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Securing Austria's Electricity Supply in Times of Climate Change

Demet Suna, Gustav Resch, Franziska Schöniger, Florian Hasengst,
Nicolas-Pardo-Garcia, Gerhard Totschnig, Peter Widhalm,
Herbert Formayer, Philipp Maier, David Leidinger, Imran Nadeem

The research project SECURES (Securing Austria's Electricity Supply in times of Climate Change) analysed challenges and opportunities for the electricity system of tomorrow to ensure a reliable, sustainable and cost-efficient power supply under climate change. Combining detailed climate and energy system modelling with an intense stakeholder dialogue served as a basis for that. The analysis shows that for an adequate modelling of future energy systems, it is highly relevant to consider the effects of climate change, specifically extreme weather events like heat waves.

1 Introduction

The transition of Austria's electricity system towards a safe and sustainable future in times of climate change brings a broad range of challenges and opportunities into the policy debate where timely decisions on the way forward are of key relevance. On the one hand, energy and specifically electricity demand are expected to undergo significant changes through new demand patterns impacted by climate change and increased sector coupling. On the other hand, a significant transformation process is necessary for the supply side to comply with decarbonisation targets. Within Austria as well as the whole European Union, electricity supply will rely on renewable energy sources (RES), serving as key pillar for a carbon-free electricity supply. Austria has for example set a policy target to generate renewable electricity by 2030 to the extent that the national gross electricity consumption is fully covered (at a yearly balance) – cf. the National Energy and Climate Plan (NECP) (BMNT, 2019). Apart from Austria, also the whole European Union (EU) and its energy system face significant challenges as the EU aims to be climate-neutral by 2050, ten years later than Austria.

The planning and operation of electricity systems are increasingly impacted by climate change and meteorological conditions have become more relevant due to increasing weather-dependent RES shares. The project SECURES (Securing Austria's Electricity Supply in times of Climate Change) analysed challenges and opportunities for the electricity system of tomorrow to ensure a reliable, sustainable and cost-efficient power supply under climate change. Geographically the analysis was focused on Austria but involved also other European countries to reflect the interconnected character of Europe's electricity system. Combining detailed climate and energy system modelling with an intense stakeholder dialogue served as a basis for this process.

This paper provides an overview on the approach taken and some key results derived within the SECURES[1] project. The applied structure is as follows: After the introductory part an overview on the methodology is provided (cf. section 2). Next to that follows a detailed reflection on key results and findings, structured alongside the workflow of the project: In section 3, climate change projections and the processing of those, serving as input for the subsequent energy system analysis, are presented. Section 4 subsequently informs on changing patterns in electricity demand and supply driven by climate change whereas the identification of critical system conditions in the electricity sector is already described in the methodology part (section 2). All previous steps serve as basis for the subsequent electricity sector modelling which is presented in section 5. A focus is thereby laid on security of supply aspects, undertaken from a system adequacy perspective. The paper ends with a brief list of conclusions and policy recommendations on the way forward (section 6).

2 Method of approach

2.1 General methods and concepts in SECURES

The work within SECURES builds on a combination of detailed climate and energy system modelling with an intense stakeholder dialogue. It includes an in-depth analysis of structural changes in weather and electricity demand and supply resulting from two climate change projections in combination with decarbonisation pathways. In practical terms, the work in SECURES was clus-

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[1] For further background information on the SECURES project we refer to the project website www.secures.at.

tered into five topical work packages and rested on three key pillars (cf. Figure 1 on the next page). Two electricity sector transformation pathways were defined and several different weather years for the transition of Austria's electricity sector in times of climate change were assessed. The outcomes are published and documented open access. An intense stakeholder consultation was conducted throughout the project, informing on the planned approach, and incorporating their feedback on the definition of scenarios as well as other analytical steps.

Below we provide details on the underlying approach for the individual working steps.

2.2 Methods and concepts in climate modelling

The requirements for meteorological datasets for electricity modelling are high. On the one hand, a high temporal resolution is required, as the typical time step for modelling electricity production and demand is one hour. On the other hand, the European electricity market is highly connected, so pure country-based modelling is not expedient. Additionally, the spatial resolution of the dataset must be able to represent the thermal conditions, which requires high spatial resolution, at least in mountainous regions. All these requirements lead to huge data amounts for historical observations and even more for climate change projections for the whole 21st century. The final outcome of that is a publicly available dataset named SECURES-Met (Formayer et al., 2023).

The historical dataset was created from the hourly resolved 5th Generation of the ECMWF Reanalysis (ERA5) (Hersbach et al., 2020) and ERA5-Land (Muñoz-Sabater et al., 2021). Climate change projections were selected from daily resolved models from the European Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) (Jacob et. al., 2014), with the selection being narrowed by the availability of hydrological data (Donnelly et al., 2016). Two scenarios were selected, one representing a business-as-usual development (Representative Concentration Pathway (RCP) 8.5 – strong climate impacts) and another one representing carbon emissions close to the Paris Agreement (RCP4.5 – moderate climate impacts). Although the change to a new generation of climate models with the new Shared Socioeconomic Pathways (SSPs) recently was done by the community, the lack of regional downscaling with regional climate models led to the decision to keep the older generation with the Representative Concentration Pathways (RCPs).

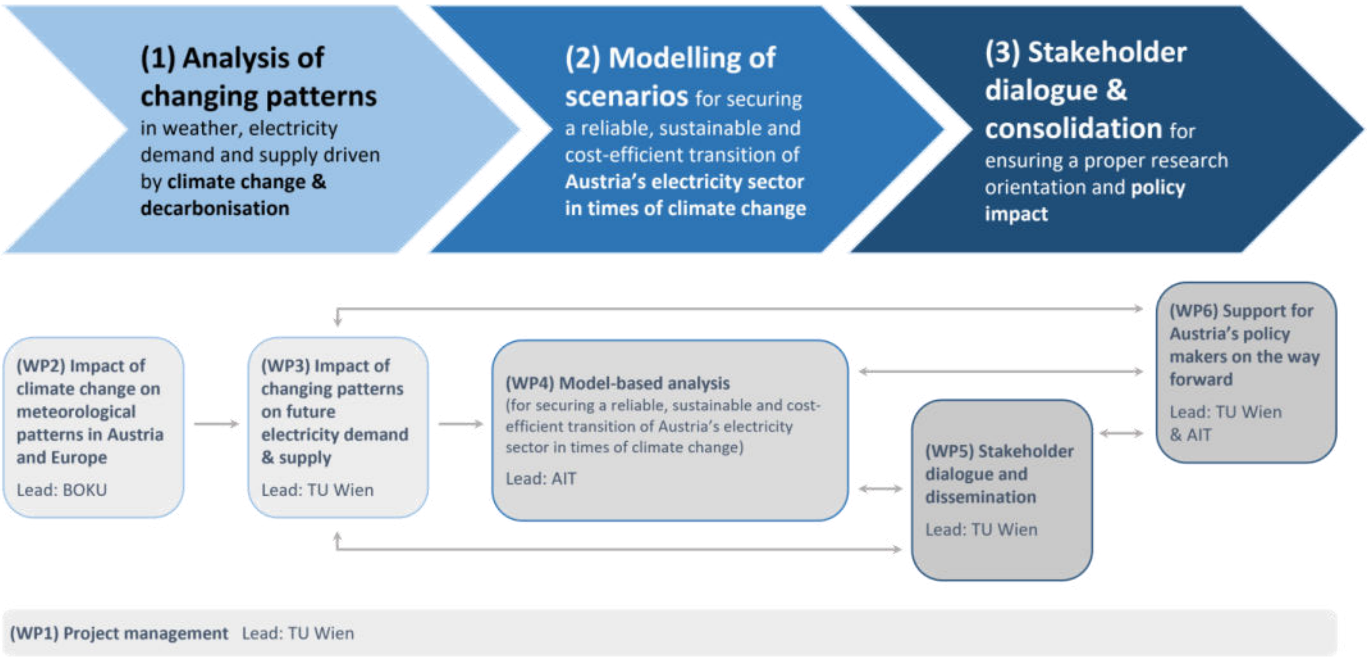


Figure 1: Work structure – the three pillars (and the corresponding work packages) of SECURES. (own elaboration)

All tables and charts in this article are the authors' own productions.

