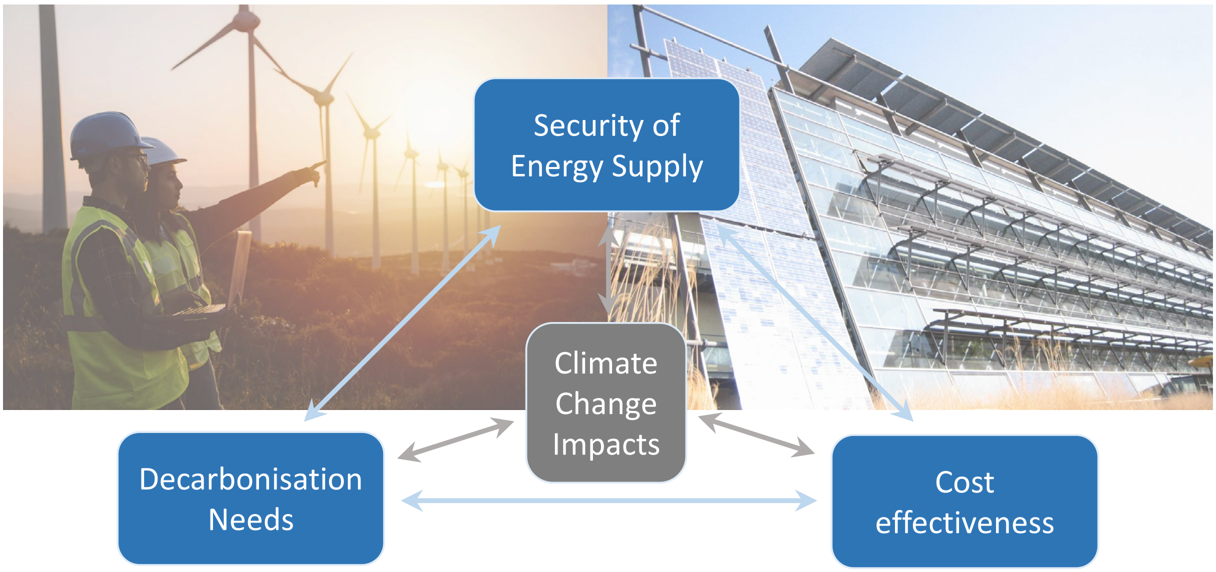
SECURES

SECURING AUSTRIA'S ELECTRICITY SUPPLY IN TIMES OF CLIMATE CHANGE



Final Report

Vienna, October 2023

The project SECURES was funded by the **Austrian Climate and Energy Fund** (Klima- und Energiefonds) under project number KR19AC0K17532.

Consortium

Franziska Schöniger
Florian Hasengst

Demet Suna
Gustav Resch
Nicolas Pardo-Gárcia
Gerhard Totschnig
Peter Widhalm

Herbert Formayer
Philipp Maier
David Leidinger
Imram Nadeem

Citation: Schöniger, F., Resch, G., Suna, D., Formayer, H., Pardo-Garcia, N., Hasengst, F., Totschnig, G., Maier, P., Leidinger, D., Nadeem, I. & Widhalm, P. (2023): Securing Austria's Electricity Supply in times of Climate Change; Final report of the ACRP12 project SECURES (2020-2023).

An updated list of project-related publications is available at: https://www.secures.at/publications

The project SECURES was funded by the **Austrian Climate and Energy Fund** (Klima- und Energiefonds) under project number KR19AC0K17532. Note: This final report version has not yet been approved by the Climate and Energy Fund (13th October 2023).

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Kurzfassung

Der Klimawandel beeinflusst zunehmend die Planung und den Betrieb von Stromsystemen, da dessen Auswirkungen einerseits intensiver, andererseits die Wettereinflüsse aufgrund des steigenden Anteils erneuerbarer Stromerzeugung immer relevanter werden. Das Projekt SECURES (Securing Austria's Electricity Supply in Times of Climate Change) analysierte Herausforderungen und Chancen für das zukünftige Stromsystem Österreichs in Zeiten des Klimawandels und der Dekarbonisierung.

In einem interdisziplinären Ansatz zwischen Energie- und Klimamodellierung wurde ein umfassender meteorologischer Datensatz (SECURES-Met) für Österreich und Europa erstellt, um den Anforderungen der Energiesystemmodellierung gerecht zu werden (NUTS0-NUTS3-Ebene, stündliche Auflösung). SECURES-Met deckt die Jahre 1981–2020 für den historischen Zeitraum und bis 1981–2100 für zwei Treibhausgasemissionsszenarien ab (RCP 4.5/8.5). Basierend auf den untersuchten meteorologischen Variablen Temperatur, solare Einstrahlung sowie Windkraft- und Wasserkraftpotenzial, wurden stündlichen Profile aller relevanten, wetterabhängigen elektrischen Erzeugungs- und Nachfragekomponenten abgeleitet. Weiters wurden Extremereignisse und Wetterjahre aus meteorologischer und energiesystemischer Sicht identifiziert und verglichen. Diese Profile (SECURES-Energy) bildeten die Grundlage für die durchgeführte Energiesystemmodellierung und können an viele weitere Kontexte angepasst werden. In den betrachteten Emissionsszenarien zeigt sich kein starker Trend bzgl. der Volllaststunden von Solar-, Wind- und Laufwasserkraft in Österreich. Die stärkste interannuelle Variabilität der Volllaststunden jetzt und in der Zukunft wurde für die Laufwasserkraft beobachtet, wobei diese mit zunehmendem Klimawandel in Österreich steigt. Darüber hinaus zeigte sich aus den Klimaprojektionen, dass die Laufwasserkrafterzeugung im Sommer ab- und im Winter zunimmt, was eine Abflachung des saisonalen Profils und des damit verbundenen Speicherbedarfs im Vergleich zu heute bedeutet. Am Ende des Jahrhunderts (2071-2100) wird ein stark sinkender Wärmebedarf (-35 %) und ein stark steigender Kühlbedarf (+144 %) im starken Emissionsszenario (RCP 8.5) im Vergleich zum Referenzzeitraum (1981-2010) sichtbar (reines Temperatursignal). In den Szenarien nehmen kritische Residuallastsituationen im Sommer zu, was die steigende Bedeutung von Hitzewellen zeigt, während im mitteleuropäischen Stromsystem weiterhin mit den meisten kritischen Situationen im Winterhalbjahr zu rechnen ist.

Geografisch und zeitlich umfasste die Energiesystemmodellierung Österreich und Europa in der nahen (2030) bis mittleren Zukunft (2050). Der zentrale Aspekt der Szenariogestaltung bestand in der Kombination zweier unterschiedlicher Energiesektorpfade für Österreich/Europa bis 2050 mit den oben beschriebenen Klimaszenarien. Im Referenzpfad (REF) und entsprechenden Szenarien strebt Österreich eine erneuerbare Stromversorgung bis 2030 und darüber hinaus an. Allerdings repräsentiert er in anderen Sektoren und EU-Ländern geringere Dekarbonisierungsambitionen und geht dementsprechend mit einem starken Klimawandelszenario einher (RCP 8.5). Der Decarbonisation Needs (DN)-Pfad stellt ein starkes Dekarbonisierungsziel in der gesamten EU dar und impliziert Netto-Null bis 2050. Folglich wird ein starkes Wachstum der Stromnachfrage erwartet, angetrieben durch eine starke Sektorkopplung zur Dekarbonisierung anderer Sektoren wie Industrie und Mobilität. DN wurde mit einem mittleren Klimawandelszenario (RCP 4.5) gekoppelt. Aufgrund des analytischen Schwerpunktes auf der Versorgungssicherheit wurden für beide beschriebenen Pfade zusätzlich Wetterjahre analysiert, die extreme Wetterbedingungen (z. B. Dunkelflaute und Hitzewellen) für die mittlere Zukunft (2050) widerspiegeln.

Ein Vergleich der Ergebnisse beider Energiesektorpfade (REF vs. DN) zeigt, welche Herausforderungen die aus klimatischer und gesellschaftlicher Sicht unverzichtbare Energiewende mit sich bringt. In REF steigt der Bruttoendstrombedarf bis 2050 im Vergleich zu heute (2021) um 55 %, während der DN-Pfad ein Wachstum von 140 % impliziert. Folglich ist auch ein deutlich stärkerer Ausbau von Wind und Photovoltaik (PV) auf der Erzeugungsseite notwendig. Mit zunehmender wetterabhängiger Erzeugung

nehmen die kurzfristigen Schwankungen der entsprechenden Stromerzeugung stark zu und erfordern ein hohes Maß an Systemflexibilität, um die Übereinstimmung von Stromnachfrage und -angebot in jeder Stunde sicherzustellen. Somit zeigt ein Vergleich zwischen DN und REF, dass bis 2050 deutlich mehr flexible Speicher- und Erzeugungsanlagen sowie nachfrageseitige Flexibilität benötigt wird. Laut Modellierung ist der Gesamtbestand an Speichern und ausgewählten nachfrageseitigen Flexibilitätskomponenten in Bezug auf die Kapazität in DN bis 2050 ca. 170 % höher als in REF.

Auf der Nachfrageseite zeigen sich bei normalen Wetterbedingungen nur marginale aggregierte Auswirkungen des Klimawandels, was zum Teil auf die sich kompensierenden Effekte von Heiz- und Kühlbedarf und zum Teil auf den geringen Anteil der wetterabhängigen Last am gesamten Strombedarf in dekarbonisierten Energiesystemen zurückzuführen ist. Auf der Angebotsseite sind starke interannuelle Schwankungen erkennbar und die Auswirkungen hängen stark vom gewählten Wetterjahr ab. Im Einklang mit den langfristigen Klimaprojektionen weisen bei normalen Wetterbedingungen mit Klimawandel Wind- und Laufwasserkraft eine leicht höhere jährliche Erzeugung auf, während bei PV in den modellierten Normalwetterjahren vernachlässigbare Unterschiede zu beobachten sind. Von zentraler Bedeutung ist die Berücksichtigung extremer Wetterbedingungen, da mit fortschreitendem Klimawandel die Häufigkeit und Dauer solcher Ereignisse gemäß der Klimaprojektionen zunimmt. In der Analyse dienten eine Hitzewelle und eine Dunkelflaute als Stresstest für die Versorgungssicherheit. Ergebnisse aus 2050-DN-Szenarien zeigen, dass für die Sicherstellung der Stromversorgung unter diesen extremen Bedingungen im Vergleich zu einem normalen Wetterjahr eine stärkere Nutzung der Windenergie aus Gesamtkostensicht sinnvoll erscheint. Für Speicher und nachfrageseitige Flexibilitätsanlagen zeigen sich sowohl Gemeinsamkeiten als auch Unterschiede zwischen einer Hitzewelle und einer Dunkelflaute: Für beide Ereignisse erhöht sich in der Modellierung der Bestand an Elektrolyseuren sowie begleitenden Wasserstoffspeichern. In der Dunkelflaute erscheinen thermische Speicher aufgrund der zunehmenden Sektorkopplung sowohl auf der Wärme- als auch auf der Stromseite zur Lastverschiebung sinnvoll. Während einer Hitzewelle mit wenig Laufwasser- und Winderzeugung erweisen sich Batterien zentral für das System, um die hohe PV-Einspeisung tagsüber in die Abendstunden zu verlagern.

Die Ergebnisse von SECURES sollen österreichische politische Entscheidungsträger*innen und Interessengruppen dabei unterstützen, mögliche Konflikte in den politischen Zielen für die Notwendigkeit der Dekarbonisierung, eine sichere Energieversorgung und die Folgen für die österreichische Wirtschaft, die alle von den zunehmenden Auswirkungen des Klimawandels betroffen sind, zu überwinden.

Executive Summary

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 renewable electricity generation shares. The project SECURES (Securing Austria's Electricity Supply in times of Climate Change) analysed challenges and opportunities for Austria's future electricity system 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 this process.

The overall methodological approach included an in-depth analysis of structural changes in weather and electricity demand and generation due to climate change and decarbonisation. 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 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). Variables include temperature, radiation, wind power and hydropower potential (separated into run-of-river (RoR) and reservoir). We developed and applied interdisciplinary methods to identify extreme events and weather years from a meteorological and an energy system perspective.

Based on the meteorological dataset, hourly profiles of all relevant, weather-dependent supply and demand components were generated: solar, wind onshore/offshore, hydro reservoir and hydro RoR generation profiles and e-heating, e-cooling, and e-mobility demand profiles for the years 2011-2100. The dataset SECURES-Energy provided the basis for the energy system modelling within the project and can be adapted and applied to many different contexts. Regarding full-load hours, no strong trend (neither strongly increasing nor decreasing) could be observed for solar, wind, and hydro RoR in the considered emission scenarios in Austria. The strongest interannual variability of full-load hours now and in the future was observed for hydro RoR with higher interannual variability with increasing climate change impact in Austria, which poses a challenge for highly hydro-dependent electricity systems. Additionally, seasonal patterns are affected: Hydro RoR generation is expected to decrease during summer and increase during winter, implying a flattening of the seasonal profile compared to today. For heating demand, a strong decrease (-35%), and for cooling demand, a distinct increase (+144%) in the strong emission scenario (RCP 8.5) at the end of the century (2071-2100) compared to the reference period (1981-2010) was observed (pure temperature signal). There is a relative shift of critical residual load situations to the summer, showing the increasing relevance of heat waves, while most critical situations are still expected to occur during winter in the Central European electricity system.

On the energy side, modelling was conducted by use of the open-source energy system model Balmorel. Geographically, modelling covered Austria but also other European countries to represent the interconnected character of Europe's electricity system. Time-wise, we modelled specific focal years in the near (2030) to mid-future (2050). The central aspect of scenario design comprised the combination of two distinct energy sector pathways for Austria/Europe up to 2050 with the climate scenarios described above. In the *Reference (REF)* pathway and corresponding scenarios, Austria aims to achieve a RES-based electricity supply by 2030 and beyond. However, it represents less decarbonisation ambition in other sectors and EU countries and is accordingly matched with a strong climate change scenario (RCP 8.5). The *Decarbonisation Needs (DN)* pathway represents a strong decarbonisation ambition across the whole EU, implying net zero by 2050. Consequently, a strong growth of electricity demand is expected, driven by strong sector coupling for decarbonising other sectors like industry and mobility. *DN* was coupled with a medium climate change scenario (RCP 4.5). Since in our energy system analysis, we focus on security of supply, for both pathways described above,

we additionally analysed weather years reflecting extreme weather conditions (i.e. dark doldrums and heat waves) for the mid-future (2050).

A comparison of the results of both energy sector pathways (REF vs. DN) 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%. Consequently, a significantly stronger uptake of supply-side assets is also applicable, specifically in wind and photovoltaics (PV). With higher amounts of weather-dependent generation, short-term fluctuations in corresponding electricity generation grow strongly, requiring large amounts of system flexibility to ensure the match between electricity demand and supply in every hour. Thus, 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 by 2050 is ca. 170% higher in DN than in REF.

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 low share of weather-dependent load in overall electricity demand in decarbonised energy systems. On the supply side, high interannual variations are visible and impacts highly depend 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 is the consideration of extreme weather conditions since, with ongoing climate change, the frequency and duration of such events increase according to climate projections. In our analysis, a heat wave and a dark doldrum served as a stress test for security of supply. Results from 2050 DN scenarios show that for safeguarding electricity supply under these extreme conditions, in comparison to a normal weather year, a stronger uptake of wind energy appears useful from a least-cost system perspective. 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 suggested increasing the H_2 electrolyser stock as well as accompanying H_2 storage, allowing a system-friendly operation of the electrolyser fleet. In a dark doldrum, thermal storage is useful for load shifting, both at the heat and the electricity side, as a consequence of increased sector coupling. 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 the day to the evening when the sun is not shining.

