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B) Project overview

1 Kurzfassung

Wie kann Österreich bis 2040 Klimaneutralität erreichen? Da verschiedene plausible Wege zu diesem gesellschaftlichen Ziel existieren, stehen politische Entscheidungsträger*innen vor wichtigen Abwägungen. Überraschenderweise gibt es fast keine Szenarien, die schnelle Emissionsreduktionen für Österreich bis 2040 untersuchen. Darüber hinaus ist wenig über das gesamte Energiesystem bekannt, das Klimaneutralität aus einer angemessen detaillierten techno-ökonomischen Perspektive behandelt.

Im Rahmen des NetZero2040-Projekts liefern wir die ersten unabhängigen und von Wissenschafter*innen und Stakeholdern gemeinsam entwickelten Szenarien zur Klimaneutralität in Österreich aus der ganzheitlichen Perspektive des gesamten Energiesystems. Wir konzentrieren uns auf alle energetischen Emissionen, die etwa 80% der Gesamtemissionen Österreichs im Jahr 2018 abdecken, untersuchen die Dekarbonisierungsanforderungen unter Annahme nicht-energetischer Emissionsszenarien und bewerten im Detail den Beitrag des Energiesystems zu Dekarbonisierungsszenarien.

Alle Szenarien wurden unter Anwendung eines etablierten Protokolls zur Definition und Bewertung von Szenarien erstellt, das die Integration von Stakeholdern zur Ko-Produktion von Wissen unterstützt. Die im Stakeholderprozess entwickelten qualitativen Narrative wurden in Folge mit quantitativen Energie- und Stromsystemmodellen verknüpft. Das Protokoll erhöht die Transparenz des Prozesses und die Reproduzierbarkeit der Ergebnisse und ermöglicht eine Quantifizierung entscheidender Parameter für die Szenarienunterscheidung durch Stakeholder. Die Stakeholderzusammensetzung deckt verschiedene Wissenskategorien, eine Vielzahl von Interessen und Präferenzen ab. Damit soll die Legitimität der neu entwickelten Szenarien erhöht werden. Eine etablierte Online-Szenarioplattform und eine öffentlich zugängliche Web-Benutzeroberfläche zum Vergleich von Szenarien-ergebnissen unterstützen die Bewertung der Resultate.

In Summe haben wir vier Hauptszenarien zur Klimaneutralität entwickelt und um eine breite Palette von Sensitivitätsszenarien ergänzt. Alle Szenarien erreichen bis 2040 Klimaneutralität, unterscheiden sich jedoch in den Dimensionen "Energiebedarf" und "Importe von Energieträgern". In den qualitativen Szenarionarrativen erklären Variationen in Lebensstilen und die lokale Akzeptanz von erneuerbaren Energien diese Hauptunterschiede. Gleichzeitig betonen alle vier Szenariennarrative das erforderliche Engagement aller gesellschaftlichen Akteure, um bis 2040 Klimaneutralität zu erreichen. Die quantitativen Modellszenarien beruhen auf einer fast vollständigen Elektrifizierung des Landverkehrs und einer umfangreichen Elektrifizierung der Wärmeversorgung, sowie auf dem raschen Ausbau von erneuerbaren Energien (+45 TWh) bis 2030. Diese Maßnahmen sind

zentral, um kurzfristig Treibhausgasemissionen zu senken. Langfristige Entwicklungen in den quantitativen Modellszenarien unterscheiden sich deutlicher zwischen den Szenarien und zeigen entweder erhöhte Importe synthetischer Brennstoffe (einschließlich synthetischer Gase) oder eine noch stärkere Ausweitung der heimischen erneuerbaren Stromerzeugung.

Eine detaillierte Bewertung des gesamten Energiesystems zeigt, dass ein größerer Anteil an Windenergie kosteneffizienter ist als ein ausgeprägter Ausbau der Solarenergie. Würde die Windkraft nicht weiter ausgebaut, stiegen die Kosten eines klimaneutralen österreichischen Stromsystems um 20% an. Darüber hinaus ist die vorhandene Stromspeicherung in Österreich in Verbindung mit anderen vorhandenen Flexibilitätsquellen, wie der internationalen Strommarktintegration, in der Lage, die meisten kurzfristigen Schwankungen in der intermittierenden erneuerbaren Energieversorgung auszugleichen. Der Ausgleich saisonaler Variationen ist deutlich kostspieliger. Durch eine hohe Durchdringung von Windenergie kann dem von Wasserkraft und Photovoltaik herrührenden saisonalen Erzeugungsprofil mit einem Sommerhoch und einem Winterdefizit entgegen gewirkt werden. Dies setzt allerdings die volle Verfügbarkeit eines unterstützenden Stromnetzes voraus.

Obwohl alle Szenarien technisch-ökonomisch machbar sind, ist die erforderliche Geschwindigkeit des Wandels in der Geschichte des österreichischen Energiesystems beispiellos. Die Szenarien wurden unseren Stakeholdern und einem breiteren Publikum durch eine erfolgreiche Platzierung in wichtigen Medien, auf unserer Website https://ww.netzero2040.at und im interaktiven NetZero2040 Scenario Explorer, der von IIASA unter https://data.ece.iiasa.ac.at/netzero2040 gehostet wird, bekannt gemacht. Darüber hinaus sind die Szenarien ein wichtiger Beitrag zur derzeit laufenden Entwicklung des Zweiten Österreichischen Sachstandsberichts zum Klimawandel (AAR2), wo sie zu den wenigen Szenarien gehören, die eine Dekarbonisierung des österreichischen Energiesystems bis 2040 vollständig beschreiben. Die im Projekt entwickelte Nomenklatur und der Szenario-Explorer werden von der breiteren österreichischen Energie- und Modellierungscommunity im Rahmen des AAR2 verwendet, um Szenarien vergleichbar zu machen. Dies ist ein wichtiger Beitrag zur Standardisierung von Datenformaten und Analysewerkzeugen für die österreichische Modellierungscommunity und zukünftige Modellierungsprojekte.

Unsere Szenarien unterscheiden sich bis 2030 nicht wesentlich. Nach 2030 weichen die Szenarien jedoch stark voneinander ab. Eine genauere Bewertung der Szenarien nach 2030 ist daher von höchster Bedeutung, da damit verbundene Infrastrukturentscheidungen schnell getroffen werden müssen. Wir haben daher ein Projekt im letzten ACRP-Call eingereicht, um diesen Zeitraum im Detail zu bewerten.

2 Executive Summary

How can Austria reach climate neutrality by 2040? As several plausible pathways towards this societal goal exist, policymakers face important trade-offs. Surprisingly, there are almost no scenarios exploring rapid emission reductions for Austria until 2040. Furthermore, little is known about the complete energy system in a climate neutral world from a fine-grained techno-economic perspective.

In the NetZero2040 project we deliver the first independent Austrian scenarios towards carbon neutrality from the holistic perspective of the whole energy system in a structured process that integrates modellers and stakeholders. We focus on all energetic emissions covering about 80% of the total Austrian GHG emissions in 2018, examine decarbonization requirements given non-energetic emission scenarios, and assess in detail the contribution of the power system to decarbonization scenarios.

We generated scenarios towards a climate-neutral Austria by 2040 by extending and following an established protocol for defining and evaluating scenarios with the extensive engagement of experts and stakeholders and linking the qualitative narratives developed in the stakeholder process to quantitative energy and power system models. The protocol increases the transparency of the process and the reproducibility of results and allows a quantification of crucial parameters for scenario differentiation by stakeholders. We gathered a diverse group of experts and stakeholders to cover different categories of knowledge, consider a variety of interests and preferences, and thus increase the legitimacy of the newly developed scenarios. An established online scenario platform and a publicly accessible web user interface for comparing scenario results supports the evaluation of scenario results.

We have delivered four scenarios to climate neutrality, and a wider set of sensitivity scenarios for each of the four main scenarios. All scenarios reach climate neutrality by 2040, but the four scenarios differ along the axes "energy demand" and "imports of energy carriers". In the scenario narratives, variations in sufficiency lifestyles and the local acceptance of renewables explain these main differences. At the same time, all four scenario narratives emphasise the required commitment of all societal actors to reach climate neutrality by 2040. We find that the quantitative model scenarios consistently point at a wide-ranging electrification of land transport and a more extensive use of electrification in heat supply, and the rapid build-out of renewables (+45 TWh) until 2030 to achieve short-term mitigation goals. Long-term developments in the quantitative model scenarios are more diverse and focus either on elevated imports of synthetic fuels and gas or on a more pronounced expansion of domestic renewable energy supply.

A detailed assessment of the power system shows that a larger share of wind power is more cost-effective than a more pronounced expansion of solar photovoltaics. Furthermore, existing electricity storage in Austria, in conjunction with other existing sources of flexibility, such as international electricity market integration, is able to balance most short-term variations in intermittent renewable supply. However, seasonal variations are harder to balance unless a high wind power penetration is achieved, which reduces the seasonality in electricity supply. However, these results rest on the assumption of the full availability of a supporting electric grid.

While all scenarios seem to be techno-economically feasible, the required speed of change is unprecedented in the history of the Austrian energy system. The scenarios have been disseminated to our stakeholders, and more widely to the public through successful placing of the scenarios in important media outlets, on our website https://ww.netzero2040.at, and in the interactive NetZero2040 Scenario Explorer hosted by IIASA at https://data.ece.iiasa.ac.at/netzero2040. Furthermore, the scenarios are a highly important contribution to the currently ongoing development of the Second Austrian Assessment Report on Climate Change (AAR2), where they are among the few scenarios which fully describe a decarbonization of the Austrian energy system until 2040.

The nomenclature developed in the project and the scenario explorer are now used by the wider Austrian energy and climate modelling community in the Second Austrian Assessment Report on Climate Change (AAR2) to make scenarios comparable and accessible to a wider public audience. This is a crucial contribution to standardisation of data formats and analysis tools in the Austrian modelling community, and future modelling projects, including the ones funded by the ACRP, should make use of that infrastructure as far as possible.

In terms of our own future research, our scenarios do not differ substantially until 2030. However, post-2030, scenarios deviate strongly. A more fine-grained assessment of post-2030 scenarios is therefore of highest importance, as associated infrastructure decisions have to be taken rapidly; we have submitted a project to the last ACRP call to assess this time period in detail.

3 Background and Objectives

Limiting global warming to well below 2°C requires rapid reductions in global greenhouse gas (GHG) emissions globally (IPCC, 2023). At the global level, anthropogenic GHG-emissions must reach netzero permanently around the middle of the century to have a reasonable chance of staying within the emission boundaries implied by the goals of the Paris Agreement. Accordingly, Austria has committed to achieving "climate neutrality" by 2040 (Bundeskanzleramt Österreich, 2020).

However, while the IPCC's Sixth Assessment Report (AR6) (IPCC, 2023) provides a large variety of global and regional scenarios towards this goal, national scenarios for Austria are scarce. In fact, there is currently only one alternative (almost) netzero scenario by 2040 by the environment agency Austria, the "Transitions" scenario (Krutzler et al., 2023). The scenario design and development is, however, not fully transparent, and there are no alternatives explored, i.e. only one single scenario has been published. Other existing climate and energy scenarios for Austria largely aim at evaluating current or proposed additional policies (Bundesministerium Nachhaltigkeit und Tourismus, 2019; Krutzler et al., 2017, 2016), represent narrow stakeholder interests (Krutzler et al., 2016; Veigl, 2017; Windsperger et al., 2018), focus on specific sectors (Geyer et al., 2019; Windsperger et al., 2018), and mostly achieve climate neutrality by 2050, if at all.

Therefore, these scenarios do not provide the comprehensive, balanced picture that is necessary to assess potential alternatives towards climate neutrality. Furthermore, there are methodological limitations of existing scenarios: first, they are frequently missing a detailed representation of the increasingly relevant power sector, which is however crucial to assess the techno-economic feasibility of netzero scenarios which frequently rely on very high shares of intermittent renewable energies. Second, they were developed by a relatively small panel of experts without broader stakeholder engagement, therefore not representing wider societal views on the necessary transformation options. Third, they mostly lack scenario narratives which are essential in communicating scenario results (Trutnevyte et al., 2014). Consequently, they are of limited relevance for the current policy ambition.

Beyond the Austrian context, calls for stronger stakeholder integration into modelling or even participatory modelling approaches are increasingly voiced to improve societal assessments of such scenarios. A close interaction between stakeholders and modellers in developing netzero emission scenarios is, however, rare in the literature. Existing work mainly relied on expert modelling approaches with either no stakeholder integration at all or providing information about results to stakeholders at the end of the modelling process.

We close these gaps in the availability of Austrian netzero scenarios and international activities on stakeholder engagement in netzero scenario building by establishing the first set of comprehensive and consistent independent scenarios for achieving climate neutrality in Austria by 2040, complementing quantitative modelling efforts with a broad, structured, iterative stakeholder process that informs scenario development and evaluates modelling results. The central objective of our research is the design and execution of a scenario development process, which

i. addresses the co-production of knowledge between the modelling team, and stakeholders to increase legitimacy, facilitate acceptance of final scenarios, and allow their use as guiding principles within the stakeholders' organizations

ii. ensures techno-economic consistency by the application of an integrated modelling framework for the energy system, with a particular focus on power systems, and

iii. covers a broad range of desirable future developments and derives feasible scenarios under these assumptions, while ensuring diversity of results.

4 Project content and results

In this section, we first describe the work done in the project, structured according to our work packages. Subsequently, we report results for all work packages.

Project content

WP1 Project Management: In the project management work package, we ensured communication between project partners online as well as offline, using online communication tools, e-mail, zoom meetings, and in-person meetings.

