# The Relevance of European Cooperation for a Cost-Effective Energy Transition

## Deep insights from cross-sectoral energy system modelling

APG TRANSNET BW d-fine swissgrid CBS COPENHAGEN SCHOOL OF ENERGY INFRASTRUCTURE

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# Inhalt

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# Executive Summary

This study employs a collaborative approach that leverages shared knowledge and expertise among the involved parties. The methodological framework utilizes a sector coupled European Energy System Model based on the open-source PyPSA framework, designed to optimize investment and dispatch strategies with the aim of minimizing system costs. The modelled region is Europe, but evaluation focus is set on Germany, Austria, and Switzerland.

The study aligns with the objectives of the European Green Deal, targeting individual country goals for achieving climate neutrality, and incorporates the Effort Sharing Regulation extended to non-EU countries. The Clean Industrial Deal by the European Commission points out that accelerating decarbonization while enhancing the competitiveness and resilience of European industries is a clear goal of the European Commission.

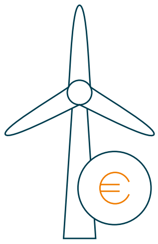
Key data inputs are obtained from the participating TSOs, the TYNDP, and various national plans including the NEP, ÖNIP, and EP2050+. The applied Energy System Model follows a holistic cross-sectoral approach, considering all energy sources (electricity, gas, hydrogen, biomasses, liquids, etc.) as well as all sectors from primary generation to storage and conversion to end-use sectors such as industry, households and services and the transport sector.

Most technologies can be optimized without restrictions. However, in some cases fixed installation capacity trajectories are provided. This approach is intended to highlight individual cost-optimal system configurations across three scenarios in comparison to a base case. Within this framework, three theses are analyzed:

### Coordinating the energy transition across European countries enhances the cost-efficiency of the energy system.

A comparative analysis of two scenarios – a cost-efficient European transition pathway with improved interconnection capacities versus a scenario focusing on at least 80 % national self-sufficiency with considerable restrictions on cross-border electricity transport – illustrates the growing necessity for enhanced connectivity and integration within Europe. Such integration is vital for transitioning to a cost-effective, carbon-neutral energy system across Europe.

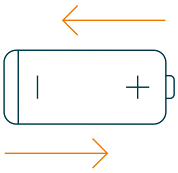
- The average marginal cost of electricity is significantly lower when market integration across Europe is facilitated through sufficient electricity transport corridors. The marginal cost of electricity in the two scenarios is [cost-effective transition / transport corridor expansion stop]:
  > DE: 69 / 80 €/MWh · AT: 71 / 143 €/MWh · CH: 75 / 150 €/MWh
- Limited interconnection leads to +56 % more total annual system costs than a well-connected European energy system.
- The additional accumulated investment costs until 2050 for the larger national generation system (incl. storage and conversion), due to a lack of transport corridor capacities and high national self-sufficiency ambitions sum up to:
  > DE: +124 bn. €
  > AT: +19 bn. €
  > CH: +3.8 bn. €



## The integrated and coordinated transition to a cost-efficient renewable energy system reduces Europe's dependence on imports and avoids compensation costs in individual sectors.

Failing to achieve national renewable expansion goals leads to a more expensive energy system and higher dependencies on non-European imports. The effects of a 50 % reduced wind park expansion until 2050 were analyzed:

- Electrification of demand sectors decreases. Gas utilization in Europe in 2050 increases by +49 %.
- The imports of energy carriers in the form of (renewable) methane and hydrogen in Europe increase by +36 %. (Methane +66 %, $H_2$ +4.7 %)
- The average marginal cost of electricity in Germany, Austria and Switzerland increases by +62 %, +61 % and +52 % respectively.



## An energy system built upon renewable sources requires cross-regional and local flexibilities.

In a scenario with significantly reduced storage and demand side management options, the importance of interconnected European energy infrastructure as well as a back-up system in the generation park becomes apparent. The result in this scenario is a significant higher demand for gas power plants to bring production side flexibility into the energy system in 2050 compared to a base scenario without reduced storage capabilities:

- +29 % in Germany and +54 % in Austria

Furthermore, marginal cost spikes may occur as continental renewable doldrums cannot be compensated in a cost-efficient manner.

# 01. Introduction and Motivation for Sector-Coupled-Model-Based Analysis

Europe has set the goal of achieving climate neutrality by 2050. Electrification of demand sectors and the expansion of renewable energies and the necessary grids are central pillars of the energy transition. The Clean Industrial Deal by the European Commission [1] points out that accelerating decarbonization while enhancing the competitiveness and resilience of European industries is a clear goal of the European Commission. Among other aspects, it includes plans to lower energy prices, provide financing for the transition and work on global partnerships. This study is motivated by the need to emphasize European cooperation as a crucial element in the transition towards a $CO_2$-neutral economy. Achieving these goals demands the integration of renewable energy sources, where cross-border cooperation and system flexibility present a more cost-effective solution compared to isolated national efforts.

The dynamic nature of international energy markets necessitates systems that are resilient and adaptable to fluctuating conditions, induced by the volatility of renewable energy sources. By adopting a holistic analysis with a European perspective at high spatial and temporal resolution, this study investigates the interdependencies of the energy system, assessing both cross-sectoral relations and geographic distinctiveness.

## 1.1 Cooperation on a European Level

This study was developed within a cooperation of multiple partners, bringing together diverse expertise to achieve a comprehensive analysis of Europe's energy system and its cost-efficiency. Each partner has played a critical role in contributing to the depth and scope of this study, enhancing our understanding of cross-sector and cross-border challenges and opportunities.

**Cooperations partners:**

- **TransnetBW (TBW), Austrian Power Grid (APG), Swissgrid:** Cooperating team of Transmission System Operators in the DACH-region. The sector-coupled energy system model utilized in this study is hosted and developed in a cooperation of TransnetBW and Austrian Power Grid.
- **d-fine:** Provided support in the conception and implementation of the study.
- **Copenhagen School of Energy Infrastructure (CSEI):** Provided scientific assistance during scenario building.

## 1.2 Goal and Structure of the Study

By utilizing a sector-coupled modeling approach, the configuration of the European energy supply system can be rigorously analyzed through various scenarios. This method enables the quantitative assessment of the impacts associated with different risks, such as restricted availability of transport corridors between countries or diminished expansion of renewable energy sources. Additionally, it facilitates the examination of medium-term investment trajectories extending up to the year 2050. The goal of this study is to provide valuable insights into the European energy system and introduce a high-performance tool designed for the quantitative evaluation of strategies pertaining to the energy transition. By incorporating a broad spectrum of perspectives, the findings are robust and aligned with various national targets. This collaborative approach underlines the importance of joint efforts in addressing complex energy system challenges and facilitating a transition to a sustainable, $CO_2$-neutral European energy system. Based on the scenario results the following statements shall be analyzed:

- **Coordinating the energy transition across European countries enhances the cost-efficiency of the energy system.**
- **The integrated and coordinated transition to a cost-efficient renewable energy system reduces Europe's dependence on imports and avoids compensation costs in individual sectors.**
- **An energy system built upon renewable sources requires cross-regional and local flexibilities.**

The study is organized to begin with a methodology section that explicates the modeling techniques utilized and outlines the foundational elements of the input data. Subsequently, an overview of the scenario framework, detailing the structure of the scenarios alongside essential background information necessary for comprehending their design, is provided. Each scenario is meticulously analyzed, delineating its unique context, and evaluating the associated model results in relation to the research theses. Through comparative analysis of these scenarios, interpretations are derived that underscore significant trends and effects. The study concludes by noting its contribution to common tools for energy system planning and collaboration across Europe.

