Towards an Open Austrian Sector-Coupled Energy System Model within a European context

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Abstract

Austria has committed to climate neutrality by 2040, placing the energy sector at the core of the transition. Energy system models (ESMs) are therefore indispensable planning tools for least-cost pathways under net-zero emission scenarios. We introduce the design of a high resolution nationally tailored sector-coupled ESM for Austria, PyPSA-AT, building on existing frameworks in the PyPSA ecosystem. Compared with the pan-European PyPSA-EUR, this Austria-tailored model yields materially different pathways concerning variable renewable energy deployment, trading patterns and energy carrier usage. Results show that national policy choices influence not only domestic outcomes but also system-wide dynamics stressing the need for nationally tailored ESMs. PyPSA-AT is open-source and implemented as a soft fork within the PyPSA-ecosystem, enabling transparent analyses for Austria while contributing to the broader community.

Keywords: energy system model, ESM, net-zero emissions, infrastructure planning

1 Introduction

The Paris Agreement provides the overarching framework for national decarbonisation strategies, within which Austria has committed to climate neutrality by 2040 and to achieving a 100% renewable electricity supply in national balance by 2030 [1] [2]. Currently, the energy sector is the main source of carbon dioxide emissions and is therefore at the centre of the transition to climate neutrality [3].

Meeting these targets requires an accelerated transformation of supply, transmission, conversion, and end-use of energy, with rapidly rising shares of variable renewable energy (VRE) and extensive end-use electrification in transport, buildings and industry sectors [4]. This transition not only necessitates an extensive expansion of renewable energy capacities and far-reaching adaptions in infrastructure but also implies operational balancing challenges from sub-hourly to seasonal timescales. Historically siloed infrastructures for electricity, gas/hydrogen, and heat are becoming increasingly interdependent, raising overall system complexity while simultaneously enabling new flexibility interactions. Also, as a balancing

option, trade in electricity and other energy carriers within Europe and beyond gains in importance in a highly renewable energy system.

Given the strongly interconnected nature of the energy system, both spatially as well as in terms of sectors, sector-coupled energy system models (ESMs) are indispensable tools for infrastructure and policy planning as they allow for the identification of least-cost pathways that meet emissions constraints. As they co-optimise investment and operation across energy sectors and technologies, ESMs can reveal system-wide synergies and trade-offs between generation, storage and flexibility options when implemented with sufficiently high spatial and temporal resolution. If calibrated to historical data, ESMs accurately represent the current state of the energy system and can therefore be used to identify pathways for energy system transitions.

For Europe, several open-source, state-of-the-art energy system modelling frameworks exist, covering different temporal scales and spatial resolutions and tailored to various specific focuses. Despite their great value in energy system planning on an international scale, European sector-coupled models are not detailed enough to tackle some country-focused analysis questions. This in particular includes the need for thorough information on future energy infrastructure (such as hydrogen networks, CO2 pipelines or renewable gas systems), the integration of detailed national policy goals and frameworks and the ability to realistically model the transition from existing energy systems to climate neutrality in high spatial detail. Under these circumstances, there is a need to complement this ecosystem with nationally tailored energy system models including international energy trades and infrastructure.

In this paper we introduce an approach for a sector-coupled ESM tailored to Austria and embedded in a European setting, PyPSA-AT. The model represents the electricity, heating, transport, and industry sectors and the energy carriers hydrogen, methane, fossil fuels, biomass, renewable oil and gas and electricity from various renewable and non-renewable sources. Carbon Dioxide flows are explicitly accounted for to capture the interactions that shape climate neutrality pathways.

Spatially, PyPSA-AT resolves Austria in high granularity (up to 30 regions) and represents neighbouring countries to maintain realistic cross-border exchange and reflect Austria's role in the interconnected European energy system; temporally, it uses up to hourly resolution, over a full year to capture the integration requirements of VRE and to inform infrastructure needs, consistent with best practice in European sector-coupled modelling. In this context, a variation in the used weather years is possible. The workflow will integrate detailed brownfield information on existing infrastructure, national policies and policy goals and technology constraints.

2 Modelling concept

2.1 Design principles

Nationally tailored ESMs are designed to answer concrete national planning questions while maintaining a robust link to the international system. While over-regional ESMs model a system of equally treated regions, nationally tailored ESMs are focused on the respective nation

embedded within other regions. This purpose implies three core design principles we consider as the main difference between nationally tailored ESMs and over-regional models.

