Integrated Power and Economic Analysis of Austria's Renewable Electricity Transformation
START2030 Working Paper #1

Robert Gaugl [1,*], Mark Sommer [2], Claudia Kettner [2], Udo Bachhiesl [1], Thomas Klatzer [1], Lia Gruber [1], Michael Böheim [2], Kurt Kratena [3], Sonja Wogrin [1]

[1] Institute of Electricity Economics and Energy Innovation (IEE)/Graz University of Technology, Graz, Austria

[2] Austrian Institute of Economic Research (WIFO), Vienna, Austria

[3] Centre of Economic Scenario Analysis and Research (CESAR), Vienna, Austria

[*]Corresponding author: Robert Gaugl; robert.gaugl@tugraz.at

January 2023

Abstract

In this paper, we present a novel approach of linking the technical model of the continental European electricity system *ATLANTIS* with the macroeconomic model *DYNK* to provide comprehensive integrated power and socio-economic analyses. We thoroughly describe both models and explain the work that has been done to interlink the models. Further, we take Austria's generation expansion plans to transform the electricity sector to 100% renewable energy sources (national balance) by 2030 and analyze the effects of different CO_2 prices on the electricity demand that couples the two models via a feedback loop. As the electricity price and demand are interlaced and influence each other, the linked models are solved iteratively until convergence, i.e., until the change of the electricity demand from the *DYNK* model does not affect the electricity price in the *ATLANTIS* model anymore. The results show that coupling a technical and macroeconomic model is possible and convergence is achieved after just a few iterations.

Keywords:
renewable energies; macroeconomic modelling; electricity economics; DC-OPF; model linkage; Austria

1 Introduction

The European Union (EU) has set the target to achieve climate neutrality by 2050 EuropeanCommission (2019) to comply with the Paris Climate Agreement's goal of keeping global warming well below 2°C or even 1.5°C United Nations (2015) compared to pre-industrial levels. As an intermediate step for 2030, the EU proposed the "Fit-for-55" package European Commission (2021) in July 2021 that aims at reducing greenhouse gas (GHG) emissions by at least 55% while increasing the share of renewable energy sources in the overall energy mix to at least 40%. In response to the disruption of global energy markets in 2022 and the associated challenges, the REPowerEU program European Commission (2022) proposed to increase the goal for renewable energy to 45% and, among other things, focuses on ambitious energy saving targets and a ramp-up of green hydrogen production. Electricity from renewable energy sources (RES-E) is expected to play a key role in the energy transition. This is also reflected in Austria's Renewable-Expansion-Act ("Erneuerbaren Ausbau Gesetz", EAG) Nationalrat (2021) that was passed in July 2021 stipulating a goal of 100% RES-E on a national balance[1] by 2030. In order to achieve this target, the EAG defines that +27 TWh of RES-E (+11 TWh photovoltaic (PV), +10 TWh wind, +5 TWh hydro and +1 TWh biomass) have to be added between 2020 and 2030. This fundamental structural change of Austria's electricity system demands a substantial increase in infrastructure investments.

Techno-economic implications associated with the transformation of the Austrian energy system have been assessed in previous studies. For example, in the context of *MonMech* the effects of the current policy mix and an extended set of policy instruments on Austrian GHG emissions were analysed in (UBA, 2017; Kratena, 2014; Sommer and Kratena, 2017; UBA, 2019). Another example is *el.Adapt* Bednar-Friedl et al. (2013), which focused on the required adaptations of the Austrian electricity sector due to climate change until 2050. However, in these studies, the electricity sector was either modeled in a very simplified way, or the distributional impacts of a transition to 100% RES-E in Austria were not addressed. Moreover, these studies were based on less ambitious targets for 2030.

In this work, we present an innovative approach of linking the technical model of the continental European electricity system *ATLANTIS* Stigler et al. (2015) with the macroeconomic model *DYNK* Kirchner et al. (2019) and evaluate what effects on wholesale electricity prices and electricity demand are induced by different CO_2 prices in the interlinked model system. With this approach of linking an electricity model with a macroeconomic model, all relevant feedback mechanisms can be considered and the analysis is expanded into the areas of energy and socio-economics.

The structure of the paper is as follows: In section 2 the macroeconomic model *DYNK* and the model of the European electricity system *ATLANTIS* are introduced and their linking is explained. Section 3 gives an overview on the scenarios for the Austrian and Continental European electricity system and section 4 explains the methodology of the iterative process. Section 5 shows the results of the interlinked models and presents sensitivity analyses with respect to the CO_2 price. Finally, section 6 discusses the results and concludes the paper.

2 Model Descriptions and Interlinking

This section introduces the macroeconomic model *DYNK* and the electricity-economic model *ATLANTIS* and explains the linking between these two models.

2.1 DYNK

The *DYNK* model resembles an Input-Output-Model in its core and expands this approach by specific production and consumption functions, a commodity price system, wage bargaining on the labour market, and a commodity and production taxation system. Due to these expansions *DYNK* bears some similarities with DSGE (Dynamic Stochastic General Equilibrium) models, since it explicitly describes an adjustment

[1] I.e. national renewable electricity generation should at least equal national electricity demand; a complete phase-out of fossil fuel based electricity generation is not required.

path towards a long-term equilibrium. The *DYNK* model treats Austria as a single integrated economy and traces the inter-linkages between 76 industries as well as the consumption of ten household income groups using 59 consumption categories.

Four different sources of technical change are modeled in *DYNK* at a disaggregated level: total factor productivity (TFP), factor-bias and material efficiency in production and energy efficiency in private consumption. These components of technological change – together with changes in relative prices – drive economic growth and resource use and therefore decoupling. The term 'New Keynesian' refers to the existence of a long-run full employment equilibrium which will not be reached in the short-run due to institutional rigidities. These rigidities include liquidity constraints for consumers (deviation from the permanent income hypothesis), wage bargaining (deviation from the competitive labour market) and an imperfect capital market. Depending on the distance to the long-run equilibrium, the reaction of macroeconomic aggregates to policy shocks can differ substantially. *DYNK* links physical energy and material flow data to real sectoral activities, intermediate inputs in production and consumption activities. This covers the final energy demand in detail of up to 22 energy types[2]. Due to its detailed modeling structure of consumption and production activities the *DYNK* model is well suited for the analysis of the driving forces of resource use (energy and materials) in the Austrian economy.

The current model comprises eleven modules. The solution process is an iteration over all modules until convergence is achieved. Each of these modules is presented shortly in the following sub-sections. Except for the newly developed module "Electricity Generation", a more detailed description of modules and data sets used in *DYNK* can be found in Kirchner et al. (2019).

2.1.1 Module 1: Commodity market

This module represents the input-output core of the model. The commodities demanded by public and private consumers, investment and exports are supplied by a set of sectors. The production necessary to satisfy the demand is calculated using a Leontief-equation. Thereby it is guaranteed that the demand of commodities equals supply. The results of this module are employment, value added and production value per sector. The data set used are Statistics Austria (2021b) of the Austrian Economy for the year 2017.

2.1.2 Module 2: Disposable income

Disposable income for private households is derived from value added that is generated in the sectoral production activities. Pre-defined transfers and unearned income are added and taxes and social contributions are subtracted using tax rates of the respective year. This yields 'disposable income' for private households which is the basis for consumption in the next modules. Data sources are the national Statistics Austria (2021d) of private households for the year 2017.

2.1.3 Module 3: Private Consumption

The consumption decisions of private households (part of final demand) are simulated in this module using several behavioural equations that apply coefficients estimated by time series analysis using Austria-specific data. These equations comprise consumption of energy products (space heating, electricity for appliances and vehicle utilization), durable commodities (housing and vehicles) and a bundle of residual non-durable and non-energy commodities. The commodity composition of this residual bundle is defined by the application of an AIDS (Almost Ideal Demand System). In all equations estimated coefficients and prices define the commodity structure in the respective simulation. The resulting consumption vector is part of final demand and therefore input in module 1. The applied data comprises a wide range of consumption related data taken from data bases of EUROSTAT and Statistik Austria (for details see Kirchner et al. (2019)).

