Transformation to a Renewable Electricity System in Austria: Insights from an Integrated Model Analysis
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Abstract

We analyse the (techno- and macro-)economic and distributive effects of a transformation to a renewable electricity system in Austria by 2030, as stipulated by the Austrian government. For the analysis, the macroeconomic model *DYNK* and *ATLANTIS*, a partial model of the electricity market, were expanded and linked. Four transformation scenarios conforming with the 100% renewable electricity target in Austria on a national balance are examined, integrated into a consistent scenario for the development of the European electricity system. Additionally, sensitivity analyses with respect to the gas price are performed. Although all scenarios achieve 100% RES-E on a national balance, the analysis shows that electricity from gas-fired power plants will still be needed in 2030 to balance variable renewable generation, to avoid grid congestion, and for heat generation from combined heat and power plants in winter months. Another main conclusion from the simulations is that the transition towards a renewable electricity sector is almost neutral from a socio-economic perspective. It does neither reveal harmful impacts nor lead to high multiplier effects from additional investment. With high natural gas prices in the sensitivity scenarios a decrease in GDP and household income, which might motivate redistributive policies, can be observed.

Keywords:
renewable electricity; Austria; model linkage; macroeconomic model; electricity system model

1 Introduction

To mitigate the climate crisis ambitious emission reductions and respectively rapid and far-reaching transitions in energy infrastructure (including transport and buildings) as well as industrial systems are required that are unprecedented in terms of scale. In the wide portfolio of mitigation options renewable energy sources will play a key role in delivering the aspired emission reductions, together with efficiency improvements and structural changes.

The Austrian government has stipulated a goal of 100% renewable electricity (RES-E) supply in Austria on a national balance[1] by 2030 in the Austrian Renewable Energy Expansion Act (*Erneuerbaren Ausbau Gesetz, EAG*; Austrian National Council (Österreichischer Nationalrat), 2021). As of 2020, RES-E held a share of 78% in total electricity generation in Austria (Statistics Austria, 2021a). For bridging the gap to the 100% target over the next decade, renewable electricity generation should be increased by 27 TWh compared to 2020 according to the Austrian government (Austrian National Council (Österreichischer Nationalrat), 2021). This implies a pronounced acceleration of RES-E deployment in Austria compared to the previous decade in which (normalised) electricity generation from renewable energy sources grew by only 9 TWh (Statistics Austria, 2021a), and will require considerable investments and changes in the Austrian electricity system.

This paper provides comprehensive analyses of the economic incidence and distributional impacts of a transition to a 100% RES-E system in Austria by 2030. Four scenarios in which the 100% target is achieved were analysed (embedded in a consistent scenario for the European electricity system) to depict the broad range of potential effects associated with the transformation. The value added of the project compared to the existing literature consists of an integrated view of energy, environmental, economic and social aspects of a transition in the electricity system. The synthetic view, on the one hand, refers to the simultaneous analysis of the different areas by considering all relevant feedback mechanisms via an inter-linked model system. On the other hand, the project expands the analysis in the areas of energy and socio-economics. That applies to including the different grid levels (and not only electricity generation) and decentralised generation (e.g. prosumers) and including distributional aspects as well as the economic impact of intra-industrial change in the electricity sector in the analysis.

For the EU and its Member States, scenarios for a transformation of the energy - and electricity system - have been e.g. performed in Knopf et al. (2015), European Commission et al. (2016, 2019), or Nijs et al. (2017). For Austria, the effects of a transformation of the energy system have been analysed in a number of projects, for instance in the context of monitoring and reporting requirements under Regulation (EU) 2018/842[2] (*MonMech* – e.g. Environment Agency Austria, 2019, 2017b; Sommer et al., 2017). In *MonMech*, the effects of the current policy mix (With Exisiting Measures, *WEM*, Scenario) and an extended set of policy instruments (With Additional Measures, *WAM*, Scenario) on Austrian greenhouse gas (GHG) emissions are analysed. The effects of the policy scenarios on electricity supply in *MonMech* are modelled with the Austrian *TIMES* model, the model *DYNK* (see section 2.1.1) is applied to estimate the development of final energy demand of the industry and service sectors and to evaluate the economic effect of the policy measures. In Bednar-Friedl et al. (2013), adaptations required in the Austrian electricity sector due to climate change until 2050 were analysed. For this analysis, the electricity system model *ATLANTIS* was coupled with an economic Computable General Equilibrium model and a special focus has been set on the changing (see section 2.1.2) hydro-power production based on different climate scenarios. These studies, however, have not addressed the social aspects of a transition towards a 100% RES-E in Austria. Statistics Austria (Statistics Austria, 2018; Hyll, 2019; Wegscheider-Pichler, 2021) analysed the status of energy poverty in Austrian households. For 2018/2019, the study showed that Austrian households on average spend 1.9% of their total disposable income on electricity. The data suggested that lower-income households in Austria face a considerably higher electricity burden than middle- and high-income households: Low-income households spent about 3.5% of their income

[1] I.e. the yearly produced RES-E needs to be equal or higher than the domestic electricity demand. Trade and interim fossil based electricity generation is possible.

[2] European Commission (2018)

on electricity, middle-income households about 2.2% and high-income households only about 1.3%. For households at risk of poverty and energy-poor households[3] average shares are even 5.1% of their income on electricity. Such results often raise concern whether a decarbonisation of the energy/electricity system will imply an additional burden to vulnerable households. Our analysis addresses how a transition of the electricity system towards 100% renewables will affect different household groups in the future.

The structure of the paper is as follows: In section 2, we describe the modelling approach and the scenarios used for the analysis. This is followed by a presentation and discussion of simulation results in section 3. Section 4 provides conclusions and policy recommendations.

2 Methodology

2.1 Modelling Framework

We link the macroeconomic model *DYNK* and the electricity system model *ATLANTIS* to study the transition towards an electricity system based on 100% renewable energy sources on a national balance in Austria by 2030. The following subsections provide a short overview of the two models and the approach followed for linking.

2.1.1 The DYNK model

The macroeconomic model used for the simulations is the DYnamic New Keynesian model *DYNK*. The *DYNK* model describes the interlinkages of 74 NACE[4] industries as well as household consumption by 47 consumption categories (COICOP[5]) in the Austrian economy.

DYNK is a hybrid between an econometric input-output (IO) model and a Computable General Equilibrium (CGE) model[6].

Similar to Dynamic Stochastic General Equilibrium (DSGE) models, the model explicitly describes an adjustment path towards a long-run equilibrium, especially with respect to the consumption block and the macroeconomic closure, via a fixed short- and long-term path for the public deficit. The model follows a *New Keynesian* approach in the sense that a long-run full employment equilibrium exists, while in the short run no equilibrium can be achieved due to institutional rigidities, including liquidity constraints for consumers (deviation from the permanent income hypothesis), wage bargaining (deviation from the competitive labour market) and an imperfect capital market.

DYNK is an input-output model in the sense that it is demand-driven, which means that all goods and services demanded are produced. With respect to the price block, the model resembles a CGE model with user-specific prices, margins, taxes less subsidies, and import shares. In addition to the price block, also other parts of the *DYNK* model – particularly the labour market block – have specifications similar to a dual CGE model (see for example Conrad and Schmidt, 1998, or Löfgren et al., 2001)[7]. The unit price functions and the labor market therefore represent the supply side in the *DYNK* model. The main difference to most CGE models there is that the capital market is not modelled explicitly and that the labor market is not competitive, but represented by a wage function, where wages react to labor market tightness.

In *DYNK* the production structure of each sector is determined by a five-factor production function[8] where the own- and cross-substitution elasticities of and between those factors are endogenous and

[3]Energy-poor households with high energy costs are defined as households with incomes below the at-risk-of-poverty threshold and with equivalent energy costs above 140% of the median for all households. In 2018/2019 the share of energy-poor households was 3.0%; for the heating periods 2013/2014 and 2015/2016 the share of households considered as energy poor was 3.1%.

[4]Nomenclature Statistique des Activités Économiques dans la Communauté Européenne (Statistical Classification of Economic Activities in the European Community).

[5]Classification of Individual Consumption by Purpose.

[6]A comparison of these model types is e.g. provided in Kratena (2017).

[7]The dual model is based on price and cost functions instead of production functions and therefore these models in a certain sense are also 'demand-driven', especially if constant returns to scale do not allow for price setting on the supply side.

[8]The five factors are: Capital, Labour, Energy, Imported Goods, Domestic Goods (KLEMD).

determined by estimated coefficients using a translog specification[9]. This means that the factor shares are endogenous and react with respect to their relative price constellations whereas the sub-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 *FIDELIO 2* (Kratena et al., 2017). A second translog function is applied to determine the mix of energy commodities in each sector. As in the production-related translog, five commodities[10] are reacting endogenously depending on their price (including the price of CO_2 permits) relations.

