitigation, adaptation and socio-economical changes.

The climate impacts, whether in the static mode for 1.5, 2 and 3 degree warming, or in dynamic scenarios for 2050, are obtained by comparison of two sets of scenarios that model or not the impacts on electricity production, everything else being equal.

Figure 11: POLES model general scheme



Source: JRC, 2018.

Final demand

The final demand evolves with activity drivers, energy prices and technological progress. The following sectors are represented:

- industry: chemistry (energy uses and non-energy uses are differentiated), non-metallic minerals, steel, other industry;

- buildings: residential, services (specific electricity uses are differentiated, different types of buildings are considered);

- transport (goods and passengers are differentiated): road (motorcycles, cars, light and heavy trucks – different engine types are considered), rail, inland water, international maritime, air domestic and international;

- agriculture.

Complementary information on the impact of climate on residential buildings is given in the section "Methodology" above.

Power system

The power system describes capacity planning of new plants and operation of existing plants for 40 technologies.

The planning considers the existing structure of the power mix (vintage per technology type), the expected evolution of the load demand, the production cost of new technologies, and resource potential for renewables.

The operation matches electricity demand considering the installed capacities, the variable production costs per technology type, the resource availability for renewables.

The electricity demand curve is built from the sectoral distribution over 12 representative days (at hourly time-step) obtained by a clustering algorithm applied on several years of load, wind and solar load curves for each country or region.

Electricity price by sector depend on the evolution of the power mix, of the load curve and of the energy taxes (by default kept constant).

Other sectors

The model also describes other energy transformations sectors: liquid biofuel (BTL), coal-to-liquid (CTL), gas-to-liquid (GTL), hydrogen (H2), direct air capture.

Oil supply

Oil discoveries, reserves and production are simulated in 80 individual countries and for 6 types of fuel: conventional crude & NGLs (inland and shallow water), tar sands, extra heavy oil, oil shale (kerogen), deepwater and arctic oil.

The capital and operational costs of production are represented in detail. The market is structured between large producers, small producers and demand markets. The global Reserve / Production ratio is monitored. Price to consumer considers the evolution of taxation, including the impact of a carbon value.

Gas supply

Gas discoveries, reserves and production are simulated in 80 individual countries or regions for 4 types of gas: conventional gas (inland and shallow water), shale gas, deepwater and arctic gas. They supply 15 regional markets, made up of the national gas demand of the 57 countries and regions. 37 of the producers are considered as key producers with a capacity to export on international markets through trading routes. Gas transport is done through inland pipeline, offshore pipelines or LNG.

Gas price is simulated for 3 regional markets: Europe, America, Asia. It depends on the transport cost, the regional R/P ratio (long-term trend), the evolution of oil price and the development of LNG (integration of the different regional markets). Price to consumer considers the evolution of taxation, including the impact of a carbon value.

Coal supply

Coal production is simulated in 74 individual countries or regions. Some countries (USA, Australia, China, India) have two or more production regions to better represent transportation costs which can represent a significant share of the coal delivery cost. They supply 15 regional markets, made up of the national coal demand of the 57 countries and regions. 26 of the producers are considered as key producers with a capacity to export on international markets through trading routes.

Coal delivery price for each route depends on the transport cost (international and inland), the mining cost, and other operation costs. An average delivery price is calculated for each of the 15 consuming markets. The model also calculates an average international price for 3 "continental" markets: Europe, Asia, America. Price to consumer considers the evolution of taxation, including the impact of a carbon value.

Biomass supply

The model differentiates 3 types of primary biomass: energy crops, short rotation crop (cellulosic) and wood (cellulosic). They are described for each of the 57 country through a potential and a production cost curve – in the case of SRC and wood this is derived from look-up tables provided by the specialist model GLOBIOM-G4M (Global Biosphere Management *Model)*.

Biomass can be traded, either in solid form or as transformed liquid biofuel.

Wind, solar and other renewables

These renewables are associated to potentials per country, which can be more detailed (in the case of wind and solar, where supply curves are used) or less (hydro, geothermal, ocean where only a potential figure is used).

GHG emissions

CO_2 emissions from fossil fuel combustion are derived directly from the energy balance, that is influenced by mitigation policies (carbon value, support policies to technologies, energy efficiency targets).

Other GHGs from energy and industry are simulated using activity drivers identified in the model (sectoral value added, mobility per type of vehicles, fuel production,..) and abatement cost curves.

GHG from agriculture and LULUCF are derived from GLOBIOM-G4M lookup tables.

