Bio-FlexGen

Literature review to list existing forecasts of future prices of market and services that are relevant

Deliverable 3.5

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List of Acronyms

SVK	Svenska kraftnät
CHP	Combined heat and power
SR	Small Scale Renewable
MR	Mixed Route plans
EP	Electrification Plannable
ER	Electrification Renewable
CCGT	Combined-cycle gas turbine
CHP	Combined heat and power
DSM	Demand side management
ENS	Energy not supplied
ETS	Emission trading system
LNG	Liquified natural gas
MIP	mixed-integer programming
NECP	National energy and climate plan
PSH	Pumped storage hydro
PV	Photovoltaic
TTF	Title Transfer Facility

Summary

Two forecast tools are described in this report for Sweden and Spain. The tools apply different methods and scenarios to forecast future data for spot market prices of electricity and different unit productions. Corresponding differences between markets and use cases in the countries, different scenarios and data are considered for forecasting.

In Sweden, Svenska kraftnät (SVK) has developed scenarios and identifies challenges and needs for the power system in long-term market analysis. SVK is a state-owned company managing Sweden's electricity transmission network, which includes lines for 400 kV and 220 kV with stations and foreign connections. SVK develops the transmission network and the electricity market to meet society's needs for a safe, sustainable, and economical electricity supply. Since 2016, the recurring work has been called short-term market analysis and long-term market analysis. A forecast is made for the next five years in a short-term market analysis repeated for every year. In long-term market analysis, scenarios are developed for the power system in the 10–30-year horizon. This is done for every second year. The scenarios (developed by SVK) have been implemented for the analysis years 2035 and 2045 in the SVK's electricity market models. 2045 is an important year for Sweden regarding the climate goal of net-zero greenhouse gas emissions by 2045. In the power system development scenarios, the installed capacity of different generation units is varied to create a picture of how different development paths affect the system. Four scenarios have been developed and analysed considering different criteria, including changes in electricity demand, the expansion of different renewable production, and changes in other production units such as thermal production. In all scenarios, the same biomass prices, based on a method developed by Danish Energy Agency, have been considered for the selected year. Furthermore, corresponding to the purpose of the project, which is studying and evaluation of participation of the Bio-FlexGen combined heat and power (CHP) in the ancillary service market, the price of some ancillary services is estimated for future. Prices for mFRR up and down markets can be estimated using the existing relation between day-ahead and ancillary service prices based on historical time series with hourly resolution considering 2021 as a reference year. In addition, three years of historical heat demand data has been received from Tekniska Verken AB i Linköping is used to estimate forecast heat demand for 2035 and 2045.

For Spain, an open-access commercial model openTEPES is selected as a forecasting tool to model future scenarios. This model was developed by Universidad Pontificia Comillas and has been used to support the Spanish Ministry for Ecological Transition and the Demographic Challenge in simulating future energy scenarios. Two objective scenarios will be considered for 2030 and 2050. Relevant publicly available scenarios will be studied as sensitivities to the main scenarios, for instance, hydro scenarios, as they are key to determining the final generation and storage mix and role of new technologies. Based on reference price scenarios, ancillary services prices will be estimated considering the historical relation between wholesale and ancillary services prices.
Biomass and hydrogen scenarios to explore the economics of the Bio-FlexGen CHP reflect an energy system-oriented perspective by studying hydrogen availability and biomass prices under consideration of competition and crowding out effects. Taking a long-term price equilibrium perspective, future biomass prices may correlate with the cost of consuming natural gas, while hydrogen availability is linked both to the technical advances of electrolysers and the role of volatile electricity generation in the future energy mix.