The energy block of *DYNK* derives physical energy demand of industries from their energy commodity input in real terms while energy consumption of private households is calculated in form of econometrically estimated service energy demand equations. CO_2 emissions caused by energetic use (combustion) are obtained by using emission coefficients and energy consumption. Sectoral process emissions are linked to sectoral real production levels. The annual amount of motor fuels that are bought in Austria but used outside the country, so-called fuel export in vehicles, is set constant for this analysis. Non-CO_2 emissions are not included[11]. *DYNK* is a one-region model that covers Austria's economy. Imports and exports react differently. Imports change based on relative price changes and the substitution reaction in each sector's production function. Import shares of commodities bought by private households are constant. Exports (except electricity exports) are constant in nominal terms. In real terms this is equal to a price elasticity of -1 for each commodity[12]. This elasticity represents the worsening of the terms of trade if domestic prices increase.

For analysing the transition towards 100% renewable energy sources in the Austrian electricity system, the representation of the electricity sector in *DYNK* has been expanded (see Gaugl et al., 2023). The energy sector (NACE 35) was first disaggregated into the three subsectors electricity generation and supply (NACE 35A), gas supply (NACE 35B) and heat and steam generation and supply (NACE 35C) in the input-output table incorporated in *DYNK* based on a special evaluation by Statistics Austria. In order to integrate these subsectors in *DYNK* not only a disaggregation, but also a disaggregated modelling of these commodities with respect to demand (private consumption, external trade) and supply (wage formation, input demand, output prices) was required. The electricity sector (NACE 35A) is further modelled in more detail in a newly developed module of *DYNK*. This module comprises distinct input structures[13] for different electricity generation technologies that correspond to the technologies in *ATLANTIS*. These structures are based on the latest "EXIOBASE" release [14]. Each input structure consists of weighted cost components[15]. The structure of the electricity sector in the input-output part of *DYNK* is then defined by the weighted sum of active technologies and the composition of each technology's cost components. Both, the technology mix and the shares of cost components can be set exogenously and are taken directly from *ATLANTIS'* output.

Another relevant output of *ATLANTIS* are investments per power generation technology. These investments are transferred into a commodity structure based on literature reviews focusing on the three most relevant 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; Fechnter, 2021; Resch et al., 2017) in order to be processable by *DYNK*. The investments were applied as additional investments of the energy sector (NACE 35) with respect to the baseline and amount from €1,000 million to €1,600 million annually in the EAG Expansion scenarios (see section 2.2 below)[16]. Reciprocal financing is not considered in the final simulations. However, as a check, simulations that consider financing were

[9]Translog stands for transcendental logarithmic and is an approximation of the Cobb-Douglas case of a Constant-Elasticity-of-Substitution function.

[10]Coal, oil, gas, biomass and electricity.

[11]I.e. *DYNK* covers 85% of Austria's 81 million tons GHG emissions (UNFCCC, 2022) and 100% of the CO_2 emissions in 2017 according to Statistics Austria (2019).

[12]An increase in commodity prices by 1% leads to a reduction in real exports by 1%.

[13]Input structures in this sense are cost shares of a sector's inputs, i.e. intermediate commodities and value added components.

[14]EXIOBASE is a project to construct multi-regional Input-Output-Tables with strong sectoral disaggregation (www.exiobase.org).

[15]Fuels, operation & maintenance, labour compensation, interest rates, run-up, depreciation, surplus and CO_2 permits.

[16]Differences in the annual values mainly reflect differences in new hydro installments. Additional investments in oCS are similar to those in the EAG Expansion Scenarios (CS and AS), for the scenario oAS annual investments are slightly lower.

realised by a reduction of the average investments of the energy sector (NACE 35). The macroeconomic differences of simulations with and without financing were minor due to the high import shares (direct and along the value chain) of both investment variants. Due to these high import shares the macroeconomic impact of additional investments in power plants is small compared to other relevant effects as the increase in electricity exports which directly contribute to GDP.

In addition, the household sector in *DYNK* has been split up into ten different household groups, five income quintiles and two types of dwellings (i.e. single- and two-family houses vs. multi-family houses)[17]. For these household groups, disposable income as well as consumption expenditures by detailed category have been derived from *Austrian Household Budget Survey* (Statistics Austria, 2021b) and aligned with the totals from National Accounts. Moreover, prosumer activity of households has also been modelled. For this purpose, the impact of electricity price increases on production capacity for electricity by prosumers has been calibrated, based on assumptions about feed-in activities of prosumers and on the price elasticity of electricity demand (for details please refer to Kettner et al., 2022).

For a more detailed description of the *DYNK* modelling approach please refer to Sommer and Kratena (2017), Kirchner et al. (2019) or Sommer and Kratena (2020).

2.1.2 The ATLANTIS model

The *ATLANTIS* model is a realistic representation of the continental European electricity industry. It combines the technical aspects of the electricity system with economic aspects. On the technical side it includes 79,146 power plants (including thermal generators, hydro power plants and aggregated PV and wind power plants), 6,864 transmission lines, 1,471 transformers and 4,022 substations (called nodes) with associated demand distribution. Each individual power plant is mapped with parameters such as gross and net power, feed-in nodes, geographic location, efficiency, availability and monthly generation characteristics for supply-dependent energy sources. The transmission lines are also modelled with physical parameters (line impedance, length, thermal power limit, ...). The combination of power plants, lines and demand per node allows for an integrated load flow calculation, which is done with a DC-optimised power flow (DC-OPF) algorithm.

The economic side includes market models at different levels of detail and lead to economically relevant results that are fed into the *DYNK* model, such as fixed (depreciation, fixed operation and maintenance) and operational (labour, interest, fuel, CO_2, variable operation and maintenance) costs as well as the market price for electricity, costs/revenues from electricity trading and investments. This fusion of a technical and an economic model part represents a valuable combination. For example, purely economic models or pure market models often do not include a timeline (technical or economic lifetime of power plants, lines, etc.) or they do not consider the physical constraints of the grid and assume a "copper plate" (or "single node") for the system.

The initial step in *ATLANTIS* is to determine whether the annual peak load can be covered by the available generation capacity given the constraints of the transmission infrastructure. The DC-OPF method is used to determine the load flow in the transmission grid. If generation capacity is too low to cover the demand with the given constraints, additional power plants are built based on an algorithm which identifies the grid nodes at which a minimum of additional feed-in power can cover the demand and solve the grid congestion. In this analysis, the future power plant park was fixed by input data, which reassured that the amount and location of future power generation capacities were sufficient. This annual peak load check is done for both summer and winter peak load, as the second is more important for southern countries.

The subsequent step is to determine the dispatch of the power plants to cover the demand on a monthly basis. Each month is split into a peak and an off-peak period, each with two sub-periods. The 48 periods per year turned out to be a good compromise between accuracy and tolerable model calculation times. *ATLANTIS* offers four different models with different levels of detail to determine the dispatch of the

[17] The latter distinction results from the fact that in Austria the share of PV systems is significantly higher in single- and two-family houses due to institutional barriers for installing PV systems in multi-family homes.

power plants: Two models without transmission grid constraints (Copper Plate Model and Zonal Pricing Model) and two load flow-based models (Total Market Model and Redispatch Zonal Pricing Model).

The Copper Plate Model allows to determine the Europe-wide optimal power plant dispatch without considering grid restrictions (hence the name copper plate model). The result of this model is the cheapest possible power plant dispatch for the whole European market if the power grid would not be a constraint.

For the Zonal Pricing Model each zone/country is its own copper plate and trading between the zones is limited based on ”Net Transfer Capacities” (NTCs). Within a zone, the cost-optimal power plant dispatch is calculated taking into account the NTCs and the respective zonal price (market clearing price of each zone) is determined. Trading between a ”cheaper” zone and a ”more expensive” zone can thus occur while respecting the commercial restrictions (NTCs). The Zonal Pricing Model provides the (zonal) price per country, the trade flows between countries, and the produced energy per power plant. This model can be used to calculate the cost-optimal power plant dispatch within a country, assuming an ”ideal” grid (i.e. copper plate; no bottlenecks).

The Total Market Model performs a DC-OPF and thus takes the grid restrictions into account. The DC-OPF has been shown to be sufficiently accurate in the high and extra high voltage grid. However, commercial trading constraints between zones based on the NTCs are not considered.

The Redispatch Zonal Pricing Model combines the Zonal Price and the Total Market Model: In contrast to the zone pricing model, the Redispatch Zonal Pricing Model also takes into account physical line restrictions (thermal limits) in addition to commercial restrictions between countries (NTCs). The load flow is calculated using a DC-OPF. In addition, in case of grid congestion a redispatch is allowed. First an intra-zone redispatch is performed and if this is not sufficient, a multi-zone redispatch is performed. In addition to the results of the Zonal Pricing Model, the Redispatch Zonal Pricing Model also provides the power line utilisation. Since this model takes into account both commercial market constraints (NTCs) and physical line constraints, it best represents real power plant dispatch and thus has been used for the analyses in this paper.

For a more detailed description of the model the reader is referred to Stigler et al. (2015).