First, over-regional ESMs rely on international datasets with limited intra-country granularity, constraining their ability to accurately represent region-specific infrastructure siting, demand patterns or local constraints to name a few. Nationally tailored ESMs therefore must integrate high-quality national inputs (such as demand patterns, resource potentials, brownfield assets, local geographical conditions or policy constraints) while still remaining compatible with international dataset to ensure consistent cross-border modelling and comparability.

Second, restricted spatial granularity in over-regional models cannot represent spatial balancing and infrastructure needs in specific regions of a country. Moreover, highly resolved national input data requires an equally high spatial resolution in the modelling framework to fully preserve and exploit the additional information it contains. Consequently, nationally tailored ESMs must capture the spatial heterogeneity of the respective country in sufficient detail, while remaining computationally traceable for full-year analyses.

Third, in pan-regional models, regions are treated uniformly as part of an international energy system, irrespective of country boarders. In the optimization capacities are consequently allocated to minimize system-wide costs, leading to e.g. coastal wind concentration and large transmission expansions. An ESM tailored to one nation on the other hand must preserve a plausible import/export portfolio for that particular country while representing it as a part of an international energy system.

On top of that, for pathway analysis, a transparent validation and calibration of the model energy flows with official energy balances of the respective country is essential. The following section dives deeper into the three aforementioned aspects.

2.2   Spatial Granularity and country-specific input data

High-resolution spatial information on existing brownfield infrastructure – power plants, district heating networks, storage assets, transmission lines and pipeline capacities to name a few – is a prerequisite for cost-efficient infrastructure planning, including asset refurbishment or repurposing options such as gas-to-hydrogen pipeline repurposing. In contrast, incomplete or mission spatial information distorts least-cost pathways resulting in a less accurate representation of feasible system configurations and binding constraints.

National policy frameworks must be reflected in nationally tailored ESMs, for example through model constraints, explicit targets or cost adjustments such as subsidy schemes. Depending on the country, this typically involves a range of policy elements, including national emission trajectories or carbon budgets consistent with climate neutrality goals, renewable electricity targets, phase out dates for carbon-intensive technologies, efficiency standards, regulatory technology constraints on technology deployment, and nationally specific subsidies. Additionally, technology costs have a direct impact on modelling outcomes and therefore need to be tailored to the respective country.

Over-regional models typically adopt coarse national-scale spatial aggregation to control computational complexity, which limits the spatial fidelity of results on a sub-national basis. Aggregating technology portfolios at a single node per region provides only weak guidance on

the siting of assets within a country, particularly for variable renewable generators. As transmission can be represented only between model regions, the chosen aggregation directly conditions inferred network expansion requirements. Moreover, large regions implicitly smooth sub-regional demand–supply heterogeneity, leading to systematic underestimation of the need for transmission, storage, and other balancing resources.

Nationally tailored ESMs thus need to combine high regional disaggregation for the area of the respective country with prudent temporal aggregation to make national infrastructure and detailed siting information possible.

2.3 Inter-connection of respective country in international energy systems

National energy systems are structurally embedded in European networks. Existing and new infrastructure of various carriers such as electricity, gas or hydrogen systems, are and will be tightly coupled to trading partners. This cross-border energy exchange directly affects national balancing needs and cost outcomes. (International) transmission – especially for electricity – is vital for integrating a high share of VRE, shifting surplus across regions to mitigate local congestion or extremely high storage needs.

In over-regional ESMs that optimize the entire system for minimum total cost, a country-centric perspective can inherit artefacts that are misaligned with national planning realities. System-wide optimisation tends to exploit cheap renewable potentials and deploy large interconnector capacities, wherever they are most cost-effective globally. For the whole modelled area, such outcomes may be reasonable, yet when the analytic focus is on a single country, this may lead to an unrealistic dependence on energy imports or overestimation of generation capacities and investment costs.

Consequently, for a nationally tailored ESM, it must be ensured, that the respective country with all its regions is treated as a unit embedded in a system instead of a collection of regions in an international system and that import and export flows reflect physical bottlenecks and political circumstances. By ensuring that international interactions are realistic, the model avoids artificial autarky or overreliance on imports to create a credible view of an optimal mix of domestic investments and cross-border engagements.

2.4 Model calibration

When applying a national model to derive transition pathways, a validation of model outputs against official energy statistics is essential. A basic approach is therefore to compare domestic electricity generation, primary energy use, inputs and outputs in conversion processes, and final energy to national energy balances. Through a transparent mapping of carriers and processes to official reporting standards, a model validation reports deviations. Model calibration techniques can then help to move model outputs closer to observations.