WP2 Scenario development and stakeholder engagement: In this work package, we followed a structured stakeholder engagement process for developing and evaluating scenarios, extending a protocol initially developed by Mitter et al. (2019) to increase transparency and reproducibility of our results. We first identified an extensive list of relevant stakeholders[1], and updated this group before every stakeholder workshop. In total, we held two virtual stakeholder workshops (on February 17th, 2022, and on November 3rd, 2022), and a final in-person workshop at BOKU University in Vienna on November 30th, 2023. The selection of stakeholders was based on consultations with experts from the energy and mobility sectors as well as project-related research on stakeholder engagement in Austria (e.g. Abstiens et al., 2021). The 117 entries for system-relevant representatives were specified with respect to three characteristics: (i) field of activity[2], (ii) sector[3], and (iii) scale[4]. The project team compiled a priority list for invitations to ensure heterogeneity according to these characteristics.

The engagement process focused on three workshops and an online survey, which aimed to (1) identify and prioritise drivers of the Austrian energy system and discuss plausible development directions of the scenario characteristics; (2) co-develop qualitative scenario narratives, (3) quantify selected drivers for its application in modelling; and (4) review scenarios. A total of 35 invitations were sent out for the first workshop, of which 28 confirmed participation. 14 (18) of the 27 (28) invited stakeholders participated in the second (and third) workshop, respectively. Due to COVID-19 restrictions, the first and second workshop had to be conducted online via *Zoom*-video conferences, whereas the third workshop took place in person in Vienna. The digital whiteboard tool '*Mural*' was integrated in the online workshops to enhance teamwork and collaborative exchange of ideas. All plenary and small group workshop sessions were recorded and transcribed for qualitative content analysis.

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[1] https://www.netzero2040.at/unsere-stakeholder

[2] Public administration, cooperation network and consulting cluster, energy supplier, industrial supply company, mobility-transport operator, energy network operator (regulated), lobby group, science and research institution, political non-governmental actor or organised civil society actor (non-profit), social movement

[3] Public, private, public-private, club-association, NGO, individual

[4] Local-regional, state, national

The scenario matrix for the 2040 climate neutrality was developed by the research team and is structured along two main dimensions: low or high final energy demand scenarios and low or high imports of energy carriers. In the first workshop, the participating stakeholders identified 207 drivers for these four scenarios. The drivers influence Energy demand for (1) residential and buildings, (2) industry, (3) and transportation, and (4) Energy imports. A team of researchers clustered these drivers, which resulted in a list of 44 drivers that was shared with the stakeholders for review. Stakeholder feedback on the list of drivers and the qualitative scenario-narratives and their respective titles, which were developed based on the list of drivers by the research team, was obtained in two online consultations, as well as during the second and third workshop. During the third workshop, the final scenarios were presented and discussed with the stakeholders, and adaptation to scenario titles were proposed. In addition, stakeholders reflected on facilitating and hindering factors as well as social justice challenges related to the build-out of energy supply and energy infrastructure, potential demand reductions, and the import of energy carriers. Finally, the stakeholders were asked which scenario they consider the most likely and, in contrast, which scenario they would prefer.

Furthermore, stakeholders quantified parameters differentiating the four scenarios in an online survey before and after the second workshop. In particular, the stakeholders were asked to quantify 6 of the identified drivers in 2 survey rounds - the first round took place before the second stakeholder workshop, the second round afterwards and was directed to stakeholders who did not respond in the first round. The indicators assessed by the stakeholders are listed in Table 1. The questionnaire showed a figure with the respective indicator for the period 2004 – 2021 and respondents were asked to indicate which value is in line with the high import or high demand and the low import or low demand scenario in the year 2040. Furthermore, we posted the survey on our Twitter/X account @netzero2040 and we sent it internally to experts (Energy agency and Energycluster at BOKU Vienna). Table 2 shows the number of respondents in the surveys. We only used the responses from stakeholders in this process, while responses from other groups were used for validation only.

During the scenario development process, living standard considerations were implicitly included. A combination of a low energy demand scenario (Grubler et al., 2018) and the decent living standards (DLS) framework (Rao and Min, 2018) was used to define the lower threshold of the demand reduction potential in Austria. The DLS is a set of universal, irreducible and essential material conditions for achieving basic human wellbeing. The DLS dimensions are quantified indicators and quantitative thresholds, that identify a minimum level of housing, mobility, clothing, social services, etc. for every citizen, all of which encompass energy consumption levels specific to the local conditions, customs, energy systems, and preferences. We incorporated these considerations at various levels of the stakeholder process, though not fully explicitly to eliminate influencing the stakeholders as much as possible.

Table 1: Final input parameters for scenarios as defined by stakeholders

	Last year of observation	Value of last observation	High scenario	Low scenario
Car use (km/capita/year)	2018	9400	9000	5400
Building area (m2/capita)	2021	46	56	41
Modal split train (% of freight transport)	2021	20	20	46.5
Industrial value added (% of 2021)	2021	100	128	97
Electricity imports (% of electricity consumption)	2019	5	20	0
Energy imports (% of gross domestic consumption)	2018	64	52	24

We included stakeholders with social and consumer expertise, and during the identification of barriers, during finalisation of narratives, and quantification of input parameters we ensured that the DLS service levels are respected, as all demand scenarios remain above the minimum threshold.

The assumptions on the decarbonization pathway are another important model input. Stakeholders demanded using a carbon-budget approach consistent with the Paris goals. We therefore based our budget on Steininger et al. (2021). We did not update the budget after data on emissions in 2022 became publicly available. However, observed emissions in 2022 and 2023 were close to the prescribed decarbonization pathway and its adaptation would have implied very minor changes to the total overall budget. We split emissions between the modelled (i.e. energy related) and other sectors and assume for both sectors that they have to become carbon-neutral. This implies that we do not balance positive emissions in the energy sector with e.g. negative emissions from forestry.

WP3 Improvement of MEDEA: During the project, the existing power system model MEDEA's model structure (see "Methods" for a detailed description of the model) was adapted in several ways. We allowed for multi-input to multi-output processes to adequately represent potential future energy conversion processes. Additional energy carriers, hydrogen and synthetic gases, and the extraction and use of CO2 were introduced to the MEDEA model. In effect, the model can now also represent the conversions of electricity to hydrogen, hydrogen to synthetic methane and vice versa.

MEDEA additionally endogenously determines optimal storage investments for heat, hydrogen, synthetic gases, and CO2 in its improved formulation. Further model equations were introduced to allow for time shifts in electricity consumption (so-called "demand-side management", DSM) in MEDEA. However, as it turned out, a linear programming formulation of the model cannot strictly constrain the temporal shift in consumption to the given, exogenous shift-time parameter. In consequence, the provided flexibility even from a demand shifting technology with an exogenous shifting potential of a single hour may effectively be unlimited in the linear model. Constraining the demand-shifting potential properly is possible only in mixed-integer model formulations which would result in substantially higher computational burdens. Facing this trade-off, we decided not to implement DSM. Contributing to this decision was also the early insight that existing flexibilities in the Austrian power system are likely sufficient for renewables integration at the scale modelled.

We increased the spatial resolution at which renewable resources are represented in MEDEA. For this purpose, we developed the python-package "cleo" (https://github.com/sebwehrle/cleo), which leverages the Global Wind Atlas 3 and allows for the assessment of wind resources globally in a very high spatial resolution of approximately 200 m by 200 m. Moreover, the package supports the analysis of spatial indicators, for example from Corine Land Cover or the World Database on Protected Areas. Building on the cleo package, we developed a methodology for assessing wind power potentials based on suitability of a comprehensive set of locational characteristics. The corresponding paper was submitted to Energy Economics (Wehrle et al., 2023, current status: revise & resubmit). After the identification of wind power potentials, we simulated renewable resources at various spatial resolutions based on ERA-5 reanalysis data. Extensive testing has shown that implementing six distinct wind power zones in Austria strikes a good balance between model run-time and adequate representation of wind resources. To counterbalance the resulting increase in run-time, we undertook efforts to achieve a sparser and more compact model formulation. Ultimately, we were able to achieve acceptable run-times, thanks to improved model formulation and algorithmic improvements. To represent the technical and economic characteristics of the added technologies, we reviewed potential data sources and decided to rely on unified and consistent technology data provided by the Danish Energy Agency "Energistyrelsen'' (Danish Energy Agency, 2023) and prepared the data for further use in our models (see WP5). Timeseries of demand are derived from different data sources (see WP5).

Table 2: Number of respondents in survey

Survey	Number of participants
Stakeholder wave 1	12 (out of 27)
Stakeholder wave 2	10, 3 of them have responded already in survey wave 1 (out of 27)
Stakeholder total	19 out of 27 (+ 3 double responses)
Social media	25
Internal experts	6

WP4 Improvement of TIMES: For the development of the scenarios of energy supply and demand for the complete Austrian energy system, we used an energy system model that has been implemented using the TIMES model generator. TIMES has been developed by the IEA-ETSAP group (IEA-ETSAP, 2024a, 2024b) and allows the development of scenarios with cost optimal pathways of a detailed energy system representation with perfect foresight under given technical constraints and policy targets. (see "Methods" for a detailed description of the model).

The TIMES model for Austria is aligned with official Austrian energy statistics provided by Statistik Austria. This alignment refers to the sectoral structure of the model by disaggregating the energy system into six sub-sectors for energy demand[5] as well as several sub-sectors for energy supply[6]. Additionally, all energy carriers covered by the energy statistics are explicitly accounted for. Enhancements to the model in this project include the integration of hydrogen and synthetic fuels and gases and their respective transformation processes. This approach ensures ease of comparison and validation. Within the energy sector, the seasonal storage of gaseous fuels is calculated endogenously.

Some features of the TIMES model allow the development of scenarios with a high level of detail in selected sectors, mainly the commercial building sectors. This level of detail has the disadvantage of increasing the computation time, while having only a minor impact on the quality of the results required for the scenarios of this project. To alleviate the burden on computing time, we simplified the currently implemented approach. Furthermore, the goal to achieve a full decarbonisation of the Austrian energy system requires the use of new technological options, and substantial changes of the utilisation of current technologies. We expected the range of scenarios that shall be developed within this project to be very broad, and have therefore both included technologies that have not been considered relevant so far, and expanded the ranges of their application beyond historical observation.

The coupling of the TIMES and the MEDEA model allows to assess the feasibility of the results of the TIMES model, requiring the exchange of data in both directions, and the adjustment of parameters in the TIMES model to reach consistency between the results of both models. We therefore identified the necessary parameter interface and developed the required routines and data formats. Originally, the Austrian TIMES model is running within the software framework VeDA which allows to modify the model structure, import necessary data, and combine data sets representing scenario assumptions. This framework creates the input file for the GAMS optimization tool and prepares the results for further analysis. As this framework cannot be used on the Vienna Scientific Computing

5 Households; services; industry including a bottom-up-model of steel production; agriculture and transport.

6 Production of electricity and district heat, synthetic fuels, biogenic fuels and fossil fuels; fuel imports and domestic production.

grid, its workflow had to be implemented in the Python programming language. We extracted the basic model input files from the existing VeDA framework, and developed a small set of routines that solve the model using only these basic files. Additionally, we implemented routines that can integrate data from other sources (such as parameter definitions by stakeholders and MEDEA model outputs), by converting this data into the TIMES data format and exporting them to be used with the basic TIMES model. Finally, we developed a compact naming convention to assure that both model input and the results files for each scenario can be stored and managed in an automatic workflow.

WP5 Model coupling & runs: we started working on model coupling by harmonizing parameter assumptions of the TIMES-Austria and MEDEA models. We identified relevant parameters shared by both models and compiled their sources. Furthermore, we coordinated with WP2 to specify which parameters are determined by stakeholders. We decided to base our techno-economic parameters on the consistent technology data set provided by the Danish Energy Agency whenever possible. In addition, we reviewed the available literature on renewable potentials in Austria and established a dataset containing domestic potentials for hydro power, wind power, photovoltaics (rooftop, open-space, agricultural co-use), bioenergy (agricultural biomass, forestry, residues), geothermal energy, carbon capture and storage. In a second step, we compared results from the TIMES and MEDEA models to build a shared understanding of model capabilities and definitions. These insights served as the basis for developing a standard nomenclature to streamline the model-coupling and validation process. The definitions of variables to describe the energy system and corresponding units in the pyam format are managed through a public, open-source GitHub repository[7].

Aligning our definitions with work in the Horizon2020 project openENTRANCE and with the definitions and categorizations by "Statistik Austria" should foster a broad uptake in the Austrian community of modellers and stakeholders. For interfacing TIMES and MEDEA, we use the developed nomenclature in combination with the pyam-package to generate standardised, interoperable data packages. A prototype of the interface between both models has been successfully tested. MEDEA was set up on the Vienna Scientific Cluster (VSC-4, cf. WP3). Before its deployment on the VSC-4, the TIMES-Austria model had to be disentangled from its VeDA front- and backend (cf. WP4).

Actual model coupling was achieved by, in a first step, executing the TIMES model to determine the primary energy demand and energy imports required to satisfy useful energy demand, taking into account all necessary intermediary fuels and the technology capacities required for converting or using these fuels under the given scenario assumptions for the years 2025 to 2040. From this comprehensive set of results, the annual consumption of electricity, district heat, and synthetic gases for each of the model's sectors, and the installed capacities of energy

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[7] https://github.com/netzero2040/netzero2040

conversion technologies are being extracted. This data is then passed on to the MEDEA model in pyam-format.