[2] based on the pyhsical energy flow accounts of Statistik Austria https://www.statistik.at/statistiken/energie-und-umwelt/energie/physische-energieflussrechnungen

2.1.4 Module 4: Production and Prices

In this module a Translog production function specification is applied. The function determines, based on input commodity prices and technology, factor and investment demand as well as output prices. Own- and cross-price elasticities are applied to determine the composition of 5 input-bundles (factors) - i.e. Capital (K), Labour (L), Energy (E), Imported commodities (M) and domestically produced commodities (D), or KLEMD in total. This means that the five factor shares react to relative price constellations whereas the sub-commodity-structure of the factors is constant (Leontief technologies). The principle of the Translog estimations and equations can be found in (Sommer and Kratena, 2017) or in the documentation of FIDELIO2 (Streicher et al., 2017). The module applies production functions with a Translog specification for each sector. To estimate the coefficients of the Translog equations, system estimations and the seemingly unrelated regression (SUR) estimation method are applied for each specific sector. The coefficients are seen as exogenous in this model. The primary source for the estimations were derived from the WIOD (World Input Output Database, Release 2013 and 2016) data set that contains World Input Output Tables (WIOT) in current and previous year's prices, Environmental Accounts (EA), and Socioeconomic Accounts (SEA).

2.1.5 Module 5: Investments

In DYNK, each sector has a specific commodity structure of its investment based on the Input-Output-Tables of Statistics Austria. The change in each investment level is linked to the moving average of the economic surplus[3] (factor K) of the sector of the previous 5 years. By this approach investment needs to satisfy changes in demand (rising production leads to rising value added) as well as investments due to shifts to the factor capital via the production function (Module 4).

2.1.6 Module 6: Labour market

The labour market determines the price index for the factor labour which is one of the five factors in production function (Module 4) and thereby influences the sectoral production prices throughout the economy. The labour market simulates wage bargaining, formalized in wage curves by industry. These wage curves are specified as the employees' gross wage rate per hour by industry. The labour price (index) of the Translog model is then defined by adding the employers' social security contributions.

2.1.7 Module 7: Energy

In this module derives the final energy demand of the economy from the economic development. Here the real[4] inputs of energy commodities in production and consumption are linked to the physical energy consumption of each sector and households via energy intensity coefficients (Terajoule per €) . The coefficients are derived from the monetary values in the Input-Output-Table and the physical units provided by the Physical Flow Accounts of (Statistics Austria, 2021e).

2.1.8 Module 8: Emissions and Carbon pricing

The energy related carbon emissions are linked via carbon intensity coefficients to the energy consumption derived in Module 7. I.e. these emissions are linked to the respective fuel use based on sectoral emissions provided by (Statistics Austria, 2021c). Process emissions that occur due to processes other than combustion are linked to real production values of the respective sectors, again via emission coefficients. An exogenous carbon price is used to derive additional costs for the emissions, i.e. the combustion of fuels or process emissions. The derived costs are used as a mark-up on the commodity taxes system of the Input-Output-Tables. Thereby the (gross) prices for specific carbon-containing commodities increase and lead to substitution and saving reactions throughout the system.

[3]Gross surplus is a part of value-added

[4]I.e. nominal values deflated by the respective gross commodity price

2.1.9 Module 9: Fuel Substitution

The sub-structure of commodities of each of the five factors in Module 4 (KLEMD) are constant, i.e. ”Leontief technologies”. The sole exception is factor energy (E). This factor energy comprises six commodities[5]. They represent the input of energy in form of coal, oil, gas, electricity, district heat and renewables in the production process. Five of the six shares of these energy factors are defined by another Translog specification as in Module 4[6]. Hence these factors are also endogenous depending on relative (gross) prices and trends. The main sources for the estimation of the translog coefficients were EUROSTAT energy balances and WIOD (revision 2016) environmental accounts as well as fossil energy carrier prices from the IEA database. The method here is again a system estimation using the SUR (Seemingly Unrelated Regression) estimation method to estimate the parameters of equations of the shares and the unit costs for each specific sector.

2.1.10 Module 10: Government

In module 10 the revenues and expenditures of the regional government are simulated. If expenditures exceed revenues the difference (net lending) is added to the public debt. Only a few elements of revenue and expenditure can be derived from the SUT structure (taxes in Module 1) and the household's income composition (taxes in Module 2). Hence the public household is simulated in a relatively simple fashion. Nevertheless, a mechanism is applied that allows choosing whether or not public debt is endogenous or exogenous. This enables the model to run specific scenarios that focus on the impact of and on public net lending.

2.1.11 Module 11: Electricity Generation

This new module represents the interface to the *ATLANTIS* model and allows to simulate changes of the annual physical electricity generation (and their cost) in DYNK. A necessity to simulate changes in electricity generation in *DYNK* was to extract the NACE[7] sector ”Electricity generation” from the sector ”Electricity, Gas and Heat generation and supply (NACE D35) in all Input-Output-Tables of DYNK. This disaggregation has been based on a custom analysis of relevant primary statistics by Statistics Austria. The input structure of the electricity generation sector was then further differentiated into eleven technology-specific costs structures according to the technologies in *ATLANTIS* plus a residual that represents grid and distribution services. The production value of the eleven technologies is based on the production costs provided by *ATLANTIS*; their commodity structure is based on the structures of respective electricity generation technologies for Austria in the multi-regional Input-Output-Table EXIOBASE (www.exiobase.eu).

The inputs from *ATLANTIS* are investments in electricity generation technologies, the generation costs of the respective electricity generation mix as well as electricity generation costs and wholesale price.

The investments in electricity generation technologies are translated into a commodity structure based on literature reviews focusing on the three most relevant[8] technologies wind(Kaltschmitt et al., 2020; Wallasch et al., 2019; Resch et al., 2017), hydro (Aufleger et al., 2020; Resch et al., 2017) and PV (BMK, 2021; Bründlinger et al., 2020; Fechner , 2021; Resch et al., 2017). The resulting investment vector is then transferred to the electricity sector's investment in Module 5. The wholesale price of electricity is translated to end-user prices by adding grid costs, fees and taxes. The resulting price determines the output price index of the electricity sector in Module 4. The generation mix defines the commodity input structure of the electricity sector by using weighted input structures for each technology. The weight is determined by the results of *ATLANTIS*. Furthermore, variations in cost components (costs of operation,

[5] CPA05_07 Mining of fossil fuels, CPA16 wood products, CPA19 mineral oil products, CPA35.1 Electricity, CPA35.2 Natural Gas, CPA35.3 District heat

[6] The share of district heating is unchanged because our Translog specification can only handle 5 factors and the share of district heating in the affected ETS industries is negligible.

[7] Statistical Classification of Economic Activities in the European Community

[8] Most relevant in the sense, that changes in electricity generation capacity occur almost exclusively in these technologies compared to the reference scenario.

fuel, emission permits, labour compensation and depreciation) are considered as well. The adapted input-structure is transferred to a change in intermediate inputs of the sector in the Input-Output-Tables in Module 1.

2.2 ATLANTIS

In this section, we provide a brief overview of the *ATLANTIS* model Stigler et al. (2015) developed at the Institute of Electricity Economics and Energy Innovation (IEE), Graz University of Technology.

ATLANTIS is a techno-economic model of the continental European power system that incorporates both the technical and economic aspects of the power system for long-term scenario simulations. The technical aspects of the model include, inter alia, the continental European electricity system based on 4,022 nodes (power stations) with regionalized demand distribution, the transmission grid (including 6,864 lines and 1,471 transformers), and 79,146 generators (including thermal power plants, renewables, and storage units). The power flow is modeled as direct current (DC) optimal power flow (DC-OPF), which is a good approximation of reality in the transmission grid. Due to the scale of the continental European power system, the temporal framework is based on discretized time duration curves. Since the model is intended for long-term system planning and given the uncertainty of input data over such lengthy time frames this is reasonable. The economic aspects of the model include information about electricity companies, fuel prices, inflation rates, etc. to calculate electricity trading between companies, market prices as well as balance sheets and profit and loss accounts for the included companies.