3 Methods

In the following, we focus on our work, creating PyPSA-AT as implementation of the concepts discussed in section 2. As PyPSA-AT currently is under development, we here focus on

aspects already implemented in the framework and quantify their influence on the energy system model compared to the over-regional model PyPSA-EUR.

3.1 Methodological foundation and model lineage

The methodological foundation for an Austria-focused ESM is build up by two main frameworks: PyPSA-EUR [5], [6], [7] offers high spatio-temporal, sector-coupled optimisation across Europe, while PyPSA-DE demonstrates how national adaptations can embed country-specific policies and data and, critically, can reveal savings from integrated sector-coupled planning compared to siloed approaches [8].

In the PyPSA-EUR-framework, investment and operation of generation, storage, conversion and transmission of various energy carriers are co-optimised for the European system with explicit carbon accounting. The framework comes with high temporal granularity for the integration of VRE. The sizing of energy balancing management, such as storage and transmission capacities is determined by production variability from intra-day to seasonal horizons. Coarse temporal aggregation or sub-year optimization periods therefore risk underestimating balancing needs and biasing infrastructure recommendations. A sub-daily temporal resolution is therefore indispensable to quantify balancing needs arising from VRE integration, capturing daily solar cycles, multi-day events such as "Dunkelflauten" to seasonal patterns.

Besides, PyPSA-EUR is a fully sector coupled energy system model. As discussed in prior studies, full sector coupling is a basic important requirement for holistic energy system modelling on a national scale. As electrification progresses, cross-sector flexibility, using electric vehicle smart charging, heat pump thermal storage or electrolyser operation to name a few, becomes even more central for cost-optimal planning and price formation.

Technically, PyPSA-AT is implemented as a soft fork of PyPSA-DE to remain aligned with upstream developments while enabling Austria-specific extensions and modifications. Whenever possible, all modifications are introduced as stand-alone tasks in the workflow, that do not touch the underlying PyPSA infrastructure to facilitate maintenance and reuse.

3.2 Temporal and spatial granularity and European embedding

Increased spatial or temporal resolution in energy system models always comes with extended computational needs. Therefore, we provide two default Austrian regionalization modes, to allow for faster runs or higher spatial resolution: (i) a 10-node NUTS-2-clustering and (ii) a 30-node-clustering, mainly based on NUTS-3-regions providing a more detailed view for infrastructure planning in Austria. Currently, a full NUTS-3-resolution is not yet implemented, as the spatial representation of the transmission grid, the clustering is based on, is not high enough to represent all NUTS-3-regions. Outside Austria, Germany is represented with five regions to reflect its role as dominant trading partner, while other countries are represented by a single region, with separate nodes for islands to respect grid topology. The network topology is shown in Figure 1 (left), Figure 1 (right) shows the high-resolution clustering of 30 regions in Austria. This representation of the European energy system incorporates international electricity generation and energy conversion systems and preserves key transmission corridors relevant for Austria while keeping the problem tractable.

Concerning temporal resolution, building upon PyPSA-EUR, we implement a resolution of three hours over a full weather year as default resolution, with efforts to keep an hourly resolution of the system still solvable. We see a temporal resolution of three hours as a good balance between accuracy and computational effort ensuring robust quantification of balancing, transmission and storage sizing needs for the whole system.
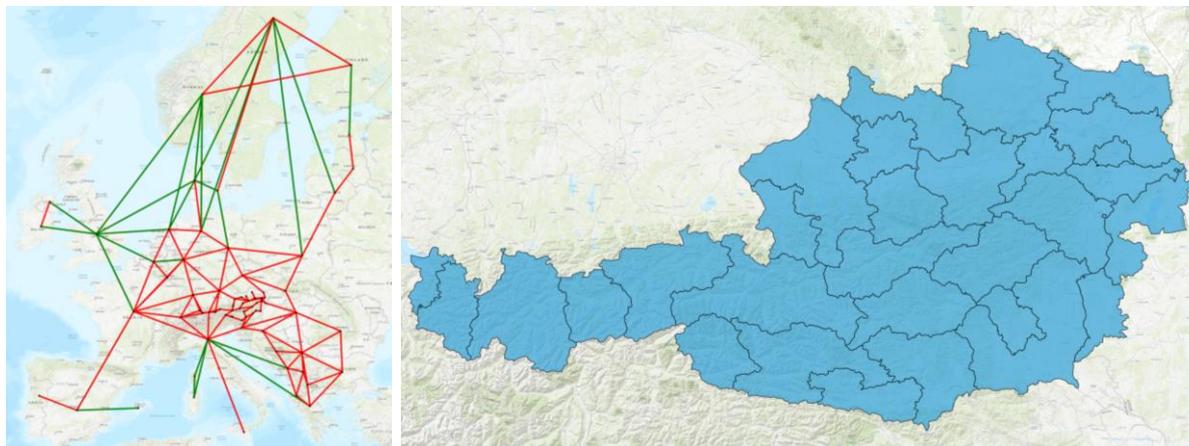