## 02. Methodology of Study

This chapter describes the methodology employed in the study for modeling the European energy system. A bespoke version, called PyPSA-TSO, of the open-source project PyPSA-Eur-Sec [2], tailored specifically to meet the requirements of Transmission System Operators, serves as the foundation for this analysis. It follows a holistic cross-sectoral approach, considering all energy sources (electricity, gas, hydrogen, biomasses, liquids, etc.) as well as all sectors from primary generation to storage and conversion to end-use sectors such as industry, households and services and the transport sector. The objective is to optimize system investments and dispatch decisions to minimize total annualized costs. Different scenarios are investigated, which are compared against a base case to assess their impacts on the energy system.

Most European countries are modelled (Micro-States, Belarus, Iceland, and Ukraine are excluded). However, the evaluation focus is on the DACH-region (Germany, Austria, and Switzerland).

### 2.1 Model Development Must Keep Pace with the Speed of Regulation and Transition in Europe

The underlying model is a sector-coupled representation of the European energy system, designed to optimize both dispatch and investment decisions. The objective is to minimize system costs across the European energy network. This optimization explicitly considers all commodities, fixed and variable operation and maintenace expenses, as well as capital costs associated with investments in power plants, storage facilities, and transport corridors, among other infrastructure elements. The implementation of an extensive range of constraints facilitates the identification of cost-optimal energy systems tailored to specific scenarios. This analytical approach enables the differentiation of the requisite efforts needed to meet energy demands while achieving $CO_2$-neutrality. The optimization process utilizes a myopic approach, wherein the system configuration derived from the optimization in one year serves as the foundational input for the subsequent year. The specific future years analyzed in this study are 2030, 2040, and 2050. Within each of these years, the optimization is conducted for all regions at a high temporal resolution, ensuring a detailed examination of system dynamics. The model primarily employs spatial resolution at the national level. However, in the focus region, a more detailed spatial resolution is applied. Austria is subdivided into ten regions, each corresponding to a state, with an additional region designated for the enclave of East Tyrol. Similarly, Germany is divided into five regions: Bavaria, Baden-Württemberg, Western Germany, Northern Germany, and Eastern Germany. In contrast, other European countries are represented as single regions. This differentiation allows to reach a high temporal and regional resolution as well as a detailed view on different sectors in primary energy production, energy conversion as well as different demand sectors such as households & services, industry, and transport. Furthermore, the holistic approach allows to model the electricity-, gas-, hydrogen-, heat- and other fuels (liquids-, biomass) sectors. A key feature of the utilized energy system model is the explicit modelling of the capacity expansion and utilization of transport corridors for electricity, gas, and hydrogen between modelled regions. It should be noted that the import and export of electricity is restricted to the model region, while the global import of other energy resources is permitted. For an overview of the dimensions of the Energy System Model see Figure 1.

Key inputs for the model encompass renewable potentials, capacities installed today, and their respective development pathways. Additionally, techno-economic parameters for each technology, as well as the demand projections across different sectors, are integral to the model's functionality. The model also permits the inclusion of constraints, such as emission limits or self-sufficiency targets.

**PyPSA-TSO – A Conceptual View**

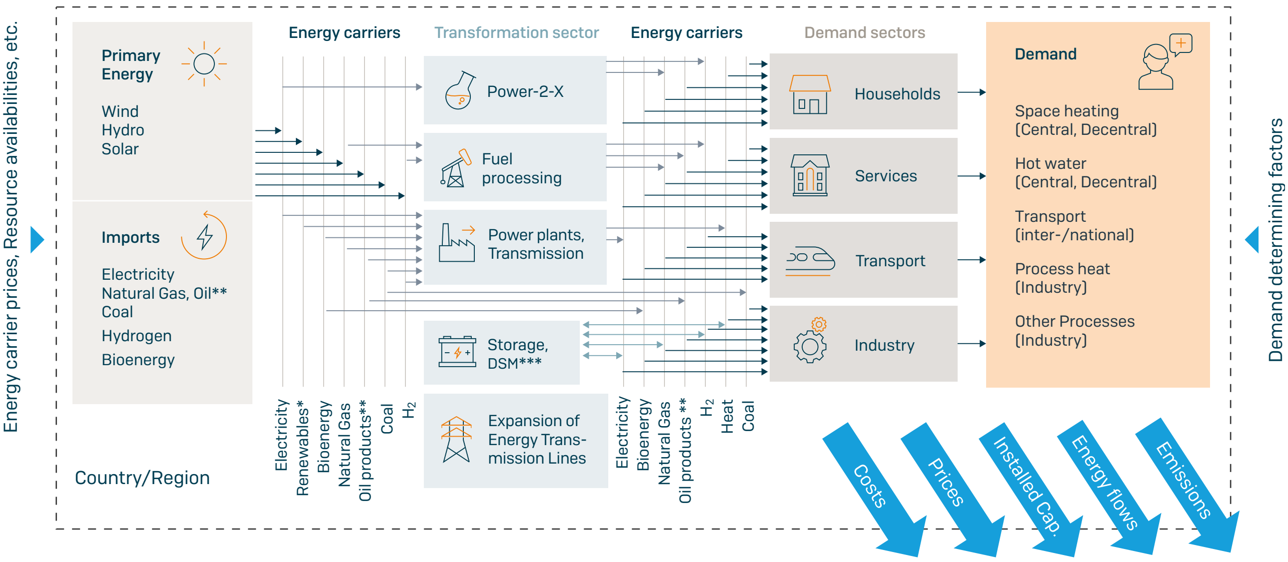



**Figure 1:** Conceptual visualization of the energy system model structure and methodology.
* Renewables include energy sources such as wind, photovoltaic (PV), and others.
** Oil products encompass petroleum (crude oil) as well as naphtha (used in the chemical industry) and kerosene (used in aviation) derived from the Fischer-Tropsch synthesis.
*** Demand-Side Management (DSM) covers the residential, industrial, and transportation sectors, including Vehicle-to-Grid (V2G) applications in the transportation sector.

## 2.2 Scenario Framework

In this study, four scenarios were developed to address critical questions regarding a cost-efficient, holistic energy transition path for Europe. The results are drawn from comparisons to the base scenario that represents an ambitious energy transition path (Figure 2).

**Scenario Overview**


**Figure 2:** Overview of the scenarios. Results are derived from comparisons with Base.

The general parameterization is established in the base scenario, serving as the foundation from which other scenarios are derived. Variations from the base scenario are confined to minor adjustments, facilitating precise conclusions through comparative analysis. Detailed explanations of each counter scenario will be provided in their respective chapters.

Most of the data for countries outside of the DACH-region (DE, AT, CH) comes from **TYNDP-2022** [3] and **TYNDP-2024** [4]; the countries corresponding to the co-operation partners were **adjusted using current national studies or data from legal planning processes of transmission system operators** [5, 6, 7, 8, 9]. Today's energy system, encompassing existing plants, demands, and grids, functions as starting point. This energy portfolio is subsequently extended into future years, factoring in the lifespan of various technologies. For the target years of 2030, 2040, and 2050, the model is permitted to invest in additional capacities across generation plants, grids, power-to-X facilities, and other technologies. These investments must adhere to regional boundaries defined by national goals or natural potentials. Such national goals may include coal and nuclear phase-out strategies, as well as for example targets for the deployment of battery-electric vehicle fleets.