The sketched outcomes of SECURES can support Austrian policymakers and stakeholders to overcome and solve possible conflicts in policy targets for security of energy supply, the need for decarbonisation, and the consequences for the Austrian economy, all affected by increasing impacts arising from climate change.

1 Project background and research objectives

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 demand in general, and especially electricity demand, will undergo significant changes through new demand patterns impacted by climate change and increased sector coupling. On the other hand, the supply side of the system has to undergo a major transformation process. Austria's electricity sector has to comply with ambitious decarbonisation targets, for example, concerning the domestic expansion of renewable energy sources (RES) where the Austrian government aims to generate renewable electricity by 2030 to the extent that the national total electricity consumption is fully covered (at a yearly balance) – cf. the Austrian Climate and Energy Strategy #Mission2030 (BMNT and BMVIT, 2018), the National Energy and Climate Plan (NECP) (BMNT, 2019), or the government programme published in 2020 (Republik Österreich, 2020). Austria's electricity sector will consequently have to deal with increasing flexibility needs because of high shares of non-dispatchable RES and reduced thermal generation capacities. Moreover, electricity generation patterns of hydro, wind, and solar photovoltaics (PV), as well as thermal power plants, will be increasingly affected by changing weather conditions caused by ongoing climate change in the future.

The overarching goal of SECURES was to provide targeted support to Austrian policymakers by taking a closer look at the challenges and opportunities arising for Austria's electricity system in future years, acting as a safeguard for securing a reliable, sustainable and cost-efficient electricity supply in times of climate change.

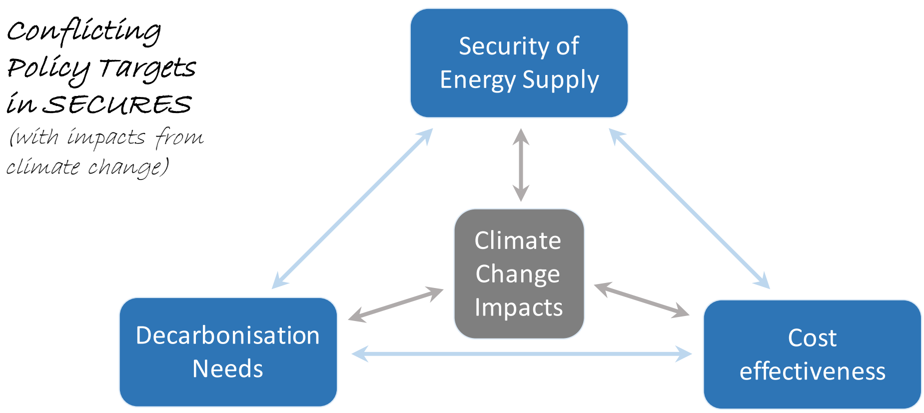


Figure 1. The policy target conflict analysed in SECURES

The three key objectives of SECURES were:

- Conducting an in-depth analysis of changing patterns in weather, electricity demand and supply driven by climate change and decarbonisation;
- Providing open-access datasets and model-based decision support for securing a reliable, sustainable and cost-efficient transition of Austria's electricity sector in times of climate change;
- Ensuring a proper research orientation and a high impact through continuous and in-depth stakeholder involvement and dialogue.

Based on these objectives, the following research questions were addressed:

- *What is the expected impact of climate change on energy systems, specifically on the Austrian and European electricity sectors, considering different climate scenarios and decarbonisation paths?*
- *How does the anticipated rapid transition of Austria's electricity, i.e. the anticipated strong expansion of renewable energies for electricity supply and impacts of climate change, affect supply security?*
- *Can we solve the target conflict between supply security and decarbonisation needs in a cost-effective manner – and how does climate change impact these (conflicting?) policy targets?*

The aim of the analysis was to update former assessments, using the latest climate scenarios that provide a current picture of expectable meteorological changes, and to extend the scope of the energy system analysis by including the thermal power units where operational conditions might be negatively affected during extreme events like droughts.

Our brief hypothesis on the questions raised above is that despite the anticipated radical changes in electricity supply, supply security can be maintained – if adequate accompanying measures are taken. Past analyses (Haas et al., 2017; Suna et al., 2022) indicated that in the case of a rapid renewables expansion, our electricity system has to cope with increasing flexibility needs – but that options would be available to meet that demand, including storage, cross-border exchange etc. if adequate measures are taken in time. However, it requires a thorough and scientifically sound analysis of all relevant aspects concerning supply security to provide clarity on that. In this context, apart from technical aspects, expected impacts on our energy system driven by climate change have to be considered.

In SECURES, we conducted such a holistic analysis that focused on supply security, identifying future flexibility needs and options to cope with these needs in case of a fast and deep decarbonisation and climate change impact. We also informed on and incorporated expected changes in electricity supply and demand driven by ongoing climate change.

Further research questions that were tackled within SECURES include:

- *What are the specific challenges of a low/zero carbon electricity system in a changing climate?*
- *How can we assess the possible impacts of extreme events (dark doldrums and heat waves) on the electricity system?*
- *Which adaptation measures to climate change simultaneously lead to a low/zero carbon energy system and increase the resilience of energy systems in light of possible energy crises, shocks, and trends?*

2 Content and results

2.1 WP2: Impact of climate change on meteorological patterns in Austria and Europe

2.1.1 Motivation

Europe's energy system faces great challenges as it aims to be climate-neutral by 2050. Climate change towards higher temperatures could increase demands over additional cooling requirements, amongst others. As many types of renewable energy production rely on the current and long-term weather, climate change also threats decarbonised energy systems with more frequent extreme weather occurrences like dark doldrums and heat waves.

For the modelling of electricity production and demand, meteorological conditions, therefore, are becoming more relevant due to the increasing contribution from renewable electricity production. The requirements for meteorological datasets for electricity modelling are high. One challenge is the high temporal resolution, as the typical time step for modelling electricity production and demand is one hour. On the other side, the European electricity market is highly connected, so pure country-based modelling is not expedient, and at least the whole European Union area has to be considered. 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.

Thus, the goal of this work package WP2 was to create the aggregated European-wide dataset SECURES-Met (Formayer et al., 2023b) that has a temporal resolution of one hour, covers the whole EU area, and has a reasonable size but is considering the high spatial variability. The dataset should enable studying the impact of climate change on meteorological patterns in Austria and Europe in a way suitable for energy system modelling. This dataset should cover the meteorological variables temperature, wind speed (converted to potential wind power), global radiation (as mean global radiation and direct normal irradiation) and hydropower potential (divided into reservoir and run-of-river (RoR)) for optimal use.

2.1.2 Preparation of climate change projections

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). The stakeholders' request was to provide at least two scenarios, where one represents the business-as-usual scenario and one represents carbon emission close to the Paris Agreement. 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). RCP 8.5 resembles the business-as-usual scenarios with an additional radiative forcing of 8.5 W/m² at the end of the century, whilst RCP 2.6 represents Paris-agreeing carbon emissions with 2.6 W/m² additional forcing. In the new Shared Socioeconomic Pathway (SSP) models, it is highly debated, if SSP5-8.5 should not be treated as the business-as-usual standard, but rather the SSP3-7.0 scenarios, which are overall less extreme in temperature.

Two EURO-CORDEX models from the Global circulation model (GCM) ICHEC-EC-EARTH and the Regional Circulation Model (RCM) KNMI-RACMO22E were chosen. Out of the emission scenarios, RCP 4.5 and RCP 8.5 were chosen. In Figure 2, the temperature anomaly for Austria of the models to the median of the state-of-the-art SSPs is visible. The RCP 8.5 model has lower temperatures than the SSP5-8.5 10-90 % percentiles and, therefore, behaves more like an SSP3-7.0 scenario. A similar situation applies to the RCP 4.5 scenario, which falls in the temperature range of the SSP1-2.6 models. The models operate close to the desired SSP median, although the radiative forcing would indicate otherwise at first glance. These two models were, therefore, the best available choice.

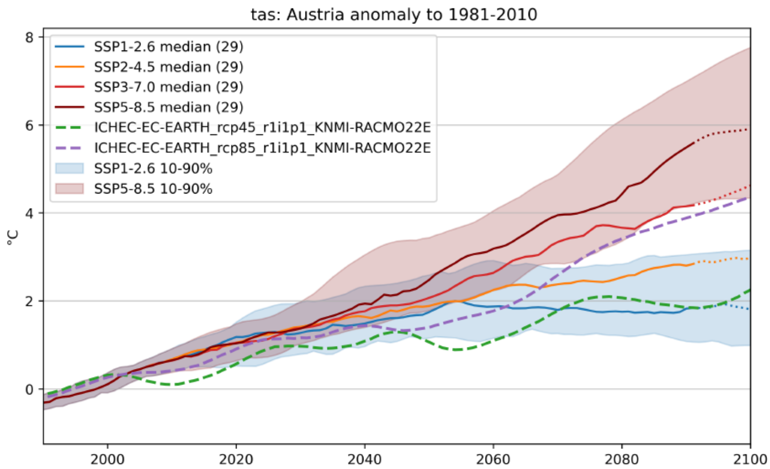


Figure 2: Comparison of available climate models to the median and percentiles of SSP scenarios. The chosen RCP 8.5 model behaves similarly to the SSP3-7.0 median, and the RCP 4.5 model similarly to the SSP1-2.6 median.

To be able to make the absolute values of the climate change projections comparable to historical data, all models were regridded to a combined ERA5 and ERA5-Land grid, which has a spatial resolution of 0.1° (approx. 11 km) using patch interpolation (ESMF Joint Specification Team, 2023). Afterwards, a bias correction was performed on the EURO-CORDEX models using the historical data of 1991-2020 from ERA5 and ERA5-Land. For that, a quantile-quantile-mapping procedure was used, which adjusts the distribution of the models to the historical climatologies and their quantiles (Lehner et al., 2023).

As the climate change projections only provide daily data, a temporal disaggregation was required. For that purpose, the surface wind and global radiation were disaggregated using a statistical approach. Historical hourly ERA5 and ERA5-Land (1991-2020) data were used to build an average day-curve for every day of the year. This curve was further smoothed by applying a seven-day rolling mean for every hour individually. The mean values of two consecutive days were averaged during the hours near day changes to ensure continuous data at day changes. Temperature was disaggregated by modelling altering minimum and maximum temperatures of consecutive days with a cosine function following Förster et al. (2016). For that purpose, the declination was calculated with the methods of Bourges (1985) and Spencer (1971). The minimal temperature was assumed to occur at sunrise, rounded to the full hour, and the maximal temperature two hours after noon, also rounded to the full hour.

2.1.3 Available time periods and aggregation levels

Final historical data is provided from 1981-2020 whereas climate change projections cover 1981-2100. As a 120-year-long Europe-wide dataset on an hourly basis with a spatial resolution of approximately 11 km is an amount of data difficult to handle (namely hundreds of TB), an aggregation to a more suitable size was done as a final step. The data was, therefore, for Europe aggregated to the levels of

NUTS0, NUTS2, and to Economic Exclusive Zones (EEZ) (offshore wind only), and to NUTS3 for Austria only. NUTS0 is equivalent to the European states, which are part of the European energy market. NUTS2 describes provinces, and NUTS3 describes Austrian districts. These levels and the domain are visible in Figure 3.

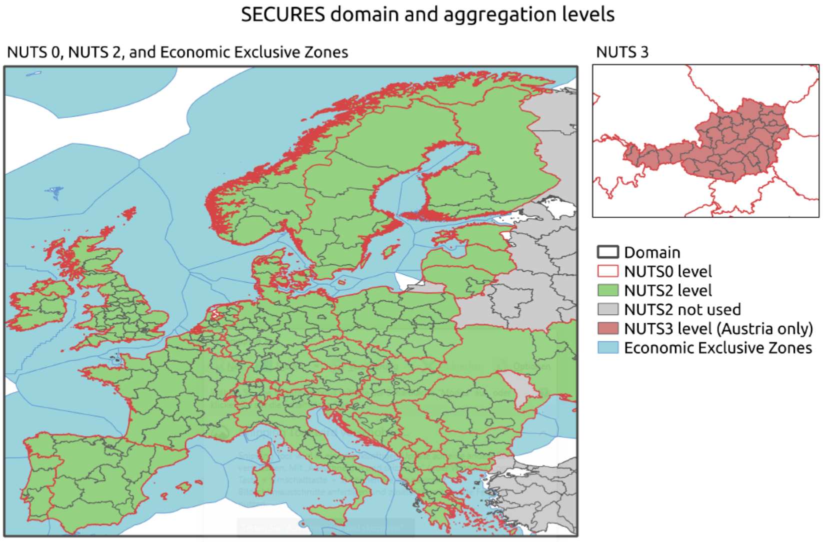


Figure 3: SECURES domain, divided into different aggregation levels, which are visible in the legend.

The aggregation step ensures that the dataset is fit for energy system modelling as the size decreases dramatically. Every variable hereby was aggregated with different state-of-the-art methods, especially considering the requirement of energy modelling (for detailed description, cf. Section 4.2). The final output variables are visible in Table 1.

Table 1: Final output variables of the meteorological dataset. All variables are aggregated to different NUTS levels using the stated aggregation methods and are available for the historical period (1981-2020) and two future emission scenarios (1951-2100).

Variable	Short name	Unit	Aggregation methods	Temporal resolution
Temperature (2m)	T2M	°C °C	spatial mean population-weighted mean	hourly
Radiation	GLO (mean global radiation) BNI (direct normal irradiation)	Wm-2 Wm-2	spatial mean population-weighted mean	hourly
Potential Wind Power	WP	1	normalized with potentially available area and power curve	hourly
Hydro Power Potential	HYD-RES (reservoir) HYD-ROR (run-of-river)	MW 1	summed power production summed power production normalized with average daily production	daily

2.1.4 Quality Control and Anomaly Development

After aggregating meteorological variables to a size fit for energy modelling, quality control was done on the data. Bias correction was verified by observing the 10th, 50th and 90th quantiles for the historical period over the whole of Europe. The quantiles of the bias-corrected climate scenarios do not differ more than 4 % compared to the ERA5(-Land) reanalysis. Bias correction was therefore judged to be successful.

Afterwards, the temporal behaviour of temperature was observed, which displays the expected climate change. In summer over Europe, the maximum historical temperature anomaly of 3°C (4.2°C) is exceeded a total of 32 (50) times for RCP 4.5 (RCP 8.5), where the most overshoots are registered in the last period around the end of the century (2076-2100) with 19 (39) times. In winter, temperatures never drop below the historical anomaly values of -6.11°C (-6.91°C) in any future period. Therefore, more heat waves and milder winters can be expected. The RCP 4.5 temperature trend in Austria is less pronounced compared to the rest of Europe. Only in the RCP 8.5 model, the trends for Austria and Europe align. For wind and hydropower potential, no clear pattern is visible in Austria or Europe. Radiation is determined by cloud cover and sun circles. Especially for the minimum in winter, a trend towards less radiation with time is visible, where RCP 4.5 displays this trend more strongly.

2.1.5 Detection of meteorological extreme years

For modelling the European energy market and its limitations, possible critical years were observed from two different perspectives. First, meteorological extreme years, where the choice of extreme and reference years was driven by temperature. Second, for the energy modelling, the residual load for every month was calculated, and crucial residual load years were compared with the meteorological extreme years (cf. Section 4.4.3).