Figure 1: left: Schematic representation of the model topology; black dots: nodes, lines: AC (red) and DC (green) lines; right: clustering regions inside Austria based on NUTS-3 regions

3.3 Emission tracking and policy encoding

To align the model with Austria's Net Zero greenhouse gas objective by 2040, we implement national greenhouse gas constraints alongside system-wide emission budgets. Within Austria, we therefore identify all processes with positive or negative emissions. Positive emissions arise for example from the combustion of fossil fuels or from industrial processes, while negative emissions are delivered by direct air capture (DAC), synthesis pathways that bind CO_2 (e.g. methanolization of hydrogen), or biomass-applications with carbon capture and sequestration (BECCS). For combustion, we make no distinction between fossil and renewable fuel categories. As a result, combustion of renewable fuels encounters positive emissions, while the production of renewable fuels leads to negative atmospheric emissions.

No trading of emissions is allowed in the system, so e.g. Austrian firms cannot buy certificates in the ETS. Outside of Austria, perfect emission trading is assumed for all sectors, as the model does not differentiate in which region abatements and combustion occur. Emissions from domestic aviation are represented by scaling total aviation emissions according to a domestic-to-total ratio computed from model outputs. International aviation is excluded from the national emissions inventory.

Figure 2 schematically shows the most important correlations of the national Carbon Accounting mechanism.
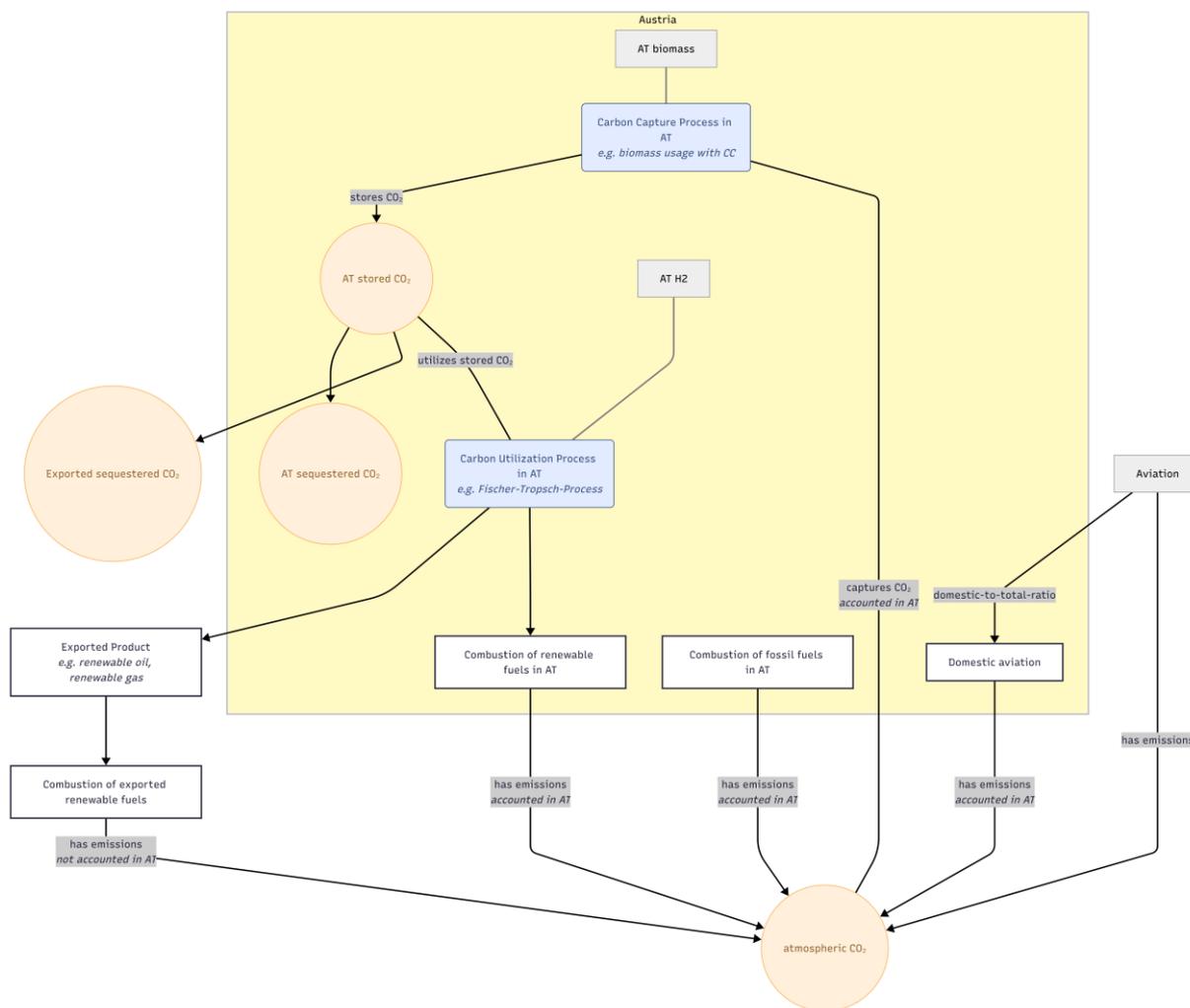
Figure 2: Schematic representation of the national emissions accounting mechanism in PyPSA-AT. Stored CO_2 Emissions can be exported via pipeline for sequestration in another country or via a Carbon Utilization Process and export of the corresponding product.