The further comprehensive processing comprised various steps, including for example:

- a conversion ("regridding") in accordance with land use and population data,
- bias corrections using historical data of 1991-2020 from ERA5 and ERA5-Land via a quantile-mapping procedure that adjusts the distribution of the models to the historical climatology and their quantiles (Lehner et al., 2023),
- a temporal disaggregation from daily to hourly data, using statistical approaches, and
- individual processing steps for solar radiation, wind and hydro as described in the Final Report of the SECURES project (Schöniger et al., 2023)

Finally, geographically detailed climate data had to be aggregated again to allow for the further use in energy system modelling where individual countries are typically represented by one single node (NUTS0).

2.3 Methods and concepts in energy system modelling

At the energy side, various steps are required to conduct the analysis of both the decarbonisation needs and the climate impacts on Austria's electricity sector of the future, embedded in the European context. Below we describe the approach taken for the individual steps in further detail.

2.3.1 Assessing climate change impacts on future electricity demand and supply

Since meteorological parameters cannot be used directly in energy system modelling, a conversion to supply and demand profiles as commonly applied in energy system models is required. Thus, based on the meteorological variables derived from the two climate scenarios (cf. section 2.2), the dataset SECURES-Energy was created. This dataset contains hourly weather-dependent electricity generation and demand profiles that can be used in energy system modelling. In practical terms, the hourly time series of these climate data were retrieved and further converted to electricity demand and supply profiles.

On the generation side, generation profiles of wind power, hydropower (run-of-river (RoR) and reservoir), and solar photovoltaics (PV) were generated. Additionally, the impact of temperature on thermal power plant efficiency was considered. On the demand side of the system, electricity demand profiles for heating, cooling, and e-mobility charging were generated. Details on the approach taken for that purpose are described in the Final Report of the SECURES project (Schöniger et al., 2023).

2.3.2 Definition of scenarios for the electricity sector transformation

The main aspect of scenario design comprised the combination of energy transition pathways for Austria/Europe up to 2050 with appropriate climate scenarios formed from simulations in accordance with the two RCPs. Accordingly, **two distinct energy transformation pathways** have been identified – i.e., a Reference (REF) and a Decarbonisation Needs (DN) pathway for the focal years 2030 and 2050:

- For the REF pathway and corresponding scenarios, Austrian and EU-wide existing measures and goals, including 2030 emissions targets, were considered as identified in the national trends scenario of TYNDP2022 (ENTSO-E and ENTSOG, 2022). It relies on the 100% RES-based electricity system for Austria by 2030 (national balance sheet). However, it represents less decarbonisation ambition in other sectors and EU countries and is accordingly expected to match with a strong climate change scenario (RCP 8.5).

- On the contrary, the DN pathway represents a strong decarbonisation ambition across the whole EU based on Resch et al. (2022) and was coupled with a medium climate change scenario (RCP 4.5). Here, the measures are considered to achieve full decarbonisation by 2050. That implies a strong sector-coupling and decarbonisation of other sectors, such as industry and mobility.

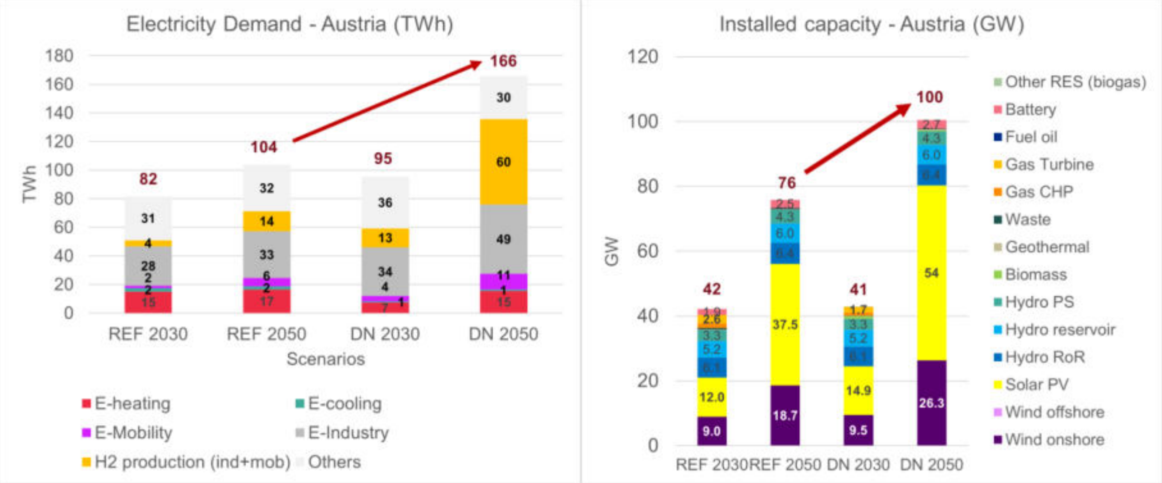
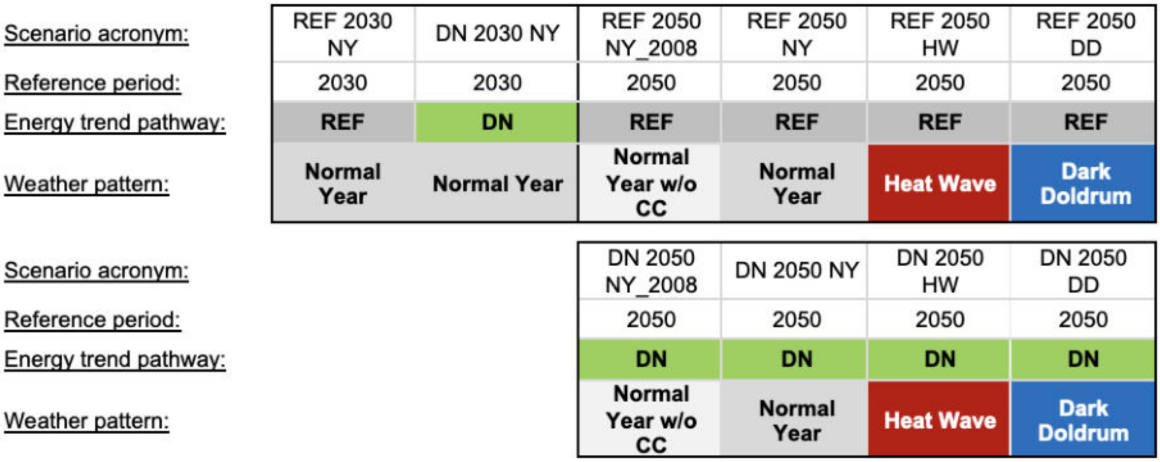