The *ATLANTIS* model is structured into six different modules, as can be seen on the left side of Figure 1. In the first step, the database and scenarios are implemented. The database includes ATLANTIS-specific information, e.g. the power plants, the transmission network, load profiles, etc. as well as other exogenous parameters that are aligned with the *DYNK* model such as fuel prices, CO_2 prices, inflation rates, etc.

In the following step, system adequacy is evaluated. This entails assessing whether the winter and summer peak load can be covered with the existing generation capacities given the restrictions of the existing transmission grid (based on a DC-OPF). As a result, a lack of generation and/or transmission capacity is identified.

For this study, each month was divided into two peak and two off-peak periods in order to strike a reasonable balance between accuracy and computational time. *ATLANTIS* runs two different models per period, where the results of the first model (Zonal Pricing Model) set the initial values for the second one (Redispatch Zonal Pricing Model) for faster model run times. The models are explained in detail in the following sections.

2.2.1 Single node per country - Zonal Pricing Model

In the Zonal Pricing (ZP) model, the Merit-Order is calculated per country/zone with the Net Transfer Capacities (NTCs)[9] allowing a coupling between the markets. Within a zone, the cost-optimal dispatch of power plants is calculated by defining a linear optimisation problem with the objective of maximizing social welfare as defined in Equation 1a. With this the respective zonal price (market clearing price for each zone) is determined. Trading between "cheaper" and "more expensive" zones can thus arise while complying with the commercial restrictions of the NTCs. The ZP-Model provides the zonal price per country/market, the trade flows between the countries/markets as well as the ideal dispatch per power plant (no grid restrictions). The following constraints have to be considered: maximum supply in a market 1b; maximum demand in a market 1c; limit of trading between two markets based on the defined NTCs 1d; and balance constraint 1e.

[9]NTCs cause restrictions in electricity imports and exports between the countries.

$$\max_{qD,qS} \left\{ \sum_i \left[\sum_n (qD_{n,i} \cdot pD_{n,i}) - \sum_a (qS_{a,i} \cdot c_{var} S_{a,i}) \right] \right\} \tag{1a}$$

subject to:

$$qS_{a,i} \leq qS_{max_{a,i}} \tag{1b}$$

$$qD_{n,i} \leq qD_{max_{n,i}} \tag{1c}$$

$$export_{i \to j} - import_{i \to j} \leq NTC_{i \to j} \qquad \forall (i,j | i \neq j) \tag{1d}$$

$$\sum_a qS_{a,i} - \sum_n qD_{n,i} + \sum_{i \neq j} import_{i \to j} - \sum_{i \neq j} export_{i \to j} = 0 \qquad \forall i \tag{1e}$$

with: i, j .... countries, market areas
k .... defined technical profiles between market areas
n .... block bid of demand
a .... block bid of supply
$qD_{n,i}$ .... cleared part of demand block n in market i [MW]
$qS_{a,i}$ .... cleared part of supply block a in market i [MW]
$pD_{n,i}$ .... demand price [€/MWh]
$c_{var} S_{a,i}$ .... marginal costs of supply block a in zone i [€/MWh]
$import_{i \to j}$ .... import in market i from market j [MW]
$export_{i \to j}$ .... export from market i to market j [MW]
$NTC_{i \to j}$ ...... net transfer capacity between market i and j [MW]

As this model considers every zone/country as a single node where all the power plants are connected to and all the demand occurs, the dispatch of the power plants does not consider restrictions related to the grid because of congested lines.

2.2.2 Grid restrictions with DC-OPF - Redispatch Zonal Pricing Model

The Redispatch Zonal Pricing (RDZP) model takes the results of the power plant dispatch from the ZP model as starting values for the solver but incorporates the grid restrictions by implementing a DC-OPF. The DC-OPF is defined as a mixed-integer linear optimisation problem with the objective of minimizing overall system costs 2a. The first sum defines the cost of power plant dispatching, the second sum describes the cost of using phase shifting transformers and the third sum defines the costs for cross-market redispatch. Constraint 2b defines the equilibrium of generation, demand and the power flows to and from a node; 2c represents the unit commitment[10] for thermal power; load flow limits of lines are set with 2d for AC-lines and 2e for DC-lines; 2f ensures the power balance between generation demand and export/import per market; 2g sets the limits for the control angle of phase shifting transformers and 2h limits the angle of power lines (since the DC load flow is a simplification of the AC load flow, which requires a very small phase angle along a line).

[10] If the power plant is dispatched or not.

$$\min \quad \left\{ \sum_{G} c_{var,G} \cdot p_G \cdot P_{Base} + \sum_{l} (\alpha \cdot \Lambda_{l,DC} + \lambda \cdot \sigma_{l,PST}) + \sum_{Cl} \delta \cdot H_C^+ \right\}$$
$$H_C^+ \in \{0,1\}_Z \tag{2a}$$

subject to:

$$\sum_{G} p_{G,n} - \sum_{D} p_{D,n} = \sum_{m} flow_{n \to m} - \sum_{m} flow_{m \to n} \quad \forall \text{ m} \tag{2b}$$
$$p_{min,G} \leq \beta \cdot p_G \leq p_{max,G} \qquad \beta \in \{0,1\}_Z \tag{2c}$$
$$-p_{ACmax,l} \leq flow_{n \to m} \leq p_{ACmax,l} \qquad \forall \text{ AC lines} \tag{2d}$$
$$-p_{DCmax,l} \leq flow_{n \to m} \leq p_{DCmax,l} \qquad \forall \text{ DC links} \tag{2e}$$
$$\sum_{G} p_{G,C} - \sum_{D} p_{D,C} - saldo_C^{LF} = 0 \tag{2f}$$
$$-\sigma_{max,PST} \leq \sigma_{l,PST} \leq \sigma_{max,PST} \quad \forall \text{ l} \tag{2g}$$
$$-\Lambda_{max,DC} \leq \Lambda_{l,DC} \leq \Lambda_{max,DC} \quad \forall \text{ l} \tag{2h}$$

with:
G .... generation units
D .... demand
C .... market areas, bidding zones (countries)
n, m .... nodes
$c_{var,G}$ .... marginal generation costs [€/MWh]
$p_{G,n}$ .... (optimised) power injection of unit G at node n [p.u.]
$p_{D,n}$ .... demand at node n [p.u.]
P_{Base} .... power base for per unit calculation [MW]
α, δ, λ .... penalty weights
β .... binary switching variable for unit commitment [-]
$\sigma_{l,PST}$ .... (optimised) angle of phase shifter [rad]
$\sigma_{,ax,PST}$ ...... maximum angle of phase shifters [rad]
$flow_{n \to m}$ ..... active power flow on line l between node n and m [p.u.]
$p_{min,G}$ .... minimum power of unit G [p.u.]
$p_{max,G}$ .... maximum power of unit G [p.u.]
$p_{ACmax,l}$ ..... maximum allowed transmission capacity of AC line l [p.u.]
$p_{DCmax,l}$ ..... maximum power of DC line l [p.u.]
$\Lambda_{l,DC}$ .... (optimised) commitment of DC links [rad]
$\Lambda_{max,DC}$ ..... maximum controlling range of a DC link [rad]

In many countries the heat produced by combined heat and power (CHP) plants is needed in winter months for district heating purposes, making them must-run power plants that have to produce even if they would not be dispatched based on the Merit-Order system. For this model run, power plants with heating output have a must-run flag set in the winter months (November, December, January, and February) and are therefore forced to produce. According to Austria's energy balance from Statistics Austria, in 2021 heating demand for district heating was 26 TWh. CHP plants contributed 14.7 TWh, showing the importance of the heat production of CHP plants Statistics Austria (2021a). Some industrial power plants are also needed throughout the year and, for that reason, have a must-run flag set for the whole year.