2.1.3 The linked model system

The switch between technologies modelled in *ATLANTIS* as well as investments in power plants can be fully transferred to *DYNK*. The switch between technologies is simulated by using specific technology and cost data for the different generation technologies (costs of operation, fuel, emission permits, labour compensation and depreciation) as well as the electricity output price. They all stem from the *ATLANTIS* model results, although part of these variables would also be a result of the *DYNK* solution (see Figure 1). The data set from *ATLANTIS* has been applied for calibrating the base year and will as well be taken from *ATLANTIS* in the different scenarios. A detailed description of the approach for linking the two models is provided in Gaugl et al. (2023).

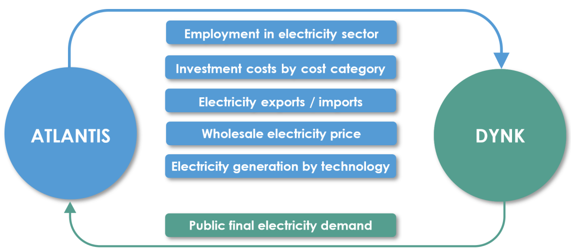


Figure 1: Data exchange between *DYNK* and *ATLANTIS*.

2.2 Transformation Scenarios

To analyse the potential effects of a transformation of the electricity system in Austria, four scenarios were developed:

- Conservative Scenario (CS),
- Ambitious Scenario (AS),
- Cost-optimised Conservative Scenario (oCS), and
- Cost-optimised Ambitious Scenario (oAS).

Scenario results are compared to a Baseline Scenario (BL). For the Ambitious Scenario (AS), sensitivity analyses with respect to the level of the gas price, i.e. a higher gas price of €100/MWh (AS100) and €300/MWh (AS300), was conducted.

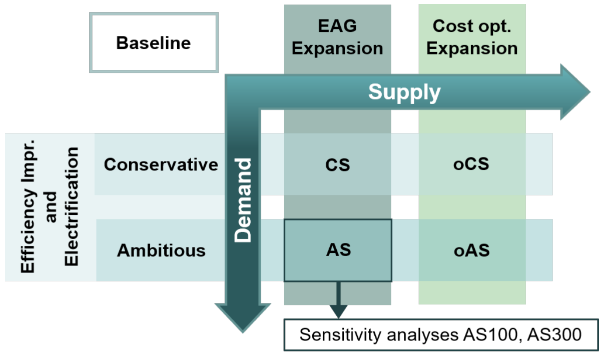


Figure 2: Scenario matrix with different development paths on the supply and demand side.

The scenarios differ in terms of renewable generation expansion as well as regarding the assumed efficiency improvements and level of electrification by 2030 (Figure 2). The scenarios hence depict a range of different futures but share one key assumption, i.e. that the share of 100% RES-E in Austria is achieved in 2030. To reach this target, different pathways are possible, depending on several parameters. First, this refers to the extent to which individual RES-E technologies contribute to the achievement of the target, including the future role of prosumers. Second, this refers to the development of electricity demand that will be influenced e.g. by the diffusion of e-mobility, the use of heat pumps or energy efficiency improvements.

While with respect to the supply side, RES-E potentials ultimately determine the framework conditions, electricity demand can develop along several pathways. Therefore, a Delphi approach was used to craft the demand-side parameters.

2.2.1 Demand-side assumptions in the transformation scenarios

A group of experts from different disciplines (most notably engineering, economics, energy planning) and stakeholders (from public administration, interest groups and social partners as well as NGOs) has participated in a Delphi approach to define the demand-side assumptions in the transformation scenarios. The Delphi technique was developed as a forecasting tool under uncertainty by the RAND Corporation in the early 1960s (Grime and Wright, 2016). It is a systematic, multi-stage survey method with feedback and is often used as a tool to assess future events, trends or technological developments. Each Delphi is based on an expert panel and aims at integrating the judgments of experts from different disciplines or with different viewpoints. The approach has been widely applied for forecasting and supporting decision making processes (see e.g. Gupta and Clarke, 1996; Landeta, 2006; de Loë et al., 2016).

For developing the transformation scenarios, a classical Delphi approach has been combined with a Group Delphi (see e.g. Schulz and Renn, 2009; Wassermann et al., 2011; Webler et al., 1991): During an online workshop with live voting in April 2021, the experts involved in the Delphi first discussed the issues covered to ensure that a common understanding of the survey for the second Delphi round, which was conducted via an online questionnaire, has been reached. In the first round of the Delphi the status quo of the different parameters as well as scenarios for their future development as derived from a literature survey (Environment Agency Austria, 2017a,b, 2019; IEA, 2020; ENTSO-E, 2018) were presented. For each parameter, the workshop participants were then asked to give a judgement about its future development in a conservative scenario via live voting. Afterwards, the results of the voting were discussed. For the second round of the Delphi, the participants took part in an online survey to give their judgement about the development of the parameters for both the conservative and the ambitious scenario. Finally, based on the results of the Delphi, the development pathways for the different parameters in the two-demand side scenarios (CS and AS) were defined.

The assumptions of the three demand-side scenarios (BL, CS and AS) are displayed in Tables 1 and 2. For the Baseline Scenario (BL), the assumptions on the development of the electrification of the households' heating systems and motorised individual transport were based on Environment Agency Austria (2019), which constitute the official Austrian energy and emission scenarios as reported to the European Commission.

In the Conservative Scenario (CS) moderate improvements in the energy efficiency of dwellings as compared to BL are assumed. With respect to the development of the efficiency of the car stock, a constant development as in BL is presumed. With respect to technology diffusion, CS shows a higher penetration with renewable heating systems[18] and PV systems. Moreover, a higher share of electric drives and diesel-driven passenger cars than in BL is assumed in CS.

The Ambitious Scenario (AS) is characterised by stronger energy efficiency improvements than CS and a higher degree of electrification. The latter refers to a higher share of heat pumps in Austrian residential buildings as well as a considerably higher share of electric drives in the car stock. In addition, a stronger diffusion of household PV systems is assumed.

With respect to population growth, the assumptions used in Environment Agency Austria (2019) were followed; the same holds true for the development of fuel prices (see Appendix B). The assumptions on the development of the carbon price in the EU Emission Trading System (applicable to energy supply and emission-intensive industry) were derived in the Delphi, since the prices assumed in Environment Agency Austria (2019) were significantly lower than observed prices in 2019 and 2020. Assumptions on fuel[19] and carbon prices as well as on population growth are identical in all demand-side scenarios.

Table 1: Assumptions on energy efficiency developments

Efficiency Parameters	**2017**	**2030**		
		BL	**CS**	**AS**
Heat energy demand [kWh/m^2]	127	102	93	86
Fuel consumption of cars				
Petrol-driven [l/100km]	8	8	8	7
Diesel-driven [l/100km]	7	7	7	6
Electrical drive [kWh/100km]	15	15	15	12

2.2.2 Supply-side assumptions in the transformation scenarios

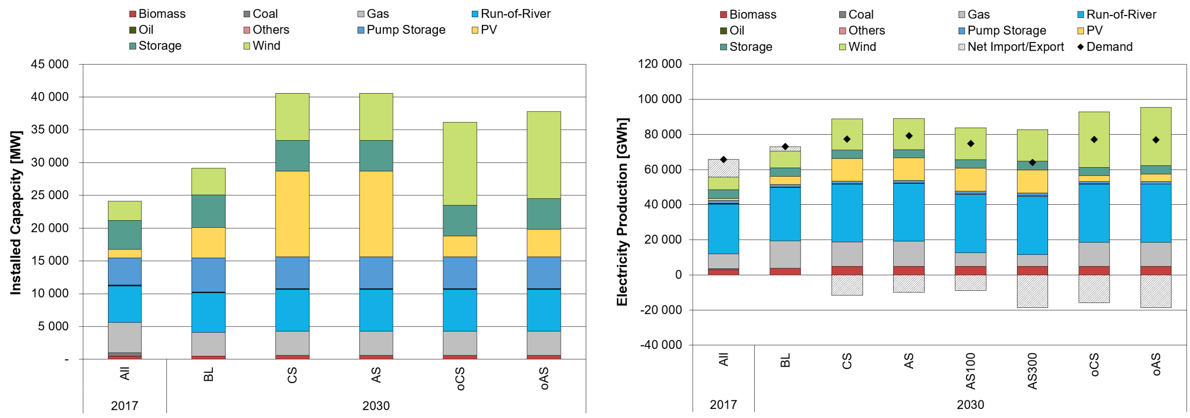
With respect to the supply side, one pathway depicts the additional RES-E capacity as envisaged by the Austrian Renewable Expansion Act (*Erneuerbaren Ausbau Gesetz; EAG*), while the other aims at illustrating a cost-optimal RES-E mix.

In order to define the Baseline Scenario (BL) for electricity supply in Austria, the changes in installed capacities from 2018 to 2020 are extrapolated linearly until 2030 for all power plant types. The result can be seen in Figure 3a and Table 3a: Installed capacities increase for PV (+3,336 MW; +265%), wind

[18]However, the share of heat pumps is lower, since a higher share of traditional electric heating systems (included in the category 'Other' in Table 2) is assumed.
[19]Except for the development of the gas price in the sensitivity scenarios AS100 and AS300.