Regional coverage

Table 3: POLES-JRC regional coverage (66 countries and regions, incl. 28 EU Member States)

Europe and CIS	America	Africa and Middle East	Asia	Oceania – Pacific
Detailed EU	Canada	Egypt	Japan	Australia
United Kingdom	USA	Morocco & Tunisia	Korea, Rep.	New-Zealand
Switzerland	Mexico	Algeria & Lybia	China	Rest of pacific countries
Norway	Brazil	South Africa	Indonesia	
Iceland	Chile	Rest of Sub-Saharan Africa	India	
Turkey	Argentina	Mediterranean Middle East	Vietnam	
Rest of central Europe (incl. Balkans)	Rest of Central America	Saudi Arabia	Thailand	
Russia	Rest of South America	Iran	Malaysia	
Ukraine		Rest of Gulf	Rest of South-East Asia	
Rest of CIS			Rest of South Asia	

Source: JRC, 2019.

Annex 3: Details of the climate impact modelling methodology

Climate scenarios considered

A total of 22 climate scenarios are studied, based on 11 climate models from the EURO-CORDEX database and two sets of climate projections (RCP 4.5 and 8.5). The climate indicators used are the daily average values of near-surface air temperature, bias-adjusted (Dosio and Paruolo, 2011, Dosio et al., 2012, Dosio, 2016, Dosio, 2018), the bias-corrected near-surface wind speeds and the river runoff (discharge for each cell, in m^3/s). While the air temperatures and the winds are direct outputs from EURO-CORDEX climate models, the river runoff is computed with the LISFLOOD 2.0 hydrological model (Van Der Knijff et al., 2010). LISFLOOD is a GIS-based spatially-distributed hydrological rainfall-runoff model. Based on several climate variables such as bias-corrected precipitations and temperatures, the LISFLOOD model calculates a complete water balance at a daily time step simulating the most important physical processes (e.g. surface runoff, infiltration, evapotranspiration) for every grid-cell (5x5km). LISFLOOD has been applied at European, African or global scale for applications of flood projections (Alfieri et al., 2017) or of climate change impact assessments (Bisselink et al., 2018).

The data used in the spill-over study were downloaded and treated like the EURO-CORDEX data, for both RCP 4.5 and 8.5. The ISIMIP Fast track project has five Global Climate Models[7]; we selected five hydrological

[7] One of the ISIMIP Fast-track global climate model (IPSL-CM5A-LR) is almost identical to a EURO-CORDEX GCM (IPSL-IPSL-CM5A-MR)

models for the water analysis on each of these GCMs. Therefore, there are 10 scenarios for wind speeds and temperatures and 42 scenarios for water runoff (some hydrological models were not run in all climate scenarios with RCP 4.5). The geographical detail of all of these scenarios is global but do not use the same grid as the EURO-CORDEX scenarios[8].

Data treatment

The model used, POLES, describes each day with representative days, chosen by a clustering algorithm applied on load, wind and solar conditions for each country. Each representative day is described in terms of temperature and seasons (summer, winter and swing season components). Therefore, each set of climate data is translated into seasonal patterns at the country scale (or regions of POLES), which are then used to characterise each representative day and observe the impacts of climate change. The input climate data are also averaged in 30-year time windows.

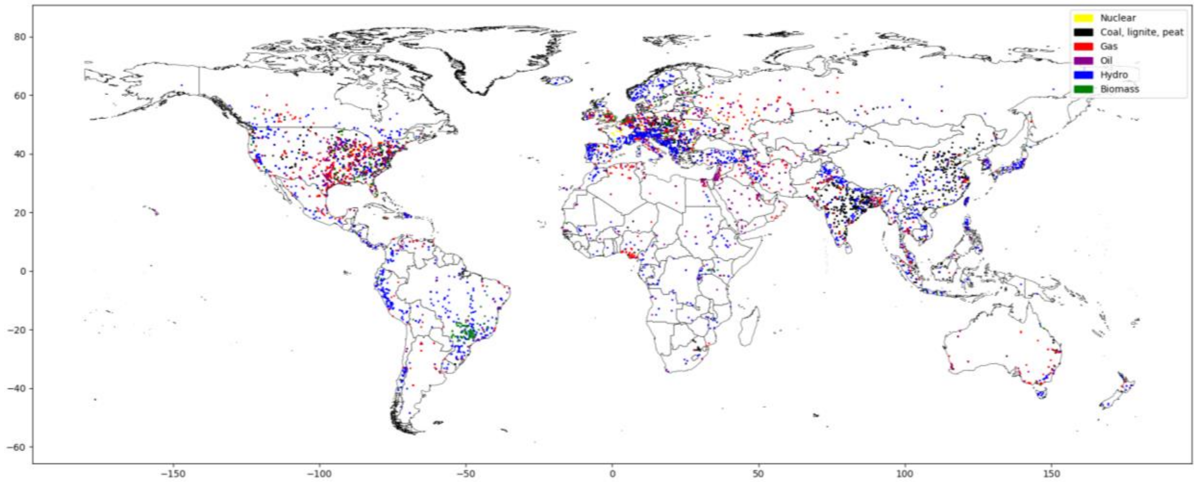
The daily temperature data is thus translated into a temperature for each representative day and at the country level, like in PESETA III (the population density is used as the weighting factor). This temperature then evolves based on the climate change scenarios.