In case of line congestions, an intra-zonal redispatch is carried out and, if this is not sufficient, a redispatch across zones is done. In addition to the results of the ZP-Model, the RDZP-Model also provides the line utilization and the "positive" and "negative" redispatch for each power plant.

2.3 Model Linkage

The basis for linking *ATLANTIS* and *DYNK* is handling the *ATLANTIS* model's output as a disaggregate technological representation of the different electricity sub-sectors. The *ATLANTIS* solution's data on electricity generation and distribution of the RDZP model is linked to the corresponding variables in the *DYNK* model. For example, in *ATLANTIS* the simulation yields results for fixed (capital) and operational (energy, labour, materials) costs as well as produced electricity per power plant type which is fed into DYNK. The resulting electricity price of the *ATLANTIS* model is linked to the output price index in DYNK. In the other direction, the resulting electricity demand of *DYNK* is fed into the *ATLANTIS* model. This is done until convergence is reached. Due to technical and practical reasons, the data exchanged between *ATLANTIS* and *DYNK* comprises full scenario results (up to 2030). Both models were calibrated to the year 2017 and the simulations cover the period from 2017 to 2030.

The different modules of the *ATLANTIS* model as well as the links between *ATLANTIS* and *DYNK* are depicted in Figure 1.

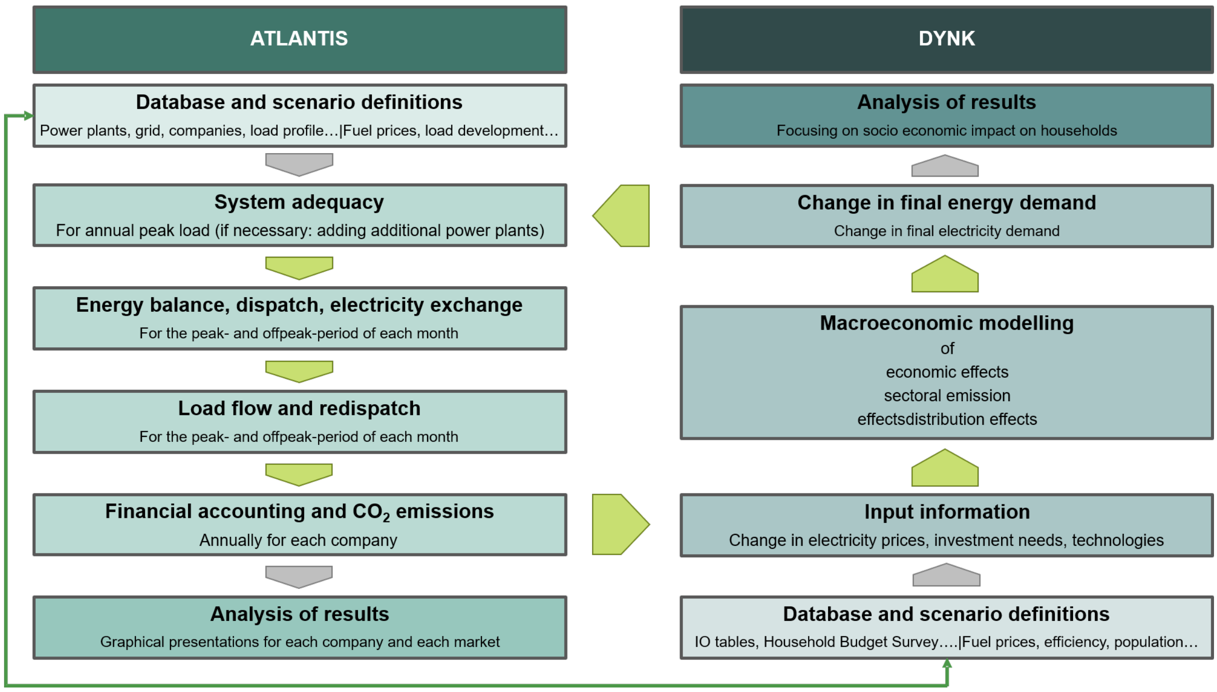

Figure 1: Flow chart of the model system showing the structure of the *ATLANTIS* model on the left side, the *DYNK* model on the right side and the interlinks between the models.

As the models are operated by two different organizations, cloud servers are utilised to exchange the results. An ad-hoc data structure based on Excel files was developed for exchanging data between the two models. For this, the data input mechanisms of the two models have been adapted. Likewise, the output of the *ATLANTIS* model was updated to specifically write the results needed for *DYNK* (installed capacity per power plant type and year, produced electricity per power plant type and year, electricity price, and fixed and operational costs per power plant type and year) into a single file.

3 Scenario Description

To analyze the effects of the transition to 100% RES-E in Austria (on a national balance), a scenario was developed based on the EAG which is explained in more detail in Section 3.1. This Austrian scenario is embedded into a European scenario that is explained in Section 3.2.

3.1 Renewable Expansion Act Scenario

To analyze the effects of the planned generation capacity expansion of the EAG a scenario was developed, where the added capacity is based on the goals and the full load hours (FLH) defined in the EAG. According to the EAG, production from PV should increase by +11 TWh from 2020 to 2030, while production from wind, hydro and biomass should increase by +10 TWh, +5 TWh and +1 TWh respectively. With the FLH specified in the EAG (PV: 1,000 h, wind: 2,500 h, hydro ¡1 MW: 4,000 h, hydro ¿1 MW: 5,000 h, biomass: 6,850 h) this results in additional capacities of +11,000 MW for PV, +4,000 MW for wind, +1,111 MW of hydro[11], and +146 MW of biomass that are added linearly from 2020 to 2030.

The installed power plant capacities for the scenario can be seen in Figure 2. Between the base year 2017 and 2020, the installed capacities per power plant type are based on E-Control (2021). As the locations of future power plants are not known and not defined in the EAG, but influence the DC-OPF, the following approach has been used: For wind generation, the expansion is based on Gaugl et al. (2021), which uses an optimizer to distribute the wind power plants based on the calculated technical expansion potential. PV is distributed based on the population per node with the assumption that rooftop PVs are preferred to reach the EAG goals. Other power plants are located in already existing locations for that power plant type. This assumption can be made because no new fossil power plants will be added, a large part of the additional run-of-river production will come through revitalization, and existing (pump) storage power plants will be expanded.

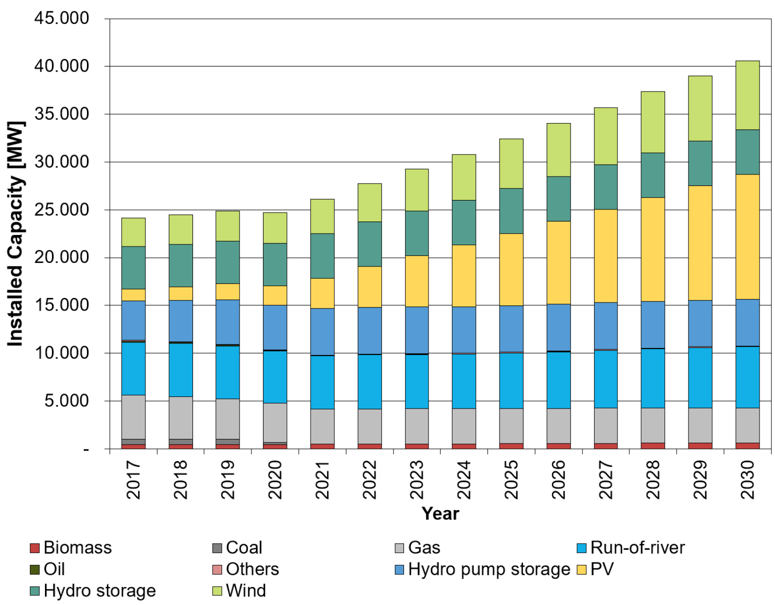

Figure 2: Development of the installed capacities per power plant type for Austria from 2017 to 2030.