Subsequently, aggregated annual time series from the TIMES model are disaggregated to hourly resolution for use in MEDEA. Hourly consumption profiles were used to generate time series of the electricity demand from electric mobility, including passenger cars, light, and heavy duty vehicles (Fattler, 2021; Wermuth et al., 2012) and from 11 industrial subsectors (Ganz et al., 2021). To generate a profile of residual electricity consumption from the agricultural, household, and service sectors, we calibrated the synthetic load profiles to the year 2020 and computed the residual hourly load from the difference between observed and synthetic loads. Hourly time series of district heat consumption were generated based on natural gas load profiles for heating by households, and commercial and service (sub)sectors (Almbauer et al., 2021; Almbauer and Eichsleder, 2008). Consumption of hydrogen and synthetic gases in the industry sectors was assumed to be constant in each hour of a model year.

The MEDEA model was then initialized by applying the generated hourly profiles to annual aggregate consumption as reported by TIMES. Moreover, MEDEA determines optimal investment starting from actual installed capacities (2020) or capacities from the preceding TIMES-base year (2025 and beyond). Based on these inputs, import prices of hydrogen and synthetic methane were calibrated such that the total annual imported volumes in MEDEA match the corresponding values from TIMES. Subsequently, MEDEA was run to determine the optimal investment in and operation of all modelled technologies. Finally, technologies are aggregated by fuel and output to make them comparable to the TIMES model. Results were exported to standardized pyam-datafiles complying with the pre-defined nomenclature. If optimally installed capacities diverged substantially between MEDEA and TIMES, sanity checks on both models were conducted to identify potential causes for the divergence and to implement sufficient fixes if required. This procedure was iterated until optimally installed capacities in TIMES and MEDEA converged.

WP6 Communication and Dissemination: For an extensive description of our communication and dissemination activities, please see section 2.3. In terms of milestones, we developed and continuously updated a communication and dissemination plan, including a more detailed plan for communication on Twitter/X. The goal of WP 6 was to regularly communicate about the project's results and new developments. This included the close collaboration with our stakeholders during the project. Beside the focus on the stakeholders, we defined four different target groups, i.e. the scientific community, experts, journalists, and the public. The detailed activities are listed in section 2.3, while an overview is given below:

Workshops were a core element of the project (see description of WP2). We fostered intensive communication with and between stakeholders and other scientific projects in online and offline workshops. The three workshops enabled a bidirectional and open communication and helped to foster a common understanding of future developments and measures needed to reach climate neutrality by 2040. We targeted the scientific community through presenting at scientific conferences, in meetings of the Austrian Assessment Report 2, and in (partly submitted) peer-reviewed publications. Journalists were targeted via conventional media channels such as press releases, newsletters and background talks. We timed the public press release of our scenarios exactly at the end of COP 28 (conference of parties), therefore generating extensive media coverage. In addition, we used the alternative communication channels Twitter, Podcasts, Newsletters and our website to provide accessible channels for communication and interaction. These channels completed our communication strategy, resulting in a wider audience reach and greater project impact. Finally, we launched a public "NetZero2040 Scenario Explorer"[8] to make the project results easily accessible to a wide range of users including other modellers/researchers, policymakers, stakeholders and the public at large.

Project results

WP2 Scenario development and stakeholder engagement:

Based on the collaborative identification and description of scenario characteristics in the first workshop, and on final feedback in the last workshop, the four scenarios were entitled (A) Sufficiency and maximum expansion of renewables; (B) High resource use and international energy agreements; (C) Energy-intensive lifestyles and relative energy autonomy; and (D) Restricted expansion of renewables and energy imports (see Figure 1); and structured into the six thematic areas (i) Social acceptance and lifestyles, (ii) Politics and institutions, (iii) Energy supply and network infrastructure, (iv) Building and housing, (v) Transport and mobility, (vi) Prices and costs.

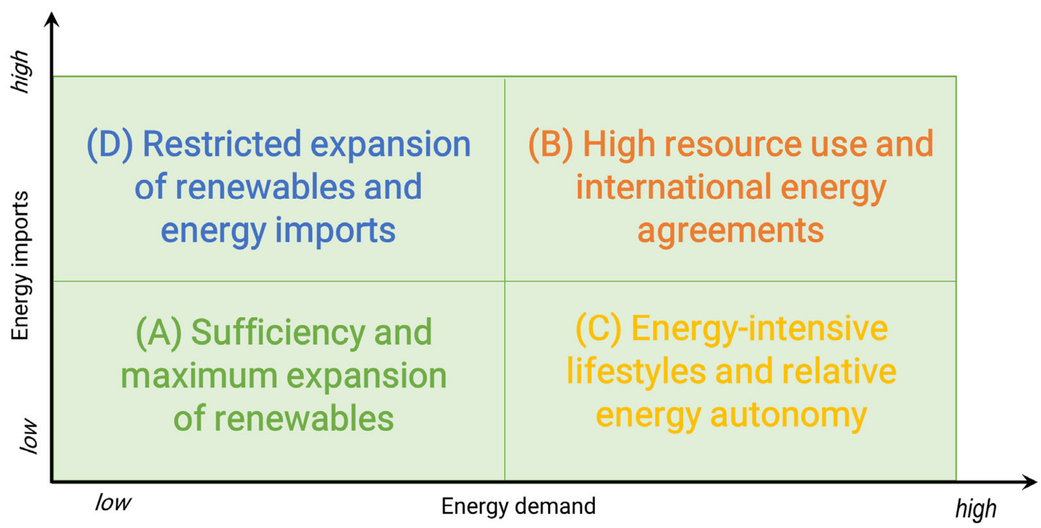

Figure 1: NetZero2040 scenario matrix

[8] https://data.ece.iiasa.ac.at/netzero2040

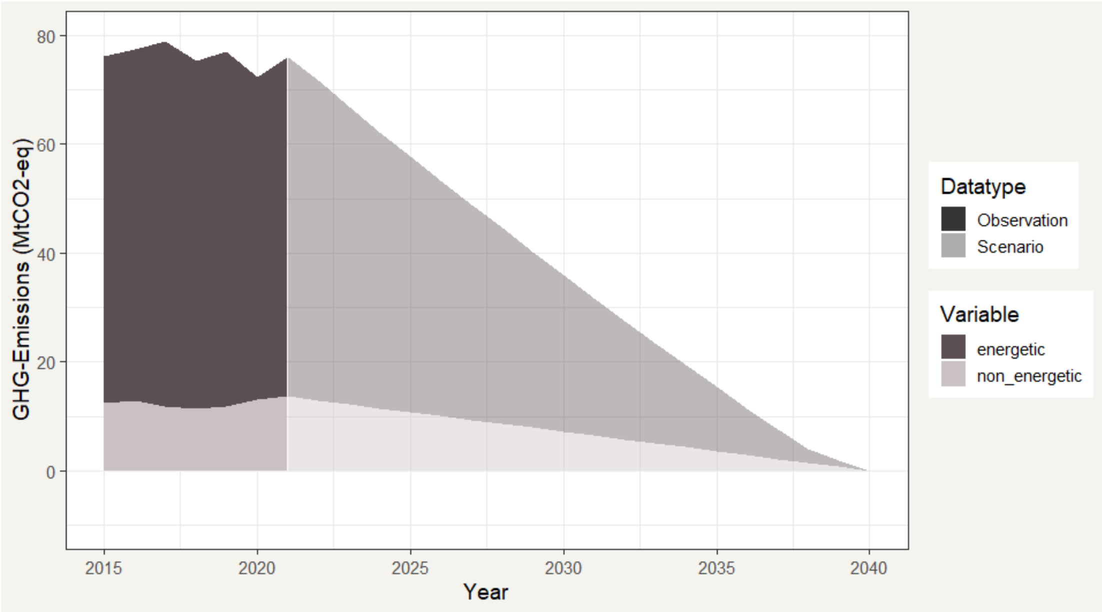

Figure 2: Emission reduction pathway assumed in NetZero2040.

Furthermore, in WP2 we defined the GHG emission reduction pathway until 2040, based on Steininger et al. (2021) , who estimate the remaining Austrian carbon budget. The corresponding emission pathway is shown in Figure 2. The pathway shows that deep, immediate emission cuts are necessary to attain full decarbonization until 2040, as otherwise the remaining carbon budget will be completely used up by 2030. It also shows that emission reductions in the energy system have to be significantly larger than in other sectors.

In WP2, we furthermore developed the qualitative scenario narratives, which are fully available online in our online appendix[9]. We briefly summarise them here: The qualitative scenario narratives are structured along the two axes of final energy demand and available imports of energy carriers. The extensive stakeholder input on the scenario narratives was structured into six thematic areas for all four scenario narratives: (i) Social acceptance and lifestyles, (ii) Politics and institutions, (iii) Energy supply and network infrastructure, (iv) Building and housing, (v) Transport and mobility, (vi) Prices and costs. Two key factors are identified for each of the four scenarios (see Table 3). However, in detail, the scenario narratives contain both differing and overlapping content regarding the five thematic fields.

Finally, we have also quantified core input parameters to the models in WP2. Figure 3 shows the main results of the corresponding stakeholder survey, which informed the model runs. The results of the survey confirm a consistent assessment of the stakeholders, i.e. the values chosen were logically consistent with the respective scenarios (e.g. in the high demand scenario, values were chosen that cause higher demand than in the low demand scenario). In general, demand was seen increasing over recent observations in the high demand scenarios, but decreasing

[9] https://zenodo.org/records/11094102

in the low demand scenarios. A notable exception is the per capita distance driven in cars: it is also reduced (slightly) in the high demand scenario, pointing to the perception of stakeholders that the transport sector crucial for achieving climate neutrality. The low demand scenarios show a structural break in all parameters, i.e. past long-term trends of increasing demand are reversed in the future. As an example, the heated building area per capita is assumed to decrease in the future, compared to recent observations.

In total, this would entail that less building area has to be heated in 2040 than today, i.e. a reduction in the total building stock used for living. Industrial production is assumed to remain at a similar level in the low demand scenario though potentially pointing at the fact that stakeholders deemed a larger reduction as implausible or socially unacceptable.

The parameters were checked against the decent living standards thresholds to identify if the potential reductions in living space, thermal comfort and mobility were not jeopardising the socio-economic wellbeing of the population on average. The relevant DLS thresholds are 14 m2/person living space and a 66.4 MJ/person/m2 energy demand for thermal comfort (Kikstra et al., 2021). These are well below the model input parameters based on the stakeholder definition of housing demand (see Figure 3). In terms of personal travel, the DLS level has been less specific in the international literature, and a universal value is difficult to state because of the high impact from local geographical situation, urbanisation, distances, types of jobs and norms of leisure, education, social structures. There is evidence that mobility is rather defined by time, because people spend on average roughly the same time on travelling over history and geographies (Schafer and Victor, 2000), though with very broad extremes. Therefore, DLS values range from 10000 pkm/year/person (Rao and Min, 2018) to 9544 pkm/year/person (Grubler et al., 2018), through a range of 4900-15000 pkm/year/person (Millward-Hopkins et al., 2020), and 8527 pkm/year/person for Austria (Kikstra et al., 2021). Based on data from Österreich unterwegs 2013/2014 survey, the DLS value stands rather at 5100 pkm/year/person. This is also in line with the lower assumptions of the motorized mobility reductions (see Figure 3).

The results of the survey have been implemented in the models, i.e. either the 25% or the 75% percentile, depending on the type of scenario, i.e. "low" or "high", respectively have been shown (for details see Figure 3). Note that with respect to the import shares of energy carriers to Austria, the stakeholders set high shares, which would imply a continuation of the status-quo by assuming that fossil fuels can be easily replaced by low-carbon energy carriers. We therefore set them as maximum constraints in the models, i.e. the high shares of imports are not necessarily attained in all scenarios.

Table 3: Key factors of the four NetZero2040 scenario narratives

Scenario title	Key factor 1	Key factor 2
(A) Sufficiency and maximum expansion of renewables	Federal state-specific and national energy policies are strongly climate-friendly. Competitive renewable energy supply and the expansion of energy infrastructure, including pipelines and storage facilities, are promoted at national level.	The sharp rise in environmental and climate awareness among the population is leading to (i) energy-sufficient lifestyles (in particular consumption, mobility and housing behaviour) and (ii) a high level of social acceptance for the mix of measures required to implement the energy transition.
(B) High resource consumption and international energy agreements	The relatively conservative environmental and energy awareness of the population and the lack of progressive policy strategies and instruments lead to a slow national expansion of renewable energy and minor changes in energy-intensive activities.	The high energy demand is covered by the high international availability of cost-efficient and CO2-neutral electricity and fuels as well as by international trade which is strengthened through trade agreements and international partnerships.
(C) Energy-intensive lifestyles and relative energy autonomy	The national transformation strategies, regulations and public investments foster relative energy independence and strengthen domestic self-sufficiency, which are supported by broad social acceptance of the expansion of renewable energy sources.	The combination of high energy availability, low energy prices, massively decreasing technology costs, and low public awareness of energy sufficiency is leading to rising resource consumption.
(D) Restricted expansion of renewables and energy imports	At national level, the reduced efforts to expand renewable energies and their comparatively high production costs - influenced by the low level of social acceptance - lead to rising imports.	Technological innovations are proactively promoted by politicians through regulatory frameworks and investments. Support is also provided by the population through energy-saving behavioural preferences.

In the final scenario evaluation, stakeholders were given the opportunity to assess the developed scenarios based on either their likelihood and their desirability. This process unveiled differences between the two criteria. Notably, 50% of stakeholders favoured scenario (B) characterized by high energy use and imports as the most likely, while 44% favoured scenario (D) featuring low energy consumption and high imports. Conversely, scenario (C) with high energy use and low imports garnered only 6% of the votes. None of the stakeholders deemed scenario (A) with low energy usage and low imports as the most probable. However, when it came to desirability, a substantial majority, 69% of stakeholders, found scenario (A) the most desirable, whereas only 31% favoured scenario (D). A survey conducted on the social media platform X corroborated these findings, revealing similar outcomes. Though these results are confined to our stakeholder group and not indicative of the broader population, they underscore a disparity between what appears feasible and what stakeholders genuinely aspire to.