Figure 2: Default demand (left) and capacity projections (right) for Austria according to SECURES energy transformation pathways (REF and DN). (own elaboration)

Figure 2 illustrates the demand (left) and installed capacity (right) projections for Austria for both the REF and DN pathways. Due to the strong sector coupling and electrification driven by decarbonisation, electricity demand in the DN scenario is forecasted to increase by approximately 70 TWh in 2050 compared to the REF. This demand is expected to be met by about 24 GW of additional capacity, mainly stemming from PV and wind. Since the overall assessment focused on supply security for both pathways described above, for the mid-future (2050), Security of Supply variants were analysed as well, assuming extreme weather conditions (i.e., dark doldrums and heat waves) in accordance with climate data coupled with conservative assumptions for critical system bottlenecks.

Table 1 presents an overview of all modelled scenarios. In this analysis, the term “scenario” is used to refer to the modelling of a full calendar year (according to climate/weather data provided on an hourly basis) in combination with a specific trend path for the transformation of the energy sector, i.e. REF or DN. In terms of time, the study analysed two key years that represent distinct levels of transformation: the near future (2030) and the mid-future (2050). According to the DN pathway, the transformation process would be completed by 2050, resulting in complete decarbonisation of both the energy sector and the wider economy. Climate impacts are presented for various weather years in 2050 scenarios, including a typical year and two extreme years, which are years with either a dark doldrum or a heat wave.

Table 1: Overview of assessed scenarios (own elaboration)



Scenario acronym:	REF 2030 NY	DN 2030 NY	REF 2050 NY_2008	REF 2050 NY	REF 2050 HW	REF 2050 DD
Reference period:	2030	2030	2050	2050	2050	2050
Energy trend pathway:	**REF**	**DN**	**REF**	**REF**	**REF**	**REF**
Weather pattern:	**Normal Year**	**Normal Year**	**Normal Year w/o CC**	**Normal Year**	**Heat Wave**	**Dark Doldrum**

Scenario acronym:	DN 2050 NY_2008	DN 2050 NY	DN 2050 HW	DN 2050 DD
Reference period:	2050	2050	2050	2050
Energy trend pathway:	**DN**	**DN**	**DN**	**DN**
Weather pattern:	**Normal Year w/o CC**	**Normal Year**	**Heat Wave**	**Dark Doldrum**

2.3.3 Approach for the identification of critical system conditions

In SECURES, the possible critical weather years for modelling were observed and identified from two different perspectives. Firstly, this was analysed from a meteorological point of view, where the choice of extreme and reference years was mainly determined by temperature patterns, and secondly, from an energy system point of view, where the indictor residual load (RL) was used. RL represents the difference between demand and variable weather-dependent RES, including solar PV, wind and hydro RoR. The negative RL indicates a surplus generation, whereas the positive RL implies the generation deficit. Here, RL is calculated for each month and the critical RL years were compared with the meteorological extreme years.

Apart from the electricity generation profile of variable RES, RL is the key parameter for identifying extreme events from the power system perspective. Following the method outlined by Dawkins and Rushby (2021), some primary indicators were calculated per country, as well as the EU and Central Europe to identify extreme weather events from the power system perspective, of which one was of key relevance for further elaborations:

Peak Periods of Residual Load (PPRL): Identified periods where, over a time span larger than seven days, the average weekly RL (sliding average of 7 days) is above its 80th percentile of the positive RL (representative for dark doldrums and/or heat waves).

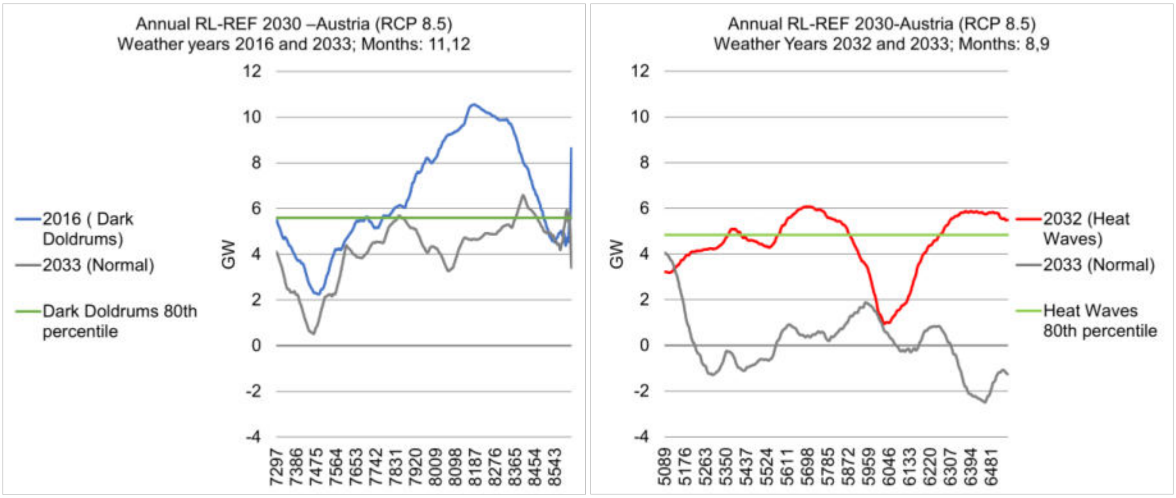


Figure 3: Representation of Peak Periods of Residual Load (PPRL) in the case of REF-2030 by considering RCP 8.5. (own elaboration)

The indicator PPRL was then used to identify the weather years used for the energy system modelling: One normal and two extreme years (with either a dark doldrum or a heat wave) were proposed for the RCP 4.5 (for DN scenarios) and RCP 8.5 (for REF scenarios), which were considered to create stress events from a system perspective, cf. Figure 3. For the selection of weather years, this indicator was not only considered for Austria but also for Central Europe, with which Austria’s power system is strongly interconnected. The overlap of the identified weather years for the energy system modelling from an energy system point of view and identified from a purely meteorological point of view was high. Table 2 shows the final list of selected weather years for the energy system modelling scenarios.

Table 2: Selected weather years based on residual load analysis & duration of Peak Periods of Residual Load (PPRL) (own elaboration)

RCP4.5 **(DN Scenarios)**	**2030**	**2050**
Representative year (Normal)	**2043**	**2062**
Heat Wave	**2028** (23 days starting in week 27)	**2046** (week 38 and 39)
Dark Doldrums	**2037** (50 days starting in week 1)	**2037** (49 days starting in week 2)
RCP8.5 **(REF Scenarios)**	**2030**	**2050**
Representative year (Normal)	**2033**	**2049**
Heat Wave	**2032** (14 days starting in week 38)	**2057** (40 days (CEU) starting in week 31)
Dark Doldrums	**2016** (9 days starting in week 3; 30 days starting in week 47)	**2047** (17 days (CEU) starting in week 47)

2.3.4 Methods and tools used in electricity sector modelling

For the modelling, the open-source **energy system modelling tool Balmorel** (Ravn, 2016) was used. This model is a partial equilibrium model for analysing the electricity and district heat from an integrated perspective. In this study, the base model structure was extended with different flexibility options.