1 Data forecasts for Sweden

1.1 Review of existing forecasting tools

In order to study the impact of high electricity efficiency of combined heat and power (CHP) technology on the future energy system or to do an investment analysis of CHPs equipped with new Biomass-fired Top Cycle (BTC) process, market prices for the products and services are needed for a relevant time horizon that covers the lifetime of the plant, for instance, 25-30 years in this case. Several forecasting methods exist in the literature. Proposed forecasting tools are based on applying methodology on historical sets to build the future pattern. Different methodologies are used in electricity price forecasting tools such as auto-regression integrated moving average (ARIMA) [1], [2] auto-regressive [3], neural network approaches [4], transfer function models [5], and hybrid intelligent systems [6].
In this project, a forecasting tool developed by Svenska kraftnät (SVK) [7] is selected for forecasting the electricity market prices and the different generation units in Sweden. SVK is the authority responsible for ensuring that the power system is sustainable, safe and cost-effective both today and in the future. This is achieved in the short term by monitoring the power system around the delivery time and in the long term by building new power lines and adapting the power system to meet tomorrow's electricity needs. Through the long-term scenario analysis, SVK identifies future needs and challenges and creates the conditions to act proactively and ensure that the requirements are fulfilled. These analyses using the future scenarios have formed the basis of SVK's planning. The scenarios must be regularly adapted to political, technological, and economic developments. Since 2016, the recurring work of developing scenarios and identifying challenges and needs for the power system has been called a long-term market analysis (LMA) [8]. Development of scenarios with the SVK tool takes place continuously at European, Nordic and national level. In SVK's electricity market models, the scenarios have been developed for the target years 2035 and 2045, using BID3 (Pöyry's Electricity Market Model) and EMPS (EFI's Multi-area Power-market Simulator). BID3 is AFRY's) electricity market dispatch model [9]. It uses linear or mixed integer linear programming (MILP) to optimise the dispatch of power stations, capacity evolution, and all other important features of power markets. EMPS is a multi-area power-market simulator for the optimisation of the operation of power systems with a certain share of hydropower [10]. In EMPS, the objective is to minimise the expected cost in the whole system subject to all constraints. A heuristic approach is used to treat the interaction between regions for multi-region problems. 2045 is an important year for Sweden regarding the climate goal of net-zero greenhouse gas emissions by 2045. The scenarios and data forecasts are presented in the following sections.

1.2 Data collection for 2035 and 2045

1.2.1 Background and purpose

The Electricity Market Analysis unit in SVK produces scenarios and data for Northern Europe's energy system. The scenarios identify future challenges and requirements in Swedish electricity transmission network and enable a proactive way of working called long-term market analysis. Investments in the power system often take a long time to be realised. The lead time for new transmission lines is currently 10-12 years from an initial decision to commissioning. In order to be able to meet future needs, it is necessary to continuously map which investments may be needed in 10-20 years. In long-

term market analysis carried out in 2021, four scenarios have been developed for 2035 and 2045. The scenarios are described in detail in the next section.

The overall goal of the short-term and long-term analyses is to contribute with increased knowledge and insight to make it easier to plan and implement measures in time to meet the challenges and needs of the future.

In Bio-FlexGen project, the forecast data are used to study the possibility of existing CHP units using new BTC technology and to make an investment analysis of CHPs equipped with this technology.
The scenarios and simulated data for long-term analysis are detailed in the next section.

1.2.2 Description of simulation data and scenarios

The weather greatly affects production and electricity consumption in the Nordic power system. In short-term and long-term analysis, historical weather data, e.g., wind, sun, and temperature, for 1982–2016 are used as input values in the models, i.e., 35 so-called weather years. The scenarios have been simulated with an hourly resolution for the 35 weather years, with 52 weeks per year. Each analysis year generates simulation results for 305,760 hours per simulated electricity area. There are ten matrixes for each simulated year of analysis. The matrixes refer to different simulation results. For simplicity, the average of 35 weather years can be applied for each simulation data. This means that the one-year hourly time series data will be used in the optimisation model (in WP 4). The simulated data are listed in Table 1.