WP3 Improvement of MEDEA: The implementation of new features, such as technologies converting multiple inputs to multiple outputs and an increased spatial resolution for intermittent electricity generation required changes to the model's underlying mathematical representation and the according input data. These features have been successfully implemented. To integrate MEDEA with TIMES, we developed an automated pipeline for data exchange based on the pyam data format. This pipeline maps the associated developed nomenclature for energy systems to MEDEA’s symbols and converts the respective data, for example to increase its temporal resolution. Moreover, MEDEA's solution can be postprocessed and mapped to the developed nomenclature and the pyam data format. Thereby, MEDEA integrates with IIASA's scenario explorer. For large-scale scenario analysis, we enabled MEDEA to instantiate large numbers of scenarios which can subsequently be processed on high-performance computing clusters such as the Vienna Scientific Cluster (VSC). While this approach allows for the parallel solution of massive amounts of scenarios, the VSC hardware is less suitable for model development, which requires rapid execution of single scenarios. Therefore, model development was conducted on hardware geared towards the peak single-thread performance required by state-of-the-art optimization solvers. Changes to the model's core and its ancillary code for data processing and model execution were thoroughly tested before they were added to MEDEA’s code base.

WP4 Improvement of TIMES: In WP 4 the qualitative scenario narratives from WP2 have been quantified with the TIMES model. The direct results of WP 4 include the development of the energy consumption of the different end-use sectors and the energy supply required to satisfy this demand. These results are given both in terms of energy quantities and technological capacities and were used as direct input for the model coupling process. The results are available on the scenario explorer (https://data.ece.iiasa.ac.at/netzero2040/#/) and discussed in greater detail in the section on results of WP5 (below).

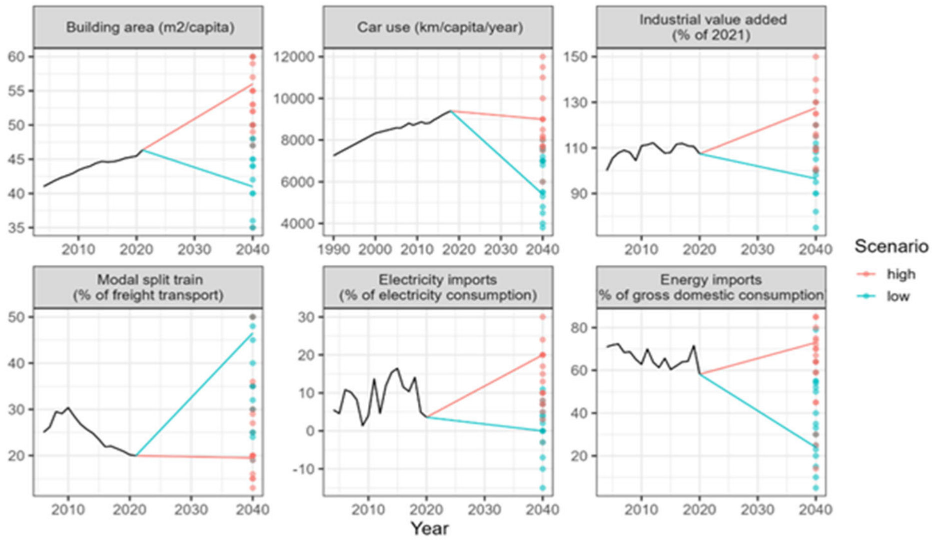

Figure 3: Historical development of indicators (black line), and stakeholder responses for the year 2040 (points). The coloured lines connect the last observation with the 25% quantile or the 75% percentile of responses, respectively.

WP5 Model coupling & runs: here we report in details on the results of model runs, in particular on the following results for the four main scenarios, and for three sensitivity scenarios building on Scenario C (high demand, low imports), with lower BEV penetration (S1), almost no imports of energy carriers at all (S2), and no additional building insulation (S3) (see Table 4 in section Methods for a description of scenarios). In all quantitative model scenarios, gross domestic energy consumption falls, amounting to only 61%-75% of the consumption observed in 2021 (see Figure 4). Variations in allowed import levels have a notable impact on gross domestic consumption, with changes amounting to between 2% - 8% for the same demand scenarios. In a further sensitivity scenario, in which imports are restricted to 5% of gross domestic energy consumption in the high demand scenario, gross domestic consumption rises by 11%. This increase is attributed to the necessity of producing synthetic gas and liquids within Austria, causing efficiency losses inherent in the production process to manifest in the Austrian energy balance. In the higher import scenarios, these efficiency losses occur in exporting regions. Moreover, demand-side measures such as reduced mobility, decreased heated area, and diminished industrial activity significantly influence gross domestic consumption (up to -10%). The primary factor contributing to lower gross domestic consumption, however, is the electrification of mobility, coupled with a lesser but still notable impact from the electrification of heating. For instance, if the expansion of electric mobility is restricted to 20% of the total fleet (scenario S1 Low BEV), this results in a notable 14% increase in energy consumption. Therefore, lower rates of electrification significantly elevate gross domestic consumption. Furthermore, thermal insulation of buildings also plays a role, albeit to a lesser extent. Without adequate thermal insulation, gross domestic consumption sees a moderate increase of 5%, as even at extremely aggressive insulation rates, only parts of the building stock can be improved, as electrification improves the efficiency of heating, and as the share of heat for building in final energy use is lower than 25%.

Although there are significant variations in input parameters, the fundamental shifts in the energy supply until 2030 remain consistent across all scenarios: a rapid expansion of renewable power generation (see Figure 5) coupled with the electrification of mobility and heating. However, differences between scenarios primarily lie in the extent of fossil fuel consumption, which is higher in high-demand scenarios, leading to limited implementation of carbon capture and storage, including direct air capture (DAC) to balance residual fossil fuel emissions from sectors, where carbon cannot be captured from the source, such as transportation. Additionally, variations exist in the amount of electricity imported, with higher levels in high import scenarios. These outcomes stem from the strong growth in electricity consumption until 2030 due to electrification. Consequently, renewable energy must expand at maximum growth rates regardless of the scenario. Notably, the growth in wind power and solar photovoltaics exceeds current government targets for the year 2030. Furthermore, the results underscore that the primary alternatives to domestic renewable expansion and electrification are imports of low-carbon fuels or carbon capture and storage, both technologies that are uncertain to scale to a sufficient level in the short term.

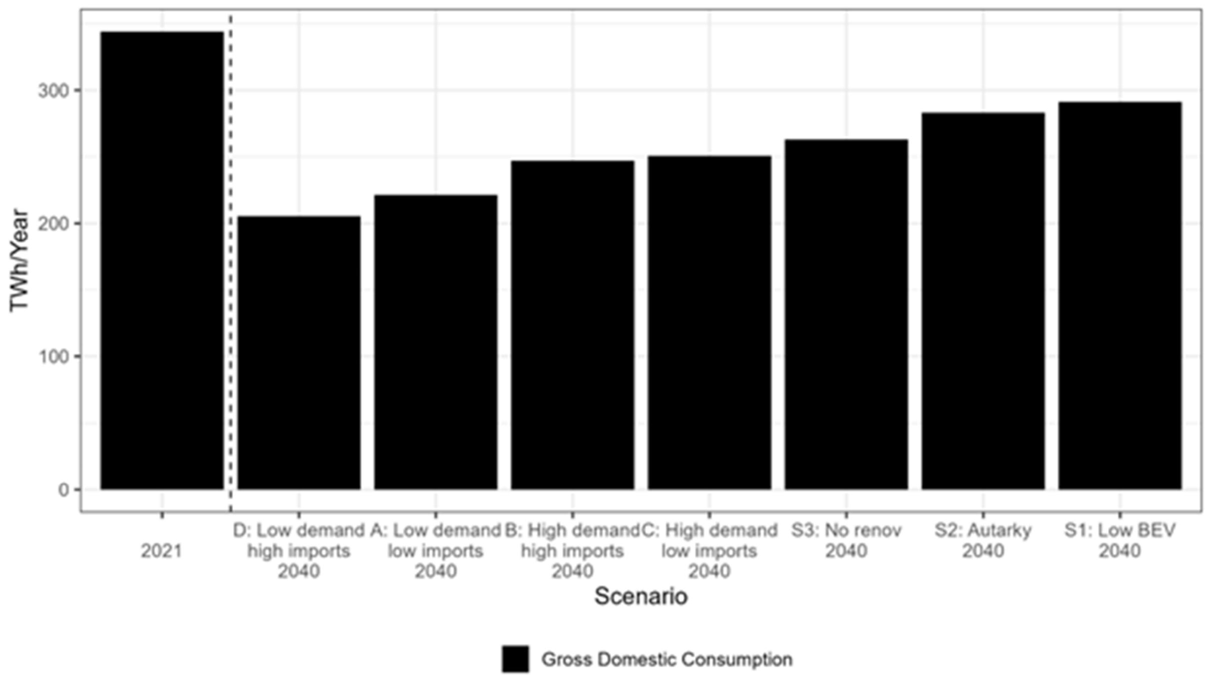

Figure 4: Gross domestic consumption in Austria in the four main scenarios and the sensitivity scenarios.

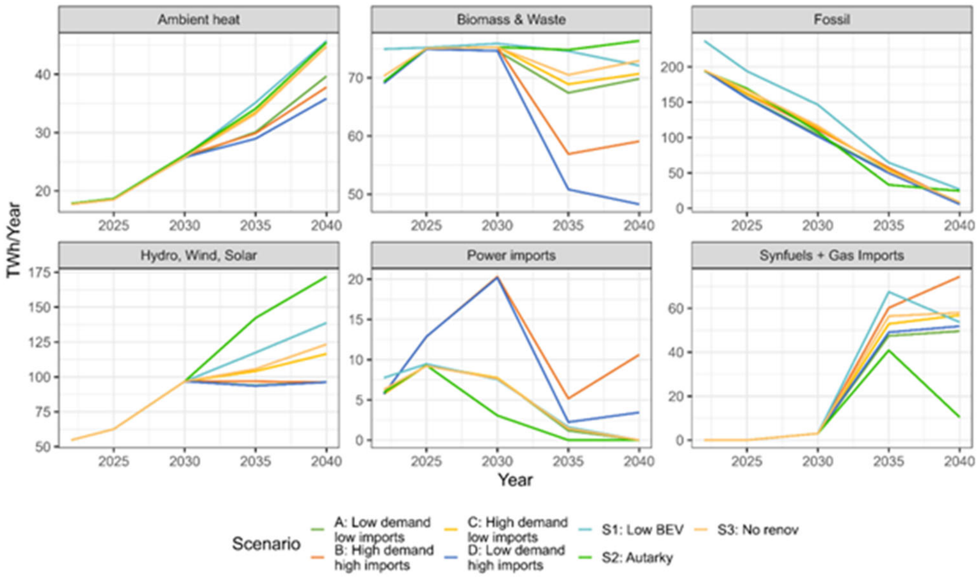

Figure 5: Gross domestic consumption by energy source in the four scenarios and three sensitivity runs

Beyond 2030, the scenarios diverge in terms of the energy supply structure. Generally, in low-import scenarios, there's a greater reliance on domestic biomass & waste and ambient heat, with reduced utilization of synthetic fuels. Moreover, in the high-demand, low-import scenario, additional expansion of domestic renewable energy generation becomes imperative post-2030, and even more so in the extreme autarky scenario, which allows only 5% of imports. This contrasts with other scenarios where imports of synthetic fuels and gas meet further growth in low-carbon energy. Notably, total imports approach the constraints specified by stakeholders in low-demand scenarios but remain well below the upper constraint in the higher-import scenario.

This suggests that domestic resources are preferred in cost-efficient scenarios even with relatively low-price assumptions for imported fuels. As an example, in the scenario with the highest utilization of synthetic fuels and gas, the quantity of those fuels is 60% less than fossil fuel and gas use in 2021, highlighting the substantial shift towards domestic low-carbon electricity sources. Note that fossil fuel use remains higher than in all other scenarios at lower penetration of battery electric vehicles, making higher amounts of carbon capture and storage necessary in 2040. Fossil fuel use in 2040 is also higher for the autarky scenario, where domestic fossil fuel resources will continue to be explored.

Our scenarios underscore the unprecedented pace of change required in Austria's power generation infrastructure (see Figure 6). The expansion of solar photovoltaic (PV) and wind power must occur at rates surpassing historical growth in solar PV and wind power and surpassing the expansion rates of Austria's other major energy generation technologies, namely hydropower and thermal power generation, since 1965.