Geographically, modelling covered Austria and other European countries (i.e., EU plus Switzerland, Norway and the United Kingdom) to accurately represent the interconnectivity of Europe's electricity system. Timewise, a focus was put on specific years in the near (2030) and mid-future (2050) whilst modelling was conducted for the whole year at an hourly resolution. The scenario design focused on combining two distinct energy sector transformation pathways (cf. section 2.3.2) for Austria/Europe up to 2050 alongside the two climate scenarios described above.

The analysis centred around the security of supply aspects, specifically related to system adequacy, done via an **assessment of future system flexibility needs** to achieve a proper match between demand and supply during all time steps, i.e., during all hours of the modelled years. Apart from the identification of the demand for flexibility, modelling also showed how that flexibility can be provided in a cost-effective manner. Thus, additional investments in certain flexibility options at the supply and the demand side as well as for storage and, to a limited extent, for the cross-border grid infrastructure to enable cross-border electricity exchange were allowed model-wise, with differences between scenarios and years:

- Flexible generation technologies: Combined heat and power (CHP) and thermal power plants (natural gas, biomass, and other power plants, including biogas engine and waste incineration),
- Curtailment to manage oversupply (PV, wind, hydropower plants),
- Transmission network (cross-border exchange) (no (2030) or limited (2050) extension, i.e. at max. +20% above planning) (ENTSO-E and ENTSOG, 2022),
- Load management via Power-to-Heat (P2H) (electric boilers and heat pumps in district heating and in decentralized buildings) (30%/7 5% flexible operation in 2030/2050),
- E-mobility (25%/75% flexible charging in 2030/2050),
- Industrial load management (5%/10% flexible operation in 2030/2050),
- Power-to-Gas (Hydrogen): electrolyser, H2 storages and re-electrification,
- (Pumped) hydropower storage plants (no extension beyond planned according to ENTOS-E and ENTSOG [2022]),
- Lithium-ion batteries and prosumers.

For the **definition of flexibility**, we followed the approach of Suna et al. (2022) who define flexibility as *"the capability to promptly (i.e., within one hour) change the generated or consumed electricity at a defined network node"*. Accordingly, we assessed flexibility needs and their coverage on the power system level (short-term, i.e., balancing hourly fluctuations within a day) and on the energy system level (incl. medium-term, i.e., balancing daily and weekly fluctuations, and long-term, i.e., balancing monthly fluctuations). This helped to elaborate on security of supply aspects at a system level and allowed for identifying key system assets for achieving the match between demand and supply under the considered time scales and system boundaries. Consequently, please note that flexibility for voltage or for solving grid congestions are not part of our study.

3 Climate change projections data

A comprehensive meteorological dataset (SECURES-Met) for Austria and Europe specifically designed for that purpose was created by an iterative creative process between meteorologists and energy modellers to fit energy modelling requirements (NUTS0-NUTS3 level, hourly resolution).

SECURES-Met (Formayer et al., 2023) covers the years 1981-2020 for the historical period and up to 1981-2100 for two GHG-emission scenarios, i.e., one with moderate (RCP 4.5) and one with stronger climate impacts (RCP 8.5). Derived variables include temperature, radiation, wind power and hydropower potential (separated into run-of-river (RoR) and reservoir).

4 Changing patterns of electricity Supply and Demand Driven by Climate Change

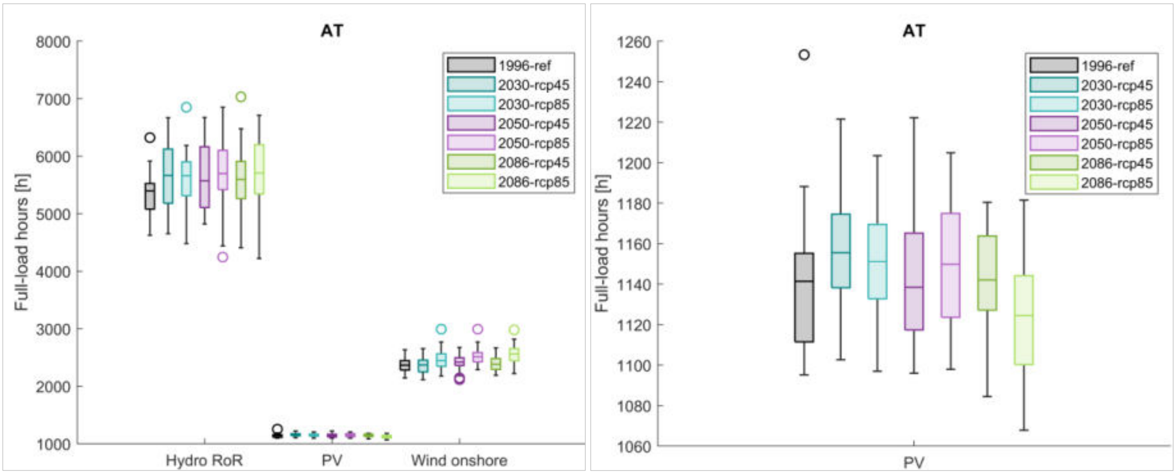
Hourly profiles of weather-dependent supply and demand components for solar, onshore and offshore wind, hydro reservoir, and hydro RoR generation were generated using meteorological variables obtained from two different climate scenarios. Also, hourly e-heating, e-cooling, and e-mobility demand profiles for the years 2011-2100 were obtained. These data formed the basis for the subsequent energy system modelling.

The development of full-load hours (FLH) of the different renewable generation technologies wind, RoR hydropower, and solar PV for Austria were analysed based on their hourly profiles until 2100. The following figures show the impact of climate change over time (2030, 2050, and 2086) and the differences between the two climate scenarios (RCP4.5 and RCP8.5). Each box represents the 30 weather years around the target year. The data for the reference period is based on the years 1981-2010 of ERA5(-Land).

The highest interannual variability is observed for RoR hydropower, while onshore wind and especially PV show lower interannual variability, cf. Figure 4, panel (a). The interannual variability of PV and the number of FLH (Figure 4, panel (b)) show no clear trend for PV in Austria in the considered climate scenario (based on the 30 weather years around the target year). In the historical period (1981-2010), one year with exceptionally high FLH is visible, which represents the very hot summer in 2003 in the ERA5-Land data.