Wind speeds (at 10 m height) are averaged at the country level with non-constant weightings describing both current and potential future wind turbines[9]. The data is also aggregated at the seasonal scale for use in POLES representative days.

Finally, water runoff is also averaged at the country level with weightings that consider the position of current plants for each main energy source (hydro, biomass, coal, gas, nuclear, oil)[10]. The river-cooled power plants referenced by Enerdata were used for the weightings (see Figure 12). The data is also used as seasonal averages.

Figure 12: Power plants registered in the Enerdata database

Note: only the plants that are more distant from the coast than 10 km are considered, to account for the approximations of coordinates and of the coastline precision.



Source: Enerdata, 2019.

The weightings chosen for the treatment of each dataset is subject to some uncertainty but is not expected to change considerably the results.

[8] While ISIMIP uses 0.5 degree grid cells, EURO-CORDEX scenario data are described with 5 km cells for hydro (Lambert azimuthal equal-area projection) and about 10 km for temperatures and winds (rotated grid).

[9] Potential sites are determined by considering sites of good resource and adequate population density (i.e. with floor and ceiling values).

[10] The power plant weights are the installed capacity for each European grid cell, provided that the computed distance between the plant and the coast is more than 10 km.

Impacts considered

In PESETA III, the climate change impacts on energy demand were studied, namely on energy for heating and for cooling in the residential sector. The PESETA IV project changes focus and analyses some impacts on power supply (van Vliet 2016, Tobin 2018). These impacts are singled out by only considering the relative differences of production of each electricity source with and without climate change impacts on electricity production (all else being equal, including impacts on energy demand).

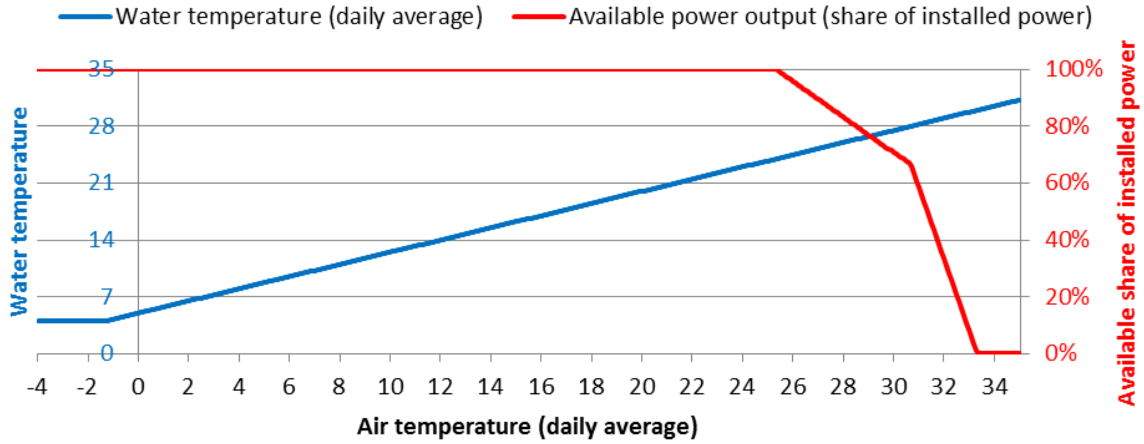
Solar photovoltaics are mostly impacted by the irradiation, which is linked to the number of sunny hours (cloud coverage), air turbidity (dust, humidity) or cleanliness of the panel (dust, sand). These are difficult to predict, being very location-specific and extremely complex systems. Another well-known factor is the PV panel temperature. There is a linear decrease of the efficiency of the panel with increasing temperatures (as in Dowling 2013). Although the local wind conditions play a role, in POLES we choose to *a minima* represent a linear link between the PV panel production and outside temperature.