Table 1. 10 matrixes of simulated data per simulated year of analysis

Number	Simulated data	Unit
1	Electricity consumption	MWh
2	Hydropower production	MWh
3	Nuclear production	MWh
4	Other thermal production (not nuclear)	MWh
5	Solar and wind power production	MWh
6	Trade flow	MWh
7	Surplus electricity production	MWh
8	Demand flexibility at certain price levels	MWh
9	Electricity use minus solar and wind power production	MWh
10	Spot prices	EUR/MWh

Demand flexibility (matrix no. 8) is modelled as a production with 100% efficiency and three fuel price levels between 200 and 500 EUR/MWh. Production starts in these units when the simulated electricity price reaches these levels. In electricity consumption, other flexible electricity demand is already included.

All simulated data are represented for all Nordic electricity regions as presented in Table 2. The columns (in the matrix of simulated data) for trade flows (matrix no. 6) represent the Nordic power flow. A positive value means trade flow from one electricity area to the next electricity area. A negative value means a flow in opposite direction.

Table 2. Columns for each electricity area

Column index	Electricity area
1	SE1
2	SE2
3	SE3
4	SE4
5	NO1
6	NO2
7	NO3
8	NO4
9	NO5
10	FI
11	DK2

The rows in the matrix consist of hours arranged in simulated weather years (1982-2016). Each weather year consists of 52 weeks and begins on a Monday. Transition to summer time/winter time is not simulated, nor are any leap years. In other words, each weather year generates simulation data for:
1 weather year x 52 weeks x 7 days x 24 hours = 8736 hours
For long-term market analysis, there is simulation data for each of the four scenarios showing in Table 3.

Table 3. Simulated scenarios for each analysis year

Long-term market analysis	
2035- Small Scale Renewable (SR)	2045- Small Scale Renewable (SR)
2035- Mixed Route plans (MR)	2045- Mixed Route plans (MR)
2035- Electrification Plannable (EP)	2045- Electrification Plannable (EP)
2035- Electrification Renewable (ER)	2045- Electrification Renewable (ER)

In the scenarios for the development of the power system, the production capacity for different types of electricity is varied to create a picture of how different possible development paths affect the system. The scenarios extend to 2050, but simulations have only been made for 2035 and 2045. The scenarios are presented in the following from [8]:

- **Small-scale Renewable (SR)**
  - Increasing electricity demand
  - Strong expansion of solar

In the small-scale renewable scenario, electricity demand increases compared to today, but not to the same extent as in the other scenarios. A strong expansion of solar power production characterises the scenario. In Sweden, electricity demand is increasing mainly due to electrification of the transport and industrial sectors. However, the electrification of the industry is less extensive than in the other scenarios. In this scenario, there is a large focus on saving resources and making energy use more efficient. Development is moving towards a small-scale, decentralised energy system. Cogeneration is somewhat expanded in urban areas. The large-scale renewable production continues to increase, but to a lesser extent than in the other scenarios. One of Sweden's nuclear power plants will be closed in 2030 and all reactors will be decommissioned by 2045. The electricity production mix is 100 percent renewable by 2045 [8]. However, this plan may be affected by different policies in the future government.

- **Mixed Route plans (MR)**
  - Increasing electricity demand
  - Expansion of wind and solar power
  - Decreasing thermal production

In this scenario, electricity consumption increases, mainly in the Nordic region. Wind and solar power are being expanded, while thermal production is decreasing. In Sweden, two nuclear power reactors continue to operate until 60 years of service life. The hydrogen economy and sector integration do not have a full impact. The renewable power types continue to increase, where land-based wind power is supplemented by offshore wind along the coasts. Falling costs for solar cells mean a large expansion, but to a lesser extent than in the small-scale renewable scenario. Production from cogeneration plants decreases as reinvestments are not profitable, and the heat demand is met through, among other things, increased recovery of residual heat. One nuclear power reactor will be closed before 2030 and another in 2040. However, with increasing electricity use, rising prices and the need for predictable production, there is interest in maintaining nuclear power, and two reactors are being extended for operation after 2050 [8]. However, different policy makers may change the plans related to production technologies in the future.