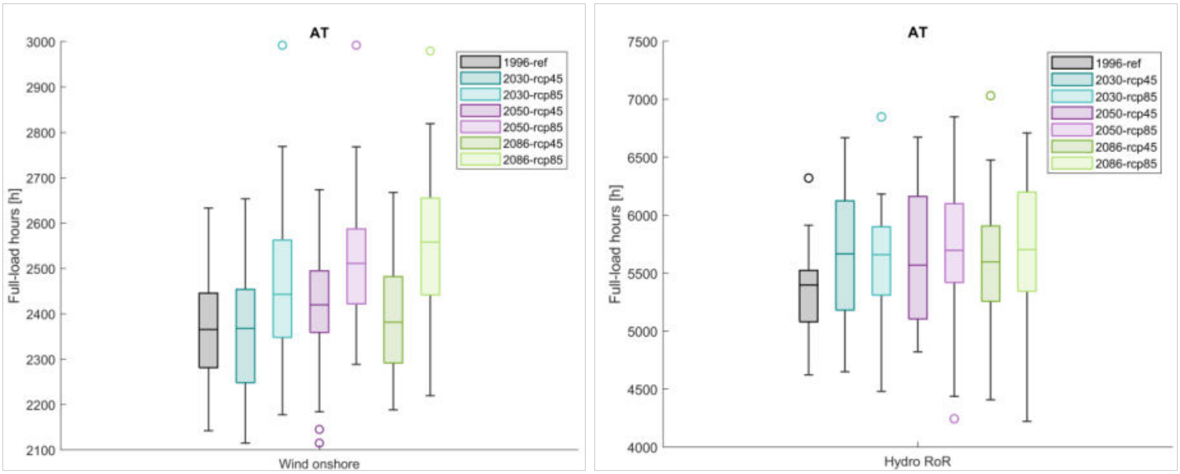
For onshore wind (Figure 5, panel (a)), no clear trend of interannual variability and number of FLH is observed in the RCP 4.5 scenario. In the RCP 8.5 scenario onshore wind FLH are higher than in the RCP 4.5 scenario in Austria in the two analysed climate scenarios.

For RoR hydropower (Figure 5, panel (b)), no clear trend regarding the FLH can be observed, with the median of FLH in the considered climate scenarios being slightly higher than in the reference period. The interannual variability increases, especially after the mid of the century in the climate scenarios. In literature, the projections of climate change on hydro RoR FLH are heterogeneous depending on the considered climate scenarios, as some former studies using older generations of climate scenarios showed decreasing FLH for RoR hydropower in Austria (Totschnig et al., 2017).



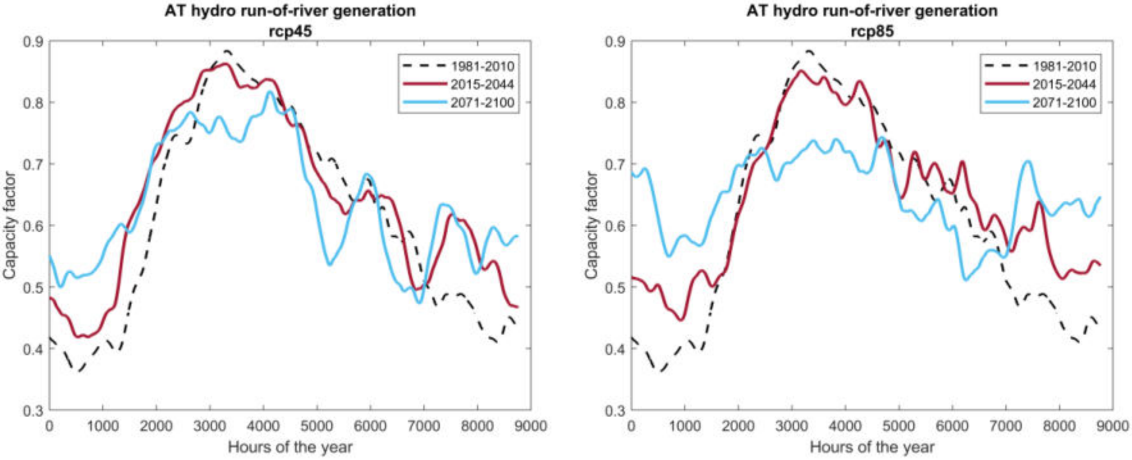
a) b)

Figure 4: Development of FLH of RoR hydropower, PV, and onshore wind (panel (a)) and PV in greater detail (panel (b)) in Austria in the two considered climate scenarios (RCP4.5 and RCP8.5) compared to the reference period (1981-2010); each box represents 30 weather years around the target year; the reference period is based on ERA5-Land. (own elaboration)



a) b)

Figure 5: Development of FLH of onshore wind (panel (a)) and RoR hydropower (panel (b)) in Austria in the two considered climate scenarios (RCP4.5 and RCP8.5) compared to the reference period (1981-2010); each box represents 30 weather years around the target year; the reference period is based on ERA5-Land. (own elaboration)

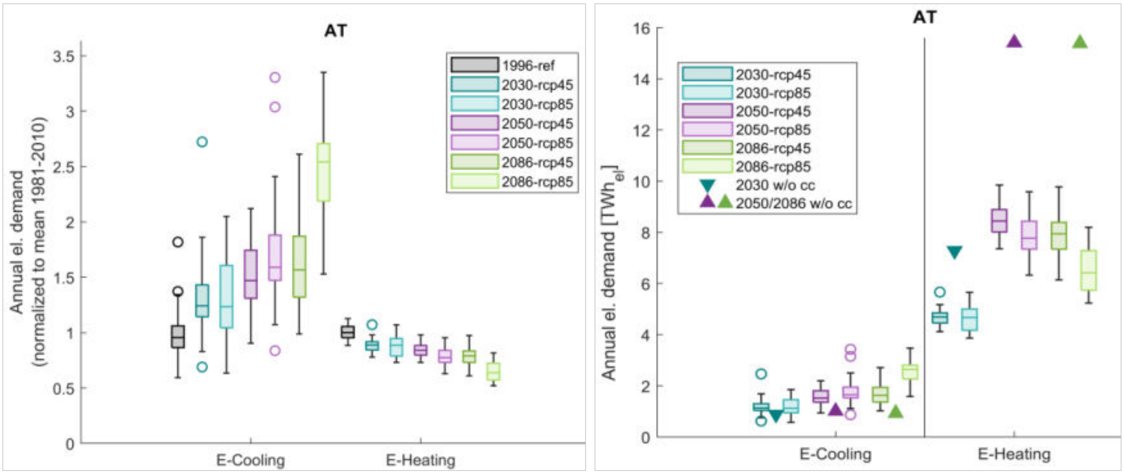


a) b)

Figure 6: Development of seasonal generation patterns of run-of-river hydropower in Austria in two emission scenarios (Panel (a): RCP4.5, Panel (b): RCP8.5) compared to the reference period 1981-2010 based on ERA5-Land.

Climate change impacts the seasonal patterns of RoR hydropower in Austria (cf. Figure 6). There is a seasonal shift towards earlier runoff in spring with ongoing climate change, accompanied by reduced generation in summer and increased generation in winter. This change is partly due to changing precipitation patterns, with rain replacing snowfall during winter, leading to higher winter runoff and reduced snowmelt in spring.