Wind power is obviously affected by wind speeds (although wind directions could affect some plants in case of an unforeseen wake effect). There is a non-linear relation: very low wind speeds do not generate power before a cut-in speed that depends on the turbine shape and technology; then the power output evolves with the cubic speed of the wind up to a maximum rated output. Finally, if wind speeds are too strong, a cut-off speed stops the power generation to protect the turbine from windstorms. In POLES, we only have daily average wind speeds so the simplified approach is to use a linear relation between yearly average wind speeds and yearly wind production. In principle a variation of the distribution of wind speeds across the year could lead to non-linear effects on power production (more storms and more still conditions could result in the same average speed but lower production) but the GCM projections do not show any consistent effect on the yearly distribution of daily wind speeds compared to the present one, so we consider no change in the expected storm or still periods and therefore no measurable non-linear effect linked to the power curve of wind turbines. Besides, the onshore wind speeds are also used as a driver of the offshore wind production. This could be further refined by using a more precise mapping of country boundaries than the half-degree map used for grouping wind data.

The **hydropower** potential production is directly impacted by the river discharge (Note that hydro plants cannot use the entire runoff because of losses for environmental reasons, e.g. fish lifts, spillway release during floods). Hydro power in POLES is split in small hydro, run-of-river, lakes and pumped hydro. Apart from pumped hydro storage, hydropower is directly affected by the variations of river runoff. Since the capacity factors are usually well below 100%, we neglect the potential overflow that could not be exploited by plants because of saturated capacities. For both wind and hydro power, the data provided by the climate and hydrological models are daily averages. We aggregate them by season and use them in POLES to describe the supply patterns as well as the yearly total production.

Nuclear and other thermal plants (coal, gas, oil and biomass) use thermodynamic processes where the cooling source is essential. Although dry cooling technologies exist, they are a minority as of today and thermal plants usually use water, which makes them vulnerable to hot and dry climates, especially those that are situated on rivers (sea-side plants are less affected and their impacts are not considered here). Indeed, thermal plants usually have constraints set by environmental regulations in order to preserve part of the natural flow of the rivers, with a minimum run-off and a maximum water temperature (low river flow or high river temperature are dangerous for fauna and flora). To respect these constraints, thermal plants have to reduce output or shut down when water is too scarce and/or warm. Their availability for power production is thus reduced. To evaluate this, we combine temperature data (translated to water temperatures with the affine relation of Mima and Criqui, 2015) and runoff data, aggregated at the seasonal and national scale, to determine when the environmental limits start to affect the national available power. The cooling technology (once-through or recirculating towers) and the design of any particular plant make a difference in their water needs, whether consumed (evaporated) or abstracted (and given back to the river, warmer). The environmental limits that we use have to be a national average of river temperatures and runoffs so they are approximate: downstream water temperature inferior to 28 degree Celsius (see Figure 13), share of water consumed and abstracted less than 5% and 50% of total run-off respectively.

Figure 13: Availability constraints on thermal plant output linked to air and water temperatures



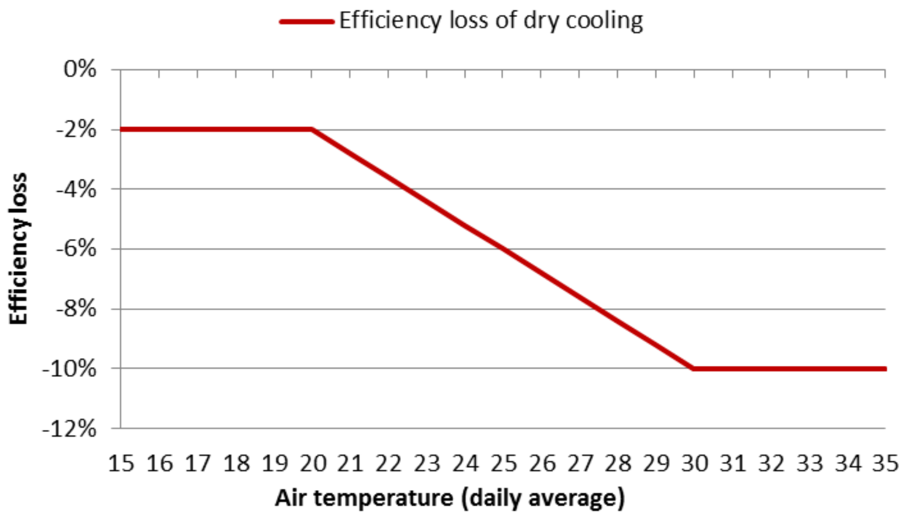
Source: JRC, 2019.