For the three selected cases of i) strong heat waves, ii) cold periods, and iii) reference years, the focus was on variable anomalies compared to the 30-year climatologies of the specific period in Austria. Afterwards, the anomalies in Europe were observed to see if the tendency in Austria result from a larger weather pattern. At last, the spatial pattern of Europe was observed.

Reference years were selected by observing the monthly mean temperature root mean square anomaly (RMSA) compared to the climatological mean and, as a second indicator, the sum of the normalised absolute variance of the other variables within one calendar year. The average years were then determined by ranking the mean temperature RMSA and observing the normalized absolute variance sum.

For heat waves, the monthly maximum temperature anomaly from May to September compared to the climatology of the corresponding period was observed. Heat waves typically have high radiation but low wind power potential, as in high-pressure centres, windspeed is reduced. Challenging for the energy system, especially for Austria, hydropower potential is then typically low as well, which was also considered.

For cold periods, the monthly minimum temperature anomaly from October to April compared to the climatology of the corresponding period was observed. Radiation is not a strong driver in the winter half-year as the absolute values in radiation flux density are low. Additional low wind power potential indicates possible dark doldrums, which are a severe challenge for the energy system.

By applying these three methods for reference years, heat waves and cold periods, diverse years for energy modelling for four time periods were identified. Results for the two emission scenarios are found in Table 2.

Table 2: Suggested meteorological reference and extreme years for the two emission scenarios, RCP 4.5 and RCP 8.5.

RCP 4.5 / RCP 8.5	1991 - 2020	2016 - 2045	2036 - 2065	2071 - 2100
Reference	1997 / 1997	2043 / 2033	2062 / 2046	2073 / 2084
Extreme Heat	2016 / 2018	2028 / 2039	2059 /2057	2085 / 2097
Extreme Cold	1992 / 1992	2037 /2016	2040 / 2047	2096 / 2073

2.2 WP3: Climate change impacts on future electricity demand and supply

2.2.1 Overview of methodological approach

Meteorological parameters cannot be used directly in energy system modelling but have to be converted to supply and demand profiles broadly applied in energy system models. Based on the meteorological variables derived from the two climate scenarios (cf. Section 2.1), the dataset SECURES-Energy containing hourly weather-dependent electricity generation and demand profiles that can be used in energy system modelling was generated. The two underlying emission scenarios (EURO-CORDEX ICHEC-EC-EARTH - KNMI-RACCMO22E RCP4.5/RCP8.5) provided assumptions for a medium (RCP4.5) and a strong (RCP8.5) climate change scenario for the whole of Europe until 2100. By the processing steps described above, the hourly time series of these climate data were retrieved and further converted to electricity demand and supply profiles. Table 3 shows the weather-dependent electricity demand and renewable supply components generated and considered in the project SECURES.

On the generation side, generation profiles of wind power, hydropower (RoR and reservoir), and solar 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. The methodological approach is described in Section 0.

Table 3: Schematic overview of weather-dependent generation and demand components represented in SECURES and the meteorological parameters they depend on

Generation	**River discharge**	**Wind speed (150 m)**	**Solar radiation**	**Temperature (2 m)***		
Wind		✓				Representative turbine types, power curves, suitable land
Hydro	✓					Mean daily generation from run-of-river and reservoir plants (eHYPE river discharge)
Photovoltaics			✓	✓ (losses)		Consideration of temperature-related efficiency losses
Demand	**River discharge**	**Wind speed (150 m)**	**Solar radiation**	**Temperature (2 m)***	**Behavioural patterns**	
E-heating				✓	✓	Hotmaps open data repositories (2019): Temperature dependence of heating and cooling demand
E-cooling				✓	✓	Hotmaps open data repositories (2019): Temperature dependence of heating and cooling demand
E-mobility charging				✓	✓	Consideration of temperature-related efficiency losses

*Population weighted

2.2.2 Climate change impact on renewable electricity generation in Austria

The development of full-load hours (FLH) of the different renewable generation technologies wind, RoR hydropower, and solar PV for Austria were analysed (cf. Figure 4) 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 Wind onshore and especially PV show lower interannual variability. The interannual variability of PV and the number of FLH (Figure 4 Panel (b)) shows 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.

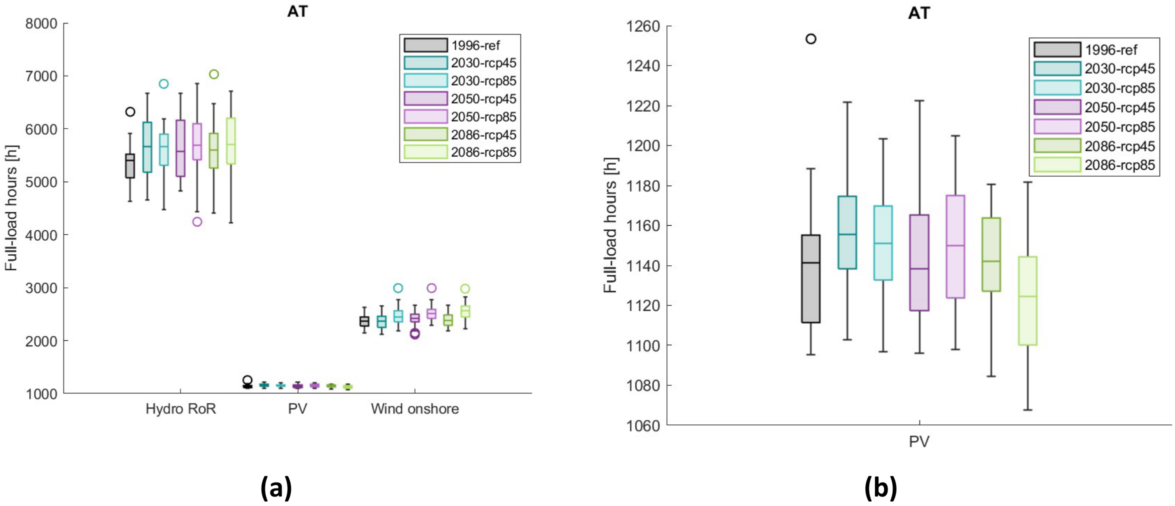


Figure 4: Development of full-load hours of run-of-river (RoR) hydropower, PV, and wind onshore (Panel (a)) and PV in greater detail (Panel (b)) in Austria in the two considered climate scenarios (rcp4.5 and rcp8.5) compared to the reference period (1981-2010); each box represents 30 weather years around the target year; the reference period is based on ERA5-Land.

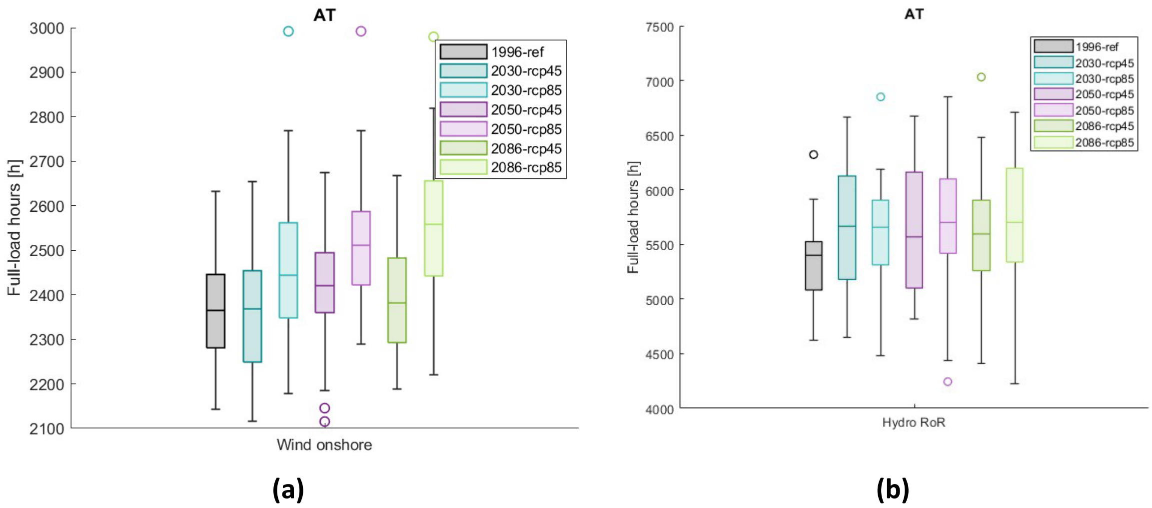


Figure 5: Development of full-load hours wind onshore (Panel (a)) and run-of-river hydropower (RoR) (Panel (b)) in Austria in the two considered climate scenarios (rcp4.5 and rcp8.5) compared to the reference period (1981-2010); each box represents 30 weather years around the target year; the reference period is based on ERA5-Land.

For wind onshore (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, wind onshore FLH are higher than in the RCP 4.5 scenario in Austria in the two analysed climate scenarios[1].

For RoR hydropower (Figure 5 Panel (b)), no clear trend regarding the full load hours 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 heterogenous depending on the considered climate scenarios, as some former studies using older generations of

[1] However, findings of Wohland (2022) suggest that EURO-CORDEX misses reductions in near-surface onshore winds that exist in the driving global models and thereby might underestimate wind speed reductions also in Austria.

climate scenarios showed decreasing FLH for RoR hydropower in Austria (Eitzinger et al., 2014; Kranzl et al., 2010; Totschnig et al., 2017; Wagner et al., 2017).

2.2.3 Changes in annual electricity demand

On the demand side, a decrease in annual heating demand (down to -50% compared to the reference period in the RCP8.5 scenario at the end of the century) and an increase in cooling demand (up to +350%) with increasing climate change impact in Austria is projected (cf. Figure 6 Panel (a)). This trend correlates with former findings (Berger et al., 2014; Bird et al., 2019; Hausl et al., 2014; Kranzl et al., 2014; Ramsebner et al., 2021; Totschnig et al., 2017). The difference between the two emission scenarios become particularly evident at the end of the century. The median cooling demand in the RCP 8.5 scenario already reaches a level in the period 2035-2064 that is only reached in 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 might, therefore, reduce seasonal storage needs in the electricity system.

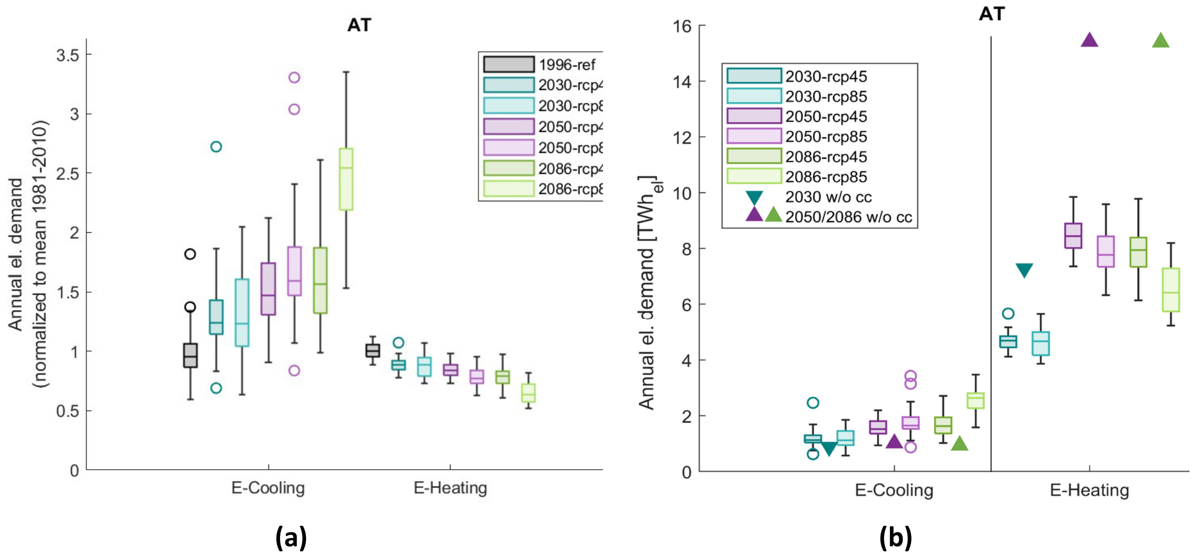


Figure 6: Panel (a): Development of e-heating and e-cooling demand in Austria (normalized to the mean of the reference period 1981-2010); each box represents 30 weather years around the target year; the reference period is based on ERA5-Land; Panel (b): Absolute values according to the DN scenario; the 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).

E-heating demand in absolute terms is much higher than e-cooling demand in Austria, so an overall negative net effect of climate change on heating and cooling demand is expected. Figure 6 Panel (b)) shows the e-cooling and e-heating demand in absolute terms based on penetration rates of heat pumps and air conditions as assumed in the DN scenario (for detailed scenario description, cf. Section 2.3). The increase in e-heating demand due to electrification between 2030 and 2050 is almost offset by the temperature increase in the climate scenarios.

2.2.4 Changes in seasonal patterns of electricity generation

Climate change impacts the seasonal patterns of RoR hydropower in Austria, as the climate scenarios show (cf. Figure 7). There is observed a seasonal shift towards earlier runoff in spring with increasing climate change, decreasing generation during summer and increasing generation during winter. This is partly due to changing precipitation patterns and because precipitation is falling as rain instead of snow during winter. This is in line with what has been found in former studies and is found quite consistently over climate scenarios (Blöschl et al., 2018; Fuchs et al., 2013; Kling et al., 2012; Kranzl et al., 2010; Totschnig et al., 2017; Wagner et al., 2017). However, the effect of glacier melting on these processes is not yet fully understood and covered by climate scenarios[2]. This is an important limitation since there are opposing trends of increased contributions of glacier-derived runoff in downstream basins during hot temperatures and decreasing glacier volumes (Wagner et al., 2017).

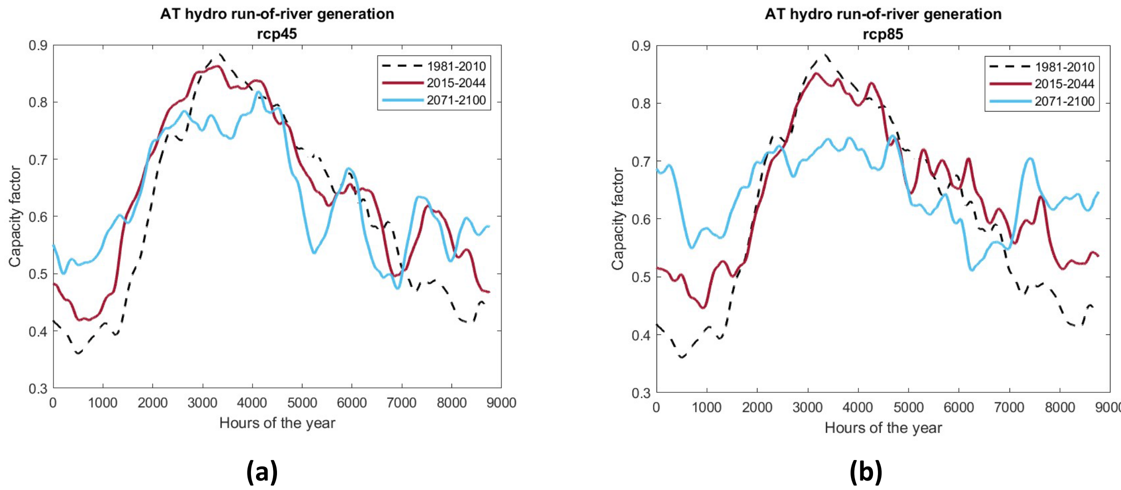


Figure 7: Development of seasonal generation pattern of run-of-river hydropower in Austria in two emission scenarios (Panel (a): RCP4.5, Panel (b): RCP8.5) compared to the reference period 1981-2010 based on ERA5-Land.