On the demand side, a decrease of the annual heating demand (up to -50% compared to the reference period in the RCP8.5 scenario at the end of the century) and an increase of the cooling demand (up to +350% compared to the reference period in the RCP8.5 scenario at the end of the century) are projected with increasing climate impacts in Austria (cf. Figure 7).



a) b)

Figure 7: Panel (a): Development of e-heating and e-cooling demand in Austria (normalized to the mean of the reference period 1981-2010); each box represents 30 weather years around the target year; the reference period is based on ERA5-Land; Panel (b): Absolute values according to the DN scenario; the reference demand without additional climate change (triangles) would be the demand in a 2030/2050 energy system but based on the mean temperatures 1981-2010 of ERA5-Land. For 2050 and 2086, the same energy system is assumed (full decarbonisation). (own elaboration)

The difference between the two emission scenarios becomes notably clear towards the end of the century. The median level of cooling demand in the RCP8.5 scenario already reaches a level in the period 2035-2064 that is not reached until 2071-2100 in the RCP4.5 scenario. The seasonal shift due to the increase of demand during summer and the decrease during winter correlates to the seasonal pattern of solar PV and (historical) patterns of hydropower generation and may consequently reduce the need for seasonal storage in the electricity system in Austria.

5 Results from the Electricity sector modelling

This section is dedicated to the results of the energy system modelling with particular emphasis on Austria's electricity sector, embedded in an interconnected European market and its growing importance within the whole energy system along the way towards decarbonisation. As described above, a broad set of scenarios has been modelled: Two distinct pathways on the energy system transformation (REF, DN) have been assessed for two focal points in time (2030, 2050). The year 2050 appears of particular interest since it marks the end date for full decarbonisation in Europe under the DN pathway.

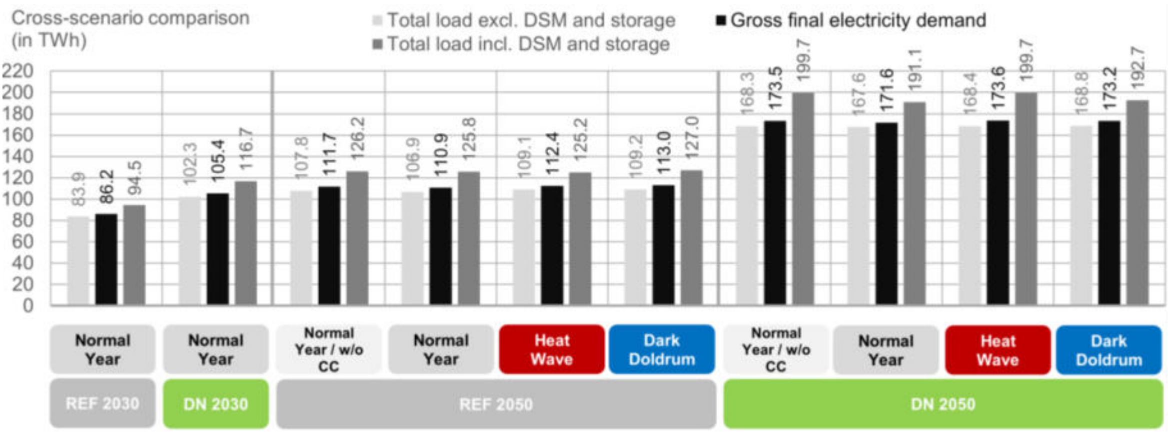


Figure 8: Comparison of electricity demand (with and without additional demand components for storage and DSM) in Austria across assessed scenarios by 2030 and 2050. (own elaboration)

Figure 8 provides a comparison of **electricity demand** (with and without additional demand components for storage and demand-side management (DSM)) for assessed scenarios by 2030 and 2050. It shows the challenges that come along with the energy transition that is indispensable from a climate and societal perspective. Gross final electricity demand is expected to grow by 55% by 2050 compared to today (2021) in REF, whereas the DN pathway implies a growth of 140%. As stated previously, the higher demand for electricity is driven by sector coupling and the ongoing electrification that comes along with decarbonising energy services in transport and industry.

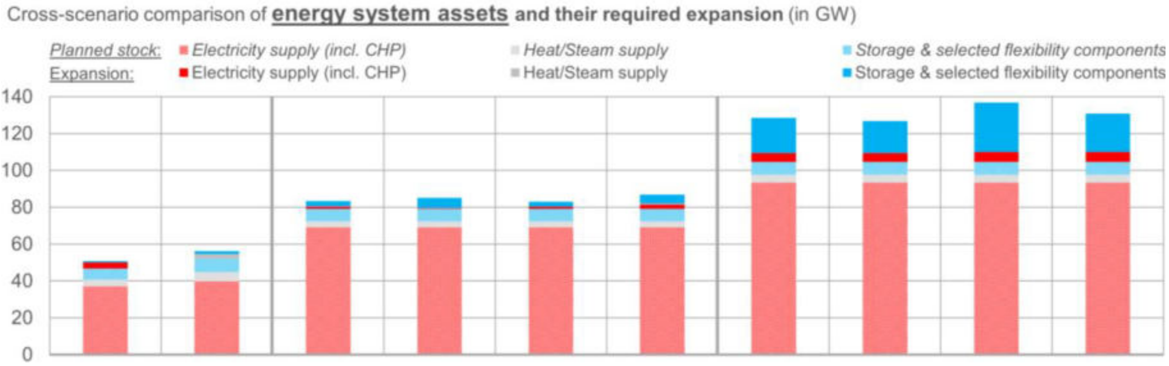
How does climate change impact the above? On the demand side, for normal weather conditions, aggregated impacts appear marginal, partly due to the compensating effects of heating and cooling and partly due to the comparatively low share of weather-dependent load in overall electricity demand in decarbonised energy systems. Thus, only small differences are applicable between default electricity demand also when considering additional demands for storage or for demand response measures. Extreme weather events like heat waves or dark doldrums affect that situation. At a yearly balance, corresponding increases in demand (compared to a normal year) are comparatively small, ranging from 1% to 2%, but during the affected time periods within a year, a demand increase of 4% to 11% is observable in the underlying load pattern.

Next, we present a focus on the **supply side and other system assets** like storage systems that provide the required flexibility to Austria's electricity system for a proper match between demand and supply. In this context, Figure 9 illustrates how the climate mitigation ambition (REF vs. DN) and climate-driven weather impacts affect the (ideal) stock of energy system assets in future. In modelling, on top of the planned stock of generation and storage assets, additional investments in certain flexibility options were allowed (cf. section 2.3.4). Accordingly, Figure 9 offers a cross-scenario comparison of these assets and thereby undertakes a distinction between their planned uptake and the required expansion.

Comparing DN and REF, a significantly stronger uptake of assets on the supply side is applicable, specifically in wind and PV. Thus, under normal weather conditions, the total stock of electricity generation assets is about 40% higher in DN compared to REF. With higher amounts of weather-dependent generation, short-term fluctuations in electricity generation grow, requiring large amounts of system flexibility to ensure the match between demand and supply in every hour. A comparison between DN and REF indicates the significantly larger amount of flexible storage, generation and demand assets required by 2050. According to modelling, the total stock of storage and selected demand-side flexibility components in capacity terms is then ca. 170% higher in DN than in REF.

Concerning climate change impacts on the supply side, high interannual variations are visible and impacts are highly dependent on the chosen weather year. For normal weather conditions, wind and RoR hydropower show a slightly higher annual generation, whereas, for solar PV, negligible differences are observable in the modelled normal weather years in line with the long-term climate projections.