Table 2: Assumptions on technology diffusion

Technology Parameters	2017	2030 BL	2030 CS	2030 AS
Heat energy mix [%]				
Oil	18	10	9	7
Gas	26	27	24	21
Renewables	25	48	49	57
of which: heat pumps	7	17	14	19
Other	19	18	18	15
Available roof area equipped with a PV system [%]				
Single- and two-family houses		23	25	40
Multi-family houses		27	30	50
Residential PV systems with battery storage [%]		10	15	25
Car fleet composition [%]				
Petrol	43	44	30	25
Diesel	57	44	46	34
Electric	1	13	24	41



(a) Installed capacity

(b) Electricity generation

Figure 3: Installed capacity and electricity generation in the base year 2017 and 2030.

(+1,128 MW; +38%), pump-storage (+1,073 MW; +26%), hydro-storage (+549 MW; +12%), biomass (+577 MW; +126%) and run-of-river (+509 MW; +9%). For coal (-546 MW; complete phase out), gas (-941 MW; -20%) and oil (-96 MW -84%) the installed capacities are decreasing. The increase in capacities and respectively renewable electricity generation in BL is not sufficient to cover electricity demand in Austria, i.e. in the baseline the target of 100% RES-E on a national level is not met.

For the supply-side scenario EAG Expansion, the goals defined in the *EAG* (Austrian National Council (Österreichischer Nationalrat), 2021) are assumed. The *EAG* states that from 2020 to 2030 electricity production from renewable energy sources should increase by 27 TWh: PV should increase by +11 TWh, wind +10 TWh, hydro +5 TWh, and biomass +1 TWh. With the full load hours defined 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)[20] this leads to added capacities of +11,000 MW of PV, +4,000 MW of wind, +1,111 MW of hydro[21] and +146 MW of biomass, which are added linearly from 2020 until 2030.

For the cost-optimal expansion scenarios, the mix between wind and PV which still leads to 100%

[20]The other scenarios share these assumptions on full load hours.

[21]As it is not known how many hydro power plants ≤1 MW and how many >1 MW are built in the future, average full load hours of 4,500 h were used. That means +5 TWh equals +1,111 MW until 2030. Furthermore, the assumption is made that the share of installed capacity between run-of-river and (pumped-) hydro storage power plants stays the same as in 2020 (Run-of-River: 39.6%; (pumped-) hydro storage: 60.4%). This results in +440 MW of run-of-river and +671 MW for (pumped-) hydro storage power plants until 2030.

RES-E (national balance) is to be determined by an optimiser with the objective to minimise total system costs, i.e. the sum of generation and investment costs. For this, the Low-carbon Expansion Generation Optimization (*LEGO*) model (Wogrin et al., 2022) was used. The *LEGO* model is a versatile tool for conducting a variety of techno-economic assessments of the energy sector and includes the option for generation expansion planning. The power plant park of 2030 from the *ATLANTIS* model was implemented into the *LEGO* model, but without the expansion of PV and wind capacities. For those two technologies candidate power plants are added that reflect the potentials per node based on Gaugl et al. (2021) for wind and Sejkora et al. (2020) for PV. In addition, the option to invest into battery storages is also enabled by adding candidate battery storage units per node. Investment costs are a critical parameter for the investments, and are taken from IRENA (2021) for PV ($857/kW) and wind ($1,325/kW) and from Nadeem et al. (2019) for batteries ($1,200/kW and $400/kWh). The cost-optimal mix of PV and wind with the option to reach 100% RES-E enabled is +1,096 MW PV and +9,504 MW wind for the oCS, and +2,141 MW PV and +10,068 MW wind for the oAS (which has a higher demand than the oCS) respectively. No battery storage systems are installed due to the higher costs. The spatial distribution of the power plants is given by the investment decisions and the added candidate power plants are implemented in *ATLANTIS*.

3 Results and Discussion

This section presents the results of the interlinked model of the continental European electricity system *ATLANTIS* and the macroeconomic model *DYNK*. Figure 3b compares demand, produced electricity per power plant type, and net import/export for the base year 2017 and the different scenarios for 2030. Final electricity consumption in Austria increases in all scenarios compared to 2017, except for the sensitivity scenario with a gas price of €300/MWh (AS300): In the Baseline Scenario (BL) electricity consumption increases by 11% (9 TWh) compared to 2017. The Conservative Scenario (CS) and the Ambitious Scenario (AS) show higher increases in electricity demand by 17% (12 TWh) and 21% (14 TWh) respectively. In AS300, by contrast, electricity demand falls by 2% (1 TWh). In 2030, in every scenario Austria is changing from a net-importing country to a net-exporting country. In 2017, hydro power plants (sum of run-of-river, storage and pump storage) make up for the biggest part of the electricity production with 35.2 TWh, followed by gas (8.3 TWh) and wind (7.2 TWh).[22] In the transformation scenarios, electricity output increases particularly for wind power and PV (for details see sections 3.1 to 3.4).

Figure 4 shows the development of wholesale electricity prices (without grid costs and taxes). Even if 100% RES-E on a national balance is achieved, there are times when electricity production from RES is not sufficient and therefore gas power plants have to be dispatched to cover the excess demand.[23] All four scenarios show a higher electricity production from gas power plants in 2030 compared to 2020. As PV and wind are highly volatile, their fluctuations have to be compensated by gas power plants. Austria's gas power plants are also used to compensate this variability in renewable generation in other neighbouring countries. Furthermore, in times with simultaneous high wind and PV production, grid congestions lead to a redispatch of power plants. The Baseline Scenario as well as the (cost-optimised) Conservative and Ambitious Scenarios show (almost) identical price increases from €30/MWh in 2017 to €138/MWh in 2030[24]. The sensitivity analysis (scenarios AS100 and AS300) shows that higher gas prices have a substantial impact on production costs of gas power plants and therefore on the electricity price. The main driver for higher production costs from gas generators remains, however, the increasing price of CO_2 certificates (see Table 4) also contributes to this development. As there are also times when RES-E

[22] The model was calibrated on the base year (2017) using real production values from Statistics Austria (2021a). The deviation of the simulated values from the realised production values is comparatively small (< 6%) and lies within the acceptable range.

[23] To achive the goal of 100% RES-E on a national balance, there have to be times when RES-E production is higher than demand and is either stored in storages or exported.

[24] The relative changes of the wholesale electricity prices in *ATLANTIS* were directly translated to changes in the net energy price part of households and industries electricity price starting in 2020. For the simulations in *DYNK*, these prices are translated into gross electricity prices according to Statistik Austria by adding grid costs, taxes and charges.

production is higher than demand in Austria (electricity is stored in pumped hydro storage plants or exported), the goal of 100% RES-E on a national balance can be achieved in all scenarios.

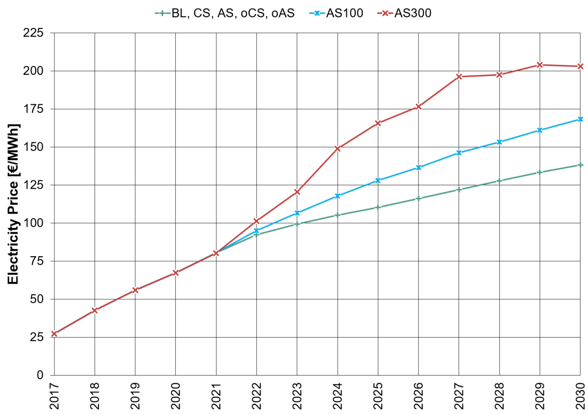


Figure 4: Development of the electricity prices for each scenario.

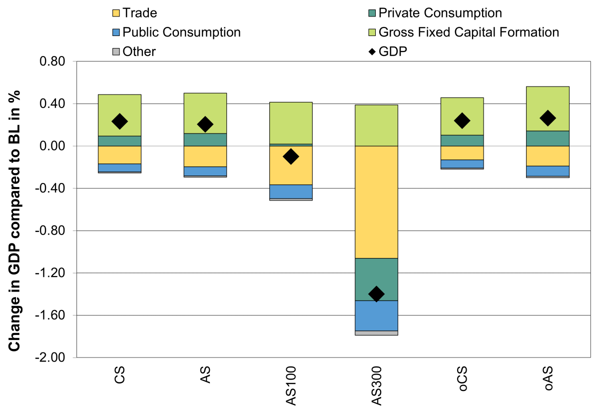
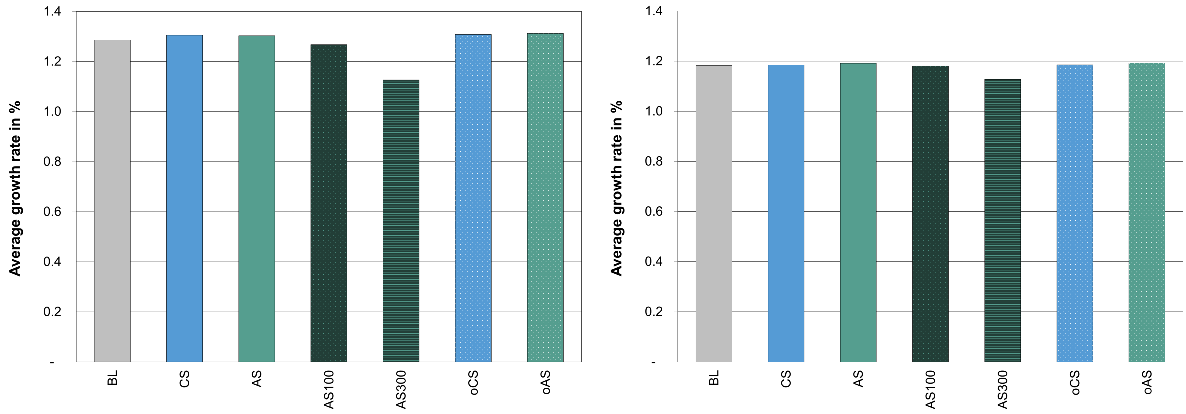


Figure 5: GDP decomposition in 2030 compared to Baseline Scenario.