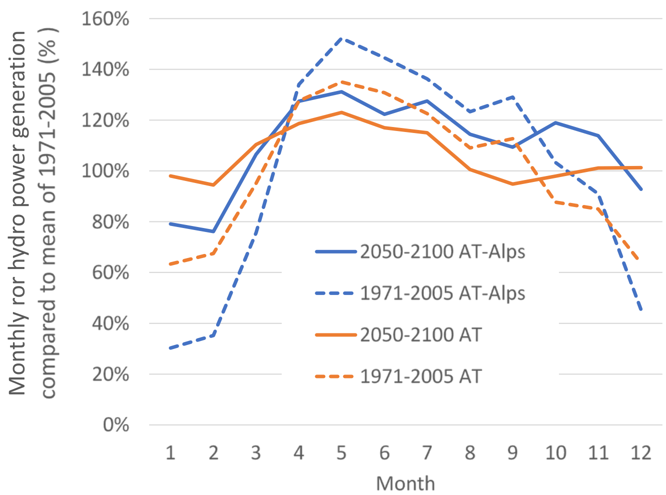


Figure 8: Changes in the monthly mean run of river hydropower generation for the Austrian Alps and the whole of Austria for 1971-2005 and 2050-2100, based on E-Hype driven by RCP 8.5 Regional circulation model RACMO22E (KNMI, Netherlands) and Global Circulation Model (GCM) EC-EARTH (ICHEC, Ireland)

The high geographical resolution (NUTS3) of SECURES-Met can provide insights into regionally specific climate change impacts. In Figure 8, the RoR hydropower generation in the Austrian Alps and the whole of Austria for the periods 1971-2005 and 2050-2100 is compared for RCP 8.5[3]. The monthly mean values for the periods 1971-2005 and 2050-2100 are compared to the mean generation of the whole period 1971-2005. The described seasonal shift from summer to winter is even more distinct for the Alpine region compared to overall Austria.

For wind, no such change in seasonal generation patterns is observed. Further analyses covering the

[2] Due to this reason, a follow-up ACRP project (HyMELT-CC, 2023) was proposed and granted to cover this research gap with great implications for Austria's hydropower-based electricity sector.

[3] E-Hype scenario run based on RCM RACMO22E and GCM EC-EARTH

whole of Europe were also conducted and can be found in the respective publication (cf. updated list at https://www.secures.at/publications).

2.3 WP4: Model-based analysis of scenarios for securing a reliable, sustainable, and cost-efficient transition of Austria's electricity sector in times of climate change

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. In this respect, WP4

- defined a suitable set of future trend scenarios for the electricity sector and
- conducted a comprehensive model-based scenario analysis of Austria's future electricity sector, targeted to secure a reliable, sustainable, and cost-efficient transition of Austria's electricity sector in times of climate change.

2.3.1 Modelling approach & scenario design

Applied energy system model and general scope

The modelling system on the energy side comprised the well-established energy system model Balmorel, an open-source model that allows for in-depth assessments of the electricity sector as well as of grid-connected heat supply (for details, cf. Section 4.4). Geographically, modelling covered Austria but also other European countries to represent the interconnected character of Europe's electricity system, where cross-border electricity exchange is a common fact today and in the future. Time-wise, the modelling was done for certain focal years in the near (2030) to mid-future (2050). The energy system modelling and the accompanying result analysis focused on assessing supply security needs to safeguard Austria's electricity supply in times of energy transition and climate change.

Definition of scenarios

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 two Representative Concentration Pathways (RCP) (cf. Section 2.1). Based on a literature survey and an in-depth stakeholder consultation process, two distinct energy transformation pathways have been identified: 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.

Since the overall assessment focused on supply security for both scenarios 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 4: Overview of assessed scenarios

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

In accordance with the above, Table 4 provides an overview of all modelled scenarios. Within our analysis, we use the term "scenario" for modelling a whole calendar year (according to climate/weather data provided at an hourly level) in combination with a specific trend pathway concerning the energy sector transformation, i.e. REF or DN. Time-wise, two focal years were thereby analysed that characterise the different states of transformation, i.e. the near future (2030) and the mid-future (2050), where according to the DN pathway, the transformation process would be completed and, accordingly, full decarbonisation of the energy sector as well as of the whole economy achieved. For 2050 scenarios, climate impacts were indicated for different weather years, i.e. a representative normal year, and two extreme years (i.e. dark doldrum and heat wave).

Modelling approach

In accordance with the above, building on the pre-processing and incorporation of climate data (WP2 and WP3, cf. Section 2.1 and 2.2), the overall approach underlying the energy system analysis comprised the following three steps:

1. **Estimation of the planned uptake in demand and supply:** Based on the literature, projections on the planned uptake of demand and supply by 2030 and 2050 in the electricity and grid-connected heat were derived. We thereby considered impacts/demands from other interconnected sectors like transport, decentral heat and industry for both distinct energy transformation scenario pathways (REF and DN) (for details on related assumptions, cf. Section 2.3.2).
2. **In-depth electricity sector modelling with a focus on system flexibility needs:** The analysis centred around 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, the 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 as described in Section 4.4.1.
3. **Detailed flexibility analysis and derivation of policy recommendations:** Building on the model results, a detailed flexibility assessment for the electricity system was undertaken, with a focus on the identification of energy system assets suitable for safeguarding future electricity supply in times of climate change. Finally, policy recommendations on the way forward were derived.

2.3.2 Estimation of electricity demand and power plant stocks in Austria and the EU by 2030 and 2050 in scenarios

For REF scenarios, the overall electricity demand for Austria and other European countries was taken from TYNDP22 (ENTSO-E, 2022), considering the National Trends scenario[4]. In this database, the National Trends scenarios cover only demand and supply trends by 2030 and 2040. Therefore, for the REF scenarios, different assumptions were made for the simulation year 2050, such as a linear extrapolation of trends in electricity demand development between 2030 and 2040.

For DN scenarios, assumptions concerning the uptake of electricity demand as well as corresponding projections for the supply side, i.e. the expected technology-specific power plant stock by 2030 and 2050, were taken from a detailed modelling exercise on future electricity sector trends in Europe as performed within the Horizon 2020 project AURES II, cf. Resch et al. (2022). According to this study, the presumed full decarbonisation of the whole EU economy by 2050 is expected to lead to more than a doubling of electricity demand by 2050 compared to today. Due to a lack of cost-effective carbon-free alternatives, sector coupling is expectably predominant and strong electrification of heating, industry, and transport will act as a driver for increases in electricity demand. As described in Resch et al. (2022), default future trends concerning electricity demand were thereby taken from the “Electrification” scenario of the recently completed EC study concerning renewable space heating under the revised EU Renewable Energy Directive (cf. Kranzl et al. (2022)). These consumption trends can be classified as being in accordance with former studies assessing the impacts of a deep decarbonisation of the whole EU economy, cf. EC (2018) or del Granado et al. (2020).

Demand components were split into two groups, namely, weather-dependent and non-weather-dependent (cf. Section 4.3.2). For the REF scenarios, the database of the National Trends scenarios from TYNDP2022 (ENTSO-E, 2022) does not provide information on the split of overall demand into different demand categories. The split and corresponding shares from the TYNDP2022 Distributed Energy (DE) Scenario were considered to make a breakdown into distinct demand categories.

Furthermore, additional domestic data sources were taken into account to enhance the precision of country-specific circumstances in **Austria**, particularly with regard to hardships in the industrial and transportation sectors' decarbonisation efforts. Thus, to estimate future demand for H_2 and electricity in the industry sector, we relied on the NEFI (New Energy for Industry) study (NEFI, 2022). As for the mobility sector, we based our assumptions on the UBA scenarios in the 2019 Austrian NECP (UBA, 2019). Specifically, we considered the following assumptions:

- In the REF scenarios, demand for direct and indirect (i.e., for H_2 production) electricity use in the industry was taken from the NEFI-BAU (business-as-usual) scenario, whereas for mobility, assumed demand trends built on the UBA WAM NEKP scenario.
- In the DN scenarios, direct and indirect (i.e., for H_2 production) electricity demand trends for the industry sector were taken from the NEFI-ZEM (Zero Emission) scenario, whereas for the mobility sector, our default assumptions based on Resch et al. (2022) remained.

Industry demand profiles were not classified as weather-dependent, estimated as flat with small differences between weekdays and weekends, based on HotMap industry demand profiles (Fallahnejad, 2019; Pezzutto et al., 2019) (cf. Section 4.3.2 for details).

Table 5 (electricity demand) and Table 6 (power plant stock) provide further details on the projected uptake in demand and supply within Austria’s electricity sector. Please note that in this overview,

[4] In TYNDP22, all scenarios are simulated for three climate years (1995, 2008 and 2009) representing three climate groups. The climate year 2009 is described as the most representative year, representing the climatic variability of the last 30 years. Therefore, for this study, the 2009 data were taken into consideration as historical basis without additional climate change for the REF scenario.

weather-dependent demand components reflect a representative normal year and ignore the impact of climate change. Thus, these demand components were then altered in the further processing steps for modelling (cf. Section 2.2), depending on the underlying climate data (weather year), resulting in the weather-dependent electricity demand components in Table 7.

Table 5: Default electricity demand projections for Austria by 2030 and 2050 for assessed scenarios (REF and DN) before considering the impact of climate change

Electricity demand projections (default)	REF 2030	REF 2050	DN 2030	DN 2050
Demand (TWh) - weather dependent	**19.2**	**24.6**	**11.9**	**27.5**
E-heating residential space heating	8.7	7.5	4.2	8.4
E-heating residential sanitary hot water*	2.2	2.8	1.1	3.2
E-heating tertiary space heating	3.2	4.9	1.5	2.5
E-heating tertiary sanitary hot water*	1.0	1.2	0.5	1.4
E-cooling residential	0.1	0.3	0.1	0.1
E-cooling tertiary	2.1	1.9	0.8	0.9
E-mobility (PKW)	1.8	5.9	3.8	11.0
Demand (TWh) - Non-weather dependent	**62.5**	**79.1**	**83.4**	**138.6**
E-Industry (flat)	27.6	32.6	34.1	48.5
Electricity demand for exogenous H2 demand (excl. H2 imports)** (industry + mobility) (flat)	4.2	14.1	13.4	59.7
Remainder of demand (appliances, lighting, etc.)	30.7	32.3	36.0	30.4
Total demand	**81.7**	**103.6**	**95.3**	**166.1**

*Sanitary hot water is not dependent on the temperature, cf. Section 4.3.2.

**Note: It is estimated that 16% of H_2 demand in Austria in 2030 and 18% in 2050 will be imported from abroad (max. value derived from the DE scenario in ENTSOE-E and ENTSOG (2022)). The value was estimated based on hydrogen demand from NEFI (2022) assuming electrolyser efficiency of 0.7.

Table 6: Default projections on the planned power plant stock in Austria's electricity sector by 2030 and 2050 for the assessed scenarios (REF and DN)

Electricity supply projections (planned stock)	REF 2030	REF 2050	DN 2030	DN 2050
Power plant stock (GW)				
Wind onshore	9.0	18.7	9.5	26.3
Wind offshore	0.0	0.0	0.0	0.0
PV	12.0	37.5	14.9	54.0
Hydro run-of-river (RoR)	6.1	6.4	6.1	6.4
Hydro reservoir	5.2	6.0	5.2	6.0
Hydro pump storage	3.3	4.3	3.3	4.3
Biomass	0.0	0.0	0.8	0.4
Geothermal	0.1	0.1	0.1	0.1
Waste	0.5	0.5	0.2	0.2
Gas CHP	1.5	0.0	0.9	0.0
Gas Turbine	2.6	0.0	1.7	0.0

Table 7: Electricity demand projections for Austria 2050 for assessed scenarios (REF and DN) with climate change impact considered (RCP 8.5 for REF, RCP 4.5 for DN); for selection of weather years, cf. Section 4.4.3)

Electricity demand (TWh) 2050 With climate impact considered	REF NY	REF HW	REF DD	DN NY	DN HW	DN DD
E-heating (space heating + sanitary hot water)	14.4	13.6	16.6	12.9	13.5	14.1
E-cooling	3.0	6.7	2.4	1.5	2.0	1.4
E-mobility (PKW)	5.6	5.7	5.9	10.3	10.5	10.6

2.3.3 Scenario results

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 (i.e. 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. Within the subsequent reporting, we put a geographical focus on Austria and show the challenges arising from the required energy system transformation, done via a cross-comparison of assessed scenarios. Moreover, in accordance with the topical focus of SECURES, we took a closer look at 2050 and conducted a detailed assessment of weather impacts expected under the growing influence of climate change.

The aggregated picture: overall electricity demand and required energy system assets for supply, storage and demand-side flexibility

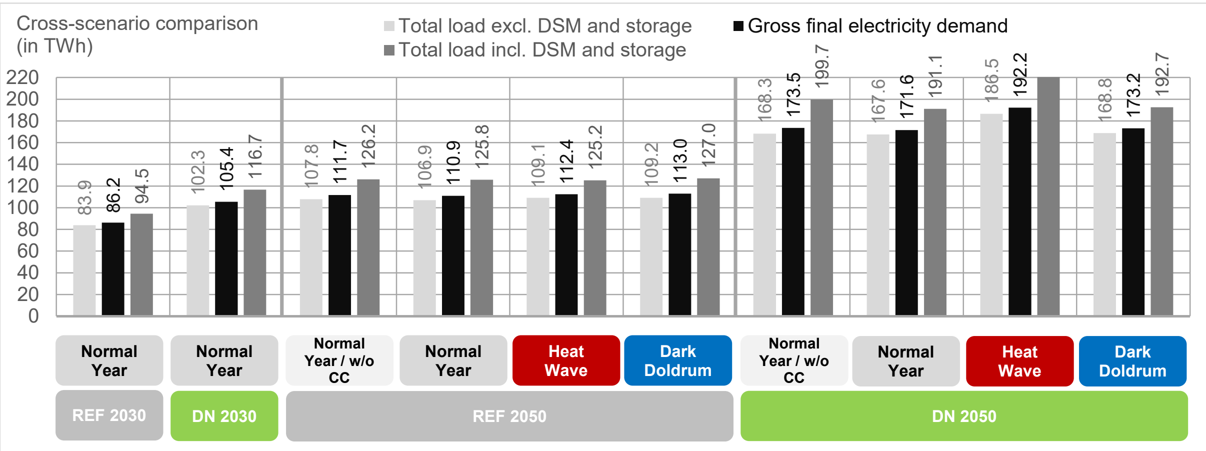


Figure 9: Comparison of electricity demand (with and without additional demand components for storage and DSM) in Austria across assessed scenarios by 2030 and 2050

The reporting starts with taking a closer look at the projected future demand for electricity. In this context, Figure 9 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. Comparing both energy sector pathways (REF vs. DN) indicates the challenges that come along with the energy transition that is indispensable from a climate and societal perspective: Taking a closer look at the scenarios that reflect normal weather conditions while excluding climate impacts (i.e. scenarios named "Normal Year / w/o CC"[5]), gross final electricity demand[6] is expected to grow by 55% in 2050 compared to today (2021) in REF whereas the DN pathway implies 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

[5] „Without climate impact" refers to the modelled weather year 2008 based on ERA5(-Land).

[6] Gross final electricity consumption is a commonly used indicator. It includes apart from default electricity demand also grid losses and own consumption of generation assets. Moreover, it also accounts for losses that come along with storing or shifting electricity consumption to other times.