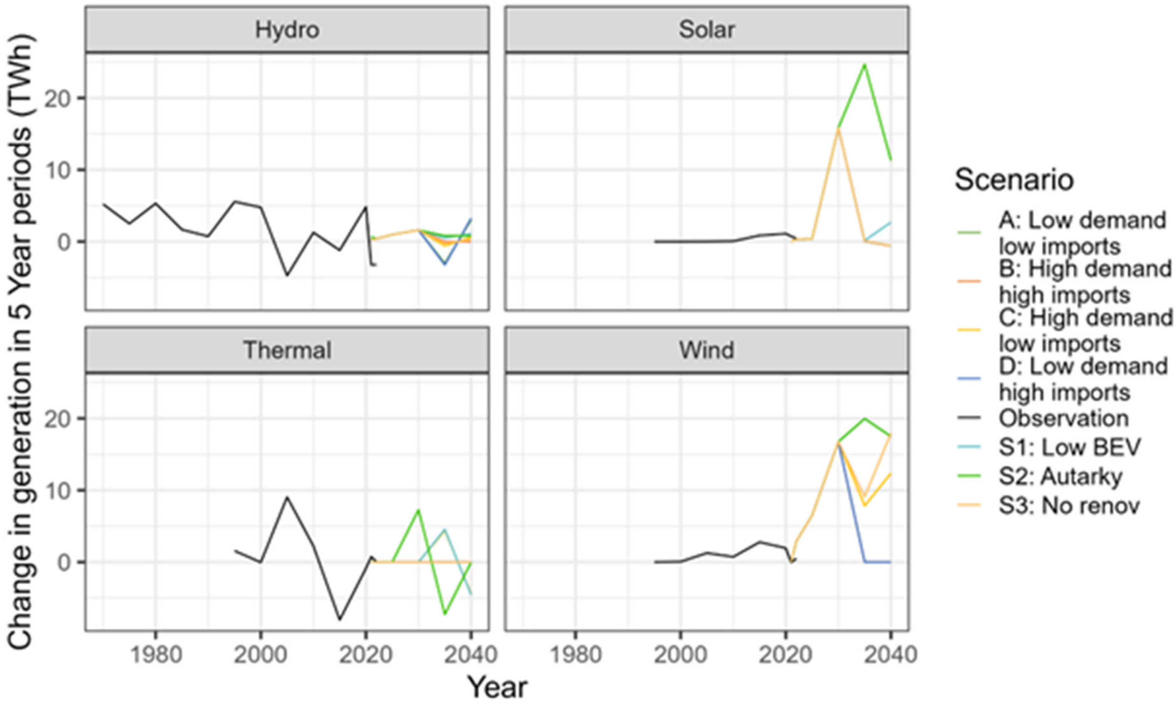

Figure 6: change in electricity generation in 5-year periods, historical observations and in the 4 scenarios and three sensitivity runs. Some scenarios are overlapping.

To provide context, Austria's fastest-growing historical energy generation technology was thermal power, which added approximately 10 terawatt-hours (TWh) during its most rapid expansion period from 2000 to 2005. In contrast, our scenarios project an addition of up to 15 TWh of solar PV and 16 TWh of wind power within a mere five-year span, and even up to 25 TWh and 20 TWh for solar PV and wind power, respectively, in the autarky scenario S2.

In all scenarios, the electrification of end-use sectors is essential for achieving climate neutrality targets. Notably, in mobility, fuel demand undergoes a drastic reduction, plummeting by over half due to the universal electrification of road transport, except for the sensitivity run "S1: Low BEV" (see Figure 7). This electrification of road transport has a significant side-effect: reductions in mobility services, such as fewer kilometers driven per person, have only a limited impact on final energy demand within the sector in 2040, owing to the remarkable efficiency of electric vehicles. This development is only possible due to an assumed rapid turnover rate of vehicles, which ensures that no fossil fuels will remain in the sector in 2040, allowing for a complete substitution of internal combustion engines by electric motors. However, achieving a full transition to electric mobility on the road by 2035, as mandated by our scenarios, poses a considerable challenge. With the average lifetime of cars and trucks estimated at 13 years, this transition is theoretically feasible. Yet, current adoption rates of electric vehicles, hovering around 20%, fall short of the necessary 100% adoption rate. In a sensitivity analysis, we therefore explore the ramifications of maintaining the current electric vehicle adoption rate (i.e., 20%) in the low-import, high-demand scenario. Such a scenario entails substantially higher fossil fuel usage by 2030 and heightened carbon capture and storage requirements, cumulatively totalling 40 million tons of CO_2 by 2040, to adhere to the carbon budget.

Furthermore, post-2030, renewable power expansion would need to exceed the baseline scenario by 22 terawatt-hours (TWh), and domestic biomass resources would be nearly maximally utilized. Thus, the dynamic implication of potentially insufficient growth in electric mobility adoption rates becomes evident. In the households and services sectors, electrification of heating and improved insulation reduces final energy demand, albeit not as significantly as in mobility. Here, biomass and district heating technologies remain crucial supply technologies. Similarly, in industry, electrification of heat supply up to medium temperature levels enhances efficiency, although these gains are offset by increased industrial output in high-demand scenarios.

Synthetic fuels and gases are mainly used for air and water transport, industrial applications, and power generation, and to replace residual fossil fuels in households and services (Figure 8). In 2040, most of these synthetic fuels can be considered carbon-neutral. The remaining use of synthetic fuels in agriculture, services, and households is explained by the lock-in effects of heating systems. These cannot be exchanged sufficiently quickly until 2040, therefore making using expensive synthetic gas or using fossil heating oil and carbon capture and storage necessary. No synthetic fuels are used in road transportation, as electric cars and trucks are completely electrified, except in the sensitivity scenario "S1: Low BEV".

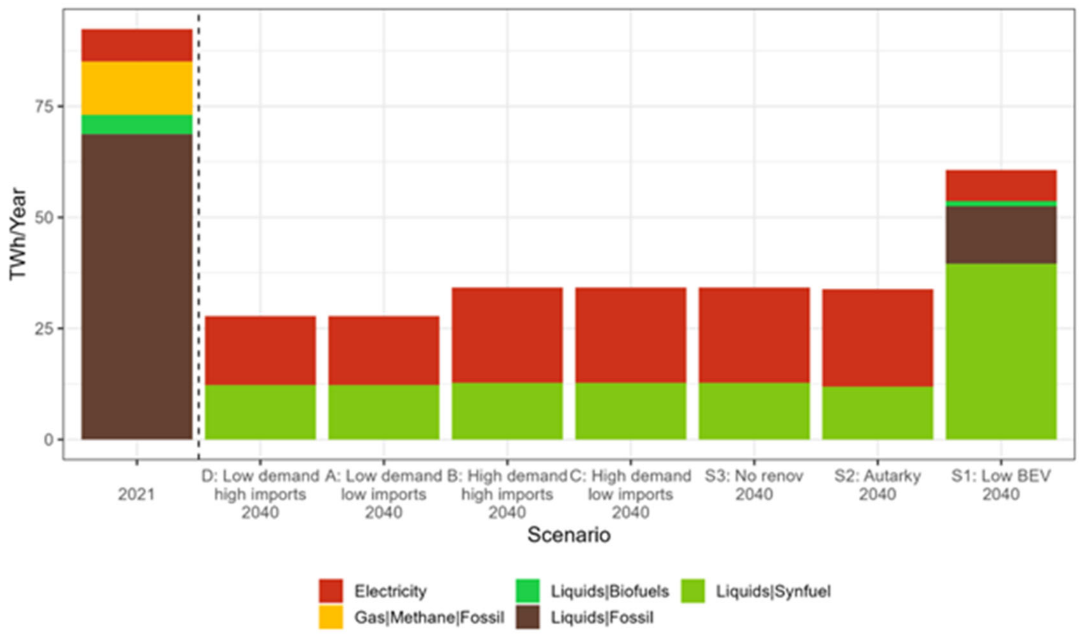

Figure 7: Final energy use in the mobility sector in 2021, in the four scenarios, and in three sensitivity runs

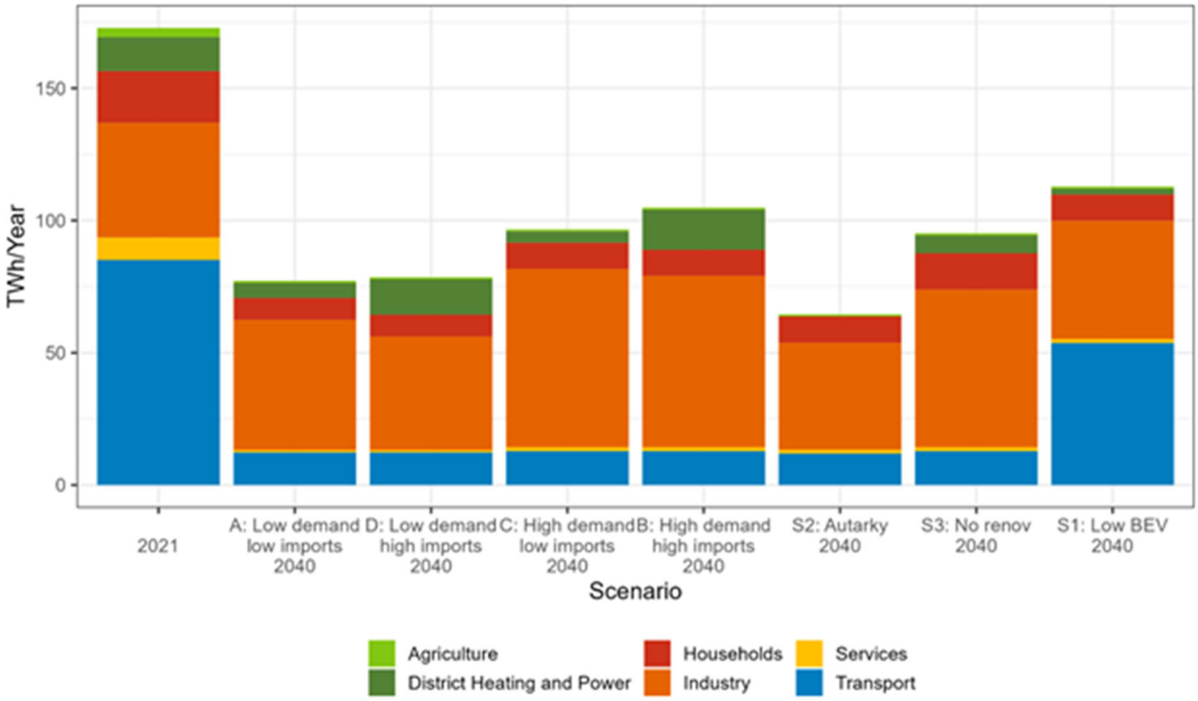

Figure 8: Use of fossil and synthetic fuels in Austria per sector.

In the low demand scenarios, less synthetic fuel is used due to lower industrial output. Power generation uses some synthetic gas in combined-heat and power plants to supply district heating and cover periods of low output of variable renewables. Synthetic fuels and gases are mainly imported, while domestic production is low, except for the autarky and the low BEV scenario. Imports in 2040 consist mainly of synthetic gas and liquids, and minor quantities of fossil fuels and methane.

In Austria, the expansion of solar photovoltaic (PV) capacity is currently progressing rapidly, while the growth of wind power is encountering obstacles. While the electricity system can operate on solar PV instead of wind power, the costs increase significantly as sensitivity runs with the power system model MEDEA show (see Figure 9). Notably, expanding wind power capacity to 15 gigawatts (GW) would decrease power system costs by nearly 20%. Beyond this threshold, further expansion can yield cost savings, albeit with diminishing marginal returns. The lower cost associated with high shares of wind power in the system can be attributed to two main factors.

First, wind power offers economic advantages due to its favorable complementarity with existing renewable sources like run-of-river hydropower, which helps mitigate seasonal imbalances inherent in the Austrian electricity system. Run-of-river hydropower and solar PV generation peak during the summer when electricity consumption is at a seasonal low. Without additional measures, this seasonal overlap would result in excess summer generation and potential deficits in winter, necessitating costly seasonal balancing strategies. Conversely, wind power generation peaks during winter when hydropower output is lower, and electricity consumption is higher. By integrating wind power, the seasonal imbalances can be alleviated, reducing total system costs.

Additionally, Austrian wind power generation exhibits a low correlation with wind power generation in neighbouring Germany, particularly in its northern, wind power-heavy regions. Consequently, Austrian wind power often generates electricity during periods of favourable market prices, resulting in high export revenues or the substitution of expensive imports. This further contributes to cost savings and enhances the economic viability of wind power expansion in Austria.

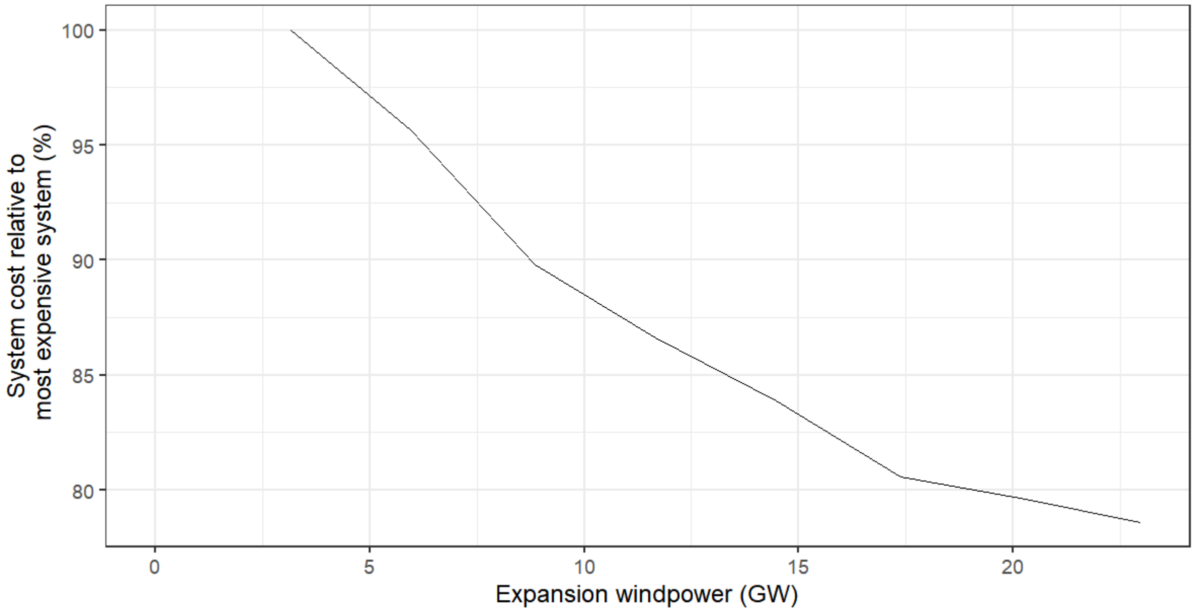

Figure 9: System cost depending on the potential for expanding wind power.