Of key importance for the analysis of climate impacts is the **consideration of extreme weather events** since, with ongoing climate change, the frequency and duration of such events increase according to climate data (Formayer et. al., 2023). In our analysis, a heat wave and a dark doldrum serve as a stress test for security of supply. Results from 2050 DN scenarios show that for safeguarding electricity supply under assessed extreme conditions, in comparison to a normal weather year neglecting climate impacts, a stronger uptake of wind energy by 20% appears useful from a least-cost system perspective. Investments in wind thereby replace those in green gas assets, as applicable in scenarios related to normal weather conditions. For storage and demand-side flexibility assets, there are both similarities and differences between a heat wave and a dark doldrum: For both events, modelling suggests increasing the H_2 electrolyser stock by 72-74% (compared to a normal year neglecting climate impacts) as well as accompanying H_2 storage, allowing a system-friendly operation of the electrolyser fleet. In a dark doldrum, thermal storage is found to be useful for load shifting at both the heat and the electricity side as a consequence of increased sector coupling via heat pumps or CHP. In the case of a heat wave, when hydro and wind generation is generally low, batteries are the key system asset since they help to shift the high PV infeed during daytime into evening hours when the sun is not shining.



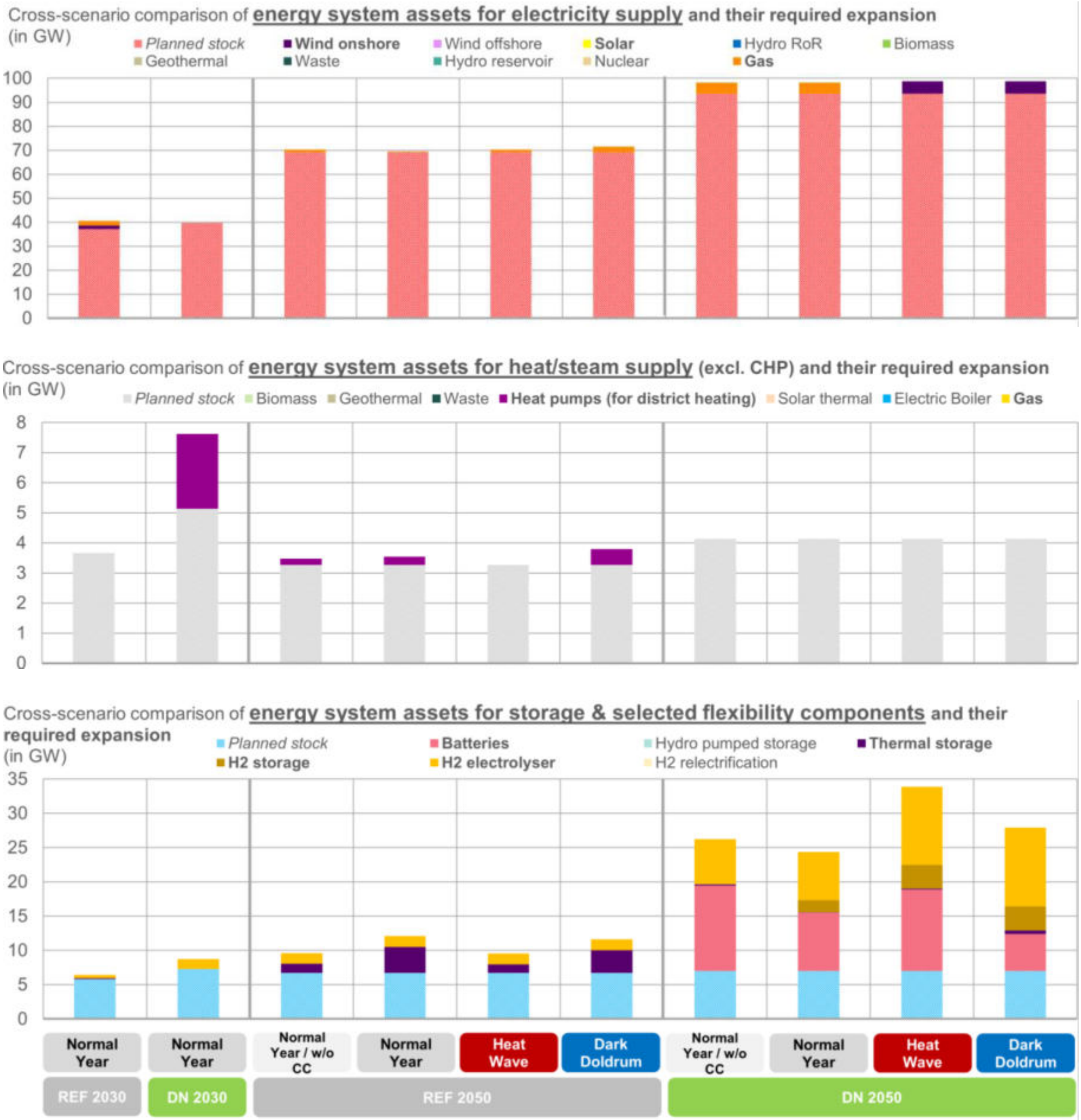


Figure 9: Comparison of Austria's energy system assets and their required expansion in aggregated terms (top), for electricity supply, heat/steam supply and for storage & other selected flexibility components (bottom) across scenarios by 2030 and 2050. (own elaboration)

Next, Figure 10 compares the identified **flexibility needs**, broken down by time period for all assessed scenarios and years (2030, 2050). A strong increase of flexibility needs is applicable when comparing 2030 and 2050 as well as with growing decarbonisation ambition (REF vs DN). For mid- to long-term flexibility, the increase is in accordance with demand growth. Short-term flexibility is, however, growing faster – here, the significant uptake of variable RES plays a key role. Complementarily, Figure 11 informs on the provision of flexibility broken down by time period for the assessed scenarios.

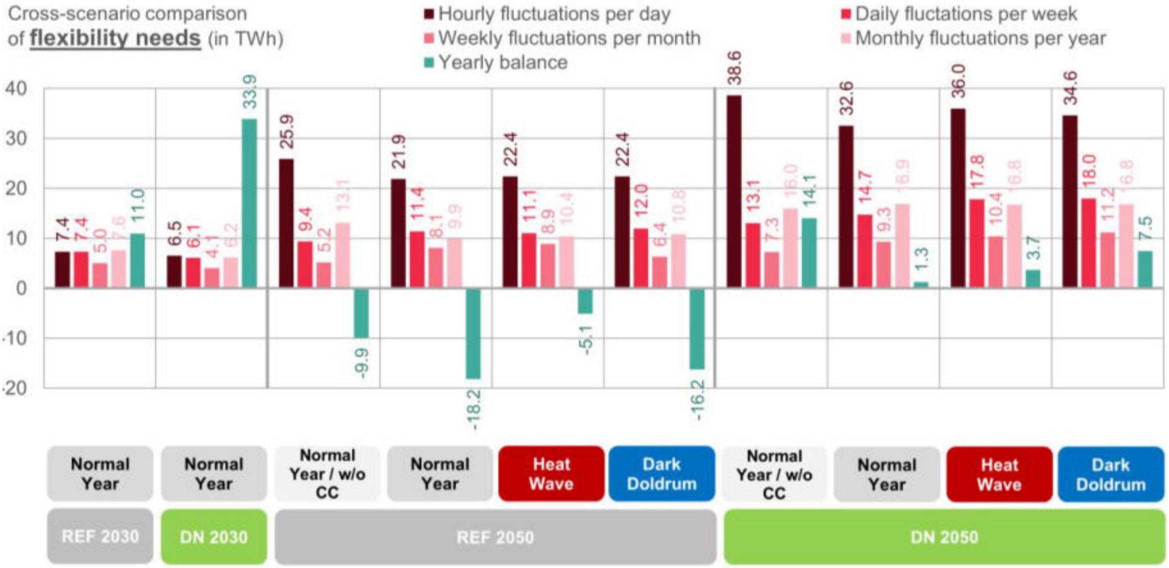


Figure 10: Cross-scenario comparison of flexibility needs under different time periods within Austria's future electricity system by 2030 and 2050. (own elaboration)