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.

A closer look at the load with and without additional demands for storage and DSM shows that the ratio between both remains in a similar bandwidth across all scenarios, ranging from 1.14 to 1.19. This indicates that for Austria, also the significantly stronger decarbonisation ambition in DN compared to REF has little impact, despite the massive deployment of variable RES in DN.

Next, we present a focus on the supply side and other system assets like storage that provide the required flexibility to Austria's electricity system for a proper match between demand and supply. In this context, Figure 10 illustrates how the climate mitigation ambition (REF vs. DN) and climate-driven weather impacts affect the (ideal) stock of energy systems 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. Sections 2.3.1 and 4.4.1). Accordingly, Figure 10 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 highly depend 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, however, the consideration of extreme weather events since, with ongoing climate change, the frequency and duration of such events increase according to climate data. 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 both at 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.

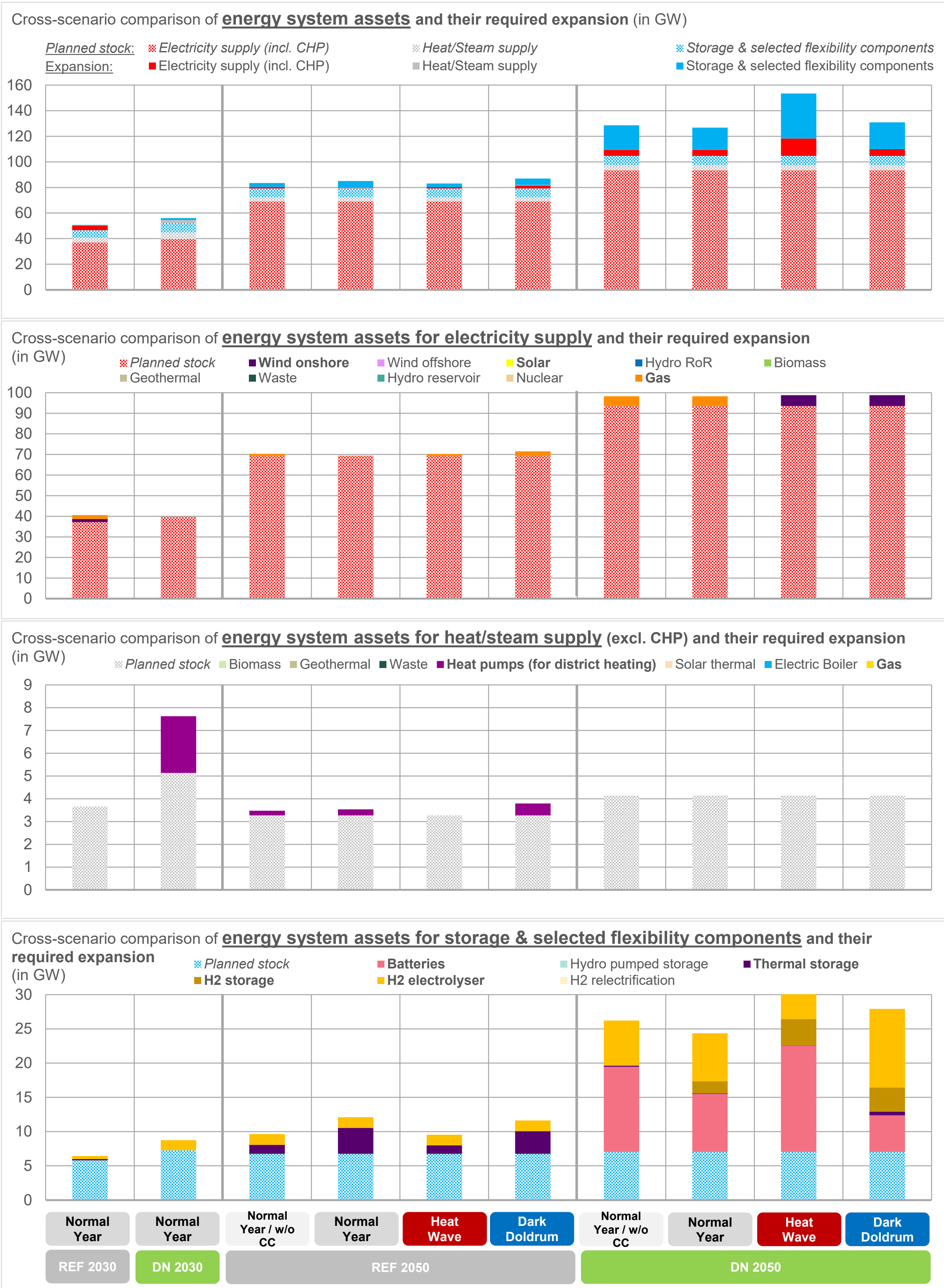


Figure 10: Comparison of Austria's energy system assets and their required expansion in aggregated terms (top), for electricity supply, heat/steam supply and for storage & other selected flexibility components (bottom) across scenarios by 2030 and 2050

The match between demand and supply in Austria's electricity sector by 2050 under extreme weather conditions

Figure 11 illustrates the match between electricity supply and demand by 2050, exemplified for critical extreme events: a dark doldrum and a heat wave. Thus, these graphs depict the operation pattern of all supply and storage assets and provide a decomposition of the demand side as well. Both extreme events are characterised by comparatively high demand and a low infeed of variable RES, specifically of RoR hydro and wind power. PV infeed is high during a heat wave but low during the dark doldrum period. System assets like hydro reservoir and pump storage (PS), batteries, thermal and H_2 storage, and cross-border exchange help to achieve a match between demand and supply. H_2 and thermal storage units also enable a flexible operation of demand components like electrolysers or heat pumps.

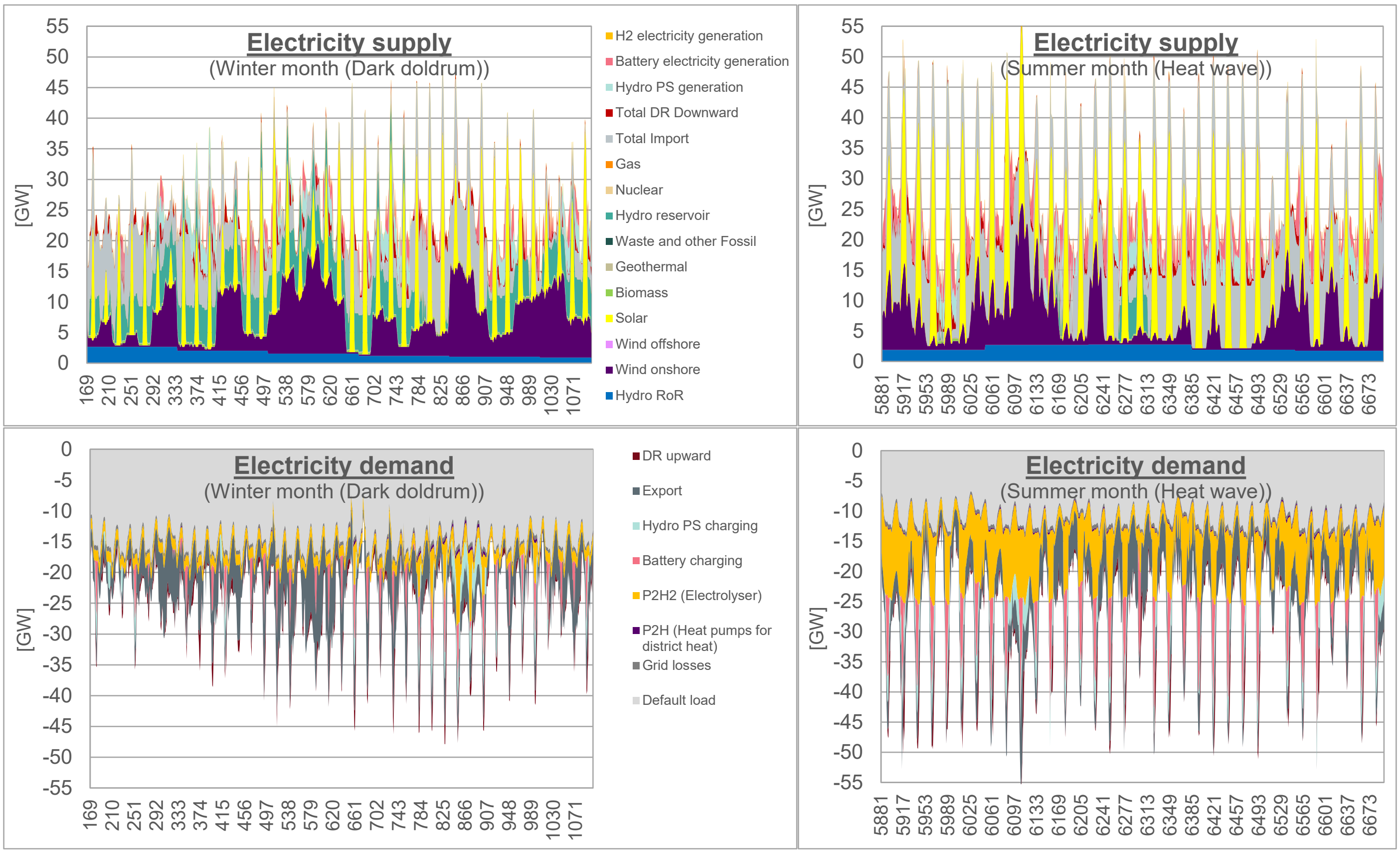


Figure 11: Electricity supply and demand in Austria by 2050 according to the DN pathway for a dark doldrum during winter (left) and a heat wave during summer (right)

Assessment of system flexibility needs and corresponding options

Complementary to the above, a structured assessment of flexibility needs arising in the Austrian future electricity system is presented. 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.[7]

[7] Please note that both flexibility for voltage and transfer capacity are not part of our study.

The starting point for determining the need for flexibility was the analysis of the residual load (RL), whereby both variables are closely related. In this context, RL represents the difference between the total electricity demand and the electricity infeed from variable RES like wind, RoR hydropower, and solar PV. We calculated flexibility needs according to the method described in Section 4.4.2, implying an analysis of the dynamics of RL on daily, weekly, monthly, and yearly levels.

Figure 12 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.

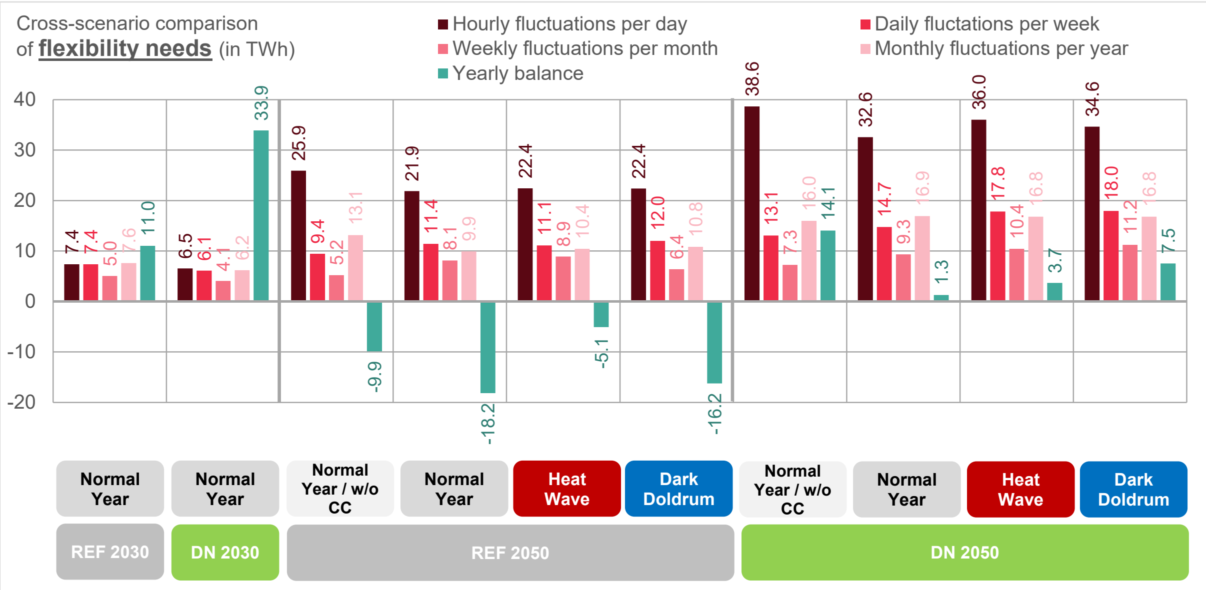


Figure 12: Cross-scenario comparison of flexibility needs under different time periods within Austria's future electricity system by 2030 and 2050

Complementary to the above, Figure 13 informs on the provision of flexibility broken down by time period for the assessed scenarios. 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 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 reservoir, the opposite trend is applicable, helping to cover seasonal imbalances and RL a yearly 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.

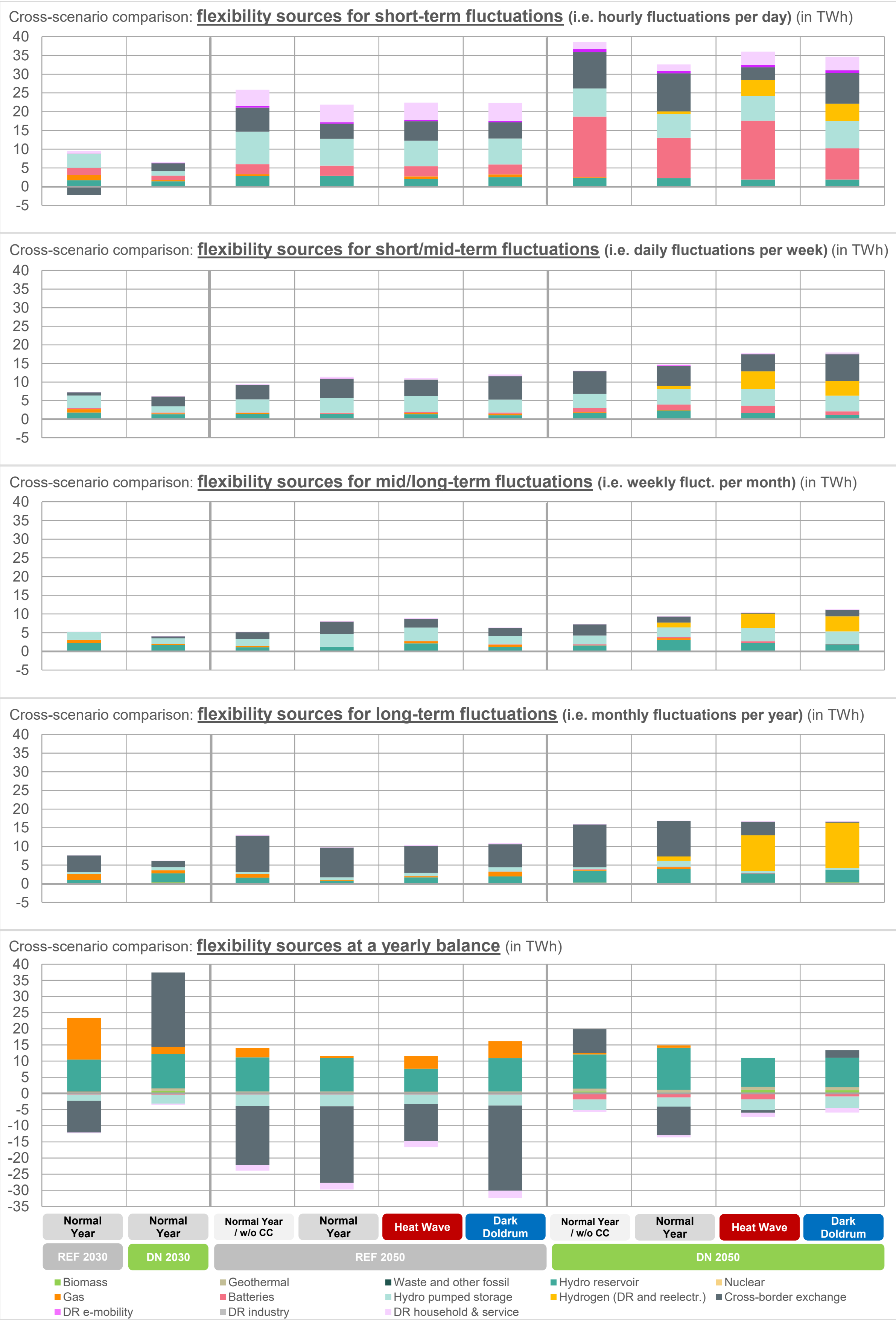


Figure 13: Cross-scenario comparison of the contribution of flexibility sources to cover needs at different time periods within Austria's future electricity system by 2030 and 2050