3.4   Optimization strategy and constraints

We adopt a myopic multi-year pathway optimization, solving separately linear cost-minimization problems for successive horizon years, for example in 5-year or 10-year steps. This approach not only provides system information for the respective timestep but also transitioning insights such as when infrastructure needs to be expanded or fossil-fuel phase-down pathways while staying within computational limits for the needed high spatial and temporal granularity. Currently, inter-step coupling is ensured by carrying forward installed capacities and imposing an expansion cap of 25% transmission between consecutive 10-year periods.

Within each timestep, the objective is taken over from the PyPSA-EUR-framework, so the model co-optimizes the investment and operation of generation, storage, conversion, and transmission infrastructures for the least-cost outcome in a single linear optimization problem.

3.5   Model validation and calibration pipeline

3.5.1   Validation data: Eurostat Energy Balance

We validate the model outputs against Austria's official Eurostat energy balance (EB) to establish consistency and credibility for policy use. As EB categories are more granular than those directly generated by PyPSA-AT, we preprocess EB data into two validation categories: primary energy supply and energy usage aggregates.

We basically consider all primary energy-supply carriers listed in the EB and aggregate these to obtain an applicable basis for a mapping to the model's carriers. We then use the following blocks of the EB for validation-purpose: total aggregated values (including imports, exports, Primary production and change in stock), Transformation input (representing energy carriers input to conversion processes) and Final energy use. We therefore perform minor adaptations to EBs grouping to align with the model's technology-carrier taxonomy.

3.5.2   Carrier-centred flow accounting

To produce EB-compatible statistics from the solved PyPSA networks, we implement a carrier-centred accounting layer to trace energy flows across model components, heavily building on the PyPSA statistics module [9]. We analyse energy flows for each primary carrier from input to end-use delivery, traversing the network components generators, conversion- and transmission links and lines, stores and storage units, loads and buses. We therefore distinguish between five carrier roles:

-   Primary carriers: including primary energy carriers and secondary energy carriers to align with the EB's reporting scheme
-   Conversion carriers: conversion of energy between different carriers applying a conversion technology
-   End-use carriers: final energy consumption carriers
-   Transmission carriers: transmission of energy between network nodes of one type of carrier
-   Storage carriers: temporal shift of one energy carrier

Because PyPSA carriers can play multiple roles (e.g. Electricity as Primary carrier, End-use carrier, Transmission carrier and Storage carrier) we tag flows contextually by component type to avoid double counting.

Mapping the model carriers to the EB proceeds in two steps: (i) Primary carriers are mapped to the aggregated EB primary-supply columns (ii) Internal carrier flows and End-use carriers are mapped to EB rows for total absolute energy, transformation input and energy end-use. Storage flows are accounted for in the total absolute energy-section. To account for the energy flows, the energy carriers of Conversion, Storage and End-use are evaluated at the respective network-components.