WP6 Communication and Dissemination: See section 8.

5 Conclusions and Recommendations

We have co-developed consistent qualitative scenario narratives and quantitative model scenarios to achieve a climate-neutral energy system in Austria by 2040 and, therefore, provide crucial input to the Austrian policy-making community, including in the context of the ongoing Second Austrian Assessment Report (AAR2), which confirmed a substantial lack in scenarios for reaching climate neutrality in Austria by 2040. While our scenarios are feasible from a techno-economic perspective, the required speed of system-level transformation is unprecedented. Although in 2022 and 2023 (projected), Austria remained almost on the path to climate neutrality in 2040, it has to be expected that these are mainly one-time effects due to high energy prices and higher awareness to switching away from fossil fuels. As indicated in the qualitative scenario narratives, national and federal-state policies must be substantially improved to keep Austria on the pathway towards climate neutrality by 2040. The emission trajectory may not remain as favourable as observed in the past two years if multi-level cooperation fails and societal support is low. In particular, more ambitious renewable energy goals and increased commitment to electrification are essential to keep Austria on a stringent emission reduction pathway.

Electrification of road transport is a crucial lever for rapidly decreasing emissions. However, the assumed adaptation of the car stock in the scenarios implies a very high turn-over rate of vehicles and an almost immediate upscaling to electric mobility for new vehicles. As this is very challenging, demand-side measures become indispensable in the short term to reduce motorized and individualized mobility levels (distance reduction or load increase). Thus, reducing energy use in road transport can allow for a slower uptake of electric cars and trucks. Also, energy demand reduction in the industry sector, e.g., by importing direct reduced iron pellets instead of producing them in Austria or using scrap steel, can lower the challenges on the demand side strongly, as industrial processes need high temperatures or chemical feedstocks. High-temperature processes frequently require energy-intensive hydrogen or synthetic fuels. This results in a significant increase in domestic energy consumption, due to both domestic production and, to a lesser extent, import of such fuels.

The netzero2040 scenarios vary in terms of energy demand and imported energy carriers. However, the stakeholders consider effective multi-level cooperation and broad support from all demographic groups and social classes for the energy transition crucial in all four scenario narratives. In the quantitative model scenarios, we have found no major differences in key features among these scenarios between 2021 and 2030, implying that the no-regret measures of electrification and expansion of renewables should be prioritized and implemented as quickly as possible. The period until 2030 is extremely challenging for all actors in the energy system, as very rapid emission cuts have to be achieved in a very short period. Notably, our emission pathway to climate neutrality in 2040 is almost in line with the goals on the European Union level until 2030, making our scenarios slightly more ambitious than required in the context of the EU climate roadmap to 2040. Uncertainty about which pathways to follow after 2030 is higher, and results for this period are not as uniform as those until 2030. After 2030, the no-regret-measures electrification and build-out of renewables will have to be accompanied by strategies to decarbonize the industry. This can be achieved by importing hydrogen and synthetic fuels or ramping up domestic renewable electricity generation and producing these energy carriers domestically. Both pathways are extremely challenging and require thorough planning. While carbon capture and storage was minimized in our scenarios due to current legal conditions in Austria and stakeholder preferences, it may be an alternative way of reducing emissions in the industry.

Our results also align with decarbonization studies for other regions, such as those provided by the IEA (International Energy Agency, 2021), which show that electrification and renewable build-out must be addressed first. We confirm these results for Austria but add nuance by indicating considerable uncertainty in post-2030 scenarios. In the only alternative scenario available for Austria, the ambitious 'Transitions scenario' by UBA (Krutzler et al., 2023), developments are comparable. The gross domestic consumption of 260 TWh in 2040 is higher than our modelled range in the four main scenarios of 200 to 250 TWh. This is mainly explained by lower imports of hydrogen and synthetic fuels into Austria in the Transitions scenario. In our sensitivity scenario, which has slightly lower imports than the Transitions scenario, gross domestic consumption is at 290 TWh, confirming that our overall magnitude of gross domestic consumption is of similar order of magnitude as the Transitions scenario. The Transitions scenario also indicates that a significant reduction in energy use in the mobility sector is a primary driver of the overall reduction in gross domestic consumption. In terms of the build-out of renewables, the Transitions scenario sees a significantly higher share of solar PV in the final electricity mix than wind power. However, the transition scenario is not based on a model with a sufficient temporal resolution to adequately reflect renewable electricity generation, and the optimal shares are, therefore, mere expert judgments. Nevertheless, we emphasize that, as far as possible, wind power is preferred over solar PV in Austria, if the minimization of total system costs is a relevant objective. Although producing electricity from wind power comes at a higher private cost than PV, Austrian wind resources exhibit favourable seasonality, which is a crucial component to reducing overall flexibility needs and, thereby, the system's total cost.

Our scenario narratives co-developed with stakeholders clearly show that climate neutrality is only possible if most, if not all, important societal actors in politics, business, industry, and civil society agree on that goal and are willing to make respective decisions. Different scenarios, which entail different distributional impacts regarding costs and domestic externalities implied by renewables, can lead to climate neutrality. However, reaching climate neutrality by 2040 will only be possible if the future debate focuses on these different worlds instead of discussing the overall need to achieve the goal. In this context, it is important to emphasize that the current EU plans for CO2-emission reductions are only slightly less ambitious than the Austrian climate neutrality goal. Achieving climate neutrality by 2040 is, therefore, comparably challenging to attain the EU targets.

In this context, we consider all of our scenarios to be transformative, as they all reach climate neutrality by 2040. However, different transformative challenges arise, depending on the scenario: in the low-demand scenarios, substantial behavioural changes and a net reduction in built areas have to be achieved, combined with an industrial policy that reduces energy use or even downsizes the industrial sector. In the high import scenarios, current trade relationships with fossil fuel exporting countries must be phased out rapidly. In contrast, trade with low-carbon energy carrier exporters has to be ramped up very quickly starting in 2030. The trade partners may change during this reorganization of trade, and it is very uncertain if the necessary levels of imports can be attained by 2040.

While our pathways are internally consistent, we cannot account for two important factors due to the chosen modelling approach. First, the models do not account for the necessary grid and pipeline infrastructure. While it is evident that a significant expansion of power grid infrastructure is necessary to allow climate neutrality, the sizing of the power grid and how different generation mixes will affect its configuration have not been assessed. Furthermore, the gas grid has to be partly adapted to new fuels, i.e. hydrogen, or has to be built back, and carbon capture and storage and associated infrastructure has to be assessed in detail. It was impossible to answer grid-related questions using our chosen modelling approach. Furthermore, we only account for interactions with Germany in the power system, but Austria is heavily integrated with other neighbours, too. Furthermore, as discussed extensively above, uncertainty concerning post-2030 scenarios is high. Therefore, there is a need for consistent assessments of decarbonization in this period and a wider economic impact assessment of the transition. Parts of the consortium have, therefore, already applied to a new ACRP project, led by the Wegener Center in Graz, where the state-of-the-art European-wide sector-coupled power system model PyPSA-EUR (Victoria et al., 2020) model will be integrated with a Computable General Equilibrium model to assess those questions in more detail.

Our results are a valueable resource for many different stakeholders. The Austrian Assessment Report 2 (AAR2) will build extensively on the netzero2040 scenarios. Both in chapter 4 and chapter 8, as well as in the summary for policymakers, the scenarios play a crucial role in communicating the challenges Austria faces to become climate neutral by 2040. Besides the Transitions scenario by Umweltbundesamt, the netzero2040 scenarios are, currently, the only scenarios available in this context. However, we hope that upon finishing AAR2, a more comprehensive set of scenarios has been assessed. In this context, netzero2040 also provides crucial infrastructure for the AAR2 in terms of the scenario explorer and the associated data standardization efforts. In the explorer, we have included the policy-wise highly relevant WEM, WAM, and Transitions scenario by

Umweltbundesamt and are going to add all alternative scenarios from relevant modeling groups in Austria.

Our scenario narratives and quantitative model scenarios are also highly relevant to policy-making, industry, business, and civil society stakeholders. Using the extensive information, including complete scenario results, provided on our website and in the scenario explorer, stakeholders can learn about potential pathways to climate neutrality in Austria and benchmark potential internal scenarios against our results. For instance, our results have already been discussed by the Austrian e-fuel alliance, have been discussed on the website of the BMK (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology), and we have been invited to a session at the "20 Jahre klimaaktiv" conference.

Furthermore, our scenarios are also interesting for the general public, as they can learn which personal decisions related to the energy system can make a difference in reaching Austrian climate goals. We hope that our emphasis on renewable energy generation and electrification can therefore spur respective private investment activities and, furthermore, demand-side behaviour adaptations.

Finally, our quantitative scenario results are of high relevance to other modelling groups as our scenarios can serve as a benchmark for their scenarios and as our input parameters, defined by stakeholders, can be used in other projects. Our results have been openly published on our website and in the scenario explorer in a well-defined and structured format. Reuse by others is therefore comparably simple, and we hope that we thus drive standardization efforts between different modelling groups. There is also proven interest from other ongoing (Integrate, CaCTUS, transfair.at) and completed ACRP projects (electrocoup) in our scenarios. Besides comparing the results of scenarios, modelling groups can also use the provided infrastructure (i.e. the scenario explorer) and provided data formats to disseminate their results and make them comparable within the community.

C) Project details

6 Methods

We follow a structured stakeholder engagement process for developing and evaluating scenarios, extending a protocol initially developed by Mitter et al. (2019) to increase transparency and reproducibility of the results (see Figure 10). In a first step, we co-designed four qualitative netzero scenario narratives with the stakeholders by initially identifying and clustering drivers and their development directions. Selected scenario drivers have been translated to parameters governing the differences between model runs. The translation was done in an online survey following qualitative discussions in the first stakeholder workshop on drivers affecting the GHG emission budget and policy assumptions in the models. We coupled a full energy and a power system model, which had to be adapted to specific tasks and model interfaces. Furthermore, a range of model parameters not defined by stakeholders was parametrized based on recent literature. The scenario narratives and the quantitative model scenarios have been checked for their consistency, and the reconciled scenarios were presented and evaluated in a final stakeholder workshop.

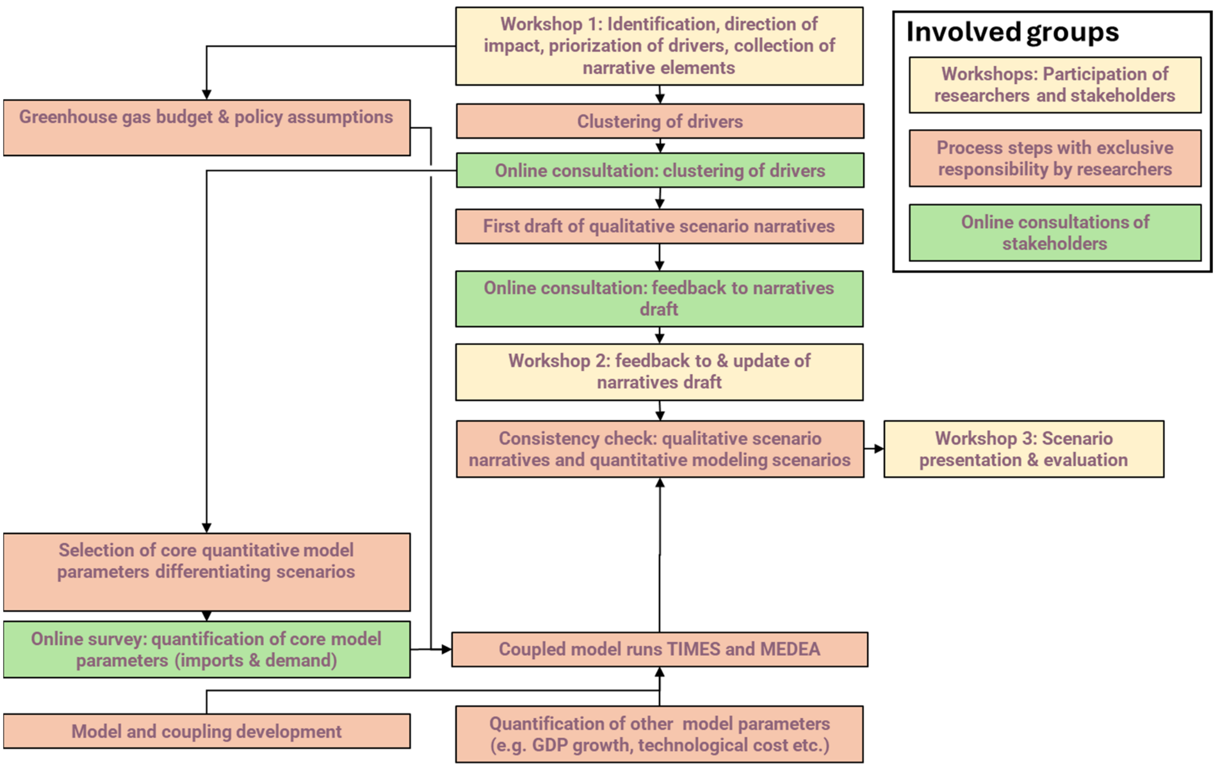

Figure 10: Scenario co-development process

Stakeholder engagement process

The primary objective of the stakeholder engagement process was to co-develop four scenarios to achieve climate neutrality. For a detailed description of the stakeholder process, see the description of the activities in WP2 in the "Project content and results" section.