With respect to demand-side factors, accelerated electrification and ambitious improvements in energy efficiency are assumed for the household sector. The respective parameters have been determined in a Delphi approach and based on a comprehensive literature survey (for details see Kettner et al. (2023)). It is assumed that the share of heat pumps in total household heating systems increases from 7% in 2017 to 19% in 2030 and that the share of electric cars in total passenger cars increases from 1% to 41% over the same period. Moreover, it is assumed that the specific energy consumption of space heating is reduced from 127 to 86 kWh/m^2, and that fuel consumption of electric cars decreases from 15 to 12 kWh/100 km. For the other areas, past improvements in energy efficiency are extrapolated and changes in the energy mix are the result of changes in the relative prices of the energy sources (see 2.1 above).

[11] The average FLH of 4,500 h was used because it is unknown how many hydro power plants ¡1 MW and ¿1 MW will be built in the future. Thus, until the year 2030, 5 TWh is equal to 1,111 MW. Additionally, it is assumed that the installed capacity split between run-of-river and (pumped-) hydro storage power plants remains unchanged from 2020 (Run-of-River: 39.6%; (pumped-) hydro storage: 60.4%). Up until 2030, this results in added capacity for run-of-river power plants of +440 MW and +671 MW for (pumped-) hydro storage power plants.

The assumed fuel prices as well as the prices for CO_2 certificates in the EU Emission Trading System (EU ETS)[12] are referenced in Table 2. In order to see the effects that a higher CO_2 price has on the results of the interlinked model system, we do sensitivity analyses where the CO_2 price is doubled and tripled from 2021 compared to the CO_2 price in Table 2 (leading to CO_2 prices of 270 €/tCO_2 and respectively 405 €/tCO_2 in the year 2030).

3.2 Scenario for rest of continental Europe

Austria is part of the synchronous grid of Continental Europe and therefore, it is important to simulate this Austrian scenario in a European context in the *ATLANTIS* model. For the *ATLANTIS* model, the information about installed capacity per country per power plant type, demand per country and grid expansion information is necessary. To get an overview of existing scenarios of the European electricity sector, a thorough literature review was done at the beginning of the study.[13] The results can be seen in Table 3. The scenarios that tick off all the boxes that are needed in the *ATLANTIS* model are the ones from the Ten Year Network Development Plan (TYNDP) of the European Network of Transmission System Operators for Electricity (ENTSO-E). The Sustainable Transition scenario was chosen for the rest of Continental Europe as it was deemed the most realistic one by the project team as well as by stakeholders and external experts participating in a project workshop on scenario development. It reaches the EU-targets through national regulation, emission trading schemes, and subsidies and therefore maximises the use of existing infrastructure. Based on this scenario, the corresponding power plant development for each power plant type (considering planned projects), demand trends, and future electricity grid projects were implemented in ATLANTIS.

4 Iterative Process

The *DYNK* and *ATLANTIS* models are linked as described in Section 2.3 and iteratively solved until convergence, i.e., until the change of electricity demand from the *DYNK* model does not affect the electricity price in the *ATLANTIS* model anymore. This process is shown in Table 1 for the standard scenario, but the same methodology was used for both scenarios of the CO_2 sensitivity analysis. To start the iterative process, in the first iteration baseline values for the electricity prices are set in the *DYNK* model[14] starting in 2017 (which was the base year for the simulations). The resulting electricity demand (Table 1, iteration 1 of electricity demand) is then fed into the *ATLANTIS* model which results in updated yearly average electricity prices (Table 1, iteration 1 of electricity prices). These new electricity prices are then inserted back to the *DYNK* model for the second iteration, resulting in a new series of electricity demand (Table 1, iteration 2 of electricity demand). The *ATLANTIS* model was updated with the new demand and because the resulting electricity prices (Table 1, iteration 2 of electricity prices) are nearly identical to the ones before, the iterative process could be stopped as without a change in electricity prices the outcome of electricity demand in the *DYNK* model would stay the same and therefore convergence has been reached. Depending on how much the results would change between iterations, the iterative process could take longer, but usually, convergence was achieved after two or three iterations.

[12]The EU ETS covers GHG emissions from energy supply and emission-intensive industry.

[13]The project began in 2020 and therefore newer scenarios that have been published in the meantime could not be considered due to the project timeline.

[14]The baseline values already have realistic electricity price assumptions implemented. Starting with realistic values reduces the number of iterations until convergence.

Table 1: Results for electricity demand and price for the iterative process.

	Electricity demand in TWh													
Iteration	**’17**	**’18**	**’19**	**’20**	**’21**	**’22**	**’23**	**’24**	**’25**	**’26**	**’27**	**’28**	**’29**	**’30**
1	65.8	66.2	66.0	63.6	67.0	68.5	70.4	72.4	74.2	75.6	76.9	77.9	78.8	79.3
2	65.8	66.2	66.0	63.6	67.0	68.4	70.3	72.3	74.0	75.4	76.6	77.6	78.4	78.9

	Electricity price in €/MWh													
Iteration	**’17**	**’18**	**’19**	**’20**	**’21**	**’22**	**’23**	**’24**	**’25**	**’26**	**’27**	**’28**	**’29**	**’30**
1	27.3	42.6	55.9	67.4	80.3	92.4	99.5	105.3	110.4	116.1	121.9	127.9	133.3	138.3
2	27.3	42.6	55.9	67.4	80.3	92.4	99.5	105.3	110.3	116.1	121.9	127.9	133.3	138.2

5 Results and Discussion

This section presents the final results of the interlinked model system for the EAG scenario in Austria as well as the sensitivity analysis examining the effects of a higher CO_2 price.

5.1 EAG scenario

The models were calibrated for the base year of 2017 and the error of the simulated values compared to the real production values from Statistics Austria (2021a) is smaller than 6%[15]. For 2017, hydro power plants (sum of run-of-river and hydro (pumped) storage) make up for the biggest part of the electricity production with 35.1 TWh, followed by gas (8.3 TWh) and wind power (7.2 TWh). The development of the electricity production per power plant type for Austria for 2017 to 2030 after achieving convergence of the interlinked model can be seen in Figure 3. Due to the (exogenous) expansion plan defined in the EAG that is the basis for this simulation (see Section 3.1), PV and wind power see the largest increase in produced electricity between 2017 and 2030 with gains of +11.7 TWh and +10.6 TWh respectively. Hydro power still remains the most important source of electricity for Austria accounting for 39.1 TWh. Counter-intuitively, larger RES-E generation also leads to more production from gas-fired power plants, because they have to compensate for the fluctuating generation from renewables. Additionally, with the assumed fuel price developments defined before the energy crisis resulting from the war in Ukraine, gas is cheaper compared to coal[16] and therefore, Austria is also exporting cheaper electricity from gas-fired power plants (in addition to RES-E) to neighbouring countries replacing electricity from coal power plants there.

[15]This is mostly due to a lower hydro production. As an average hydro year was chosen for the inflows of the hydro power plants, this small error was accepted.

[16]The project team did address the issue of higher gas prices in a sensitivity analysis which can be found in Kettner et al. (2023).