**The $CO_2$ reduction paths defined in the European Green Deal** [10] **and the Effort Sharing Regulations** [11] **must, under all circumstances, be fulfilled and are the driving forces behind the energy transition.** The minimum $CO_2$ reductions for Germany, Austria, Switzerland, and Europe relative to 1990 levels[1] are shown in Figure 3.

**Allowed $CO_2$ Emissions Relative to 1990 (in percent)**

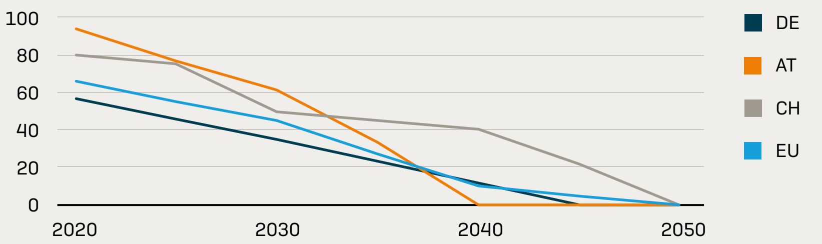



**Figure 3:** The $CO_2$ reduction path relative to 1990. Each country and Europe have their separate paths.

Reduction of $CO_2$ emissions can be achieved through the utilization of renewable energies (RE) such as wind, solar, hydro and biomass or the usage of carbon capture techniques to generate negative emissions. **Achieving the ambitious targets requires the use of carbon management options in many countries.** The model selects the most cost-effective combination of $CO_2$ reduction options to minimize total European energy system costs. Carbon management options in the energy system model reach from Direct Air Capture (DAC) to Carbon Capture (CC) at power plants and industry processes to bioenergy with Carbon Capture (BECC). DAC and BECC allow for negative emissions in the energy system model. This study did not focus on current carbon management policies but highlights that carbon management strategies need to be addressed to reach the climate neutrality goals.

The electricity sector revolves around renewable energies and the corresponding annual production potentials for solar, wind and hydro. The generation profile is dictated by the used weather year, which is 2012 for the scope of this study because it is a good proxy for a typical meteorological year and has a renewable doldrum week in February. The data stems from PECD 4.1 [12]. In combination with the given expansion paths, the annual and momentary maximum energy production is defined (curtailment is possible). **The expansion of solar and wind parks is bounded by a predefined upper limit, allowing the cost-optimized model to invest in these resources up to this maximum threshold**, as illustrated in (Figure 4).

1 The considered emissions exclude emissions for international aviation and navigation.

Renewable Expansion Paths (in GW)

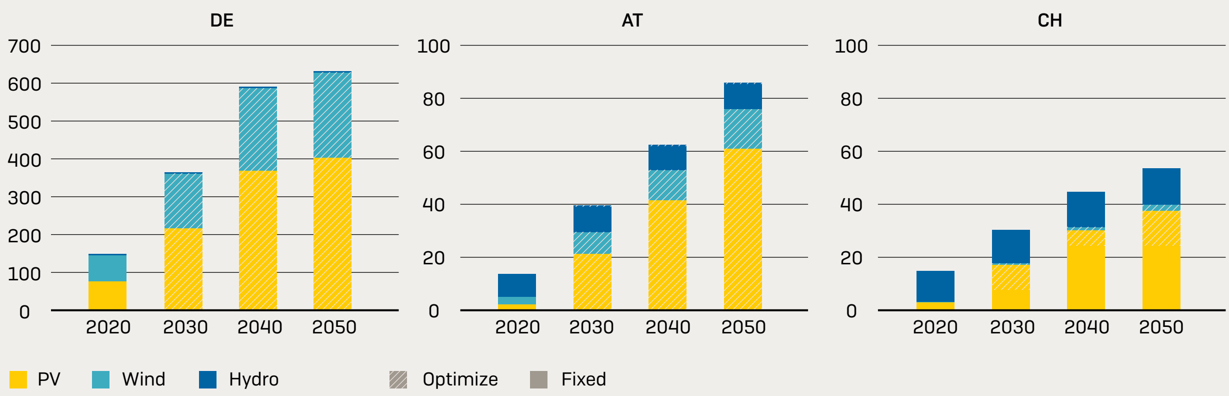



**Figure 4:** The possible capacity expansion paths for PV, wind, and hydro in GW. Hydro combines run-of-river and reservoir power plants. The filled blocks show the exogenously defined capacities, the striped blocks show the allowed optimization range. In Germany and Austria there is no lower limit for the expansion for PV and wind after today.

Due to the inherent volatility of weather-dependent renewable energies, various flexibility mechanisms are essential to maximize their potential effectively. **The energy system model includes multiple storage options** such as batteries, pumped hydro storage, reservoirs, heat storages, gas storages, and hydrogen storage. Additionally, **sector coupling** options like power-to-gas and power-to-heat, **alongside demand-side management options for mobility and industry**, are integrated within the model. Thermal power plants provide flexibility on the electricity generation side. The investment and utilization of said technologies is subject to optimization and may vary between scenarios.

**The energy system model accommodates global import options for hydrogen, methane, and other energy carriers.** However, each scenario in this study is subject to a self-sufficiency constraint, stipulating that Europe must locally produce at least 36 % of its hydrogen demand. For Austria, this requirement is set at 25 %, while Germany must self-generate 40 % of its hydrogen needs[2].

The heat demand for each region is calculated based on the used weather year 2012. It is assumed that renovations will reduce the necessary energy for heating gradually until 2050. This total **heat demand can be met through decentral technologies or district heat. The available technologies for district heat supply are invested and dispatched cost-efficiently as part of the optimization.** This leads to synergies between sectors, such as the electricity sector when using power-to-heat technologies.

The final energy demand of the sectors industry, households and transport are mostly given as exogenous demands and set by national and international studies as mentioned in the data source listing at the beginning of this chapter. **In general, electrification is the central pillar of the decarbonization throughout all demand sectors.**

2 Values are from TYNDP and expert estimations.

# Base: Collective Efforts

BS

**Base**
Collective
Efforts

The “Base: Collective Efforts” scenario serves as the foundational case for this study. It outlines an ambitious pathway towards a fully decarbonized energy transition. This scenario emphasizes on collaborative efforts, where cross-border energy transport and the required transport corridors are optimized in a cost-efficient manner. Market integration plays a central role in this pathway, facilitating seamless cooperation and energy exchange in a decarbonized Europe. **The $CO_2$ reduction paths defined in the European Green Deal** [10] **and the Effort Sharing Regulations** [11] **must be fulfilled and are the driving forces behind the energy transition.** This premise is underlying all scenarios in this study. The base scenario will be used as the reference point for following comparisons. Its parameterization is explained in chapter 2.2 Framework.

As an example, the total final energy demands (incl. energetic and non-energetic demands and conversion processes for industry) for Germany, Austria and Switzerland are listed in Figure 5. The shown values are optimization results from the energy system model for Base. **Natural gas is gradually used less until 2050.** Its importance in all sectors decreases with the **increasing role of electricity and hydrogen.** This change is partly given through the exogenous demands in industry and households but is also an expected shift due to the overall increasing $CO_2$ mitigation goal. **Biogas as a local resource and imported synthetic natural gas are also available as renewable alternatives to fossil methane. The high efficiency increase in all countries is possible through electrification of demand sectors, innovative process changes in industry sectors, renovation of buildings and the boost of circular economy.** Sufficiency does not play a role in assumptions concerning the decreasing final energy demand.

In Figure 6 the energy flow diagram for Austria in 2050 is displayed as an example. The purpose of the illustration is to convey a deeper sense for the sector-coupling in the used model. The model considers all energy carriers and the whole value chain for all modelled regions and timesteps simultaneously.