Stakeholder quantification of model input parameters

Stakeholders were asked to quantify central model input parameters based on previously identified drivers. For a detailed description of the survey, see the description of activities in WP2 in the section "Project content and results". Here, we report in more detail the results of the survey validation.

The validation process involved assessing the internal validity of survey responses and comparing the answers from our stakeholder groups with those from our other test survey groups. Figure 11 illustrates the respondents' estimation of the indicator in the "low" or "high" scenario. The results show a high level of consistency. For instance, the "Modal split train" variable, which determines the share of cargo transported by train, had a higher indicator in the low-demand scenario, in line with expectations. This suggests that respondents comprehended the task well.

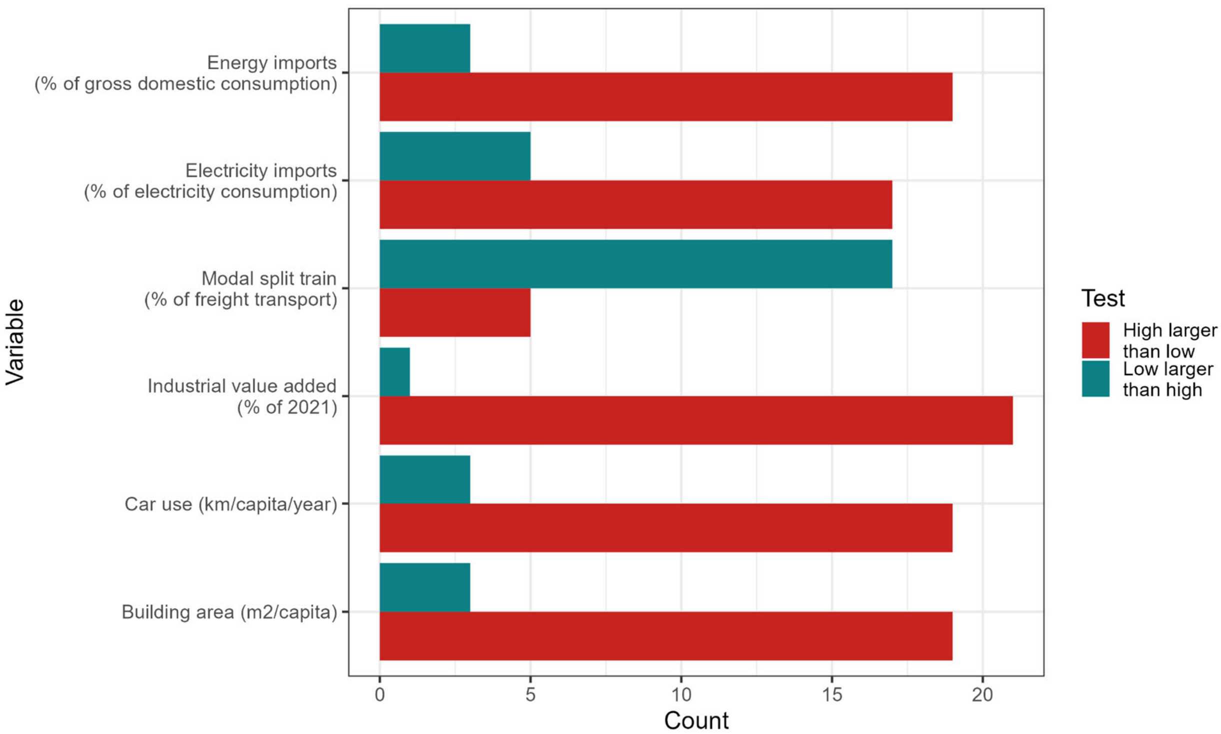

Figure 11: Consistency check for stakeholder responses

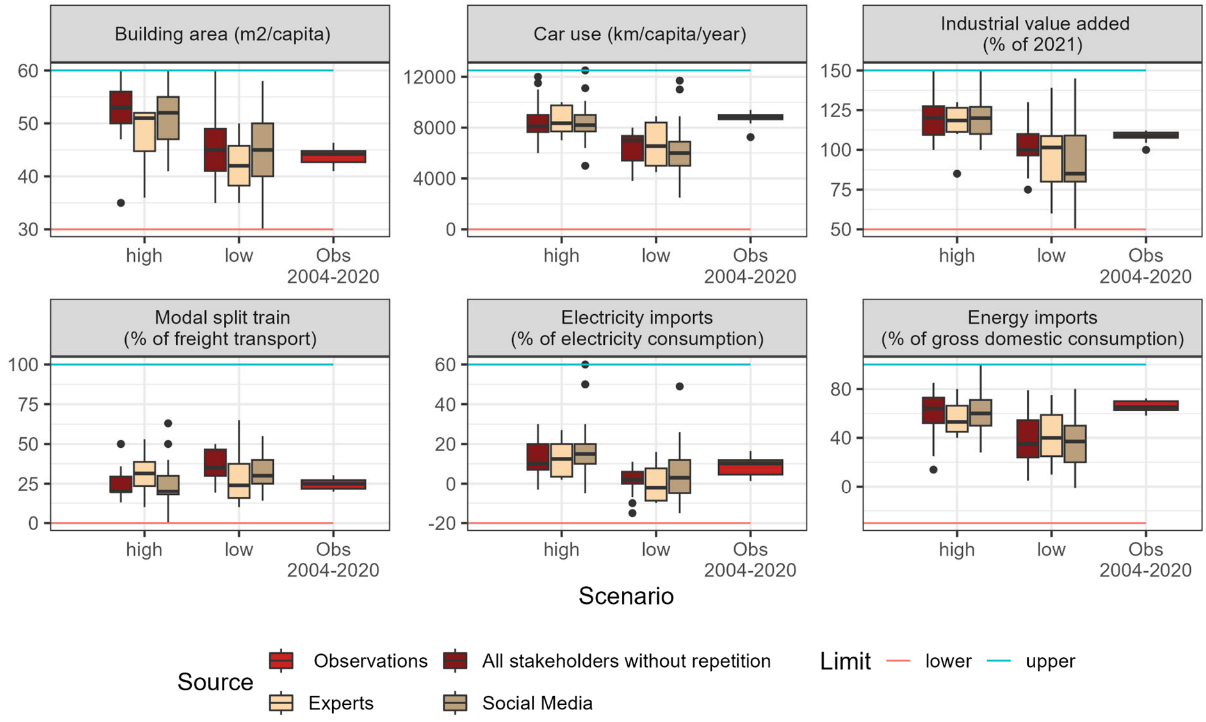

Figure 12: All responses to the survey differentiated by group of respondents

Furthermore, we assessed differences between different groups of respondents (see Figure 12). In particular, we showed differences between responses from stakeholders, experts and individuals recruited on social media, i.e. Twitter/X. In general, the median of the three groups is well aligned, while variability differs between groups (As does the number of observations). One exception is industrial energy use in the "low" scenario, where the median of social media respondents results in a decrease of 25% in industrial value added. At the same time, the other two groups see virtually no change in industrial value added in the low scenario. Furthermore, variance is quite significant, and in many instances either the low or high boundary pre-set in the survey was chosen by at least one respondent.

The largest historically observed value is mainly within the median of the "low" and the "high" scenarios, i.e., the median respondent assumes that "high" also means higher than today and "low" lower than today. Interestingly, there are two exceptions: car utilization is proposed to decrease in both the "high" and the "low" scenarios compared to today. Energy imports are also proposed to decrease in both the "low" and the "high" scenarios when compared to the median.

Model descriptions & coupling

To develop the quantitative model-based scenarios of the Austrian energy system, we coupled the energy system model TIMES with the power system model MEDEA. While TIMES covers the whole energy system, it has low temporal resolution and includes Austria only. MEDEA is power sector-specific, but has high temporal resolution and accounts for trade in electricity and other energy carriers with the largest current trade partner, i.e. Germany.

TIMES has been developed by the IEA-ETSAP group (IEA-ETSAP, 2024a, 2024b) and allows the development of scenarios with cost optimal pathways of a detailed energy system representation with perfect foresight under given technical constraints and policy targets. (see "Methods" for a detailed description of the model). The model includes driver variables (e.g. GDP or population development), technical parameters (e.g. conversion efficiencies), upper and lower limits to relevant variables (e.g. import shares, technology shares, etc.), availability of predefined technologies (e.g. Hydrogen, carbon storage etc.), prices (of technologies or fuels) or dynamic constraints such as limits to maximum or minimum annual growth rates (e.g. in PV technology deployment). These constraints are typically exogenous and are crucial in modelling the energy system's evolution over the specified period.

The MEDEA power system model co-optimizes investment and hourly operation within an integrated Austrian and German power system by 2040. The model's objective is to minimize total system cost, consisting of fuel and emission costs, quasi-fixed and variable operation and maintenance (O&M) costs, investment expenditures for energy generation, storage, and transmission assets, and potential costs of non-served load. From an economic perspective, the model reflects a perfectly competitive energy-only market with a fully price-inelastic final demand for all energy products (electricity, district heat, and synthetic gases) and perfect foresight of all actors. The modeled system is required to meet exogenous and inelastic demand for all three energy products at any hour of the year. Energy supply, in turn, is constrained by available installed capacities of energy conversion, storage, and transmission units. We do not model transmission and distribution grids within Austria or Germany. However, we allow for cross-border electricity trade between both countries, accounting for limitations imposed by the transmission grid.

Cogeneration units convert fuel to heat and power subject to a feasible operating region defined by the unit's electrical efficiency, the electricity loss per unit of heat production, and the backpressure coefficient. Electricity generation from intermittent sources (wind, run-of-river hydro, solar) is subject to spatially diverse, exogenous hourly generation profiles, scaled according to total installed capacities. Electricity from these sources can be curtailed at no additional cost (free disposal). Electricity can be stored in reservoir and pumped hydro storage, and batteries, while heat and synthetic gases can be stored in hot water storages and caverns, respectively. The capacity of hydro storages cannot be expanded, as we assume existing potentials to be exhausted. Battery, heat, and synthetic gas storage capacities, on the other hand, can be added endogenously. Generation from storage is constrained by installed capacity and stored energy. Inflows of water into reservoirs add to stored energy. Pumped hydro storages, batteries, heat and synthetic gas storages can actively store energy for later use. To better capture operational differences of hydro storage units, we model short-term, medium-term and seasonal reservoir and pumped storage plants separately. Apart from their ability to pump water, the main difference between these storages is their storage volume. Seasonal storages are modelled with an energy-to-power ratio of more than 1000 h, while medium-term and short-term storages have much lower energy-to-power ratios of about 190 h and 24 h, respectively. To ensure the stable and secure operation of the electricity system, ancillary services (e. g., frequency control and voltage support) are required. We model ancillary service needs as a minimum requirement on spinning reserves operating at any time. Thus, we assume that ancillary services can be provided by thermal power plants, run-of-river hydro plants, or any (active) storage technology. Data processing is implemented in Python, while the optimization model is written in GAMS. The model code is published at https://github.com/inwe-boku/MEDEA under an open MIT license. Wehrle et al. (2021) give a detailed description of a previous model version.

The TIMES and MEDEA models are coupled through a multi-stage process to ensure model consistency. The process is described in more detail in the report on activities in WP2 in the section "Project content and results".

Scenario assumptions

A crucial scenario input is the assumption of the dynamic emission pathway. We opted to use a carbon-budget approach (see Figure 1) consistent with the Paris goals, as stakeholders demanded this during the first workshop, and based our budget on Steininger et al. (Steininger and Kirchengast, 2021). We split emissions between the sectors we model (i.e. energy-related) and sectors not modeled (agricultural non-energetic emissions, land-use and land-use change, cement industry, f gases, solvents, fugitive emissions from waste) and assume that both sectors become carbon-neutral by 2040. This implies that we do not balance positive emissions in the energy sector with negative emissions from forestry or land-use and land-use change, for example. Furthermore, we pre-determine annual emission caps along the emission reduction pathway, using historical observed emissions up to 2021.

Scenarios (see Table 4) are differentiated by variations in demand and import shares of energy carriers. These have been defined by stakeholders and are discussed in more detail in the results section. Energy demand was varied by changing exogenous model parameters, which directly affected the demand variables in the models. To attain the required import shares, we set upper import share constraints in the models. To achieve relevant quantities of imports in the high import scenarios, however, we had to assume low import costs for synthetic fuels. Furthermore, we have constructed thematically specific sensitivity scenario runs based on scenario C (low imports, high demand). In particular, we assessed the consequences of (I) a much lower uptake rate for electric cars, (II) reducing maximum imports of low-carbon energy carriers further to 5% of gross domestic energy consumption, and (III) disabling thermal renovation of buildings. In all scenarios, we enforce the Austrian renewable expansion act until 2030.

Table 4*: Summary of the scenarios*

Scenario	**Short name**	**Description**
A: Sufficiency and maximum expansion of renewable energies	A: Low demand - low imports	See section „Stakeholder quantification of model input parameters”
B: High resource consumption and international energy agreements	B: High demand - high imports	See section „Stakeholder quantification of model input parameters”
C: Energy-intensive lifestyles and relative energy autonomy	C: High demand - low imports	See section „Stakeholder quantification of model input parameters”
D: Restricted expansion of renewables and energy imports	D: Low demand - high imports	See section „Stakeholder quantification of model input parameters”
Sensitivity runs		
S1: Low battery electric vehicles	S1: Low BEV	Based on scenario C, restricting penetration of battery electric vehicles to 20%
S2: Autarky	S2: Autarky	Based on scenario C, restricting imports further to 5% of gross domestic consumption
S3: No building renovation	S3: No renov	Based on scenario C, disabling building renovation

Furthermore, exogenous price data for Crude Oil, Natural Gas, and Emission Allowances for the five modeled years 2020, 2025, 2030, 2035 and 2040 has been compiled. To ensure these timeseries' plausibility and internal consistency, we devised a method to provide realistic price projections. These series incorporate historical market results and project future price trends, distinguishing between the past (2020 - 2022), the near future (2023 - 2029) and the far future (2030-2040).