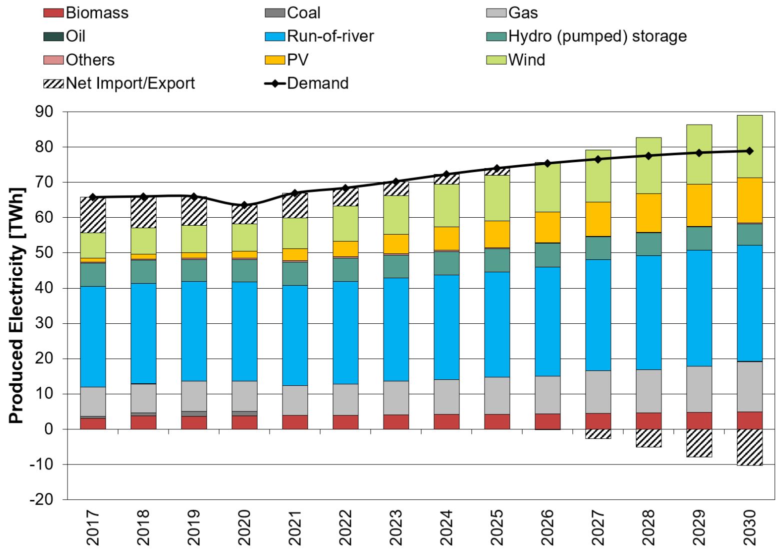

Figure 3: Development of the produced electricity per power plant type, net import/export and demand for Austria from 2017 to 2030.

Currently, Austria's electricity production is not enough to cover the domestic demand, making it a net importing country[17]. Especially during winter months, when demand is typically higher in Austria and electricity production from run-of-river power plants (Austria's most important electricity source) is smaller because of lower inflows, Austria has to import electricity from neighbouring countries (most importantly Germany). Although electricity demand is assumed to increase to 79.8 TWh in our simulations, Austria is set to become a net-exporting country by 2026. In 2030 Austria is net-exporting 10.7 TWh. Figure 4 shows the monthly electricity production in 2030, showing that the majority of exports occur during the summer months. It can also be seen, that run-of-river and PV production are higher in summer, and wind production is higher in winter months. The installed wind capacity is too little to compensate for the decreased run-of-river and PV production in winter and therefore more gas-fired power plants are needed in winter months.

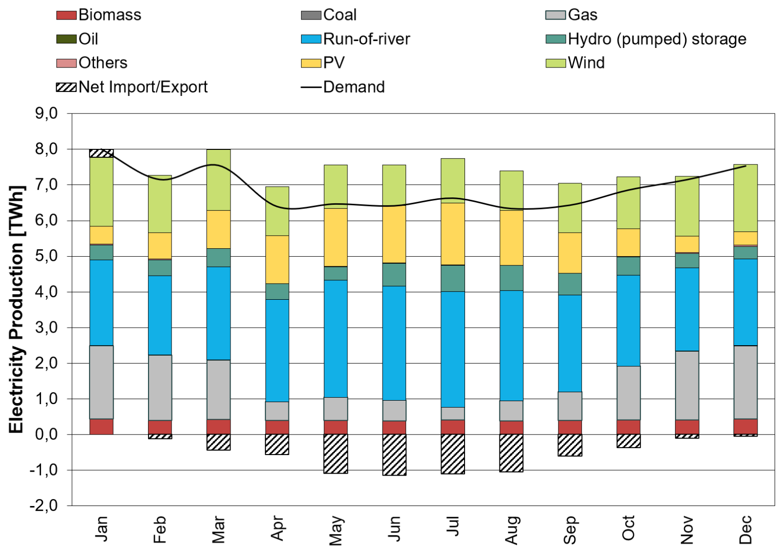

Figure 4: Monthly produced electricity per power plant type in Austria for 2030.

Despite the higher share of renewable electricity, the price for electricity[18] is still rising to 138 €/MWh in 2030 as displayed in Figure 5. With the Merit-Order system in place, where the last power plant needed

[17] Importing more electricity than exporting over a year.
[18] Energy price only. Not including taxes or grid tariffs.

to cover the demand is setting the wholesale market price, gas-fired power plants are the price-setting technology in most of the simulated periods, though a small flattening of the electricity price curve can be seen in Figure 5 with a rising share of renewables.

5.2 CO_2 Sensitivity Analysis

In the sensitivity analysis of the CO_2 price, we double and triple the CO_2 price starting from 2021. The results shown in this chapter are the final results after the linked model system has reached convergence. With higher CO_2 prices reaching 270 €/tCO_2 and 405 €/tCO_2 in 2030, the electricity price increases to 197 €/MWh and 249 €/MWh respectively as shown in Figure 5. The electricity prices for 2030 for the CO2 270 scenario are 42% higher compared to the standard EAG scenario and for the CO2 405 scenario this is a 79% increase.

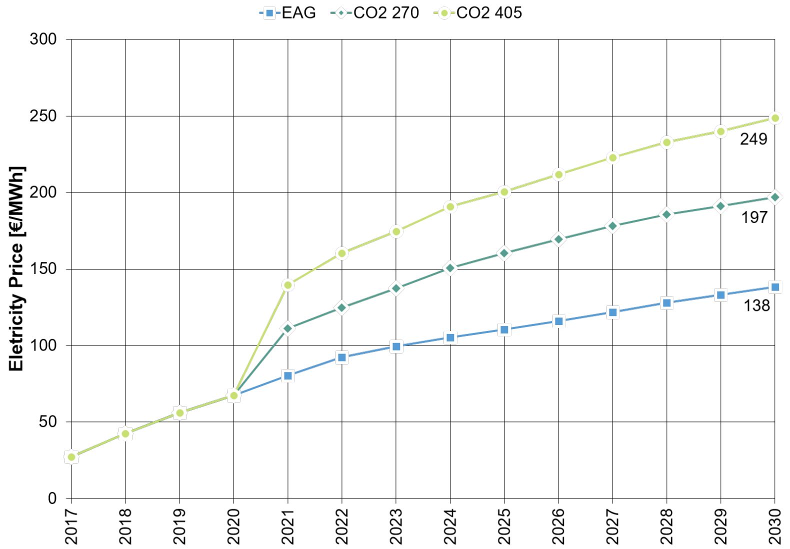

Figure 5: Annual average electricity prices in the EAG scenario as well as in the CO_2 price sensitivity analysis.

The higher electricity prices lead to a reduction of electricity demand (mainly due to a decrease in production activities) as can be seen in Figure 6. This decrease is much smaller (-2% for the 270 €/tCO_2 scenario and -3% for the 405 €/tCO_2 scenario) than the increase in the wholesale electricity price. This reflects on the one hand that the increase in consumer prices is lower than the increase in wholesale prices as these account only for one part of the prices paid by households and companies, and other price components such as grid charges are assumed to remain unchanged. On the other hand for the household sector electrification follows a predefined pathway (see section 5.1) and for the industry sector, a rising carbon price in the EU ETS does not only increase electricity prices but also - and even more pronouncedly - the costs of using gas, oil or coal, so that firms have no incentives to switch to these fuels. Finally, electricity demand is quite inelastic and so even big changes in electricity prices have only a small impact on the electricity demand when capital stocks are fixed.

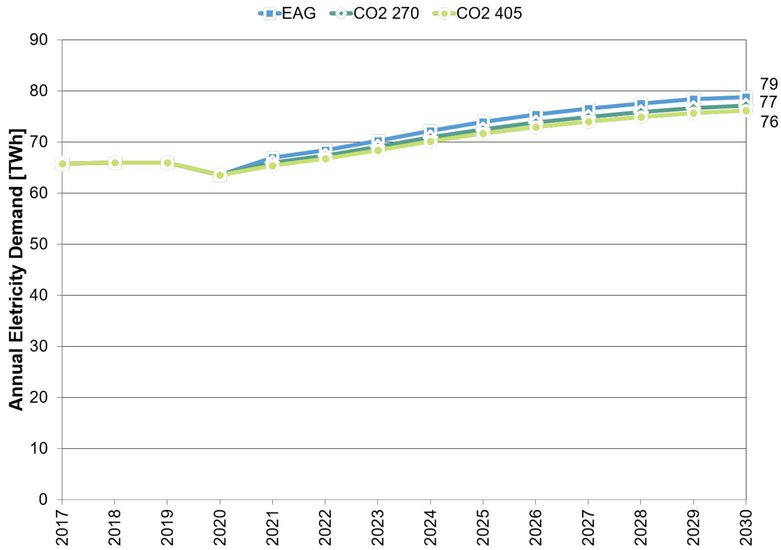

Figure 6: Demand in the EAG scenario as well as in the CO_2 price sensitivity analysis.