**Final Energy Demand in the Base Scenario (in TWh)**

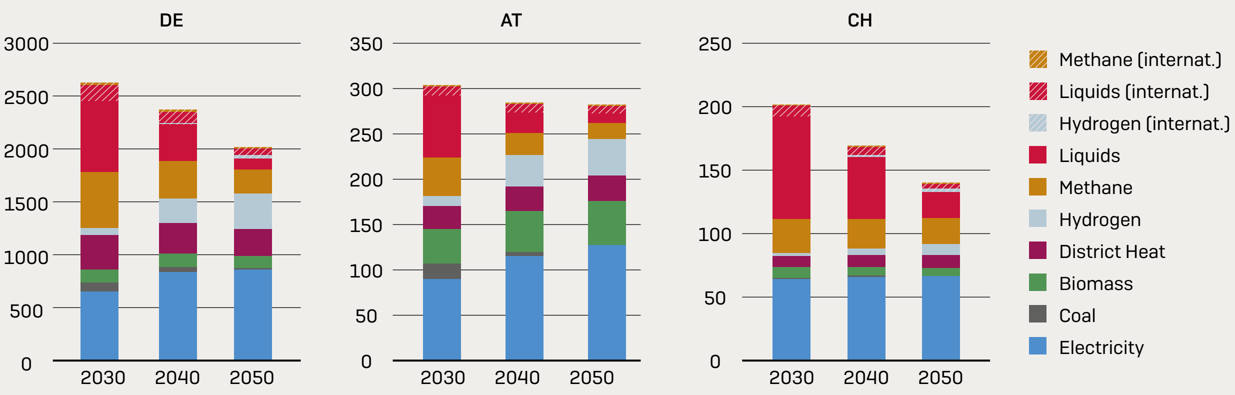



**Figure 5:** The final energy demands for Germany, Austria, and Switzerland. Industry demands include energetic and non-energetic demand as well as conversion processes for industry processes (excl. electrolysis). The crosshatched bars represent demands for international transport (aviation and navigation)

**Example for Energy Flow Diagram in 2050 (in TWh)**

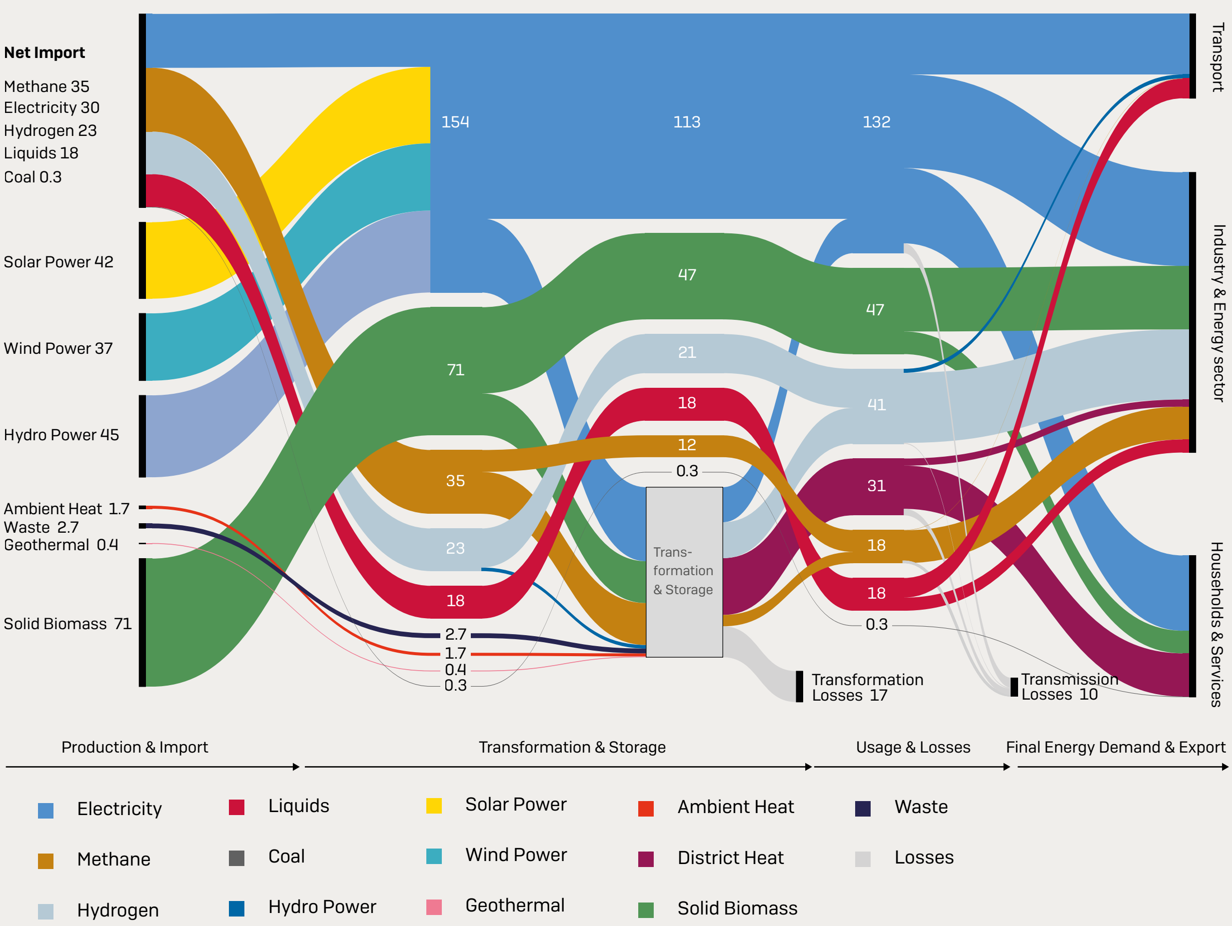



**Figure 6:** An example for the energy transitions in 2050. The shown country is Austria. On the left side the primary energy is displayed. On the right side the total final energy demands including energetic and non-energetic demands as well as conversion demands at industry processes (excl. electrolysis) and energy for international transport.

Imports represent fully decarbonized energy carriers (renewable fuels or decarbonized through carbon management). Transport includes demand for international aviation and navigation. The ambient heat shown here only includes high-capacity central heat pumps from district heating generation and not those from decentralized systems in households and industry.

# 04.

# Limited Transport Corridors: Independent Pursuit

**Limited Transport Corridors**
Independent Pursuit

In this scenario, the European countries try to achieve high levels of self-sufficiency. Facilitating energy exchange with neighboring countries is defined as a low priority and therefore the expansion of high-voltage electricity transport corridors neglected in the data-input.

The primary energy self-sufficiency goals for each country individually are 35 % in 2030, 60 % in 2040 and 80 % in 2050. These targets refer to the annual balance and may be undercut temporarily. The international electricity transmission corridors for the years 2040 and 2050 are set to capacities in 2030, which is equivalent to an immediate expansion stop of the electricity transmission corridors from 2030, even for projects already planned. This stands in contrast to the base scenario, in which the transport corridors can be cost-efficiently expanded up to 2050. Figure 7 visualizes the parameterization.