3.5.3   Further steps for model calibration

Building on this validation framework, we will define a concise set of calibration degrees of freedom affecting reconciliation with Austria's energy balance while preserving physical plausibility. We will implement a calibration strategy that minimizes weighted deviations between model-constructed EB entries and observed EB entries and possible side effects of

this strategy will be screened. The outcome will be a generalisable framework to calibrate the model to any European country using the Eurostat EB, enabling national EB-consistent applications while retaining European-context and methodological continuity with open, sector-coupled modelling practices.

4 Results

This section compares results of the PyPSA-AT model, an Austria-tailored sector-coupled model to those from the pan-European PyPSA-EUR model focusing on Austria's variable renewable electricity (VRE) deployment and cross-border energy exchanges. The models are optimized with identical configurations apart from some minor changes. The model frameworks themselves differ in aspects covered in Section 3 and aspects covered by the PyPSA-DE-Project [8]. The temporal resolution of the model runs is 6h, with a spatial resolution of one node per country, with the exceptions discussed Section 3.2. In the PyPSA-AT-model, Austria is represented by 10 nodes. Geographically, we cover the continental European power system including most of EU-27 (excluding CY and MT), UK, CH, NO and West Balkans (AL, BA, ME, MK, RS, XK). Myopic optimization is performed for the years 2020, 2030, 2040 and 2050. In PyPSA-EUR, Net-Zero policy is enforced for the full system in 2050, while in PyPSA-AT they are enforced for Austria in 2040 and for the full system in 2050.
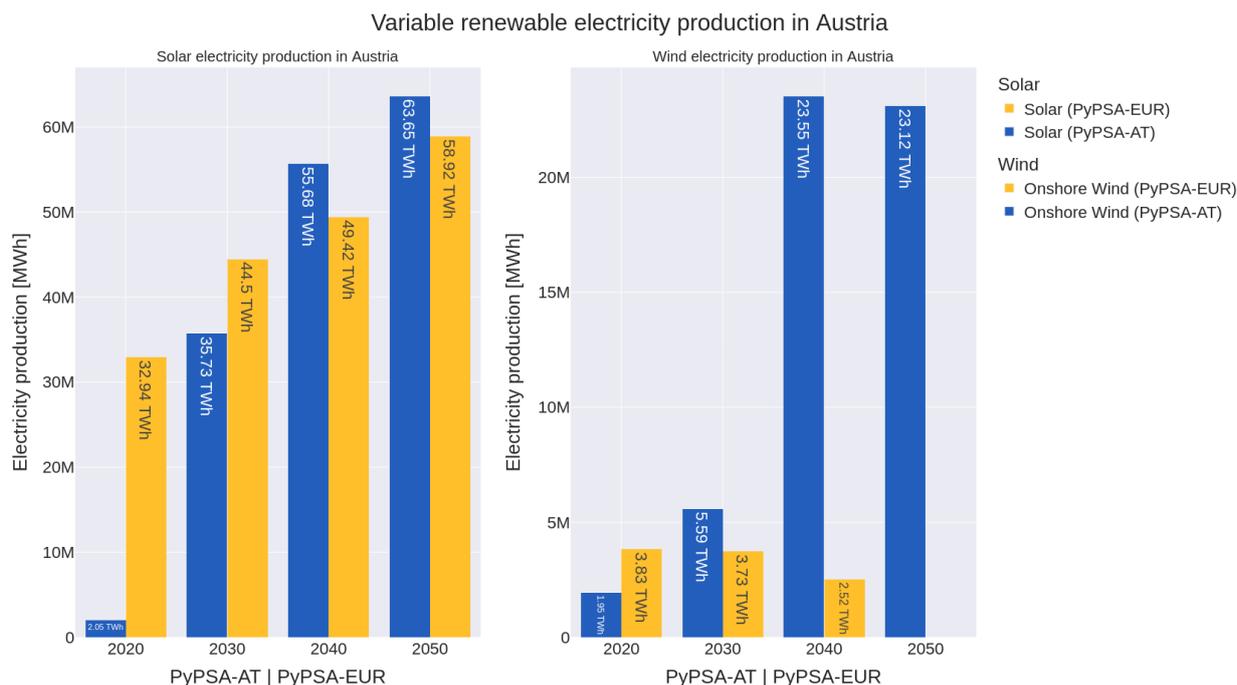

Figure 3: Solar electricity production (left) and Wind production (right) in Austria for model frameworks PyPSA-AT and PyPSA-EUR and all modelled investment years.