3.1 Baseline (BL)

Electricity demand grows by 9 TWh in the Baseline Scenario (BL). Electricity generation in Austria rises along past trends in line with capacity increases: The biggest increase in additional electricity production compared to 2017 results from gas power plants (+7.4 TWh), followed by PV (+3.5 TWh), wind (+2.4 TWh), and hydro (+1.6 TWh). With this moderate growth in RES-E production, Austria is still a net importer of electricity in 2030, despite higher production from gas-fired power plants. The share of demand covered by RES-E is only 75% and therefore the *EAG* goal of 100% RES-E on a national balance is not achieved. In Austria, demand is higher in winter months and at the same time electricity production from run-of-river power plants and PV is smaller. Therefore, more gas power plants and additional net-imports are needed as can be seen in Figure 9. During the summer months with higher inflows to the run-of-river power plants and higher PV production, electricity imports are smaller and even a small net export is achieved in July and September.

Gross domestic product (GDP) and employment increase by 1.3% and 1.2% per annum respectively. CO_2 emissions remain roughly at the same level as in the base year 2017. Emissions from the industry sector grow moderately; emissions from electricity generation show a pronounced increase of 5 Mt and respectively 89%, due to the expansion of gas based electricity generation (see above). Increasing emissions from industry and electricity generation are compensated by CO_2 emission reductions in the other sectors: The strongest reductions are found for district heating as well as heating in the household sector (see Figure 7a).



(a) Real GDP growth in %

(b) Growth in employment in %

Figure 6: Average annual development of macroeconomic indicators.

3.2 Conservative Scenario (CS)

In the Conservative Scenario (CS) electricity demand increases by 12 TWh by 2030 compared to the base year 2017 and by 4 TWh compared to the BL, particularly due to a higher penetration with electric vehicles (see Table 2).

With an additional production of +11.8 TWh, PV has the biggest augmentation in CS between 2017 and 2030. The second biggest increase is seen in wind production (+10.7 TWh), then gas (+5.6 TWh), hydro (+4.2 TWh), and biomass (+1.8 TWh). As depicted in Figure 10a, Austria becomes a net-exporting country in every month. During the summer months, gas production to balance variable generation from renewables is reduced compared to the BL scenario, but still needed to balance variable RES-E generation. The lower PV and run-of-river production in winter months is offset by the higher production of wind.

In CS, GDP is 0.2% higher than in the BL in 2030. This slight increase mainly reflects higher investment in renewable electricity generation in Austria as well as higher private consumption (see Figure 5). Electricity exports contribute positively, but imports linked to the investment in RES-E plants lead to a negative "trade" contribution. Changes in employment in CS compared to the baseline are negligible.

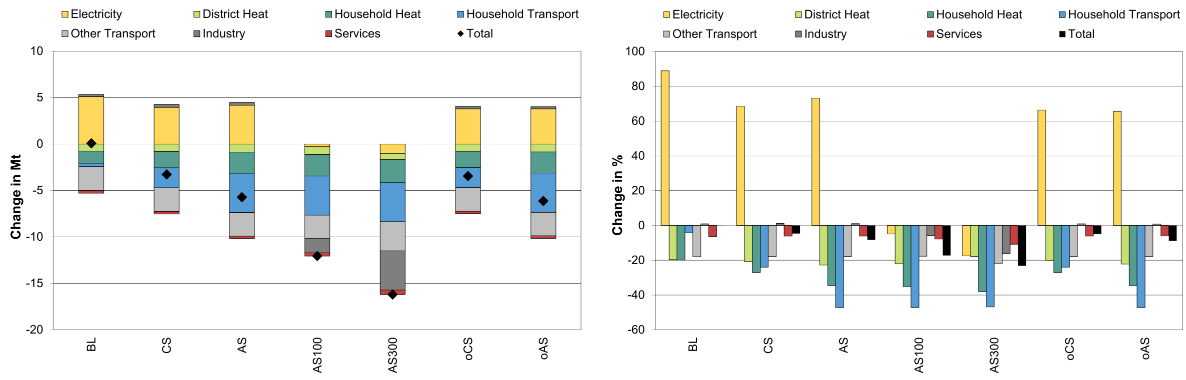
CO_2 emissions decrease by 4.7% compared to the base year 2017 and by 4.8 percentage points compared to BL. Emissions from electricity generation decline by 20 percentage points compared to the baseline but are still 69% higher than in the base year 2017. The strongest reductions are found for emissions from household heating systems and passenger transport (see Figure 7a). Since no additional measures for the sectors industry, services and non-household transport are assumed, the development of CO_2 emissions in these sectors is almost identical to the baseline.

Compared to the baseline scenario, disposable income slightly increases in all household groups in CS due to the growth in GDP and thereby wages. In absolute terms, the higher-income households benefit more strongly from the transition than low-income households due to their larger share in the distribution of wages; real disposable income in single- and two-family houses on average increases by €69 in households from the lowest income quintile and by €275 in households from the highest income quintile, and in multi-family houses by €66 and €216 respectively (see Figure 8). In relative terms, real disposable income increases by roughly 0.2% in all household groups.

3.3 Ambitious Scenario (AS)

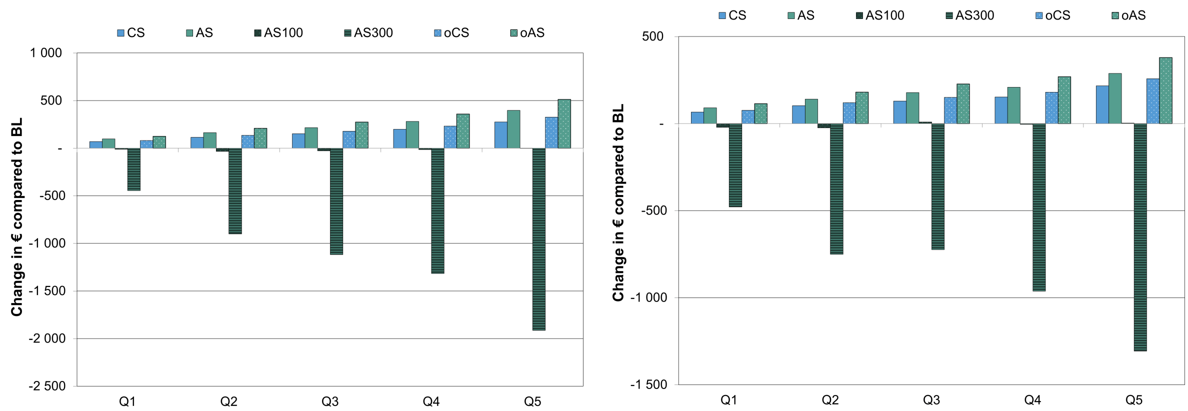
The results of Ambitious Scenario (AS) resemble those of CS. Due to a higher degree of electrification (both with respect to heating and mobility, see Table 2) electricity demand shows slightly higher increases despite stronger improvements in energy efficiency (see Table 1).

With respect to electricity generation, the slightly higher demand of +2.0 TWh compared to CS (see Figure 10b), leads to less net-exports, making January a net-importing month again. The mix of RES-E



(a) Absolute change (b) Percentage change

Figure 7: Change in CO_2 emissions in 2030 compared to 2017.



(a) Single- and Two-family homes (b) Multi-family homes

Figure 8: Change in Real Disposable Household Income in 2030 compared to Baseline.

remains unchanged, since the pathway for RES-E capacity expansion is identical in CS and AS.

In AS, employment shows slightly stronger increases compared to CS in line with higher RES-E investment, GDP growth is almost identical as in CS (see Figures 6 and 5). CO_2 emissions decrease by approximately 8 percentage points compared to the baseline scenario BL (and respectively by 8% compared to 2017). The largest portion of the additional emission reductions stems from passenger transport and results from the broad diffusion of electric drives. Changes in real disposable income compared to BL follow the same pattern as in CS, but at a higher level.