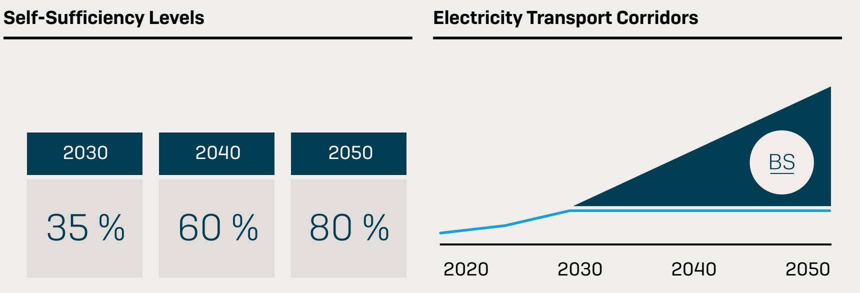



**Figure 7:** The schematic parameterization of the Limited Transport Corridors scenario. The self-sufficiency levels refer to primary energy. The electricity transport corridors are fixed after 2030, as compared to Base (BS) where optimized expansion of capacities is possible.

### Conclusion of the Scenario Results

The volatility of renewable energy sources demands flexibilities, which are partly provided through interconnection capacities with neighboring countries. The Limited Transport Corridors scenario, which restricts energy exchange, leads to increased local investment primarily in storage solutions and thermal power plants. This restriction results in a significantly higher marginal cost compared to the Base scenario, where cross-border exchange is allowed. Without the ability to import renewable energy to make up for local deficits, countries must rely on more expensive national sources of renewable power, contributing to roughly 56 % higher annual costs for Europe's overall energy supply system in 2050 in the Limited Transport Corridors scenario compared to the Base scenario.

## 4.1 Analyzing Outcomes: Model Results and Interpretation

The combination of high self-sufficiency and low transmission capacities is especially problematic due to high spatial concentration of volatile RE production, which can only partially be smoothed by interconnection with neighboring countries. In times of high production, the excess electricity cannot be exported properly which forces the system to curtail or invest in more storage or other flexibility and sector coupling options such es electrolysis. **Due to the high self-sufficiency goals,**

**overall system efficiency potentials are exhausted to minimize energy inputs. Temporal discrepancies in demand and supply are met with high storage expansions, despite incurring charging/discharging and standing losses and flexible power generation plants.** Figure 8 shows an example underlining the described effects.

### Increased Storage and Flexible Production as Compensation for Reduced Trade

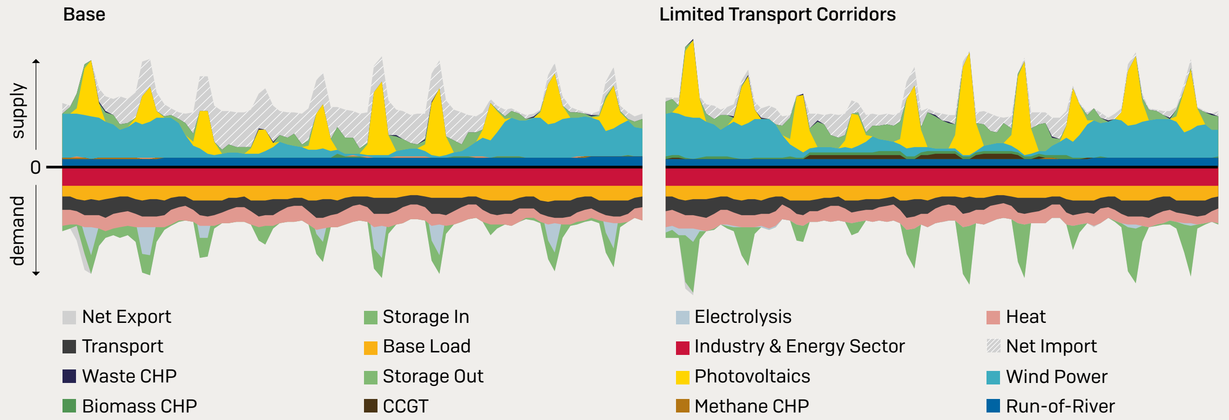
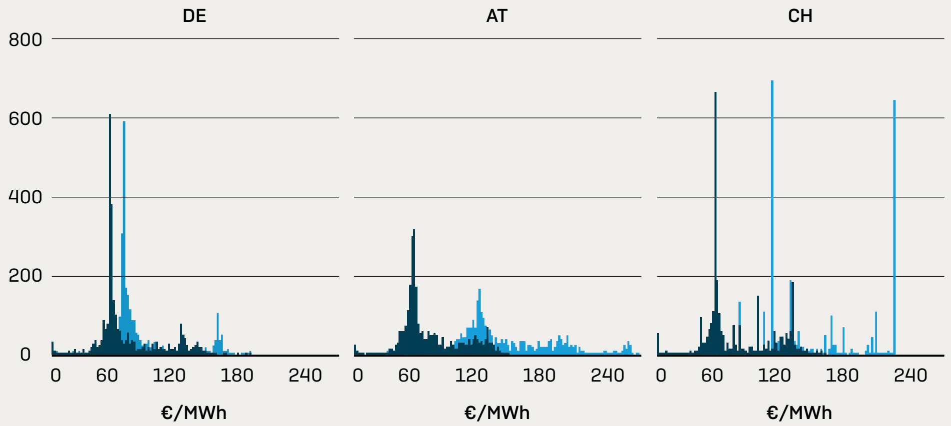



**Figure 8:** The two timeseries show the electricity production on the top half and demand on the bottom. “Storage Out” contains reservoirs, PHS and batteries.

In the Limited Transport Corridors scenario, times with low renewable production need to be compensated with thermal powerplants and storage technologies to fulfil security of supply due to a lack of import and trading options.

The shown example is from Austria between the 16th and 26th of February in 2050.

### Impact on Marginal Costs of Electricity in 2050




**Average Marginal Cost of Electricity in 2050**

| €/MWh | DE | AT | CH |
|---|---|---|---|
| Limited Transport Corridors | 80 | 143 | 150 |
| Base | 69 | 71 | 75 |

**Figure 9:** The graphs show the distribution of the marginal cost of electricity in Germany, Austria, and Switzerland in the form of histograms. The focus is on the difference between Base and the Limited Transport Corridors scenario.

In general, an overall shift to higher costs compared to Base can be observed. This is an indicator for an overall more expensive energy system due to a lack of transport corridor capacity and higher usage of expensive renewable flexible power generation plants instead of cheaper imports.

In the scenario Base the most frequent marginal cost of electricity in 2050 for all countries is around 60€/MWh, underlining the smoothing effects of high market integration between the neighboring countries.

+56 %

**in annual total European system costs of the energy system in 2050** (objective value) **excluding the final energy consumers** such as transport & decentral heat. PV rooftop is explicitly included.

**Due to the limited energy import and export possibilities, the marginal cost of electricity in 2050 is significantly higher than in the Base scenario. Furthermore, it can vary strongly between countries.** The available potential of RE sources is one of the main factors. Especially solar, wind and hydro power have pivotal roles. If the installed capacities are not sufficient to satisfy the demand, more expensive alternatives need to be used, always with the goal to stay $CO_2$-neutral. After solar, wind and hydro are exhausted, local biogas and local solid biomass are utilized. These energy carriers come with commodity costs in addition to investment costs for the power plants. Finally, with all local resources consumed, renewable imports such as renewable hydrogen, renewable synthetic methane and renewable liquids are the overall most expensive options. In a scenario with high self-sufficiency and underdeveloped electricity transport corridors, the level of local RE exhaustion has a strong impact on local marginal cost of electricity due to missing smoothing effects through trade with neighboring countries (Figure 9).