- **Electrification Plannable (EP)**
  - Sharp increasing electricity demand
  - Expansion of renewable production
  - Maintained or increasing planned production

In the scenario that electrification can be planned, there is a sharp increase in electricity use in the Nordic region. Renewable production is also expanded, and the transport sector is electrified to a large extent. However, the electrification of the industrial sector is not as extensive as we will see in the electrification renewable scenario. Weather-dependent renewable electricity production continues to grow and is combined with plannable fossil-free production capacity.

- **Electrification Renewable (ER)**
  - Sharp increasing electricity demand
  - Large scale renewable production
  - Decreasing thermal production
  - Sector integration with hydrogen economy

In the renewable electrification scenario, there is a very strong increase in electricity demand, mainly in the Nordics but also in the rest of Europe. Renewable production is being built to a large extent, while thermal production is decreasing. Sector integration combined with the hydrogen economy is at the centre. Electricity production is dominated by land-based wind power in the north and by large-scale offshore wind power along the coasts. Solar energy is built in the cities combined with batteries for short-term storage. The planned production in the form of cogeneration decreases as reinvestments are not profitable, and the heat demand is met through other production units, i.e., an increased utilisation of residual heat. The nuclear power reactors are decommissioned as they reach their 60-year lifespan. The electricity production mix is 100 percent renewable (wind and solar) until 2045.

The main focus in all four scenarios is the need for increased electricity production to meet the continuous increase in demand. This is to enable the transition from a society dependent on fossil fuels to an energy system with zero net emissions of greenhouse gases. In these scenarios, the electricity demand varies depending on the conversion rate, the impact of hydrogen production using electricity, energy efficiency, digitisation, import dependency etc. Considering the rapid development, we have

seen over the past years, for example regarding the electrification of industry, the need for electricity may be even greater than assumed in the scenarios. Figure 1 shows Sweden's simulated annual average for electricity production, consumption, and energy balance in the four scenarios. Each scenario has an assumed production capacity per type of power in Sweden. For example, in scenario EP, investments for the increasing of operation of nuclear power in Sweden are carried out. The interest in new nuclear power, for example through small modular reactors, is also gaining political and regulatory support, and nuclear power reactors are being established in SE3.

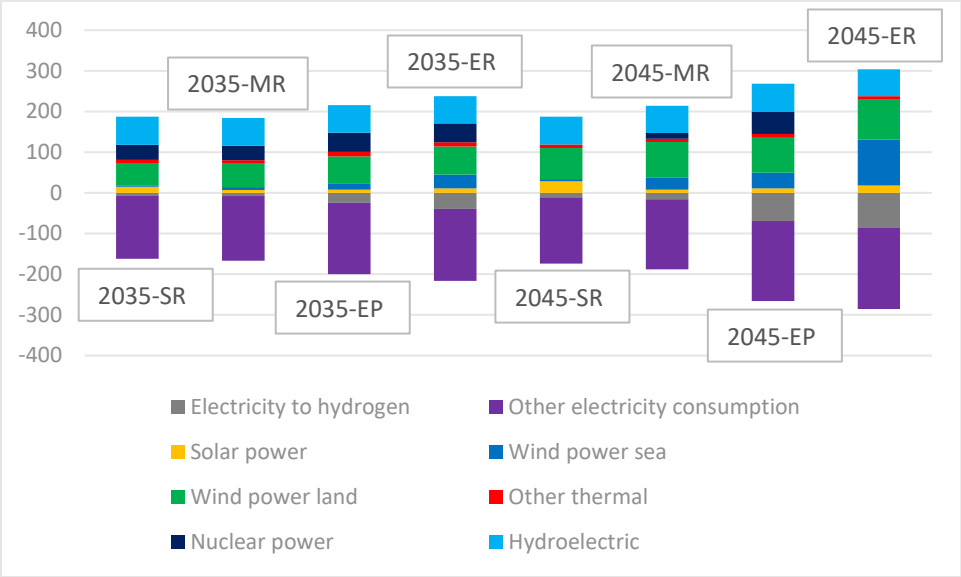


Figure 1. Simulated annual average for electricity production, consumption, and energy balance in Sweden for each scenario, TWh [8]

Based on the following aspects, scenarios have been analysed:

- Long-term transmission needs for export and import
- Consequences for power adequacy in Sweden
- Requirements for balancing the system
- Impact of the ability to maintain power system stability and additional system challenges.