3.4 Cost-optimised Conservative Scenario (oCS) and Ambitious Scenario (oAS)

In oCS and oAS, electricity demand is slightly lower than in the scenarios following the RES-E expansion path defined in the *EAG* (CS and AS) due to a lower demand of electricity in the industry sector. This is caused by less investments in power plants in these scenarios and the accompanied lower production of electric equipment and metal, for instance. This effect is relatively small since investments in power plants in Austria are characterised by a high import share. However, some components and services are produced domestically and these are less demanded in the cost-optimised scenarios oCS and oAS.

In oCS the biggest increase in electricity production is in wind power with +24.5 TWh between 2017 and 2030. Compared to the other scenarios, exports in summer months are lower (Figure 11a), which is due to lower additional PV capacity. Gas-based electricity generation is still needed, especially in the winter months, to compensate for reduced hydro generation and because of redispatch measures and heat production needed for district heating. With respect to installed capacity and electricity generation, the results for oAS are comparable to the results of oCS (as can be seen in Figure 11b).

The effects on GDP and employment are almost identical as in CS and AS. Even though higher exports of RES-E in oCS and oAS contribute positively to the GDP, the lower investment activities in RES-E cancel out the former effect (see Figure 5). Changes in CO_2 emissions are in the same order of magnitude as in the respective scenarios following the *EAG* expansion path; real disposable household income increases more strongly (see Figure 8).

3.5 Sensitivity Analyses with respect to the gas price

In the ambitious scenario with a gas price of €100/MWh (AS100), electricity generation from gas plants decreases by 6.5 TWh compared to AS. The higher gas price results in a higher electricity price (€168/MWh; see Figure 4) and therefore in lower electricity demand (-4.5 TWh compared to AS). Austria becomes a net-importing country for a few months during winter in this scenario again, as can be seen in Figure 12a in the Appendix.

In the ambitious scenario with a gas price of €300/MWh (AS300), gas production is reduced by 7.5 TWh compared to AS. The electricity price rises to €203/MWh, as depicted in Figure 4. Electricity consumption decreases in turn by 15.2 TWh compared to AS. This lower demand in Austria leads to increasing exports as shown in Figure 12b in the Appendix; in AS300 Austria is a net exporter of electricity in all month in 2030. The higher gas prices also have an impact on the generation mix of the other countries in the simulated continental European system. The electricity output of gas-fired power plants decreases by 47% in AS100 and by 54% in AS300 compared to the standard AS. As demand still needs to be covered, this decline in gas-based electricity generation is nearly completely compensated by coal-fired power plants in other countries which see an increase in electricity production of 68% in AS100 and 76% in AS300 compared to the AS[25].

In both scenarios (AS100 and AS300), the higher gas prices result in a reduction of real GDP, when compared to AS but also compared to the Baseline Scenario. For both scenarios, this development is driven by a deterioration of the trade balance. The increase of the natural gas prices does not only raise import payments but also the costs of electricity generation, hot water, district heating, private room heating and especially process heat for production activities. Hence prices increase throughout the value chain of the economy and reduce real income and GDP. Accordingly in AS300 private consumption in real terms decreases considerably due to the strong increase in prices (see Figure 5). Import prices except for natural gas are constant. Hence the rising domestic prices lead to a substitution of input factors in the production towards imported commodities, which further reduces the demand for domestic products. These demand reactions lead to lower domestic production and thereby affect employment negatively (-1% compared to AS, see Figure 6b). Furthermore increasing domestic prices reduce real exports due to the worsening of the terms of trade.

The decline in CO_2 emissions in Austria compared to BL is considerably more pronounced than in AS, especially for electricity generation (approximately -49% in AS100 and -56% in AS300 in 2030)[26]. With respect to the other sectors, industry and services show the highest reductions. This reflects on the one hand that these sectors are affected by the decrease in the demand for their products due to high prices, and on the other hand their ability to switch to other fuels based on their price elasticitites of *DYNK*'s translog production function.

In order to mitigate the negative (short-term) adjustment effects of the energy system transition on industrial competitiveness accompanying policies have to be implemented. It is crucial that EU industries do not face competitive disadvantages due to ambitious climate goals. Especially the carbon border adjustment mechanism (CBAM) seems to be a viable instrument in this respect because it contributes to keeping both European individual companies and whole industries globally competitive. According to the CBAM EU importers will have to buy carbon certificates corresponding to the carbon price that would

[25] Higher electricity production from coal-fired power plants would increase the demand for CO_2 certificates, which would imply a rise in the CO_2 price.

[26] Austria does not have any coal power plants in 2030 that could be used instead of gas power plants as is the case in other countries.

have been paid, had the goods been produced under the EU's carbon pricing rules. Conversely, once a non-EU producer can show that they have already paid a price for the carbon used in the production of the imported goods in a third country, the corresponding cost can be fully deducted for the EU importer. The CBAM will help reduce the risk of carbon leakage by encouraging producers in non-EU countries to green their production processes.[27]

The household sector in comparison reacts less strongly in our transition scenarios due to the low price elasticities for heating. With respect to real disposable household income, the results for AS100 show that the increase of the gas price cancels out the positive effects in AS compared to the level of the BL. For AS300, disposable income, by contrast, shows pronounced declines: In absolute terms, the losses increase with household income. For Q1, they are €444 per household for households living in single- and two-family homes and 479 € per household in multi-family homes, due to the higher share of gas based heating systems in multi-family houses. The losses in Q5 are €1,913 and €1,307 respectively. Here residents in single-family homes in Q5 are affected more strongly than households in multi-family homes due to their higher consumption expenditure on gas and electricity. In relative terms, disposable income declines more strongly for the lower income quintiles (on average by -2.0% for Q1 and only 1.7% for Q5).

4 Conclusions and Policy Implications

The innovative approach of coupling the macroeconomic model *DYNK* with the model of the continental European electricity system model *ATLANTIS* leads to new insights on the impacts of the transition to 100% RES-E in Austria. The linked model system shows that the changes in electricity consumption due to rising electricity prices are quite small. Only given very high gas prices (as in the scenario with a gas price of €300/MWh) electricity demand decreases considerably. This reflects the fact that electricity demand is inelastic and hence only high changes in prices will lead to a notable decrease in demand. As can be seen from the results of the electricity system model *ATLANTIS*, changes in electricity demand as illustrated by the scenarios mostly affect imports and exports. This is mainly due to the fact that run-of-river, PV and wind are (mostly) variable and cheap generation technologies which are not cut-off if not necessary (from a grid perspective).

In the cost-optimised scenarios, the installation of wind power plants is more cost-efficient than PV installations, since the full load hours for wind are much higher (as wind power is also produced during night hours), and it helps levelling out the lower generation from hydro power plants during winter months. If prices for batteries will decline in the future, this could change as excess PV production could be stored in batteries for utilisation during night hours. Moreover, the addition of around 10,000 TWh of wind capacity until 2030 is not realistic given current institutional constraints in Austria, in particular private and political opposition in some provinces. Approval and installation of PV is much easier (especially on rooftops) compared to wind and therefore also an interesting option for homeowners, especially in the context of the current energy crisis with strongly rising energy/electricity prices and potentially reduced energy security.

The analysis shows that electricity from gas-fired power plants will still be needed in 2030 although all scenarios achieve the target of 100% RES-E on a national balance (i) to level out the variable renewable generation, (ii) to avoid grid congestions (redispatch-measurements), and (iii) to deliver heat for district heating from combined heat and power plants in winter months.

In all scenarios Austria becomes a net-exporting country of electricity. However, it should be noted that the implemented European scenario is conservative regarding the renewable electricity expansion in other countries. Many countries already have updated their plans to increase renewable electricity production. If neighbouring countries also install more renewables, they might have high renewable generation at the same time as in Austria and vice versa. This could potentially be challenging regarding the export of electricity in times of high RES-E and a lack of importing possibilities in times of low production from hydro, PV, and wind. Moreover, a higher share of RES-E in neighbouring countries might result in a

[27] https://taxation-customs.ec.europa.eu/green-taxation-0/carbon-border-adjustment-mechanism-en

stronger need for electricity from gas power plants to balance variable generation, further increasing CO_2 emissions from electricity supply in Austria.

The small investment and price impacts lead to negligible macroeconomic effects. The impacts on GDP and employment are positive but very small in all main scenarios. With high natural gas prices in the sensitivity scenarios a decrease in GDP can be observed. The same holds true for distributional impacts, which are also small but positive. All households are better off in the main scenarios in terms of disposable income. In scenarios with high gas prices, household income is negatively affected and this might motivate redistributive policies accompanying the transition in the electricity sector. The main conclusion from the simulations is that the transition towards renewables in the electricity sector is almost neutral (slightly positive) from a socio-economic perspective. It does neither reveal harmful impacts nor lead to high multiplier effects from additional investment.

However these reactions in import and export have to be seen in the context of the limits of a one-region model. On the one hand, the negative effect on trade might be overestimated. The shift towards imports might be too strong since unchanged import prices are assumed while production prices in trading partner countries would also rise due to natural gas price increases. Also the decrease in real exports might be overestimated because the terms of trade for exports would not worsen so much if price levels in trading partner countries would rise as well. On the other hand, there are effects that might negatively impact the trade balance. Real production in partner countries could decrease due to rising gas prices, which again would negatively affect exports. However, to shed light on these effects a multi-regional model would be necessary.