In the Limited Transport Corridors scenario, the non-European import share is naturally smaller due to the self-sufficiency goals. On a European scope, natural gas shifts to more local biogas usage. Hydrogen is generated using electrolysis instead of being imported. The additional electricity demand for the hydrogen production needs to be provided mostly locally due to self-sufficiency constraints for all energy carriers which causes an increased investment into photovoltaic (PV) power stations. Wind power is built to its allowed maximum in the base scenario, which leaves increased usage of photovoltaic potentials as the second-best option. **The results, compared to the base scenario, are +151 GW more PV in Germany, +18 GW in Austria. In combination with effects explained above, this also causes an increase of 40 GW, 6.4 GW and 6 GW in battery (dis)charger power in Germany, Austria and Switzerland respectively.** In Switzerland, PV and wind potentials are already fully used in the base scenario, which leaves no room to produce more locally sourced renewable electricity.

**Accumulated Investment Costs for Energy Generation, Conversion and Storage until 2050 (in bn. €)**

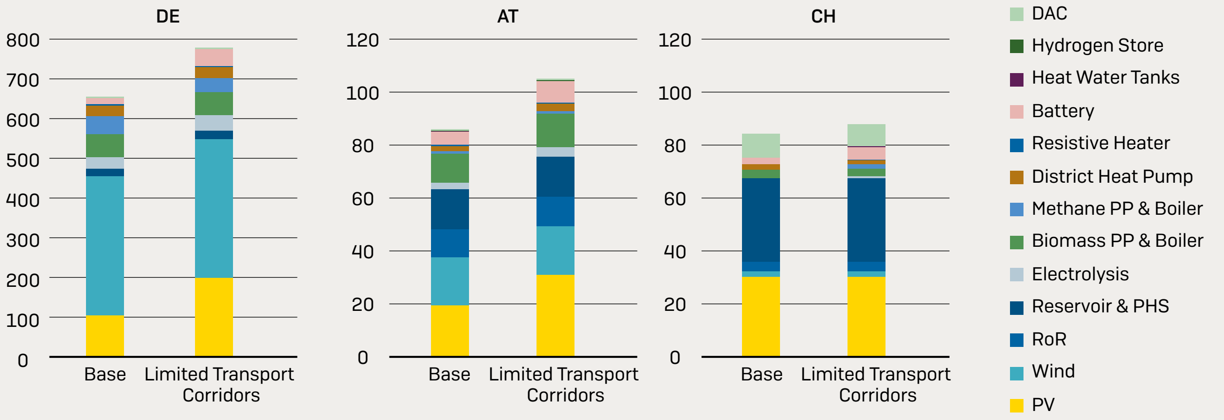



**Figure 10:** Comparison of accumulated investment costs in Energy Generation, Conversion and Storage until 2050 in Base and Limited Transport Corridors scenario. Investment costs in high voltage and low voltage grids are not shown in the graph. Furthermore, investment costs for decentral technologies at final consumers (e.g. decentral heat pumps, electric vehicles, industrial furnaces etc.) are not listed here as the focus is on the energy provision sector. Investments in existing nuclear power plants in Switzerland are not included in the graph.

The most significant increases occur for PV, which amount to 95 bn. € in Germany and 11.5 bn. € in Austria. Batteries are also affected heavily, causing additional investment costs of 23.4 bn € 3.1 bn. € and 2.6 bn. € for Germany, Austria, and Switzerland respectively

The additionally installed capacities for national flexible power generation lead to high additional investment costs. **As shown in Figure 10, the additional investments in plants for energy generation, conversion and storage causes around 20 % higher CAPEX until 2050 in Germany and 22 % in Austria.**

## 4.2 Conclusion of Scenario Results

In an energy system defined by renewable sources and with the electricity system in the center of the decarbonized energy system, interconnection capacities and the availability of sufficient electricity transport corridors are a key factor for reaching net-zero carbon emissions cost-efficiently. It allows the compensation of local energy deficiencies or abundancies caused by exploiting the diversity of pan-continental weather conditions, reducing the necessary investments into extensive national flexible power generation and storages. Furthermore, a deep market integration enables smoothing effects of marginal costs between countries, keeping energy costs low throughout Europe.

**The quantified results of the effects discussed above are:**

- **Limited interconnection leads to 56 % more total annual system costs in 2050 than a well-connected European energy system.** Total annual system costs exclude plants at final energy consumers such as decentral heating systems, vehicles, industrial furnaces etc. PV rooftop is explicitly included.
- **The additional accumulated investment costs for the larger national generation system (incl. storage and conversion),** due to a lack of transport corridor capacities and high national self-sufficiency ambitions until 2050 sum up to:
  > DE: +124 bn. €
  > AT: +19 bn. €
  > CH: +3.8 bn. €
- **The average marginal cost of electricity is significantly lower if market integration across Europe is facilitated through sufficient electricity transport corridors.** The marginal cost of electricity in the two scenarios is [Base / Limited Transport Corridors]:
  > DE: 69 / 80 €/MWh
  > AT: 71 / 143 €/MWh
  > CH: 75 / 150 €/MWh

# 05. Slow-Wind: Reduced Expansion of Wind Energy

**Slow Wind**
Reduced Expansion
of Wind Energy

The Slow-Wind scenario explores a hypothetical reduction in the anticipated expansion rate of wind power generation, in which national targets for renewable energy are not met. The purpose of this scenario is to examine whether a coordinated transition to a renewable energy system avoids compensation costs in individual sectors.

In this scenario, the growth of wind energy installations is constrained to **half of the proposed expansion from today to 2050** as outlined in the Base scenario and illustrated in Figure 11. This approach allows for the evaluation of the effects of altering the composition of renewable energy sources and the associated requirement for compensatory measures in the different sectors of the system.

### Conclusion of the Scenario Results

This analysis demonstrates that when individual countries fail to achieve their renewable energy expansion targets, it leads to an elevation in electricity costs and an increased reliance on global energy imports across Europe. Conversely, the attainment of these targets enhances the continental energy landscape, highlighting the critical importance of cohesive advancement in renewable energy deployment for the benefit of Europe in its entirety.

**Reduced Wind Expansion Paths (in GW)**

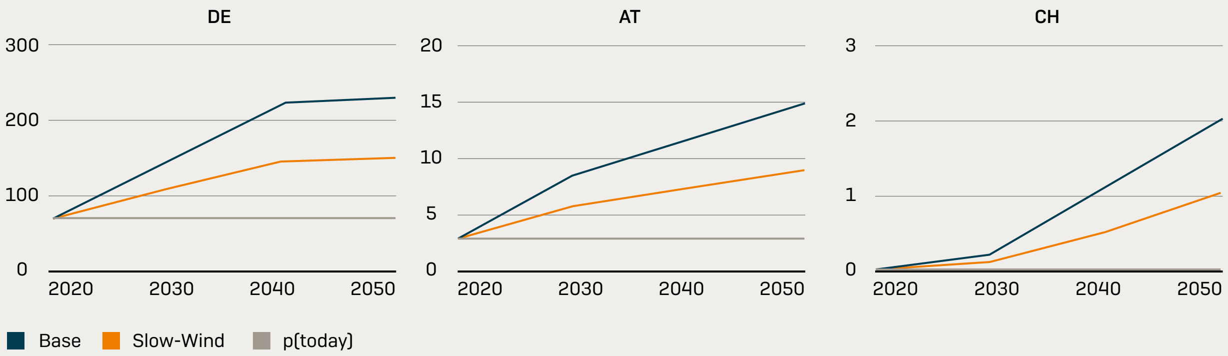



**Figure 11:** The reduced wind park expansion for the Slow-Wind scenario. Only half of the planned wind expansion path is available as realizable potential.