Higher CO_2 prices lead to lower demand, but also to (a little) higher production from gas-fired power plants in Austria and higher net exports (Figure 7). This is due to the fact, that in the European scenario, other countries still have operating coal-fired power plants. As these are much more affected by the higher CO_2 prices (because they emit much more CO_2 per produced MWh), coal generation is largely being replaced by gas generation. Furthermore, as demand is decreasing in Austria with higher CO_2 prices, the amount of electricity not used in Austria is also exported and replacing more expensive electricity in other countries.

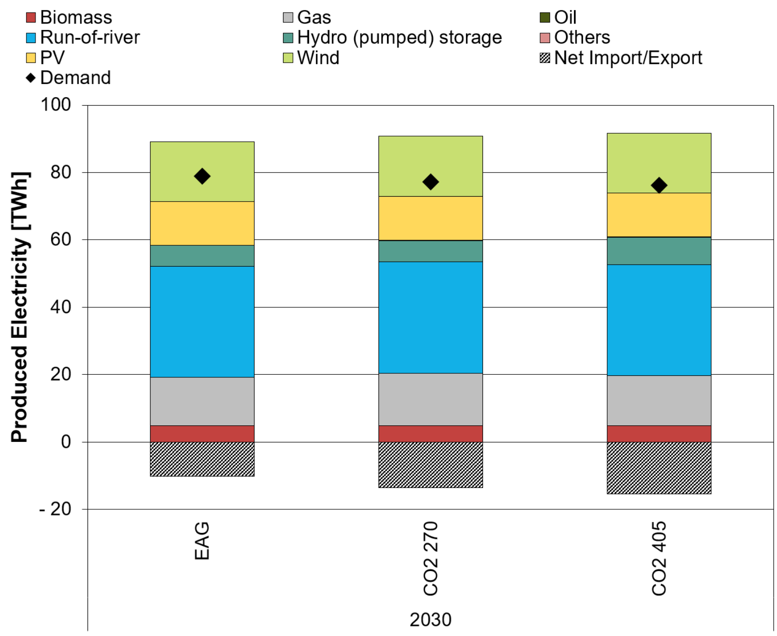

Figure 7: Produced electricity per power plant type in 2030 for the three different scenarios.

6 Conclusion

With the novel approach of interlinking the technical model of the continental European electricity system *ATLANTIS* with the macroeconomic model *DYNK* we are able to reflect the socio-economic impact of the electricity price which in turn leads to a different electricity demand. Both models were enhanced to allow a linking of corresponding variables with a cloud-based solution. The *ATLANTIS* model was updated with the expansion plans of Austria's Renewable-Expansion-Act (EAG), which sets a path to cover 100% of Austria's electricity demand by renewable energies (on a national balance) by 2030. As Austria is part of the synchronous grid of Continental Europe and is an important country to transit electricity between Northern and Southern Europe, the Austrian electricity system was implemented into a comprehensive European scenario. The *DYNK* model was expanded by a new "Electricity Generation" model that represents the interface to ATLANTIS. This module features a detailed representation of electricity generation technologies, i.e. electricity supply was first diasaggregated from gas and heat supply, and then disaggregated into eleven electricity generation technologies used in *ATLANTIS* plus a residual that represents grid and distribution services. Inputs from *ATLANTIS* to the *DYNK* model are investments in the different electricity generation technologies, the electricity generation mix and electricity generation costs as well as the wholesale price.

The interlinked model system is run until convergence is reached and the output of the *ATLANTIS* model (electricity price) does not affect the output of the *DYNK* model (electricity demand) anymore. We showed that the interlinked model system works and that convergence can be reached after just a few iterations.

The results show, that gas-fired power plants are becoming even more important with higher shares of RES-E. The fluctuating nature of renewables (especially wind and PV) requires controllable generators that counterwork the variable electricity production of RES-E and keep the electricity system stable by balancing electricity demand and electricity production. Therefore, gas-fired power plants will still set the market price for electricity in the merit order, leading to higher electricity prices in the future.

The sensitivity analyses with higher CO_2 prices result in even higher electricity prices. Electricity demand declines compared to the EAG scenario, mainly reflecting a reduction in real output due to higher prices. The decline in demand is, however, relatively small. This predominantly reflects that for the household sector the development of electrification has been fixed, and that for companies included in the EU ETS a rising carbon price increases the price of fossil fuels even further, so that fuel switches do not yield cost reductions.

As production from coal-fired power plants (in other European countries) is more affected by higher CO_2 prices, production is shifted to gas-fired power plants. This results in higher net exports from Austria and therefore also to higher electricity production from gas-fired power plants.

In the EAG scenario, Gross Domestic Product (GDP) increases by 18% in 2030 compared to 2017, mainly due to increases in exports and total factor productivity. In the sensitivity analysis, the growth is dampened due to the direct and indirect price increases (-0.9% for a CO_2 price of 270 € and -1.4% for a CO_2 price of 405 € in 2030 compared to the EAG scenario). These rather small decline reflects the higher costs of emission permits, fuel shifts to less expensive energy sources, energy savings as well as decreasing real exports[19]. It has to be noted that *DYNK* is a single-region model and therefore the effects of rising carbon prices in other European countries are not considered. The reduction in real exports might hence be overestimated as prices in other European countries would rise as well. In order to completely decarbonize the Austrian electricity system even more renewables and more storage would be needed as stated in the EAG. With more renewables and storage, surplus electricity could be stored to be used in times of low RES-E production. This could minimize or even completely prevent the need for gas-fired power plants.

Funding

This research was conducted in the project *START2030* funded by the Climate and Energy Fund (Klima- und Energiefonds) and carried out within the Austrian Climate Research Programme (ACRP).

[19]As a result of a predefined pathway for nominal exports and rising prices.

Appendix

A Fuel price assumptions

Table 2: Annual fuel prices used in the simulation

Year	Crude Oil €/MWh	Natural Gas €/MWh	Coal €/MWh	CO_2 €/t
2017	39	28	14	9
2018	42	32	14	19
2019	46	37	13	29
2020	49	42	12	38
2021	52	43	13	48
2022	56	44	13	58
2023	59	44	14	67
2024	62	45	15	77
2025	66	46	15	87
2026	69	46	16	96
2027	72	47	16	106
2028	76	48	17	116
2029	79	49	17	125
2030	82	50	18	135

B Overview literature review for European scenarios

Table 3: Overview of the literature review for different European scenarios with remarks about the information needed.

Org.	Publ.	Scenario	Cap./ Ctry.	Dem/ Ctry.	Grid Exp.
IEA	World Energy Outlook 2020	Stated Policies	No	No	No
ENTSO-E	**TYNDP 2018**	**Sustainable Transition**	**Yes**	**Yes**	**Yes**
ENTSO-E	TYNDP 2018	Distributed Generation	Yes	Yes	Yes
ENTSO-E	TYNDP 2018	Global Climate Action	Yes	Yes	Yes
ENTSO-E	TYNDP 2018	EUCO 2030	Yes	Yes	Yes
EU	EUCO 2019	EUCO 3232.5	Yes	Yes	No
WEC	WEC Scenario 2019	Modern Jazz	No	No	No
WEC	WEC Scenario 2019	Unfinished Symphony	No	No	No
WEC	WEC Scenario 2019	Hard Rock	No	No	No
Shell	Shell Scenarios 2018	Sky	No	No	No
BP	Energy Outlook 2020	Net-Zero	No	No	No
BP	Energy Outlook 2020	Business-as-Usual	No	No	No
BP	Energy Outlook 2020	Rapid	No	No	No
McKinsey	Global Energy Perspective 2019	Reference Case	Yes	Yes	No
IRENA	Global Renewables Outlook 2020	Planned Energy	No	No	No
IRENA	Global Renewables Outlook 2020	Transforming Energy	No	No	No
IRENA	Global Renewables Outlook 2020	Baseline	No	No	No
Equinor	Energy Perspectives 2020	Reform	No	No	No
Equinor	Energy Perspectives 2020	Rebalance	No	No	No
Equinor	Energy Perspectives 2020	Rivalry	No	No	No

References

Aufleger, M., Joos, F., Jorde, K., Kaltschmitt, M., Rödl, A., Schlüter, M., Sens, L., **2020**. Stromerzeugung aus Wasserkraft, in: *Kaltschmitt, M., Streicher, W., Wiese, A. (Eds.), Erneuerbare Energien: Systemtechnik · Wirtschaftlichkeit · Umweltaspekte.* Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 583–683. URL: https://doi.org/10.1007/978-3-662-61190-6_7, doi:10.1007/978-3-662-61190-6_7 .