Households owning a PV installation generally benefit more strongly from the transformation of the electricity system than others[28]. However, there is a stronger uptake of PV systems in higher-income quintiles which is not only due to income constraints of lower quintiles but also to the fact that a higher share of these households live in multi-family houses facing constraints for the implementation of a PV system. Policies supporting the installation of PV systems in low-income households would therefore contribute to further improving their participation in the electricity transformation and fostering resilience towards increases in electricity prices. Further research is needed to investigate the relationship between income level and prosumer benefits in more detail in order to identify policy leverages to increase the prosumer participation rate of lower-income households.

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[28] The benefit amounts to about €127 p.a. assuming a service life of 20 years and a discount rate of 4%.

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.

Austrian National Council (Österreichischer Nationalrat), 2021. Bundesgesetz über den Ausbau von Energie aus erneuerbaren Quellen, Erneuerbaren-Ausbau-Gesetz.

Bednar-Friedl, B., Bachner, G., Birk, S., Feichtinger, G., Gobiet, A., Gutschi, C., Kulmer, V., Leuprecht, A., Prettenthaler, F., Schinko, T., Wagner, T., 2013. ElAdapt - Impacts of Climate Change and Adaptation in the Electricity Sector. The Case of Austria in a Continental European Context. Technical Report. Wegener Center.

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_pdf/marktentwicklung-2020_web.pdf.

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.

Conrad, K., Schmidt, T.F.N., 1998. Economic Effects of an Uncoordinated Versus a Coordinated Carbon Dioxide Policy in the European Union: An Applied General Equilibrium Analysis. Economic Systems Research 10, 161–182. URL: https://doi.org/10.1080/09535319808565472, doi:10.1080/09535319808565472. publisher: Routledge _eprint: https://doi.org/10.1080/09535319808565472.

ENTSO-E, 2018. TYNDP2018 - Scenario Report. Technical Report. ENTSO-E. Brussels.

Environment Agency Austria, 2017a. Energieszenarien bis 2050: Wärmebedarf der Kleinverbraucher. Final Report. Technical Report. Environment Agency Austria. Vienna.

Environment Agency Austria, 2017b. Energiewirtschaftliche Szenarien im Hinblick auf Klimaziele 2030 und 2005. Technical Report. Environment Agency Austria. Vienna.

Environment Agency Austria, 2019. GHG Projections and Assessment of Policies and Measures in Austria. Technical Report. Environment Agency Austria. Vienna.

European Commission, 2018. Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013 (Text with EEA relevance).

European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, Zampara, M., Obersteiner, M., Evangelopoulou, S., De Vita, A., Winiwarter, W., Witzke, H., Tsani, S., Kesting, M., Paroussos, L., Höglund-Isaksson, L., Papadopoulos, D., Capros, P., Kannavou, M., Siskos, P., Tasios, N., Kouvaritakis, N., Karkatsoulis, P., Fragkos, P., Gomez-Sanabria, A., Petropoulos, A., Havlík, P., Frank, S., Purohit, P., Fragiadakis, K., Forsell, N., Gusti, M., Nakos, C., 2016. EU reference scenario 2016 : energy, transport and GHG emissions : trends to 2050. Publications Office. URL: https://data.europa.eu/doi/10.2833/001137, doi:doi/10.2833/001137.

European Commission, Joint Research Centre, Rózsai, M., Wiesenthal, T., Mantzos, L., Neuwahl, F., 2019. The POTEnCIA central scenario : an EU energy outlook to 2050. Publications Office. URL: https://data.europa.eu/doi/10.2760/32835, doi:doi/10.2760/32835.

Fechnter, 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., Wogrin, S., Jodl, S., 2021. GIS-based optimization – achieving Austria's 2030 wind energy target. e & i Elektrotechnik und Informationstechnik 138, 590–596. doi:https://doi.org/10.1007/s00502-021-00932-y.

Gaugl, R., Sommer, M., Kettner, C., Bachhiesl, U., Klatzer, T., Gruber, L., Kratena, K., Wogrin, S., 2023. Integrated Power and Economic Analysis of Austria's Renewable Electricity Transformation. START2030 Working Paper 1. URL: https://start2030.wifo.ac.at/texts/START2030_WorkingPaper_1.pdf.

Grime, M.M., Wright, G., 2016. Delphi Method, in: Wiley StatsRef: Statistics Reference Online. John Wiley & Sons, Ltd, pp. 1–6. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118445112.stat07879, doi:10.1002/9781118445112.stat07879. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118445112.stat07879.

Gupta, U.G., Clarke, R.E., 1996. Theory and applications of the Delphi technique: A bibliography (1975–1994). Technological Forecasting and Social Change 53, 185–211. URL: https://www.sciencedirect.com/science/article/pii/S0040162596000947, doi:10.1016/S0040-1625(96)00094-7.

Hyll, W., 2019. Energiearmut in Österreich 2016 - Haushaltsenergie und Einkommen. Technical Report. Statistics Austria. Vienna.

IEA, 2020. World Energy Outlook. Technical Report. IEA. Paris.

IRENA, 2021. Renewable Power Generation Costs in 2021. Technical Report. IRENA. Abu Dhabi.

Kaltschmitt, M., Özdirik, B., Reimers, B., Schlüter, M., Schulz, D., Sens, L., 2020. Stromerzeugung aus Windenergie, 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., Kratena, K., Sommer, M., 2022. The socio-economic impact of renewable electricity generation with prosumer activity. e & i Elektrotechnik und Informationstechnik URL: https://link.springer.com/10.1007/s00502-022-01072-7, doi:10.1007/s00502-022-01072-7.

Kirchner, M., Sommer, M., Kratena, K., Kletzan-Slamanig, D., Kettner-Marx, C., 2019. CO_2 taxes, equity and the double dividend – Macroeconomic model simulations for Austria. Energy Policy 126, 295–314. URL: https://www.sciencedirect.com/science/article/pii/S0301421518307535, doi:10.1016/j.enpol.2018.11.030.

Knopf, B., Nahmmacher, P., Schmid, E., 2015. The European renewable energy target for 2030 – An impact assessment of the electricity sector. Energy Policy 85, 50–60. URL: https://www.sciencedirect.com/science/article/pii/S0301421515002037, doi:10.1016/j.enpol.2015.05.010.

Kratena, K., 2017. General Equilibrium Analysis, in: T. ten Raa (ed.) Handbook of Input-Output Analysis. Edward Elgar, Cheltenham, pp. 355–371.

Kratena, K., Streicher, G., Salotti, S., Valderas Jaramillo, J., Sommer, M., 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. Publications Office of the European Union, LU. URL: https://data.europa.eu/doi/10.2760/313390.

Landeta, J., 2006. Current validity of the Delphi method in social sciences. Technological Forecasting and Social Change 73, 467–482. URL: https://www.sciencedirect.com/science/article/pii/S0040162505001381, doi:10.1016/j.techfore.2005.09.002.

de Loë, R.C., Melnychuk, N., Murray, D., Plummer, R., 2016. Advancing the State of Policy Delphi Practice: A Systematic Review Evaluating Methodological Evolution, Innovation, and Opportunities. Technological Forecasting and Social Change 104, 78–88. URL: https://www.sciencedirect.com/science/article/pii/S0040162515004138, doi:10.1016/j.techfore.2015.12.009.

Löfgren, H., Harris, R., Robinson, S., 2001. A standard computable general equilibrium (CGE) model in GAMS. International Food Policy Research Institute (IFPRI) .

Nadeem, F., Hussain, S.M.S., Tiwari, P.K., Goswami, A.K., Ustun, T.S., 2019. Comparative Review of Energy Storage Systems, Their Roles, and Impacts on Future Power Systems. IEEE Access 7, 4555–4585. doi:10.1109/ACCESS.2018.2888497.

Nijs, W., Castelló, P.R., González, I.H., 2017. Baseline scenario of the total energy system up to 2050. EU-TIMES model outputs for the 14 MS and the EU. Deliverable 5.2: Business-as-usual reference scenarios. Technical Report. Joint Research Centre, European Commission. URL: https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D5.2.pdf.

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.

Schulz, M., Renn, O., 2009. Das Gruppendelphi. Konzept und Fragebogenkonstruktion. VS Verlag für Sozialwissenschaften, Wiesbaden.

Sejkora, C., Kühberger, L., Radber, F., Trattner, A., Keinberger, T., 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(4), 843. doi:https://doi.org/10.3390/en13040843.

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

Sommer, M., Kratena, K., 2020. Consumption and production-based CO_2 pricing policies: macroeconomic trade-offs and carbon leakage. Economic Systems Research 32, 29–57. URL: https://www.tandfonline.com/doi/full/10.1080/09535314.2019.1612736, doi:10.1080/09535314.2019.1612736.

Sommer, M., Meyer, I., Kirchner, M., Kratena, K., 2017. Energieszenarien 2030/2050: Energieökonomische Auswirkungen der Realisierung von Effizienzpotentialen in Industrie und Haushalten. Technical Report. WIFO. Vienna.