2.4 Project highlights

Main contributions of SECURES:

- Consistent climate (**SECURES-Met**) and energy system (**SECURES-Energy**) datasets for two different RCPs, including the development and description of processing methods
- The experience of real **interdisciplinary scientific cooperation** to develop a suitable meteorological dataset that fulfils the needs and quality standards of all involved disciplines: a very time-consuming but highly satisfying exercise.
- Energy data in **hourly resolution,** in reasonable size but considering the high spatial variability, including **hydropower,** which is often missing in comparable datasets
- Comparison of methods for the **selection of relevant sub-datasets**, i.e. reference and extreme weather years (dark doldrums and heat waves), from a meteorological and an energy system perspective
- Results on the **impact of climate change on the most relevant electricity demand and supply components** until the end of this century
- Involvement of a wide range of scientific and stakeholder groups
- A **broad set of energy system scenarios was** simulated, reflecting two distinct pathways for the energy sector transformation (REF and DN), each connected to an RCP, i.e. strong (RCP 8.5) vs. moderate climate impacts (RCP 4.5), assessed for two distinct points in time (2030, 2050), with indication of common and extreme weather conditions (i.e. heat wave, dark doldrum)
- Two additional scenarios for REF-2050 and DN-2050 on neglecting the impact of climate change, serving as a **benchmark for climate impacts.**

3 Main outcomes and conclusions

Modelling the future electricity system in Austria requires consideration of climate change impacts on electricity demand and supply patterns and, thus, highly specific and comprehensive meteorological and energy system datasets. For that purpose, three open-access, high-resolution datasets were generated in SECURES:

- SECURES-Met: A European-wide meteorological dataset suitable for electricity modelling for historical climate and climate change projections.
- SECURES-Energy: Hourly profiles of all relevant, weather-dependent demand and supply components were generated on the NUTS0 level for 2011-2100.
- SECURES-EMod: Energy system modelling input data for modelling a broad range of scenarios covering different emission pathways, weather years, and decarbonisation scenarios for the EU + Switzerland, Norway, and the UK.

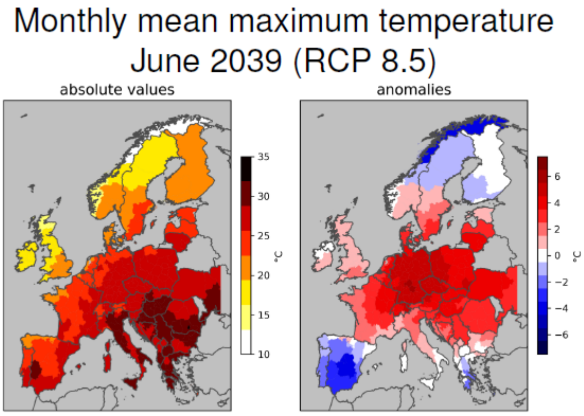
The analysis showed that climate change is expected to lead to greater interannual variability of renewable generation of wind and hydropower as well as electricity demand in Austria. Therefore, it is important that energy system planning and operation consider various weather years from different climate scenarios, including extreme years and events like heatwaves and dark doldrums. However, the decarbonisation of the energy system and electricity system design (like generation mix and availability of flexibility options, e.g., grid expansion and storage) has a much higher impact on the operations than climate-induced variations. Future-proof electricity systems have, therefore, to be designed in a way that they provide sufficient flexibility options to balance fluctuations of renewable generation and demand and are resilient to climate-induced variability and extreme events.

3.1 Specific conclusions from climate modelling

For modelling the energy and electricity system of Europe on a long-term scale, high-quality climate data for the past and future is required. Therefore, the 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 modelling experts to fit all necessary requirements. Within the process, around 4 TB of input data were used to create 1 PB of intermediate data, which then was condensed to 45 GB of final climate data by aggregating the variables to NUTS0 (country level) and NUTS2 (region level) for Europe, to EEZ for offshore wind power and to NUTS3 (province level) for Austria. The produced meteorological dataset has an hourly temporal resolution (daily for hydropower) and covers the years 1981-2020 for the historical period and up to 1951-2100 for two emission scenarios (RCP 4.5 and RCP 8.5), where the selected EURO-CORDEX models operate close to the temperature median of SSP1-2.6 respectively SSP3-7.0. It also considers local effects up to a spatial resolution of 1 km due to the intermediate processing and aggregation methods and has a size suitable for energy system modelling. Variables include temperature, radiation (global radiation and direct normal irradiance), wind power potential and hydropower potential (separated into RoR and reservoir power plants). Meteorological information from wind speed and river discharge was directly converted into power generation using state-of-the-art methods, including the current information on the location and annual average production of power plants for hydro and power curves from representative turbines for wind.

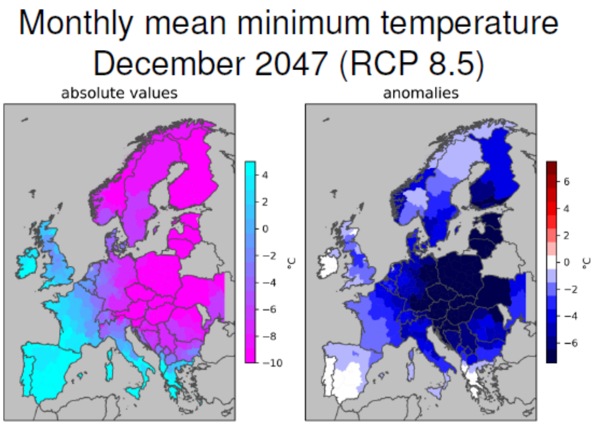
By analysing variable anomalies to the specific reference climate in future projections, extreme and average years from a meteorological perspective were recommended for energy modelling. It was expected that years which included a severe cold spell or heat wave would impose significant stress on Austria's and Europe's energy systems. Later in the project, this was confirmed by the energy modelling, although not in every case, the most severe meteorological condition yielded the most stress on the electricity system (cf. Table 9). Figure 14 (Figure 15) shows a heat wave (cold spell) in future periods with stated anomalies compared to the historical period from 1991-2020, aggregated on NUTS2 regions as one illustrative example of the application of the meteorological dataset.

The meteorological dataset has been widely used for energy modelling in the course of the project. For more comparability and transparency between different energy modelling strategies, the dataset was made available under the name SECURES-Met for free usage for the energy community by a publication in Nature Scientific Data (Formayer et al., 2023c) considering the non-meteorological target audience and a public, open-access database (Formayer et al., 2023b). The authors highly encourage the modelling community to use it, compare their findings to the results obtained within SECURES and use synergies and cooperation opportunities. The applied data manipulation routines are also openly available (Formayer et al., 2023a).



Anomalies	Austria	Europe
T [°C]	5.3	4.0
Tmax [°C]	6.3	4.4
Tmin [°C]	4.0	3.4
WP [%]	56.3	95.5
WP offshore [%]	-	92.1
Radiation [%]	120.1	110.6
HP [%]	58.2	107.5

Figure 14: Heat wave of June 2039 for RCP 8.5 with absolute maximum temperature and its anomaly plotted (left). Anomalies for temperature (T), wind power potential (WP), radiation and hydropower potential (HP) compared to the historical period are displayed in a table (right).



Anomalies	Austria	Europe
T [°C]	-5.1	-3.3
Tmax [°C]	-5.0	-3.6
Tmin [°C]	-5.5	-2.9
WP [%]	117.1	90.0
WP offshore [%]	-	94.3
Radiation [%]	98.3	93.7
HP [%]	78.8	142.7

Figure 15: Cold period of December 2047 for RCP 8.5 with absolute minimum temperature and its anomaly plotted (left). Anomalies for temperature (T), wind power potential (WP), radiation and hydropower potential (HP) compared to the historical period are displayed in a table (right).

3.2 Specific conclusions from climate change's impact on electricity generation and demand in Austria

Based on the climate dataset SECURES-Met described above, the energy system model input dataset SECURES-Energy was created containing all relevant renewable electricity generation profiles and electricity demand profiles impacted by weather. Electricity demand and supply profiles in hourly resolution were generated on the NUTS0 level for the years 2011-2100. The dataset provided the basis for the energy system modelling conducted in SECURES and can be adapted and applied to many different contexts by the scientific community and stakeholders.

The dataset has been analysed in greater detail for Austria to derive conclusions on the development of electricity generation and demand patterns in the country. For the non-dispatchable renewable generation technologies onshore wind, solar PV, and hydro RoR, the development of FLH and seasonality was analysed based on the hourly dataset SECURES-Energy. For the FLH, no strong trend (neither increasing nor decreasing) can be observed for solar, wind onshore, and hydro RoR in the considered emission scenarios in Austria. The strongest interannual variability of FLH now and in the future is observed for hydro RoR, with increasing interannual variability with increasing climate change impact in Austria. This poses a high challenge for highly hydro-dependent electricity systems like Austria. The overall hydro run-off-river generation for Austria is projected to stay around the same in the considered climate change scenarios (RCP 4.5 and RCP 8.5) but strongly changes its seasonal pattern. Generation during summer months is expected to decrease and during winter months to increase. This is due to lower run-off during summer because of hot and dry conditions and higher run-off during winter because precipitation is increasingly falling down as rain and not as snow. This impacts the snow melting processes, which are highly relevant for the run-off river seasonality as observed today in Austria. However, a limitation of the climate scenarios is that glacier melting processes and their impact on hydro run-off have not been fully understood and incorporated into these climate projections. Since these processes are highly relevant for Austria but exceed the scope of SECURES, a follow-up ACRP project (HyMELT-CC, 2023) is going to analyse these processes in more detail. For onshore wind and PV generation, there is no strong change in the seasonality of generation profiles observed.

The impact of climate change on weather-dependent demand components in Austria was also analysed: electricity demand for heating, cooling, and e-mobility, all dependent on the temperature. For heating demand, a strong decreasing trend is observed, down to -35% heating demand in the strong emission scenario (RCP 8.5) at the end of the century (2071-2100) compared to the reference period (1981-2010). For cooling demand, an even more distinct increasing trend is visible: up to +144% cooling demand in the strong emission scenario (RCP 8.5) at the end of the century (2071-2100) compared to the reference period (1981-2010). These two numbers do not consider any changes in heat pump or air condition penetration; the change is purely based on the temperature signal derived from the considered emission scenarios. However, it should also be mentioned that adaptation measures like passive cooling techniques have great potential and can reduce space cooling demand and can completely counteract the increase in cooling demand when implemented ambitiously (Mayrhofer et al., 2023).

These results show that for adequate modelling of future decarbonised energy systems, it is highly relevant to consider the effects of climate change on RES generation profiles and especially on the electric demand components like e-heating and e-cooling. Results showed that critical residual load situations are expected to increase during summer, indicating the growing relevance of heat waves and of measures for increased resilience during them (e.g., passive shading of buildings, reduced cooling demand of power plants) for the electricity system. Critical situations are, however, also still expected to occur during winter in Central Europe.

3.3 Specific conclusions from modelling the electricity system under climate change impacts in Austria

On the energy side, a combination of two distinct energy sector pathways for Austria/Europe up to 2050 with both climate scenarios described above was undertaken: In the *Reference (REF)* pathway and corresponding scenarios, Austria aims to achieve a RES-based electricity supply by 2030 and beyond. However, it represents less decarbonisation ambition in other sectors and EU countries and is accordingly matched with a strong climate change scenario (RCP 8.5). The *Decarbonisation Needs (DN)* pathway represents a strong decarbonisation ambition across the whole EU, implying net zero by 2050. Consequently, a strong growth of electricity demand is expected, driven by strong sector coupling for decarbonising other sectors like industry and mobility. *DN* was coupled with a medium climate change scenario (RCP 4.5). Since security of supply aspects formed a central element in our analysis, we also modelled weather years reflecting extreme weather conditions (i.e. dark doldrums and heat waves) in the mid-future (2050).

A comparison of the results of both energy sector pathways (REF vs. DN) 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%. Consequently, in DN, a significantly stronger uptake of supply-side assets is also applicable, specifically in wind and PV.
- With higher amounts of weather-dependent generation, short-term fluctuations in corresponding electricity generation grow strongly, requiring large amounts of system flexibility to ensure the match between electricity demand and supply in every hour. According to modelling, the total stock of storage and selected demand-side flexibility components in capacity terms by 2050 is ca. 170% higher in DN compared to REF.

The **consideration of climate impacts in electricity system modelling** provides relevant insights, namely:

- 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 low share of weather-dependent load in overall electricity demand in decarbonised energy systems.
- On the supply side, high interannual variations are visible and impacts highly depend 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 is the consideration of extreme weather conditions since, with ongoing climate change, the frequency and duration of such events increase according to climate projections. In our analysis, a heat wave and a dark doldrum served as stress tests for security of supply. Results from 2050 DN reveal:

- For safeguarding electricity supply under these extreme conditions, a stronger than planned uptake of wind energy appears useful from a least-cost system perspective.
- 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 as well as accompanying H_2 storage, allowing a system-friendly operation of the electrolyser fleet. In a dark doldrum, thermal storage is useful for load shifting both at the heat and the electricity side, as a consequence of increased sector coupling. 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.

3.4 General conclusions from SECURES

The project SECURES facilitated intense interdisciplinary exchange between energy modellers, climate scientists, and meteorologists, as well as a broad range of stakeholders. The research at the interface of energy and climate modelling provided insights into the opportunities and challenges of this interdisciplinary approach. We conducted a comparison of methodologic approaches to identify extreme weather years from a meteorological perspective versus from an energy system perspective.

One lesson learned was that there is a good overlap of both approaches in terms of identified years since temperature acts as a key weather variable here. However, from the energy system perspective, a broader geographical scope had to be considered since the European electricity market and grid is strongly interconnected. We also reviewed and developed methods for the identification of extreme events in electricity systems based on meteorological high-resolution data using the residual load in electricity systems as an indicator. The identified periods and weather years are also published open-access.

The work conducted within SECURES, especially the open-access datasets, provides a solid basis for further work on evaluating climate change impacts on energy systems in Austria and Europe within the research community and energy sector. Research gaps we've identified and possible follow-up research questions are:

- What is the impact of climate change on glacier-melting processes and in cascading effects on hydropower generation in Austria?
- What is the climate change impact on energy infrastructure like electricity grids and fuel transport infrastructure?
- Regional specifications: What are the differences in climate impact on different geographic regions in Austria, e.g. on urban and rural energy systems or Alpine regions vs. non-Alpine regions?
- How to design a robust future power system in Austria with the impacts of climate change in combination with various other uncertainties?