For historical data, we relied on actual market data, such as from spot prices. For projecting future prices, we differentiated our approach: for the near future, we used results from future markets where available. For the more distant future, we referred to the "European prices" from the World Energy Outlook (WEO) 2022 Net Zero Emissions scenario.

Table 5: Detailed Sources for price scenarios

Energy Source	***Unit***	***Historical Data Source***	***Future Data Source (2023-2030)***	***Long-term Forecast (2040/2050)***
Natural Gas (VTP-CEGH)	*EUR/MWh*	*Yearly mean of spot market prices* (European Energy Exchange AG, 2022a)	*Yearly mean of futures for AT, accessed on 1.2.2023* (European Energy Exchange AG, 2022b)	*World Energy Outlook 2022 forecasts* (International Energy Agency., 2022)
Crude Oil (Brent)	*US$/bbl*	*Yearly mean of spot market prices for Brent Crude* (US Energy Administration Service, 2022)	*Yearly mean of futures for Brent Crude for 2022, accessed on 1.2.2023* (Intercontinental Exchange Inc, 2022)	*World Energy Outlook 2022 forecasts* (International Energy Agency., 2022)
Emission Allowances	*EUR/tCO2*	*Yearly mean of EU Emission Allowance prices* (European Energy Exchange AG, 2022c)	*Yearly mean of Emission Allowance futures for 2022, accessed on 1.2.2023* (European Energy Exchange AG, 2022d)	*World Energy Outlook 2022 forecasts* (International Energy Agency., 2022)

The WEO 2022 offers two forecasts for expected prices in 2030 and 2040 for coal, crude oil, natural gas, and emission allowances, incorporating a blend of historical data, realized future data, and WEO projections. We employed interpolation for years without direct data to generate a coherent and plausible set of exogenous variables for fossil energy carriers. Currency conversions between the Euro and Dollar were conducted using annual exchange rates, with future conversions fixed at the 2022 rate. We acknowledge that this method overlooks potential price dynamics arising from demand fluctuations. Nevertheless, the WEO's Net Zero Emissions scenario prices are presumed to align with an Austrian Net Zero Emission Scenario, thus offering a solid foundation for our analysis.

Population growth assumptions were taken from the main official population projection for Austria by Statistik Austria from 2022 (Statistik Austria, 2022). GDP growth assumptions align with the Transitions scenario by Umweltbundesamt (Krutzler et al., 2023) at 1.4%. In the low demand scenario, we lowered the GDP growth to account for the lower industrial output as quantified by the stakeholders. Techno-economic assumptions for single supply technologies were based on the technological catalogue by the Danish Energy Agency (2023) except carbon storage which is not allowed in Austria and which use was also questioned by stakeholders. We therefore included it into the model as technological measure of last resort, by setting an artificially high cost for a generic carbon capture and storage technology. The respective parameters are summarized in Table 6 and Table 7.

Table 6*: Model input parameters - dynamic*

Parameter	Unit	2025	2030	2035	2040
GDP Growth high demand	% p.a.	1.4	1.4	1.4	1.4
GDP Growth low demand	% p.a.	0.8	0.8	0.8	0.8
Population	'000 people	9 193	9 363	9 521	9 654
Gas price	€/MWh	41,37	13,26	12,68	12,11
Oil price	US$/bbl	68,01	35,00	32,25	29,50
CO2-emission allowances	€/tCO2	50	100	150	200
Synthetic gas price	€/MWh	30	30	30	30
Synthetic liquid price	€/MWh	45	45	45	45
CCS cost	€/ton CO2	1000	1000	1000	1000
Adoption rate electric cars	% new cars	100	100	100	100
Growth rate solar PV	% p.a.	100	100	100	100
Growth rate wind power	% p.a.	20	20	20	20

Table 7: ***Model input parameters - static***

Parameter	Unit	Value	Source
Potential wind	TWh/a	71.6	(Höltinger et al., 2016)
Potential solar	TWh/a	1600	(Mikovits et al., 2021)
Potential expansion biogas	TWh/a	11	(Baumann et al., 2021)
Potential expansion hydro	TWh/a	11	(Pöyry, 2018)

7 Work and timeplan

	Months	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	Status
WP1	**Project Management and Dissemination**																												
T 1.1	Project coordination and risk management																												
T 1.2	Development of project management and risk management plan																												
T 1.3	Project meetings and conference calls																												
M 1.1	Project and risk management plan		M																										Completed
M 1.2	Kick-off meeting		M																										Completed
M 1.3	Project controlling meeting & interim report													M															Completed
M 1.4	Final meeting & final report																							M				M	Completed
WP2	**Scenario development and stakeholder engagement**																												
T 2.1	Formation of stakeholder group																												
T 2.2	Narrative development and quantification of scenarios													X															
T 3.3	Evaluation of scenarios																												
M 2.1	Stakeholder engagement strategy refined					M																							Completed
M 2.2	Draft of scenario elements and scenario narratives developed									M																			Completed
M 2.3	Scenario elements for model inputs quantified													M															Completed
M 2.4	Review and evaluation of impacts																										M		Completed
WP3	**Improvement of MEDEA**																												
T 3.1	Implementations of new features																												
T 3.2	Adaption of data interfaces																												
T 3.3	Implementation of MEDEA on VSC																												
T 3.4	Testing and validation													X	X	X													
M 3.1	*Model input data improved*						M																						Completed
M 3.2	*Model structure improved*						M																						Completed
M 3.1.3	*Model data interfaces updated*												M																Completed
M 3.1.4	*Model implemented on Vienna scientific computing cluster*									M																			Completed
M 3.1.5	*Verification and validation of changes documented*															M													Completed
WP 4	**Adaptation of TIMES**																												
	Reduction of model complexity													X	X														
	Adaption of data interfaces													X															
	Implementation of TIMES on VSC													X	X														
	Testing and validation													X	X														
M 4.1	Iterative adaptation of model to balance feasibility and accuracy completed						M								M														Completed
M 4.2	Data interfaces completed																		M										Completed
M 4.3	Model implemented on Vienna scientific computing grid																		M										Completed
M 4.4	Verification and validation of changes documented																		M										Completed
WP5	**Model coupling & runs**																												
	Model coupling & testing													X	X	X													
	Integration of scenario parameters																												
	Development of post-processing tool																												
	Full coupled model runs																			X	X	X							
M 5.1	Coupling and testing of reduced models completed						M																						
M 5.2	Coupling of full models completed																		M										Completed
M 5.3	Scenario parameters from WP2 integrated																		M										Completed
M 5.4	Post-processing tool completed																		M										Completed
M 5.5	Full coupled model runs completed																									M			Completed
WP6	**Communication and Dissemination**																												
	Develop communication and dissemination plan																												
	Update Scenario explorer																												
	Scientific dissemination																												
	Non-scientific dissemination																												
M 6.1	Communication and dissemination plan			M																									Completed
M 6.2	Scenario explorer updated to meet project requirements												M																Completed
M 6.3	Scientific presentations and articles completed																											M	Completed
M 6.4	Newsletters, podcasts & twitter activities completed																											M	Completed

8 Publications and Dissemination activities

Scientific publications

Schmidt, J., Baumann, M., Boza-Kiss, B., Huppmann, D., Klingler, M., Mitter, H., Wehrle, S., , Zwieb, L. (2024). Need for speed: a participatory, integrated scenario assessment for attaining a netzero energy system in Austria by 2040. In preparation.

Wehrle, S., Regner, P., Morawetz, U., Schmidt, J., 2023. Inferring local social cost from renewable zoning decisions. Evidence from Lower Austria's wind power zoning. https://doi.org/10.13140/RG.2.2.18833.81761

Scientific conferences

Schmidt, J. (2024). A speedy transition: a participatory integrated scenario assessment of attaining a netzero energy system in Austria by 2040. Klimatag 2024. Link

Schmidt, J. (2022). Fossil oil in global and Austrian emission scenarios. Research Seminar – Petroleum Engineering / Montanuniversität Leoben. 28.11.2022. Link

Klingler, M., Baumann, M., Boza-Kiss, B., Huppmann, D., Mitter, H., Rao, N., Wehrle, S., Zwieb, L., Schmidt, J. (2022). Reaching climate neutrality in Austria by 2040: engaging stakeholders for model-supported scenario development. Klimatag 2022. Link

Wehrle, S., Regner, P., Morawetz, U., Schmidt, J. (2022). Inferring local social cost from renewable zoning decisions. Evidence from Lower Austria's wind power zoning. Environmental Protection and Sustainability Forum (September 2022).

Wehrle, S., Regner, P., Morawetz, U., Schmidt, J. (2022). Inferring local social cost from renewable zoning decisions. Evidence from Lower Austria's wind power zoning. 13th Geoffrey J.D. Hewings Regional Economics Workshop (Oktober 2022).

Data sets

- Data on project website: https://ww.netzero2040.at/scenarios
- Scenario Explorer: https://data.ece.iiasa.ac.at/netzero2040/#/workspaces
- Zenodo repository with project data: https://zenodo.org/records/11094102

Software

- Power system model MEDEA: https://github.com/inwe-boku/MEDEA

- MEDEA Data for Austria & Germany: https://github.com/sebwehrle/MEDEA_data_atde
- Wind resource assessment with the global wind atlas: https://github.com/sebwehrle/cleo
- Pyam nomenclauture and style guides: https://github.com/netzero2040/netzero2040

Project dissemination to the public

Project website: https://www.netzero2040.at

Schmidt, J. (2023). Eliminating All CO_2 Emissions in Austria by 2040? A Sketch of the Challenge Ahead. In: Akademie im Dialog|Forschung und Gesellschaft – 4. Science Day: Sustainability. Diverse perspectives on the role(s) of research in mastering socio-ecological challenges. Link

Schmidt, J. (2023). Energiemärkte und Klimaschutz. Climate lectures of the Young Academy Germany, 28.3.2023. Link

Schmidt, J. (2022). Eliminating all CO_2-emissions in Austria by 2040 – a sketch of the challenge ahead. Science Day of Young Academy of Austrian Academy of Sciences, 23.September 2022. Link

Schmidt, J. (2022), Eliminating all CO_2-emissions in Austria by 2040 - a sketch of the challenge ahead. Philosophical-historical class meeting, Austrian Academy of Sciences, 13.10.2022.

Schmidt, J. (2022), Eliminating all CO_2-emissions in Austria by 2040 - a sketch of the challenge ahead. Young Science Day, Austrian Academy of Sciences, 23.9.2022. Link

Schmidt, J. (2022). Klimaneutralität bis 2040 in Österreich. Wieso sie notwendig ist & was wir jetzt tun können. Gymnasium Klosterneuburg. 28.4. 2022. Link

Schmidt, J. (2022). Klimaneutralität bis 2040 in Österreich. Wieso sie notwendig ist & was wir jetzt tun können. Vienna Business School. 8.4. 2022.

Social Media

Twitter/X Account @Netzero2040 (https://twitter.com/NetZero2040)

Dissemination in media

Outlet	Date	Title
Website Austrian Academy of Sciences	21.9.2022	Wie Österreich bis 2040 klimaneutral werden kann (link)
Profil	14.12.2024	Nach der Klimakonferenz: Österreichs Probleme bei der Energiewende (link)
DerStandard	14.12.2023	Klimaneutral bis 2040, geht sich das aus? Ja, zeigt eine neue Analyse (link)
orf.at	14.12.2023	Projekt zeigt: Klimaziele sind machbar (link)
EnergyNews Magazine	14.12.2023	Klimaziele: Gesellschaftliche Akzeptanz entscheidend (link)
DiePresse	15.12.2023	Alles und alles sofort (link)
Finanzen.at	14.12.2023	Gesellschaftliche Akzeptanz und Politik entscheidend für Klimaziele (link)
Kurier	14.12.2023	Was getan werden muss, um die Klimaziele zu erreichen (link)
BMK Infothek	15.12.2023	Projekt zeigt, wie Klimaneutralität noch machbar ist (link)
Kurier	15.12.2023	Was Österreich tun müsste, um seine Klimaziele zu erreichen
Wiener Zeitung	1.1.2024	Was Österreich schon 2024 umsetzen muss, um bis 20240 klimaneutral zu sein (link)
Ö1 Mittagsjournal	15.12.2024	Klimaneutralität in Österreich
ZIB 13:00, ORF	26.12.2023	Photovoltaikboom in Österreich
Podcast PetaJoule	22.1.2024	NetZero2040: Wie schaffen wir Klimaneutralität bis 2040 (link)

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Diese Projektbeschreibung wurde von der Fördernehmerin/dem Fördernehmer erstellt. Für die Richtigkeit, Vollständigkeit und Aktualität der Inhalte sowie die barrierefreie Gestaltung der Projektbeschreibung, übernimmt der Klima- und Energiefonds keine Haftung.

Die Fördernehmerin/der Fördernehmer erklärt mit Übermittlung der Projektbeschreibung ausdrücklich über die Rechte am bereitgestellten Bildmaterial frei zu verfügen und dem Klima- und Energiefonds das unentgeltliche, nicht exklusive, zeitlich und örtlich unbeschränkte sowie unwiderrufliche Recht einräumen zu können, das Bildmaterial auf jede bekannte und zukünftig bekanntwerdende Verwertungsart zu nutzen. Für den Fall einer Inanspruchnahme des Klima- und Energiefonds durch Dritte, die die Rechtinhaberschaft am Bildmaterial behaupten, verpflichtet sich die Fördernehmerin/der Fördernehmer den Klima- und Energiefonds vollumfänglich schad- und klaglos zu halten.