4.1 Variable Renewable Energy Production in Austria

The modelled trajectories for wind and solar capacity in Austria differ markedly between PyPSA-AT and PyPSA-EUR. In PyPSA-AT, onshore wind capacity expands strongly between 2030 and 2040, reaching a maximum of 14 GW in 2040 followed by a slight decline towards 2050. Despite this capacity adjustment, wind generation remains stable at around 23 TWh in

2040 and 2050. In contrast, the PyPSA-EUR run exhibits a continuous decline of Austrian wind power from 2020 onwards, yielding only a negligible fraction of PyPSA-AT wind capacity by 2050. This leads to divergent production rates from wind power through the whole period between the two frameworks, as shown in Figure 3 (right).

Solar photovoltaics exhibits a rapid, sustained growth in PyPSA-AT, increasing by (6-30) GW per decade to a modelled optimal capacity of 56 GW by 2050. In PyPSA-EUR, solar capacity also increases between the investment years but starting on a high level of 27 GW to be expanded to a maximum of 56 GW. Consistent with these capacity differences, annual solar generation in PyPSA-EUR exceeds the generation in PyPSA-AT by far in 2020 for 2030, 2040 and 2050 results are comparable, as Figure 3 (left) shows.
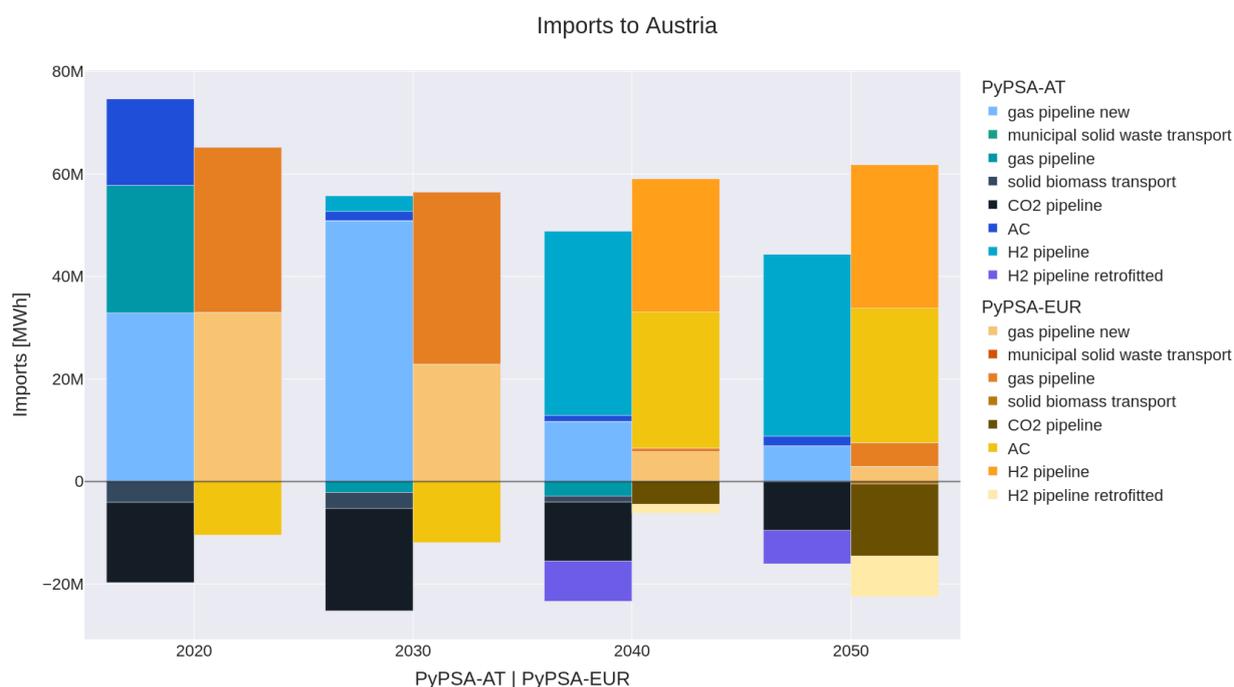

Figure 4: Netto-Imports to Austria balanced over one year for both models, PyPSA-AT (left in blue) and PyPSA-EUR (right in yellow) and all modelled investment years.

4.2   Import and Export Flows involving Austria

Figure 4 summarizes Austria's imports and exports by energy carrier and model year for PyPSA-AT and PyPSA-EUR. In PyPSA-AT, net energy imports decline to 38 GWh by 2050, whereas in PyPSA-EUR, imports remain above 53 GWh per year due to additional electricity imports of (26-27) GWh per year in 2040 and 2050.