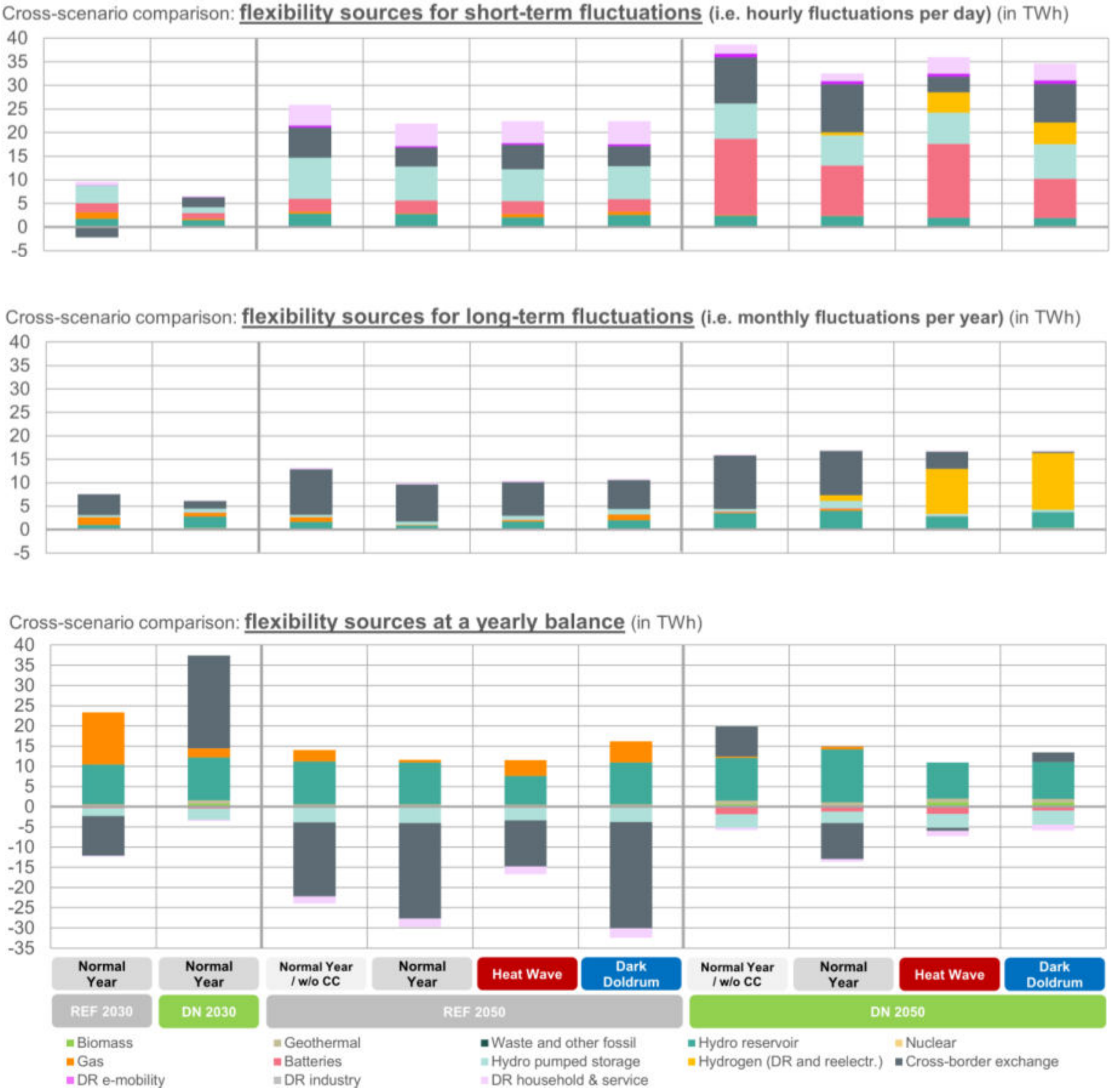


Figure 11: Cross-scenario comparison of the contribution of flexibility sources to cover needs at selected distinct time periods, short-term and long-term fluctuations as well as at a yearly balance within Austria's future electricity system by 2030 and 2050. (own elaboration)

According to the modelling, the following patterns were identified:

- Demand response in households, services, and industry, as well as in e-mobility, contributes to balancing short-term fluctuations in the RL.
- Batteries show a similar pattern as flexible consumers, helping to cope with massive short-term fluctuations, specifically under the DN pathway. They are an essential asset in extreme weather events like heat waves.
- Hydro reservoirs and Pump Storages (PS) allow for flexible use in all time ranges. Usage patterns show that for PS, the contribution is typically higher in the short to medium term, whereas for reservoirs, the opposite trend is applicable, helping to cover seasonal imbalances and the yearly RL balance. Both are relevant to cope with extreme weather events.
- Cross-border exchange of electricity remains a central pillar of flexibility in Austria's future electricity market, both to utilise surpluses and to compensate for deficits. In modelled years of extreme weather events, their contribution is, however, smaller than under normal weather patterns.
- Thermal storage and H_2 storage are essential system components of a decarbonised Austrian energy system. Specifically, H_2 storage units allow for a flexible and system-friendly operation of H_2 electrolysers, which, in turn, help to cover flexibility needs at various time scales and during critical weather extremes.

6 Conclusions and recommendations

The analysis shows that for an adequate modelling of future energy systems, it is highly relevant to consider the effects of climate change. The consideration of extreme events is crucial for planning a resilient energy system in the future, not only for Austria but also for Europe since both the short- and the long-term flexibility needs are strongly affected by changing weather patterns. The following recommendations can be derived:

- For enhancing the energy transition towards decarbonisation, strong investments in energy system assets are indispensable, be it at the generation, demand or storage side or concerning grid infrastructure. This has been demonstrated by the modelling undertaken in the SECURES project. Specifically, storage and the inclusion of the demand side appear of key relevance to safeguard the match between demand and supply in the electricity sector during all time steps.
- To best cope with future climate impacts, it is necessary to make Austria's electricity sector future-proof and climate-ready. In future years, most of the electricity supply within Austria as well as in other parts of Europe will rely on weather-dependent renewable energy sources like wind, solar, or hydro. Thus, in practical terms, this implies considering for planning purposes not only default weather conditions. Instead coping with extreme weather situations, specifically heat waves and dark doldrums, shall become the new standard in energy system planning.
- Apart from investments in various system assets, it is a key necessity to establish markets and include an increasingly broad set of actors. Today there is a gap in markets for flexibility services. Once established, rules for the participation of various market actors need to be simple and transparent for enlarging the outreach.

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