You can read more about the development in the scenarios in the report 'long-term market analysis' 2021 [8].

1.2.3 Biomass price forecast

The forecasted biomass prices considered in the scenarios are listed in Figure 2. It shows the growth of biomass prices by year from 2015 to 2050. For all four scenarios in Table 3, the same biomass prices have been considered for the selected year.

The biomass prices are based on a method developed by "Ea Energy Analyses" [11], a report produced by the Danish Energy Agency for future long-term electricity prices based on forecasts of fuel prices. The Danish Energy Agency uses fuel prices as input for analysis of future energy systems scenarios [12]. The method for predicting biomass prices has been developed through several modules of "Ea Energy Analyses". It includes prices for wood chips, wood pellets, and straw. Biomass prices, which are

expected to be roughly constant in the long-term, have also not changed so much since 2018. In the short-term, the prices increased in 2022 because of the higher electricity market prices. After that, it remains at a constant range with a 10% variation [13].

The long-term equilibrium of prices for biomass until 2050 is based on the assumption of market equilibrium and does not consider price variations on the short-term. The biomass price model is based on an oil price for the whole Europe and thus not a price only for Denmark. The source of the oil price used is the import price of crude oil from the IEA World Energy Outlook from the New Policy scenario [14]. The oil price does not have a major impact on biomass prices and only has an effect through costs for the acquisition, production, and transport of raw biomass and the finished product [15]. In the analysis, biomass prices for years 2035 and 2045 are assumed to be at 26.1 €/MWh and 27.3 €/MWh, respectively.

However, biomass is scarce and valuable. The biomass usage has increased 150% since 2000. Current plans need 40-100% more biomass than what is available and if it continues like this trend, supply and demand gap of biomass is predicted to be 40-70% by 2050 [16]. Biomass price scenarios in the SVK tools for the 2035 and 2045 indicate relatively stable biomass prices. The role of alternative long-term biomass prices scenarios can be studied by exploring additional sensitivity runs of the optimization model in WP4.

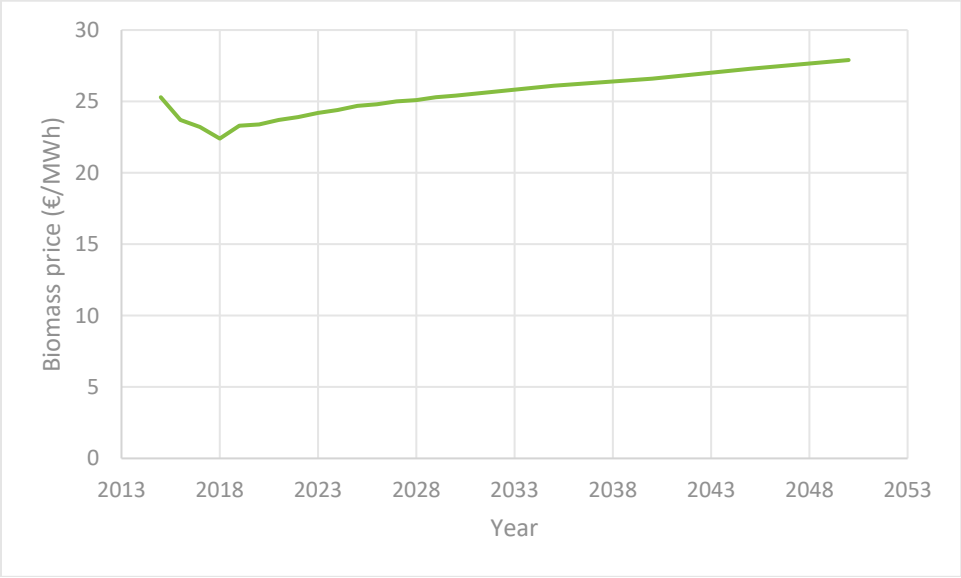


Figure 2. Danish methodology for forecasting biomass prices used in the SVKs scenarios (the data provided by SVK [7]*)*