Statistics Austria, 2018. Haushaltsenergie und Einkommen mit besonderem Fokus auf Energiearmut 2014. Technical Report. Statistics Austria. Vienna.

Statistics Austria, 2019. Luftemissionsrechnung 1995 bis 2017. Technical Report. Statistics Austria. Vienna.

Statistics Austria, 2021a. Gesamtenergiebilanz 1970-2020. Technical Report. Statistics Austria. Vienna.

Statistics Austria, 2021b. Konsumerhebung 2019/2020. Technical Report. Statistics Austria. Vienna.

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

UNFCCC, 2022. National Inventory Reports. Technical Report. UNFCCC. New York.

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=publicationFile&v=7.

Wassermann, S., Schulz, M., Scheer, D., 2011. Linking public acceptance with expert knowledge on CO_2 storage: Outcomes of a delphi approach. Energy Procedia 4, 6353–6359. URL: https://www.sciencedirect.com/science/article/pii/S1876610211009313, doi:10.1016/j.egypro.2011.02.652.

Webler, T., Levine, D., Rakel, H., Renn, O., 1991. A novel approach to reducing uncertainty: The group Delphi. Technological Forecasting and Social Change 39, 253–263. URL: https://www.sciencedirect.com/science/article/pii/004016259190040M, doi:10.1016/0040-1625(91)90040-M.

Wegscheider-Pichler, A., 2021. Erweiterte Betrachtung der Energiearmut in Österreich 2018. Technical Report. Statistics Austria. Vienna.

Wogrin, S., Gaugl, R., Tejada-Arango, D., Klatzer, T., Bachhiesl, U., 2022. LEGO: The open-source Low-carbon Expansion Generation Optimization model. SoftwareX 19. doi:https://doi.org/10.1016/j.softx.2022.101141.

Appendix

A Development of installed capacity

Table 3: Austria's Installed capacities in MW per power plant type for 2030.

Scenario	**BL** MW	**CS** MW	**AS** MW	**oCS** MW	**oAS** MW
Biomass	457	612	612	612	612
Gas	3,653	3,653	3,653	3,653	3,653
Run-of-River	6,060	6,401	6,401	6,401	6,401
Oil	19	19	19	19	19
Others	70	70	70	70	70
Pump Storage	5,214	4,887	4,887	4,887	4,887
PV	4,597	13,053	13,053	3,149	4,194
Storage	4,994	4,684	4,684	4,684	4,684
Wind	4,088	7,198	7,198	12,702	13,266
TOTAL	29,152	40,577	40,577	36,177	37,786

B Assumptions on fuel price developments

Table 4: Fuel and CO_2 price development assumed in the transformation scenarios. Based on Environment Agency Austria (2019) (fuel prices) and Delphi results (CO_2 price).

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

C Monthly electricity production per power plant type, net-import/export, and demand in 2030

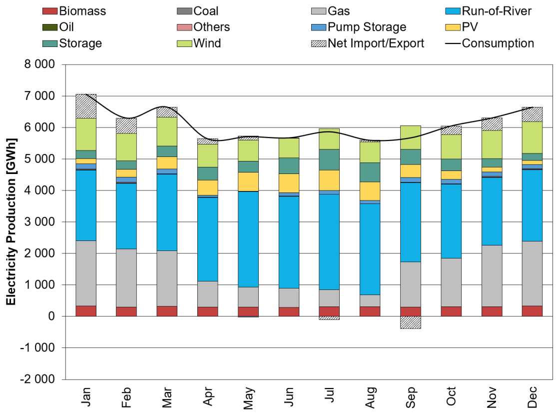
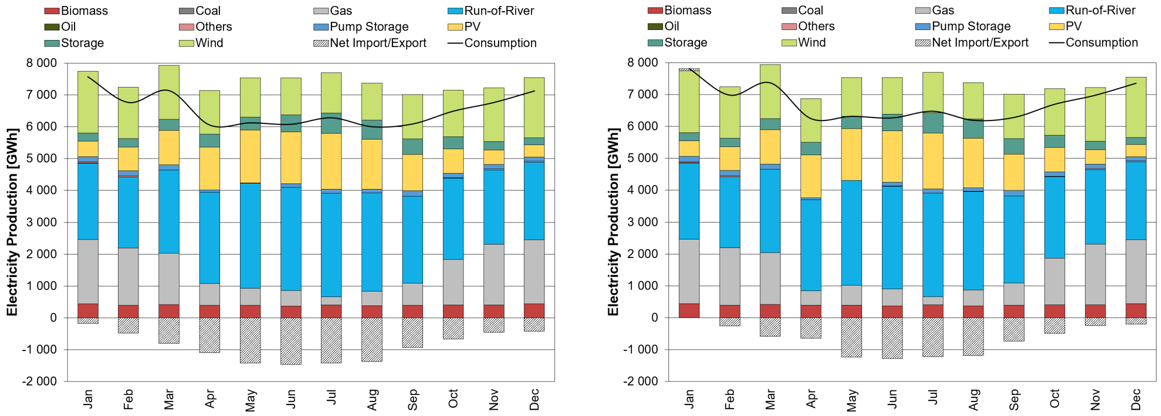
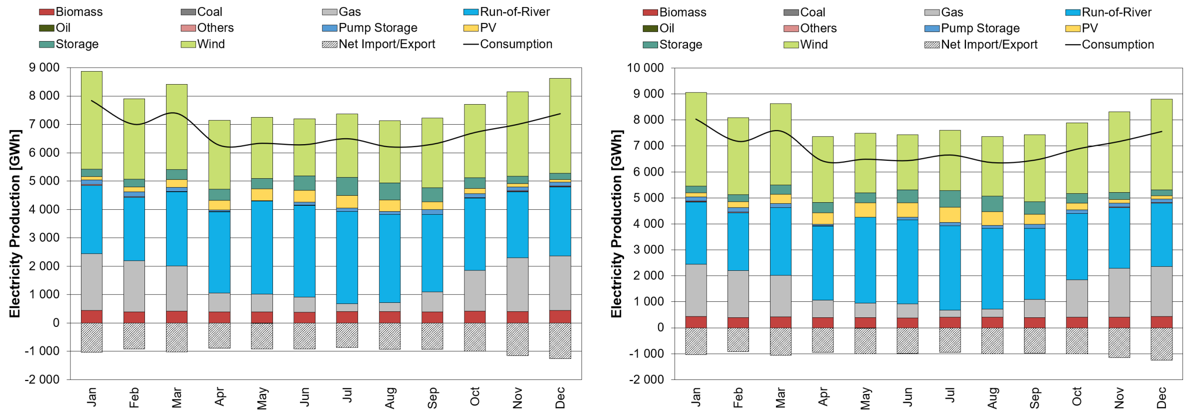


Figure 9: Monthly electricity production per power plant type, net-import/export, and demand for the BL scenario in 2030.



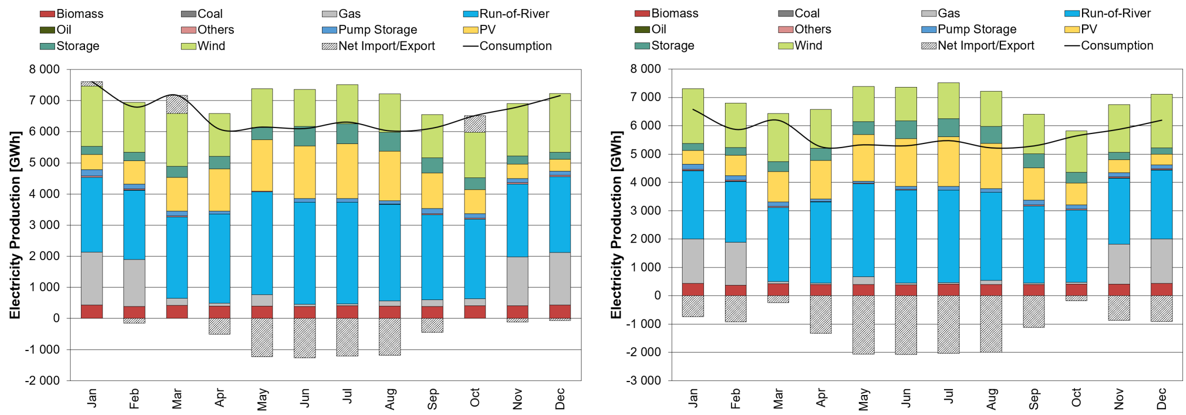
(a) Conservative Scenario (CS) (b) Ambitious Scenario (AS)

Figure 10: Monthly electricity production per power plant type, net-import/export and demand for CS and AS in 2030.



(a) Cost Optimized Conservative Scenario (CS) (b) Cost Optimized Ambitious Scenario (AS)

Figure 11: Monthly electricity production per power plant type, net-import/export and demand for oCS and oAS in 2030.



(a) Ambitious Scenario with a Gas Price of 100 €/MWh (AS100) (b) Ambitious Scenario with a Gas Price of 300 €/MWh (AS300)

Figure 12: Monthly electricity production per power plant type, net-import/export and demand for AS100 and AS300 in 2030.