All publications generated in the course of the project SECURES are available and updated at https://www.secures.at/publications.

4 Annex: Methods and concepts

4.1 General methods and concepts in SECURES

In accordance with the project objectives, the work within SECURES was clustered into five topical work packages and rested on three key pillars (cf. Figure 16). We defined two decarbonisation scenarios and several different weather years for the transition of Austria's electricity sector in times of climate change. Our outcomes are published and documented open access. We involved Austria's key stakeholders right from the start, informing them of our approach and incorporating their feedback on the definition of scenarios.

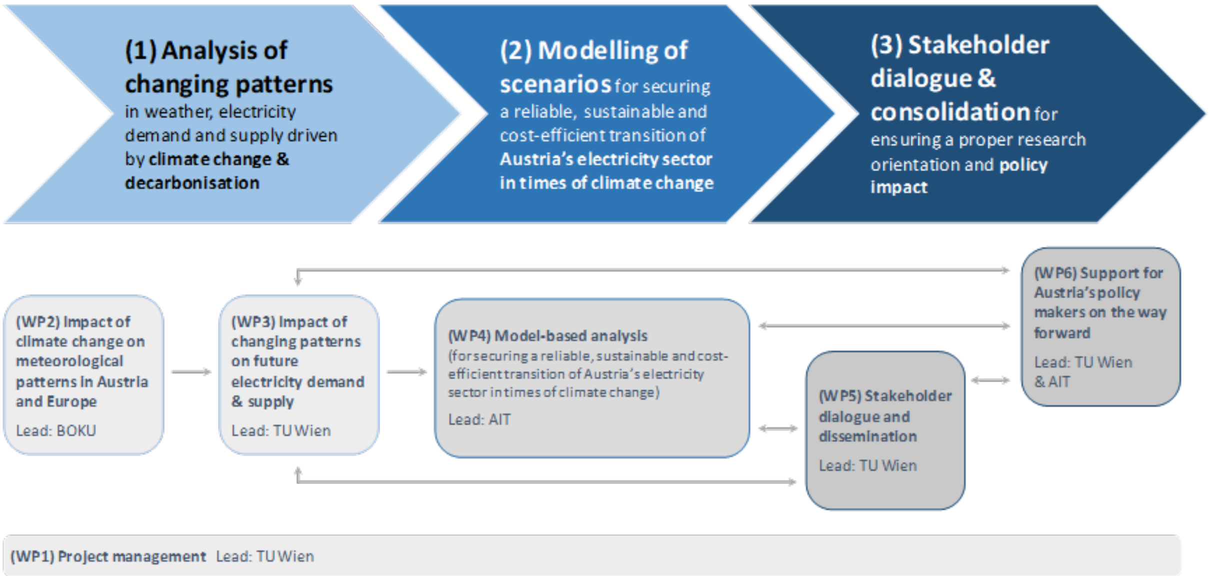


Figure 16: Work structure – the three pillars (and the corresponding work packages) of SECURES

4.2 Methods and concepts in climate modelling

This section gives an overview of the main methods applied in the climate modelling of SECURES (cf. Section 2.1 for contents and results).

4.2.1 Temperature and radiation processing

As the application of temperature and radiation data in the context of energy modelling is solar power, those variables are specifically relevant in locations with high population density and, therefore, high electricity demands. Where people live, like in valleys, it is more likely for solar panels to be set up and temperatures are higher. Therefore, the two-metre-temperature and the global radiation were calculated as

- areal mean, where every grid cell was weighted an equal amount,
- and population density-weighted mean, where Lspop population density data was used on a one-kilometre basis (Department of Economics and Social Affairs, Population Division, 2008)

during aggregation.

Radiation was provided in W/m² as two parameters: First, as the global radiation (GLO) directly available from ERA5 and the EURO-CORDEX models. Second, the direct normal irradiance (BNI), which is the radiation on a surface normal to the direction of the sun, was calculated. This parameter is required to calculate the incident radiation on an inclined surface, for example, a solar panel. The

HelioClim dataset (Blanc et al., 2011) was used to estimate BNI from global radiation for every NUTS2 region for each hour of the day. The estimation was done using quantile mapping on an eight-day basis. GLO values below 10 W/m² were not converted to BNI; here, GLO was taken directly. This approach was chosen due to the lack of data quality for low radiation. BNI exceeding the solar constant of 1361 W/m² was set to that value.

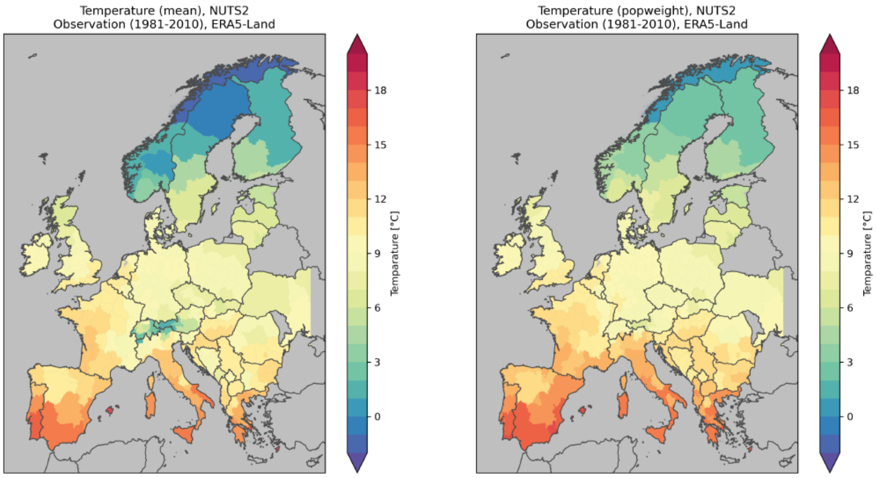


Figure 17: Comparison of temperature aggregation methods. Spatial mean (left) and population-weighted (right) temperature are both given in °C, visible in the colour bar.

As the temperature is highly dependent on altitude, a lapse rate of –6.5°C/km was applied. Temperature was provided in °C. Figure 17 shows a comparison of the spatial mean and population weighting aggregation in the period 1981-2010 as an example of the differences. Population-weighted temperature tends to be warmer because valleys, where people live, are weighted higher in mountainous regions.

4.2.2 Wind processing

As the turbine height of wind power plants is approximately 150 m above ground level, and the ERA5(-Land) and EURO-CORDEX variables provide 10 m wind speed, wind speeds had to be converted to higher altitudes. As the transfer is not linear and depends on roughness, vertical stability and topography, a statistical approach was chosen. The COSMO-REA6 dataset (Frank et al., 2020) that provides wind speed at 150 m and the period of 1995-2019 was regridded to the ERA5-Land resolution. Afterwards, the empirical cumulative distribution function was calculated for each grid point, and the 10 m surface wind percentiles of the models were mapped to the percentiles of the COSMO-REA6 to get the corresponding wind speed at 150 m. Then, the power curves for land and offshore wind turbines (cf. Figure 18 left) were applied to the wind speed. As representative turbine types, N163-4.95 was chosen for land and V164-8000 for offshore. Afterwards, a map from a former project (European Commission et al., 2022) showing suitable spots for wind power plants across Europe was aggregated to the ERA5-Land grid by the arithmetic mean, yielding the fraction of suitable area per grid box. This mask was then used as weights for the power curves to aggregate the wind power to the NUTS regions and the economic exclusive zones and is also visible in Figure 18 (right). The power output is therefore normalized to 1. Efficiency loss was not considered in this step but was applied afterwards in the energy system modelling.

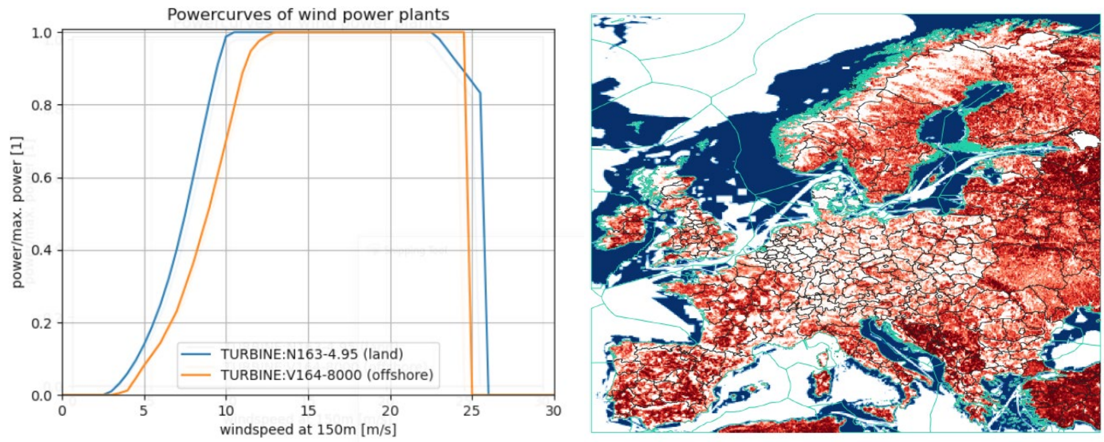


Figure 18: Components required for wind aggregation. The power curves (left) for representative turbine types for on- and offshore wind were used in combination with the potentially available area (right) for wind power plants. Darker tones of red hereby describe more potentially available areas.

4.2.3 Preparation of hydrological data

The hydrological data is based on the European hydrological impact modelling (E-HYPE) (Donnelly et al., 2016), which was forced with the same EURO-CORDEX model scenarios and ERA-Interim data (Dee et al., 2011). The latter ensures that data from the historical period is also available. The utilized variable is the daily mean river discharge in m³/s of the ensemble mean of seven configurations. As river discharge is not subject to change on an hourly basis, daily resolution is sufficient, and no temporal disaggregation was required.

The JRC Hydro Power Plant Database (European Commission, Joint Research Centre (JRC), 2019) was used for information and characteristics about the hydropower plants over Europe. Missing data of average annual generation was estimated using the representative full load hours (FLH) for hydropower in the year 1984 in specific countries.

Individual power plants were first attributed to a specific E-Hype subbasin and divided into run-of-river (RoR) and reservoir plants. The daily mean power was then assumed to be proportional to the daily mean runoff up to a maximum capacity for RoR power plants. The scaling factor between daily mean discharge and daily mean power was calculated from the mean annual energy production of each individual plant in an iterative process. Afterwards, the results in MW were normalized to 1 by dividing through the annual mean power.

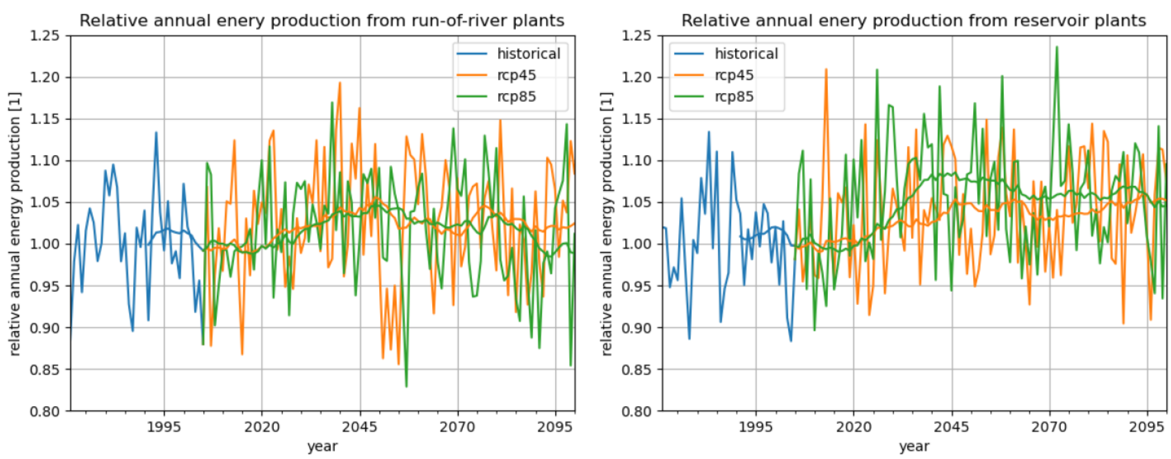


Figure 19: Relative annual energy production for European run-of-river (left) and reservoir (right) hydropower plants, normalized to 1 with the mean energy production of the period (1971-2005).

Figure 19 depicts the normalized annual energy production for RoR plants (left) and reservoir plants (right) in Europe, showing high interannual variability. Both power plant types show a small increase in the mid-century, where the RoR plants tend to return to historical levels towards the end of the century. Reservoir plants stabilize at a 5 % higher level. As power plants are not distributed evenly across countries and areas, local evolution influences this result.

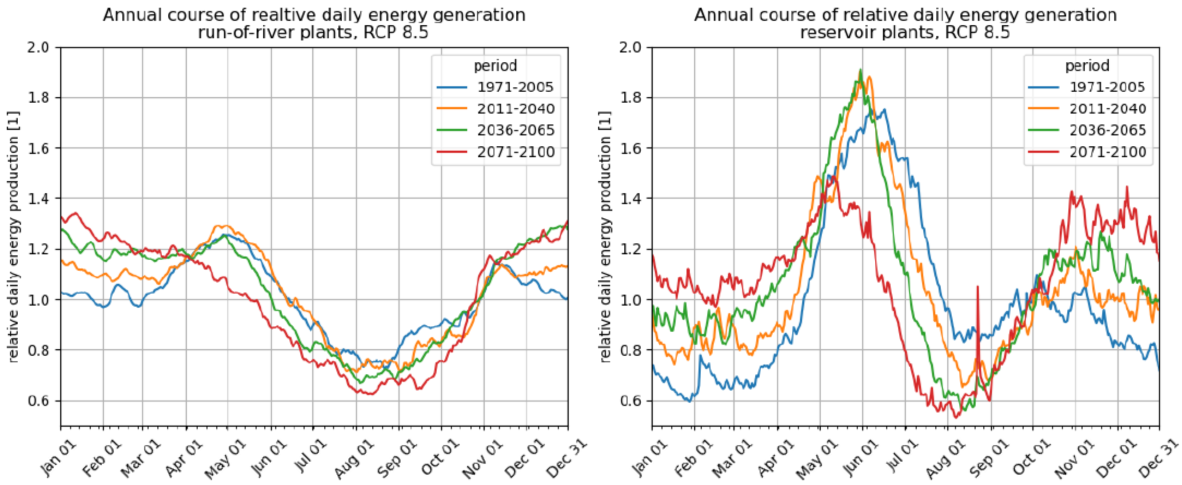


Figure 20: Annual course of energy production for European run-of-river (left) and reservoir (right) hydropower plants for the RCP 8.5 scenario, normalized to 1 with the mean energy production of the period (1971-2005).

Figure 20 shows the seasonal changes in Europe for the RCP 8.5 scenario, which shows the strongest climate change signal. All types of power plants show an increased production during autumn and winter but a decrease during spring and summer.

4.3 Methods and concepts for deriving electricity generation and demand profiles

This section describes the detailed procedure of how weather-dependent electricity demand and supply time series SECURES-Energy in hourly resolution on NUTS0 level for the European Union based on climate scenarios were calculated (cf. Section 2.2 for content and results). The basis for this was the meteorological dataset SECURES-Met (cf. Sections 2.1 and 4.2). The methodological approach consisted of calculating

1. the generation of
    a. Photovoltaic power,
    b. Wind power,
    c. RoR hydropower, and
    d. Reservoir hydropower.
2. the demand in the sectors
    a. Residential heating & cooling,
    b. Tertiary heating & cooling,
    c. E-mobility,
    d. And E-industry.