Bednar-Friedl B.; et al, **2013**. ElAdapt - Impacts of Climate Change and Adaptation in the Electricity Sector. *ISBN 978-3-9503112-8-0.*

BMK, **2021**. Innovative Energietechnologien in Österreich Marktentwicklung 2020. Biomasse, Photovoltaik, Solarthermie, Wärmepumpen und Windkraft. Technical Report.*Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK).* URL: https://nachhaltigwirtschaften.at/resources/iea/marktentwicklung-2020.pdf.

BP, **2020**. Energy Outlook 2020 edition.

Bründlinger, R., Christ, D., Fechner, H., Kaltschmitt, M., Müller, J., Peharz, G., Schulz, D., Sens, L., **2020**. Photovoltaische Stromerzeugung, in:*Kaltschmitt, M., Streicher, W., Wiese, A. (Eds.), Erneuerbare Energien: Systemtechnik · Wirtschaftlichkeit · Umweltaspekte.* Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 339–460. URL: https://doi.org/10.1007/978-3-662-61190-6_5, doi:10.1007/978-3-662-61190-6_5.

E-Control, **2021**. Bestandsstatistik Kraftwerkspark Jahresreihen.

ENTSO-E, **2018**. TYNDP2018 - Scenario Report.

Equinor, **2020**. Energy Perspectives.

European Commission, **2021**. 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. *COM(2021) 550.*

European Commission, **2022**. REPowerEU Plan. *COM(2022) 230.*

European Commission, **2019**. Results of the EUCO3232.5 scenario on Member States. *Technical Note.*

European Commission, **2019**. The European Green Deal. *COM(2019)640* .

Fechner, H., **2021**. National Survey Report of PV Power Applications in Austria 2020. *Technical Report. IEA.* URL: https://iea-pvps.org/wp-content/uploads/2022/02/NSR_Austria_2020.pdf

Gaugl, R.; Klatzer, T.; Bachhiesl, U; et al., **2021**. GIS-based optimization – achieving Austria's 2030 wind energy target. *Elektrotech. Inftech.*, *138*, 590–596. https://doi.org/10.1007/s00502-021-00932-y

IEA, **2020**. World Energy Outlook 2020.

IRENA, **2020**. Global Renewables Outlook.

IRENA, **2021**. Renewable Power Generation Costs in 2021.

Kaltschmitt, M.; Özdirik, B.; Reimers, B.; Schlüter, M.; Schulz, D.; Sens, L.; Stromerzeugung aus Windenergie, **2020**. In:*Kaltschmitt, M., Streicher, W., Wiese, A. (Eds.), Erneuerbare Energien: Systemtechnik · Wirtschaftlichkeit · Umweltaspekte.* Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 461–582. URL: https://doi.org/10.1007/ 978-3-662-61190-6_6, doi:10.1007/978-3-662-61190-6_6.

Kettner C.; Böheim M.; Sommer M.;et al., **2022**. Transformation to a Renewable Electricity System in Austria: Insights from an Integrated Model Analysis. *START2030 Working Paper 2.*

Kirchner, M.; Sommer, M.; Kratena, K.; et al., **2019**. CO2 taxes, equity and the double dividend – Macroeconomic model simulations for Austria. *Energy Policy 126*, 295-314. https://doi.org/10.1016/j.enpol.2018.11.030.

Kratena, K.; Meyer, I.; Sommer M., **2014**. Alternative Szenarien zur Entwicklung des Energieverbrauchs in Österreich. Der Einfluss der CO_2- und Energiepreise bis 2030. *WIFO-Monatsberichte 87(6)*, 427-441.

McKinsey, **2019**. Global Energy Perspective 2019: Reference Case.

Nadeem F.; Hussain S. M. S.; Tiwari P. K.;et al., **2019**. Comparative Review of Energy Storage Systems, Their Roles, and Impacts on Future Power Systems. *IEEE Access 7*. 4555-4585. https://doi.org/10.1109/ACCESS.2018.2888497

Oesterreichischer Nationalrat, **2021**. Erneuerbaren-Ausbau-Gesetz. *BGBl. I Nr. 150/2021.*

Resch, G., Burgholzer, B., Totschnig, G., Lettner, G., Auer, H., Geipel, J., Haas, R., **2017**. Stromzukunft Österreich 2030 - Analyse der Erfordernisse und Konsequenzen eines ambitionierten Ausbaus erneuerbarer Energien. Endbericht. *Technical Report.* TU Wien. URL: https://www.igwindkraft.at/mmedia/download/2018.02.05/1517824995073289.pdf.

Sejkora, C.; Kühberger, L.; Radner, F.; et al., **2020**. Exergy as Criteria for Efficient Energy Systems—A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential. *Energies 13.* https://doi.org/10.3390/en13040843

Shell, **2018**. Shell Scenarios Sky - Meeting the of the Paris Agreement.

Sommer, M.; Kratena, K, **2017**. The Carbon Footprint of European Households and Income Distribution. *Ecological Economics 136*, 62-72. https://doi.org/10.1016/j.ecolecon.2016.12.008

Statistics Austria, **2021a**. Gesamtenergiebilanz Österreich.

Statistics Austria, **2021b**. Input-Output-Tabellen 2017 Österreich.

Statistics Austria, **2021c**. Luftemissionsrechnung 2017 Österreich.

Statistics Austria, **2021d**. Nicht Finanzielle Sektorkonten, Sektor Private Haushalte 2017 Österreich.

Statistics Austria, **2021e**. Physische Energieflussrechnung 2017 Österreich.

Stigler, H.; Bachhiesl, U.; Nischler, G.; et al., **2015**. ATLANTIS: techno-economic model of the European electricity sector. *Central European Journal of Operations Research 24*, 965-988. https://doi.org/10.1007/s10100-015-0413-8

Streicher, G., Salotti, S., Valderas, J., Sommer, M., Kratena, K., **2017**. FIDELIO 2 - Overview and theoretical foundations of the second version of the fully interregional dynamic econometric long-term input-output model for the EU-27. Luxembourg: Publications Office of the EU. doi:10.2760/313390 .

UBA, **2017**. Energiewirtschaftliche Szenarien im Hinblick auf Klimaziele 2030 und 2005.

UBA, **2019**. GHG Projections and Assessment of Policies and Measures in Austria.

United Nations, **2015**. Paris Agreement.

Wallasch, A.K., Lüers, S., Heyken, M., Rehfeldt, K., **2019**. Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz. Teilvorhaben II e): Wind an Land. *Technical Report. Deutsche WindGuard GmbH.* URL: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/bmwi_de/deutsche-windguard-vorbereitung-begleitung-erfahrungsbericht-eeg.pdf?__blob=publicationFilev=7.

WEC, **2019**. World Energy Scenarios 2019: Exploring Innovation Pathways to 2040.

Wogrin, S.; Tejada-Arango, D. A.; Gaugl, R; et al., **2021**. LEGO: The open-source Low-carbon Expansion Generation Optimization model. *SoftwareX 19.* https://doi.org/10.1016/j.softx.2022.101141