High fossil gas imports of up to 58 GWh in PyPSA-AT in the year 2020 (including fossil and renewable gas) are progressively displaced by hydrogen (H2) imports. By 2050, H2 imports reach up to 29 GWh in the PyPSA-AT-model with principal origins in Germany, France and Italy. In PyPSA-AT, the biggest part of these H2 imports is used for methanol synthesis in end-use sectors. Notably, in 2040, 61% of H2 is used for Fischer-Tropsch synthesis, converting this hydrogen and CO_2 to synthetic oil in that single investment year. Apart from magnitude, these usage patterns of H2 are similar in the PyPSA-EUR model.

5   Discussion

Country-tailored energy system modelling frameworks, based on super-regional models, fill a critical gap in the energy system modelling landscape by providing detailed country specific information for policy relevant analysis within a broader energy system context. For Austria, PyPSA-AT, as a soft fork of PyPSA-DE and PyPSA-EUR is fully open source and is designed to contribute to and benefit from the broader PyPSA ecosystem. This positioning enables Austria-specific research on infrastructure needs, energy carrier pathways, cross sectoral technology needs and international energy trade to name a few, complementing continental analyses with the detail needed for national decision-making.

First results underscore the value of country-specific ESMs. Divergent wind trajectories across PyPSA-AT and PyPSA-EUR demonstrate how national policy milestones and model scope shape investment outcomes. Aligning with Austria's 2040 climate neutrality goal, in PyPSA-AT, Austria is positioned as an earlier mover in wind deployment and reduces reliance on net annual electricity imports. In 2040 and 2050, net electricity imports remain below 2 GWh per year with domestic wind production supplying a larger share of electricity demand. Conversely, in PyPSA-EUR, Austria is placed as a small contributor to the continental portfolio, only producing less than 1% of domestic wind electricity compared to PyPSA-AT and having net electricity imports of 26-27 GWh per year in 2050 and 2040 respectively. These differences reflect unbalanced European-scale coordination, allocating variable renewable energy capacity to resource-rich regions exclusively.

These findings also show that national policy choices propagate impacts beyond borders through coupled energy systems. Coordinated European pathways rely on inter-regional exchanges to balance spatial heterogeneity in VRE, manage seasonal shifts and support rapid electrification. Country specific targets consequently materially affect international energy flows and capacity siting in neighbouring regions, reinforcing the need to study national policy targets and constraints for a holistic view of international energy transitions.

The results suggest targeted adaptations to improve representation of technology use and international trade. We here focus on three critical issues:

- A pronounced single-year surge of Fischer-Tropsch (FT) in 2040 – using 61% of hydrogen (H2) in that timestep and without comparable activity in other modelling years (<10%) – is not realistic in the absence of appropriate intertemporal constraints and deployment dynamics. This artefact appears in both frameworks and is even more pronounced in PyPSA-AT. It points to the need for enhanced technology constraints and better understanding of renewable fuels and other fossil-fuels alternatives.
- Methanol is currently modelled with one single central node. Over all model-years, a big part of H2 imports in Austria is used for methanol synthesis contributing to this central methanol-node. 65% (2030) to 82% (2050) of this methanol is assigned to international shipping demand afterwards. Austrias role in meeting this shipping demand is likely overstated under this configuration, stressing the need for a more granular representation.
- Currently, emissions accounting issues can arise, when renewable oil or synthetic methane is exported. As schematically shown in Figure 2, the producing country indirectly records negative emissions from fuel synthesis. After export, these fuels are

modelled in one central node together with fossil counterparts, making source attribution infeasible; emissions are therefore counted where combustion takes place. This hidden export of emissions can lead to unrealistic results as the export of synthetic methane or renewable oil may be favored to meet national emission goals while having no influence on overall system emission balance.

6 Conclusion

To conclude, comparing a country-tailored ESM to a pan-European model demonstrates that country-specific energy system models with high spatial and temporal resolution are essential tools for answering policy-relevant questions. Country-specific policies affect not only national outcomes but also system-wide interactions across borders, reinforcing the need for integrated modelling at multiple scales. PyPSA-AT is under active development; the implemented changes already yield important implications, but further adaptations – particularly around technology utilisation, infrastructure constraints, international flows and representation of renewable fuels and CO_2 – are required. By augmenting existing frameworks, PyPSA-AT contributes to a more holistic picture of Europe's energy transition needs and supports transparent, reproducible analysis for Austria and its neighbours.

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