4.3.1 Electricity generation profiles

Photovoltaic power: The generated PV power was calculated from the time series of BNI and GLO from SECURES-Met (cf. Sections 2.1 and 4.2). In the first step, the PV potential was calculated, i.e. the yield per installed PV capacity. In the second step, the potential was scaled with the installed power to calculate the PV power actually generated. The installed PV power was specified in the respective scenario (DN and REF, cf. Section 2.3.1).

Since the PV potential depends on latitude and longitude, it was computed at the NUTS2 level using the centroid coordinates of each NUTS region and population-weighted BNI and GLO data. In the next step, the PV potential was aggregated on the country level (NUTS0).

The calculation of PV potential involved the following steps:

1. Separate GLO into BNI and diffuse radiation (DHI) according to the equation $GLO = BNI \cdot \cos(Z) + DHI$, where Z is the Zenith Angle. The computation of Z follows the method described by Honsberg and Bowden (2022).
2. Calculate the in-plane irradiance on a PV panel with a given tilt and orientation according to $E_S = BNI \cdot \cos(\theta) + DHI \cdot r_d + GLO \cdot \rho \cdot r_r$, where θ is the angle of incidence, r_d is the diffuse transposition factor, r_r is the transposition factor for ground reflection, ρ is the foreground's albedo.
3. Compute the power output considering thermal losses due to temperature. The computations follow the methods applied by Huld et al. (2010).
4. Apply a degradation factor for degradation, shading, dust, etc. The degradation was assumed to be 14% (JRC, 2022).

Onshore wind power: The climate models (RCP 4.5 and RCP 8.5) and the ERA5 climate reanalysis provided time series for the wind potential for each country as numbers in the interval [0, 1]. The calculation of these time series is described in Section 4.2 and Formayer et al. (2023c). For bias correction of the climate model data, we used a reference dataset (European Commission et al., 2022), which contains precise wind potential calculations for the control period from 1995 to 2018. The time series of the climate models were adjusted to this reference data set using Quantile Mapping. The mapping is calculated based on the quantile function F_{ref}^{-1} of the reference data set and the distribution function F_{model} of the climate model data in the control period:

$$x' = F_{ref}^{-1}(F_{model}(x))$$

We applied a loss factor of 0.85 (15% loss). Finally, the data was scaled to the installed power according to the respective scenario (DN and REF, cf. Section 2.3.1).

Offshore wind power: The wind offshore profiles generated as described in Section 2.1 were taken directly from the climate modelling steps, as now available as an open-access dataset (Formayer et al., 2023b). We applied a loss factor of 0.85 (15% loss). Finally, the data was scaled to the installed power according to the respective scenario (DN and REF, cf. Section 2.3.1).

Hydropower: The hydropower profiles (RoR and reservoir) generated as described in Section 2.1 were taken directly from the climate modelling steps, as now available as an open-access dataset (Formayer et al., 2023b). The climate models provide the time series of the daily energy generated by the RoR power plants for each country (based on the *current* installed capacity). These time series were first converted into potential time series in the interval [0, 1] by dividing the values by the current installed capacity. The potential time series were resampled to 1-hour intervals.

Additionally, the **thermal power plant** capacity was reduced to 66% during the days identified as heat waves in the respective region in the heat wave scenarios (Koch et al., 2014) to account for the thermal power plant efficiency decrease due to temperature increase and disruptions due to water discharge stop or supply issues for fuels transported on rivers.

4.3.2 Electricity demand profiles

The computation of **heating and cooling** demand time series was based on Hotmaps generic profiles (day curves in hourly resolution) for all sectors in each country (Fallahnejad, 2019; Pezzutto et al., 2019). All data was processed in NUTS0 resolution (one profile per country). As exogenous inputs were used:

- Temperature, hourly profile (generated in the climate modelling and described in Section 2.1 and (Formayer et al., 2023b))
- Day structure of the years 2030, 2050, and 2086 (weekday, weekend, etc.)
- Annual demand per sector in the reference year (2010 for DN, 2009 for REF)

As output, hourly electrical demand profiles and annual sums of the following sectors were generated (cf. Table 8).

Table 8: Demand components generated based on temperature data from the climate modelling and Hotmaps regressions and the considered input parameters and spatial resolution.

	Day type	Season	Month	Hour	Temperature	Resolution original
Residential						**NUTS2**
Sanitary hot water	X	X		X		
Space heating				X	X	
Space cooling				X	X	
Tertiary						**NUTS2**
Sanitary hot water	X			X		
Space heating				X	X	
Space cooling				X	X	

Additionally, the non-temperature-dependent **industry** demand profiles (*paper*, *non-metallic minerals*, *iron and steel*, *food and tobacco*, and *chemicals and petrochemicals)* of Hotmaps were calculated, assuming that heat demand correlates with electricity demand in the industry. For each of these subsectors, there are specific generic day profiles for each month of the year and type of day (workdays, Saturdays, Sundays). Electricity demand for electrolysis was assumed to be constant over the year but could be flexibilised in the energy system modelling.

For the load profiles of **e-mobility,** there were specific profiles for three different user groups: 1) people who load their electric vehicle at work, 2) people who use the electric vehicle to drive to work but do not load it there, and 3) people who do not drive to work. The three load profiles were combined according to the percentages of each user group defined by the respective scenario (cf. Section 4.4.1). These profiles were developed in the project Define (DEFINE, 2014), are based on a German survey (MiD, 2010), and consider different weekdays, seasons, and residential areas. A temperature correction formula based on Liu et al. (2018)[8] was used to capture the effect of ambient temperature on electricity load. The third-order polynomial (red dashed curve) was digitized (WebPlotDigitizer, 2014) into data points and was fitted to a 3rd order polynomial to determine its parameters. In order to obtain a unitless scaling function f(T) for the vehicle consumption, the data points were normalized to the mean value of the observations (0.1497 kWh/km) before the regression.

[8] In this paper, Figure 2 shows energy consumption per kilometre vs. ambient temperature; energy demand of about 500 electric vehicles depending on the temperature.

The profile of the rest electricity demand was taken from Resch et al. (2022). As the final step, the demand time series of all sectors were scaled in such a way that the annual demand of a specific (weather) year (2010 for DN, 2010 for REF) corresponded to an amount that is specified in the respective scenario (cf. Table 5). The detailed processing steps of all supply and demand components can be found in the respective publication (cf. https://www.secures.at/publications for the updated list of publications).

4.4 Methods and concepts in energy system modelling

This section gives an overview of the main assumptions and methods applied in the energy system modelling of SECURES (cf. Section 2.3 for contents and results).

4.4.1 Energy system model and consideration of flexibility options

For the modelling, the open-source energy system modelling tool Balmorel (Ravn, 2016) is used. Scenarios are simulated made for Austria and the whole EU (including Switzerland, United Kingdom and Norway) with hourly time resolution with a representative (called "normal") and extreme weather years (i.e. dark doldrums and heat waves). The Balmorel 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.

The following flexibility options were considered in the model-based assessment, whereby modelling informs on their cost-effective use according to underlying characteristics and availability:

- Flexible generation technologies: 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) (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%/75% 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): H2 storages, electrolysers and re-electrification,
- (Pumped) hydropower storage plants (no extension beyond planned according to ENTOS-E and ENTSOG (2022))
- Lithium-ion batteries and prosumers.

4.4.2 Assessing flexibility needs for different time periods

Determining the need for flexibility was conducted based on the Residual load (RL) analysis. RL expressed as an hourly power value in GW represents the difference between the total electricity demand and the electricity infeed from variable renewables, including hydro RoR, wind, and solar PV. RL can be positive (temporary generation deficit), negative (temporary generation surplus), or, in individual cases, zero (generation and consumption balanced). Based on the determination of RL, the calculation of the flexibility needs is then performed according to the method proposed by Andrey et al. (2019), which defines flexibility needs by analysing the dynamics of RL on daily, weekly and annual levels. In this study, monthly flexibility needs are included based on Suna et al. (2022). The flexibility needs identified on the respective timescales (day, week, month and year) cannot be added but rather measure the variability of RL for the corresponding timescales. It should also be noted that merely meeting the need for flexibility, i.e., balancing variability, is not sufficient to ensure supply security.

Here, it is important to maintain a holistic perspective whilst balancing the overall RL, both in positive and negative directions. Therefore, the cumulative annual balance of RL is also provided based on Suna et al. (2022).

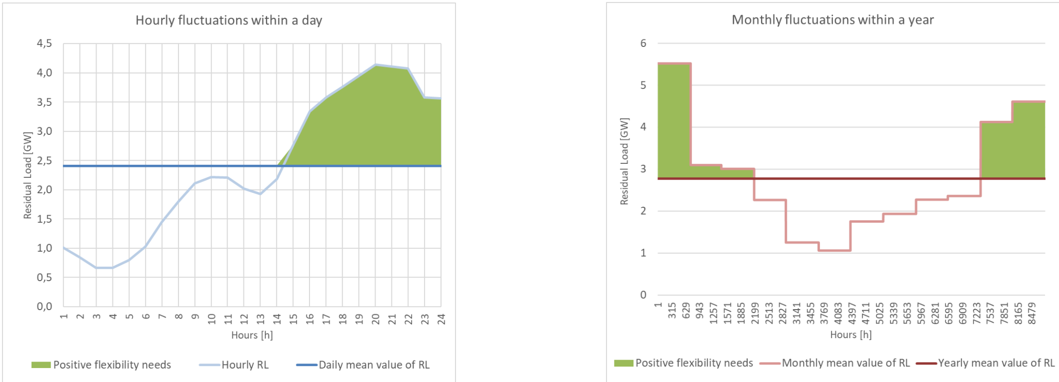


Figure 21: Definition of the flexibility needs to balance the hourly variation within a day (left) and the monthly fluctuations within a year (right), exemplified based on historical generation and consumption data for Austria in 2020 (ENTSO-E, 2021) (Suna et al., 2022).

As examples, the method for two time scales is presented here (weekly/monthly flexibility need was calculated accordingly):

Daily flexibility needs measure the hourly fluctuations within a day. They are calculated from the sum of the positive hourly deviations of RL from the respective daily mean value of RL. The daily flexibility needs over one year are determined as the annual sum of the hourly values. The shaded areas in Figure 21 (left) show the daily flexibility needs for one representative winter day. The result is quantified as energy quantity per day (e.g., MWh/day). The sum of these positive daily differences for 365 days shows the total daily flexibility needs to be covered for short-term (hourly) fluctuations within a year (e.g. in TWh/a). **Annual flexibility needs:** The green area in TWh (cf. Figure 21 (right)) is calculated by summing up the positive deviations of the monthly mean value of RL from the corresponding annual mean value of RL over the whole year.

4.4.3 Choice of weather years

In SECURES, 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 driven by temperature (described in Chapter 2.1.5). Secondly, from an energy system perspective, the RL for every month was calculated, and crucial RL years were compared to the meteorological extreme years. Apart from the electricity generation profile of fluctuating RES (wind, hydro, and solar PV), RL is the key parameter for identifying extreme events from the power system perspective. Following the method outlined by Dawkins and Rushby (2021), two primary indicators were calculated per country, as well as the EU and Central Europe (France, Germany, Belgium, the Netherlands, Luxembourg, Austria, Czech Republic, Poland, Hungary, Slovenia, and Slovakia - CEU), to identify extreme weather events from the power system perspective.

- **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)

Additionally, times of extreme surplus renewable generation were identified:

- **Surplus Peak Periods of Residual Load (SPPRL):** Identified periods where, over a time span larger than **seven days, the average weekly RL** (sliding average of 7 days) is **below its 20th percentile of the negative RL** (representative for over-coverage of renewable generation)

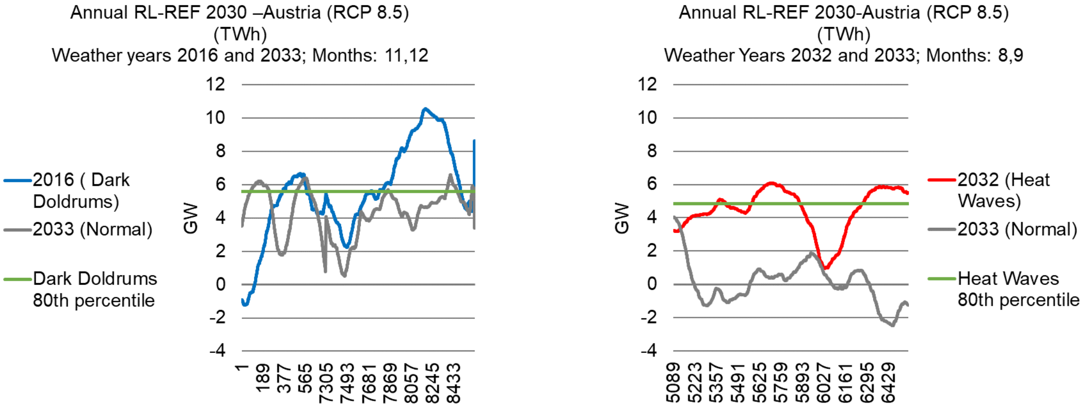


Figure 22: Representation of Peak Periods of Residual Load (PPRL) in the case of REF-2030 by considering RCP 8.5

The indicator PPRL was used to identify the weather years used for the energy system modelling: One normal and two extreme years (Dunkelflaute and heat wave) were proposed for the two emission scenarios, namely RCP 4.5 (for DN scenarios) and RCP 8.5 (for REF scenarios), which were considered to create stress events in terms of the power system perspective. For the selection of weather years, this indicator was not only considered for Austria but also for Central Europe (CEU), with which Austria's power system is strongly connected. The overlap of the identified years from an energy system point of view and identified from a purely meteorological point of view (cf. Section 2.1.5) was high. Only four weather years chosen for the energy system modelling differed from what was marked as extreme years from the meteorological perspective (cf. blue marked years in Table 9) following the RL analysis, as these years depicted longer and higher PPRL. A difference was that the energy system method considered more the interconnectedness with the neighbouring regions than the pure meteorological approach.

Table 9: Selected weather years based on residual load analysis & duration of Peak Periods of Residual Load (PPRL).

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)

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List of Abbreviations

BNI	Direct Normal Irradiance
CEU	Central Europe
DHI	diffuse radiation
DN	Decarbonisation Needs
DSM	Demand-side management
EEZ	Economic Exclusive Zones
E-HYPE	European Hydrological Impact Modelling
ERA5	ECMWF Reanalysis 5th Generation
EURO-CORDEX	European Coordinated Regional Climate Downscaling Exp.
FLH	Full-load hours
GCM	Global Circulation Model
GLO	Global Radiation
H_2	Hydrogen
HP	Hydropower Potential
HYD-RES	Hydro Power Potential for Reservoir Plants
HYD-ROR	Hydro Power Potential for Run-of-River Plants
NECP	National Energy and Climate Plan
NEFI	New Energy for Industry
PPRL	Peak Periods of Residual Load
PS	Pump Storage
PV	Photovoltaics
RCM	Regional Circulation Model
RCP	Representative Concentration Pathway
REF	Reference
RES	Renewable Energy Sources
RL	Residual load
RMSA	Root Mean Square Anomaly
RoR	Run-of-River
SPPRL	Surplus Peak Periods of Residual Load
SSP	Shared Socioeconomic Pathway
T2M	Two-Metre-Temperature
WP	Wind Power Potential