## 5.1 Analyzing Outcomes: Model Results and Interpretation

Considering the constrained development of wind energy installations, it is imperative to expand other generation technologies to meet future energy demands. **Photovoltaic systems emerge as the preferred technology to compensate for the reduction in wind energy expansion rate,** aligning with the targeted decarbonization goals and permissible maximum capacities across different regions. When compared to the Base scenario, the results indicate a substantial increase in installed PV capacity by 2050, specifically 177 GW (an increase of 79 %) in Germany and 18 GW (an increase of 42 %) in Austria, reaching the maximum allowable limits for these regions. Conversely, in Switzerland, the impact of the slower wind energy expansion on PV capacity by 2050 is less pronounced due to the full utilization of PV potential already realized in the Base scenario. Nonetheless, PV expansion in Switzerland is projected to increase by 5 GW (representing a 20 % increase) in 2040 compared to Base.

The inherent day/night cycle associated with solar potential results in PV systems within the DACH-region generally contributing to **grid feed-in simultaneously.** In combination with the diminished impact of the **negative correlation between wind and solar** power feed-in, an **increased need for battery storage and their provided flexibility** arises. In this scenario, the model results consequently illustrate that Germany undergoes a 213 % increase in battery storage capacity, corresponding to an additional 32 GW, while Austria experiences a 24 % increase, resulting in an added 2.4 GW. Here, too, Switzerland is an exception. Fewer battery storage systems are built, as excess renewable energy is used in electrolysis, reducing the need for batteries.

**Installed Power Plant and Storage Capacities in 2050 (in GW)**

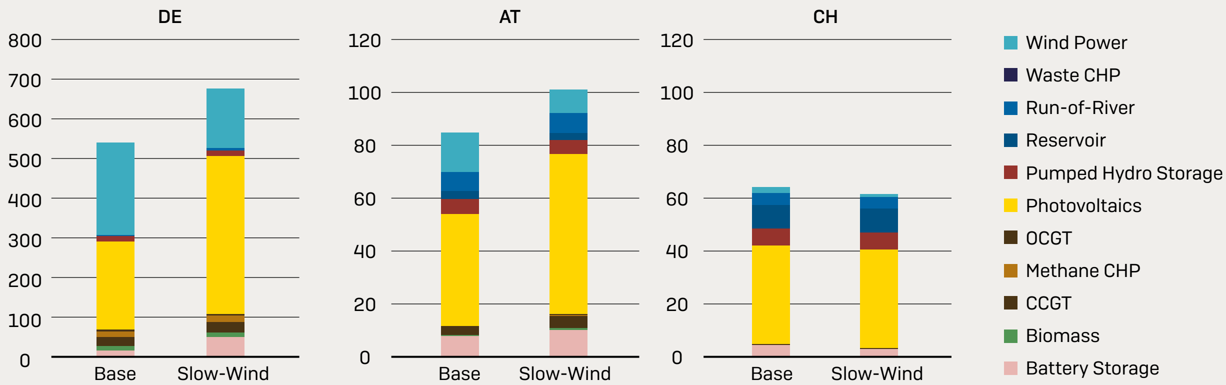



**Figure 12:** Installed capacities in the DACH-region. Pumped Hydro Storages listed in Austria are connected to Austrian control area.

In this scenario, solar power capacities in particular increase in the DACH countries. In addition, the installed capacities of battery storage systems and flexibly dispatchable gas-fired power plants increase if the wind expansion is slowed down.

+ 639 TWh
+ 66 %

global (renewable) methane imports in Europe.

In addition to the heightened demand for battery storage solutions, the energy system integrates **more flexible power generators** and strategically deploys targeted **load shedding** within the industrial sector to mitigate the shortfall in wind energy while simultaneously enhancing system flexibility. Of particular note is the **expansion of gas-fired power plants,** as illustrated in Figure 12. The increased usage of these plants leads to a rise in (renewable) gas imports, thereby increasing Europe's reliance on external regions and exposing it to potential price fluctuations driven by global events.

The requisite shift from wind-generated electricity to increased solar energy production, alongside the necessary augmentation of grid flexibilities, contributes to **elevated system costs.** As a direct consequence, these heightened system costs lead to a **significant rise in the marginal cost of electricity by 2050,** with increases observed at +62 % in Germany, +61 % in Austria, and +52 % in Switzerland.

+ 42 TWh
+ 4.7 %

global $H_2$ imports in Europe.

Restricted and slow wind expansion further influences other sectors. **Investment in electrolyzers across Europe declines, accompanied by reduced operational utilization, attributable to escalating electricity costs.** As a result, hydrogen production is reduced to its permitted minimum value for the entire model region, achieving only 36 % hydrogen self-sufficiency. Consequently, there is a **rise in international hydrogen imports** from entities beyond the model region, thereby diminishing energy independence with respect to hydrogen. Overall, the **primary energy self-sufficiency of the European model region declines** by approximately 7 % relative to the Base scenario.

The district heating sector also exhibits notable effects, characterized by **reduced electrification.** Heat generation via electricity is projected to decline by 22.3 TWh (18.5 %) in Germany and 1 TWh (35.7 %) in Austria by the target year 2050, relative to the base scenario. Switzerland experiences a less pronounced trend, attributable to the diminished role of wind energy within its energy portfolio. The reduction in electrification is offset by an **increased reliance on (renewable) gas and biomass** combustion technologies, coupled with an **enhanced integration of combined heat and power plants** to counterbalance the reduction in electricity supply, thereby capitalizing on sector coupling effects. The increased use of natural gas across both the electricity and heating sectors augments the demand for negative emission technologies, such as direct air capture systems and bioenergy carbon capture solutions, to mitigate associated emissions.

## 5.2 Conclusion of Scenario Results

**The integrated and strategically coordinated transition to a cost-effective renewable energy system enhances Europe's energy independence and mitigates high compensation costs across different sectors.**

+ 10 %

**in annual total European system costs of the energy system in 2050** (objective value) **excluding the final energy consumers** such as transport & decentral heat. PV rooftop is explicitly included.

Ultimately, it can be concluded that **inadequate attainment of wind energy expansion targets markedly elevates the costs of decarbonization across all sectors.** In the absence of sufficient wind energy production, more **costly alternatives are required** to supply the demand. Across all sectors, natural gas as well as renewable gas imports increase and the overall costs as well as overall emissions of the system rise. Consequently, there is a growing necessity for the deployment of negative emission technologies to achieve climate neutrality objectives. This development complicates and escalates the cost of the pathway toward meeting European targets. To summarize, it is essential for each country to diligently pursue its wind power expansion targets to enable both the DACH-region and Europe to realize a more cost-effective energy system.

**The quantified results of the effects discussed above are:**

- **The slowdown in wind power expansion leads to 10 % higher annualized system costs in 2050.**
- **Electrification in the demand sectors is decreasing.** The use of gas increases by 49 % as a consequence.
- **Gas imports in Europe** are **rising** accordingly:
  > (Renewable) methane: +66 %
  > Hydrogen: +4.7 %
- **The average marginal cost of electricity is significantly higher if the individual countries do not achieve their wind power expansion targets:**
  > DE: + 62 %
  > AT: + 61 %
  > CH: + 52 %

# 06. Anti-Flex: Low System Flexibility

**Anti-Flex**
Low System Flexibility

In the Anti-Flex scenario, the energy system is equipped with less flexibilities. These include approximately half the capacities of various energy storage facilities compared to Base, an inflexible charging behavior of electric cars and no option for load shedding.