One should note that the typical values used in POLES as thresholds of temperature and share of runoff that is withdrawn or consumed could actually be less strict in regions that have anticipated such conditions and are specially adapted to it.

Our modelling assumptions also mean that all impacts are felt at all plants, independently from the other plants of the country. There is no cross-effect or coupling of plants that would sit on the same river (e.g. retiring half of the national plants will not decrease the climate impact for the remaining plants).

Thermal plants with dry cooling technology also have an impact of the air temperature on their efficiency, particularly at high temperatures (see Figure 14).

Figure 14: Efficiency losses of thermal plants due to dry cooling



Source: JRC, 2019.

Modelling: model setting and limitations

The study first applies climate change conditions to the 2020 energy system, in a "static" analysis. This implies that the power system operation faces the direct climate impacts, but the longer-term dynamics of new investments (mitigation measures, socio-economic evolutions) and adaptation techniques (cooling technologies in power plants, air conditioning development) are ruled out. We only report the relative differences of electricity production between scenarios that do and do not take climate impacts into account.

In the second part of the study, we use a global climate dataset in order to compares scenarios with climate impacts on the global energy sector with scenarios that only affect the European energy sector; this allows looking at the spill-over effects from the rest of the world on Europe.

In a third section, the POLES model is used in its original setting, with dynamic scenarios up to 2050. Socio-economic conditions follow the Ageing report 2015 and technical developments are in the same line as the GECO 2018 report (Keramidas et al., 2018). The energy sector reacts to climate mitigation policies (efforts are consistent with a 2°C global warming) and climate change (in line with a 2°C world, following RCP 4.5). This includes energy demand adaptation with air conditioning, energy efficiency and energy supply transition to more sustainable technologies (fuel switch, development of renewables, etc.). Only the differences in 2050 between scenarios with and without climate impacts on electricity production are analysed (all else being equal).

Finally, the dynamic scenarios are used with an additional option of cooling technology adaptation for nuclear and other thermal plants. This is used when the corresponding technologies face water constraints. The reported impacts follow the same logic, by comparing in 2050 the results of scenarios with climate change impacts on electricity supply and adaptation with scenarios without climate impacts on electricity production.

A caveat of this analysis is that all climate impacts are applied together, so impacts on individual technologies are not assessed separately. For example, the wind or solar power impacts are negligible when combined with impacts on hydro or thermal plants. The smaller impacts on some technologies do not always show because of the many other impacts:

- other technologies may be more impacted;
- prices and demand also evolve in response to climate impacts on production;
- production has to match demand so some technologies may balance variations of other technologies.

This does not mean that these technologies face no impact, but rather that in the electricity system their impacts are dominated by other impacts.

The intrinsic limitations of the model are its temporal and geographical granularity. The model runs at yearly time-steps, each year being composed of six representative days of unequal weights, driven by different electricity load, wind and solar conditions. The six-day representation therefore introduces some significant variability of the temperatures, wind speeds and water availability, with seasonal characteristics showing. However, the extreme and exceptional events such as droughts and floods are not accounted for; only the more general tendencies are observed (e.g. lower water availability in summer), including a degree of diversity of situations (e.g. summer and winter patterns, days of high electricity demand, days of low wind speeds, etc.).

The geographical representation at the country level also has its limitations. The temperatures, wind speeds and water availability conditions have to be averaged at the country level; using weighting factors allows accounting for the current system geographical distribution. However, this does not consider future evolutions of these distributions (like the position of future plants) nor local meteorological impacts (e.g. local heat wave, wind conditions, floods or droughts).

The consequence of these limitations is that the model cannot assess the climate change impacts of an extreme weather event on a specific plant. What we assess is the evolution of climate impacts linked with tendencies at the seasonal and national scale.

Finally, the climate impacts included needed some modelling simplifications. The following linear approximations were necessary in this exercise:

- Water runoff and hydro production: where saturation and water spillage is assumed proportional to inflow, so that increased water inflow implies increased hydro production;
- Wind speeds and power production: a single wind turbine has a non-linear power curve (with cut-in speed, a cubic relation, a maximum rating and a cut-off speed) but at the national scale and based on daily averages of wind speeds, the relation is more difficult to characterize;
- Irradiation and solar PV production: the heat accumulation at solar panels is not accounted although in practice it could have a multiplier effect on ambient temperatures;
- Air and water temperatures: results show a lower role of water temperatures on thermal production restrictions compared to water runoff, but this result may change with a more precise description of water temperatures.

These approximations are necessary in a long-term energy system model like POLES but could be improved by using inputs from more detailed models, on the technical and geographical description of electric plants.

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