**Conclusion of the scenario results**

Insufficient flexibility options are faced with increased investment into energy transport corridors. The missing temporal flexibility of storage technologies is compensated by the spatial flexibility of the lines. However, continental renewable doldrums cause challenges as local supply shortages cannot be compensated by storages and cause spikes in marginal cost of electricity across Europe.

## 6.1 Analyzing Outcomes: Model Results and Interpretation

In scenarios where system flexibility is limited, there is a notable rise in demand for flexible generation options, such as thermal power plants. This is reflected in the increased installations of gas-fired power plants, with Germany seeing an 11.6 GW (29 %) increase and Austria experiencing a 1.9 GW (54 %) increase compared to the base scenario. Meanwhile, Switzerland maintains approximately the same installed capacities for open and combined cycle gas turbines and methane CHP plants, but the usage of transport corridors as well as existing plants is increased. As a result of these changes, natural gas imports across Europe rise by 9 %. The resulting increase in $CO_2$ emissions is then compensated by Carbon Capture processes.

Furthermore, there is a noticeable increase in the expansion of electricity and hydrogen grids within Europe. **Enhanced interconnection capacities between countries are utilized as an additional measure to manage generation and load peaks effectively.** This necessitates the development and expansion of transport corridors.

**Effect of Insufficient Flexibilities on the Marginal Cost of Electricity (in €/MWh)**

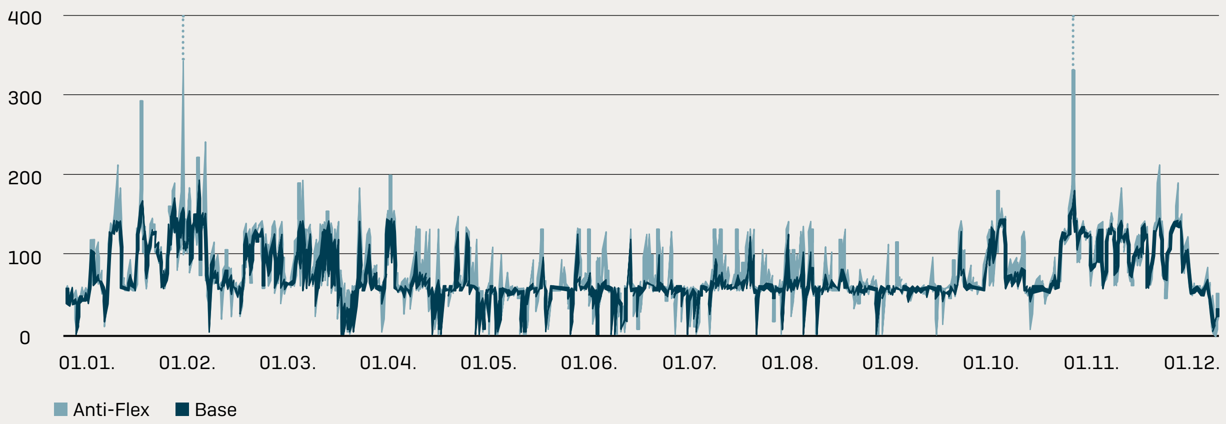



**Figure 13:** Marginal cost of electricity. At times of residual loads, marginal costs spike higher than in the Base scenario. In cases of renewable doldrums across Europe marginal costs can get especially high. For example, the peak between the first of November and the first of December reaches about 4000€/MWh and the one around the first of February 500€/MWh. This is an example curve for Germany in 2050.

Despite these efforts to address the flexibility shortfall, not all situations during the year can be regulated sufficiently. There are not enough suitable options available to adequately cover demand and adapt generation to the load profile. This leads to **significant marginal cost spikes during times of low production and high demand,** indicating a rigid energy system with bottlenecks.

## 6.2 Conclusion of Scenario Results

The results suggest that adequate flexibility is vital for a decarbonized energy system and serves as a key technological solution. With the expansion of renewable energy sources, increased volatility arises, underscoring the demand for strategies for flexibility options. Additionally, this scenario emphasizes the importance of transport corridors and interconnections with neighboring countries as an important flexibility option if other flexibility enhancements fall short of requirements.

## 07. Summary of Key Findings

The analysis of various energy system development scenarios highlights the critical importance of cross-border cooperation, strategic renewable energy expansion and technological flexibility options in achieving an efficient, decarbonized future for Europe.

The derived results should always be interpreted within the context of an optimized linear programming problem. Additionally, human, and political factors should be considered.

In scenarios where energy exchanges through interconnection capacities are restricted, the need for additional investments in local storages and thermal electricity generation capacities become evident due to the inherent volatility of renewables. Interconnection capacities are an important flexibility option especially in future systems with significantly higher electrification degree than today. Limited transport corridors and high self-sufficiency targets lead to significant increases in annual European system costs and substantial disparities in electricity marginal costs between countries, emphasizing the importance of efficient energy trade in reducing overall energy-related expenditures. These results confirm the thesis:

**Coordinating the energy transition across European countries enhances the cost-efficiency of the energy system.**

Furthermore, failing to achieve national renewable expansion goals leads to a more expensive energy system and higher dependencies on non-European imports. The effects of a reduced wind park expansion result in higher system costs and negative cross-sector effects on the European renewable hydrogen production possibilities and beneficial sector-coupling through power-to-heat. This leads to the following conclusion:

**The integrated and coordinated transition to a cost-efficient renewable energy system reduces Europe's dependence on imports and avoids compensation costs in individual sectors.**

Moreover, enhancing system flexibility in a high volatile future energy production world is a key component for a cost-efficient transition. Greater volatility introduced by renewables requires comprehensive strategies to sustain flexibility, reinforcing the need for European cohesion. In conclusion, it can be observed that:

**An energy system built upon renewable sources requires cross-regional and local flexibilities.**

In summary, achieving a sustainable, cost-effective energy future for Europe requires a balanced approach that includes coordinated investments in renewable energy sources, flexibility solutions and interconnection capacities. Cross-sectoral and international cooperation is key to a cost-efficient energy transition.

## 08. Cooperation from Planning to Implementation

This energy system study emphasizes the vital need for collaboration among European nations and identifies several promising areas for future exploration. To enhance the effectiveness and outcomes of such studies, it is crucial to engage a broad spectrum of international stakeholders. By doing so, we can develop high-performance planning tools, such as sector-coupled energy system models, and facilitate knowledge transfer effectively. Expanding participation will not only enrich perspectives but also strengthen and validate the underlying data foundation, thereby enriching the quality of insights obtained.

Applying this approach to the utilization of the underlying software reveals several benefits. With data structures known and understood by all participants, data exchange becomes quick and efficient. Moreover, computations yield comparable results as they are based on the same model, and suggestions for new modeling approaches can be more precise thanks to a shared understanding of the fundamental logic, enabling effective discussions and insights.

Continuous cooperation from planning to implementation among diverse stakeholders can drive innovation and enable the sharing of best practices across borders. As Europe moves towards a more integrated energy system, this collaborative effort will be pivotal in addressing both current challenges and future opportunities in the energy transition. Model-based energy system planning can generate signals for continuous verification and adjustments of market-economic review processes.

The collaboration of European Transmission System Operators (TSOs) in developing this energy system model promotes agility, drawing on readily available expertise about individual market regions. In the face of the ongoing energy transition, meeting legal and societal obligations requires rapid advancements in modeling. It is crucial to use a holistic European approach, as sector-coupling effects and intensified market integration can significantly impact the overall infrastructure landscape.

Strengthening the network of international collaborators and advocating for pan-European energy planning will be essential strategies in advancing the continent's energy systems, helping achieve ambitious environmental and economic targets.

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