1.3 Ancillary services price forecast

For the forecast of the ancillary services market's prices, the existing relation between day-ahead market and ancillary service markets will be used. Thus, the main inputs are 1) the forecasted day-ahead market prices for the target years 2035 and 2045, 2) the historical relation between wholesale prices and each ancillary service market price. The market prices for different Swedish electricity markets for the reference year 2021 will be used, which are shown in Figure 3. This will be done in the forecast time series generated for D3.6. Figure 3 draws the prices from SE3.

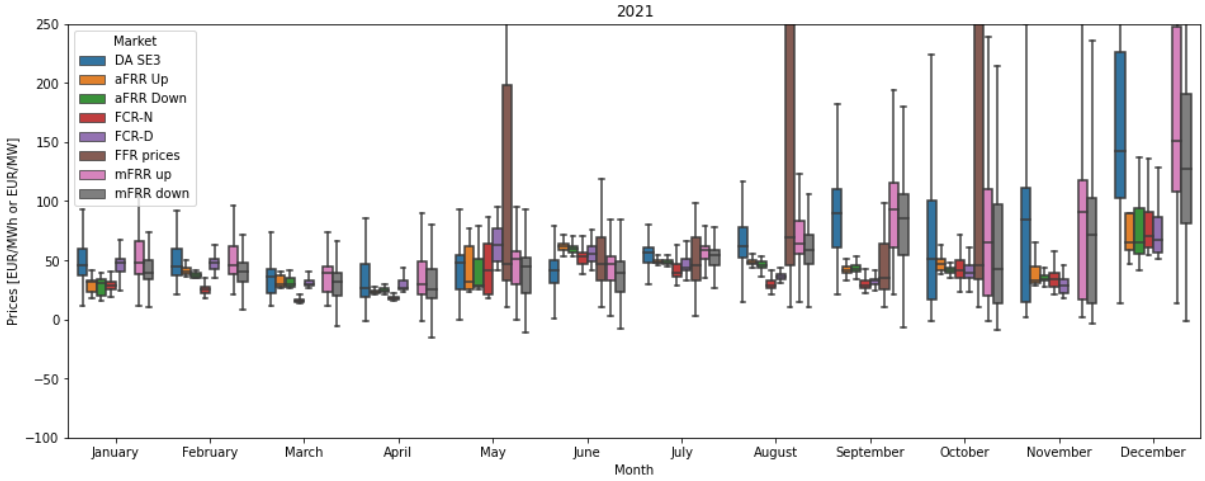


Figure 3. Comparison of all procurement prices in 2021 for Sweden. The y-axis has been capped at 250 EUR/MW for better readability.

1.4 Heat demand forecast

For heat demand, hourly district heating load data with outdoor temperature are available for 2019-2021 for Linköping. The correlation between heat demand and outdoor temperature is linear for temperatures under 17 C. For temperatures higher than 17, there is only heat demand for warm water, and space heating can be neglected. Figure 4 shows this dependency between temperature and the demand in 2021. The values of district heating data have been removed from the secondary axis of the Figure 4 for confidentiality purposes. This historical data is used to simulate the future heat demand for 2035 and 2045. The data are from [17]. Regarding global warming, the heat demand changes are not expected to be significant in the future years. Therefore, an average of the three years of available historical heat demand data is considered to derive the heat demand time series with hourly resolution for the target years.

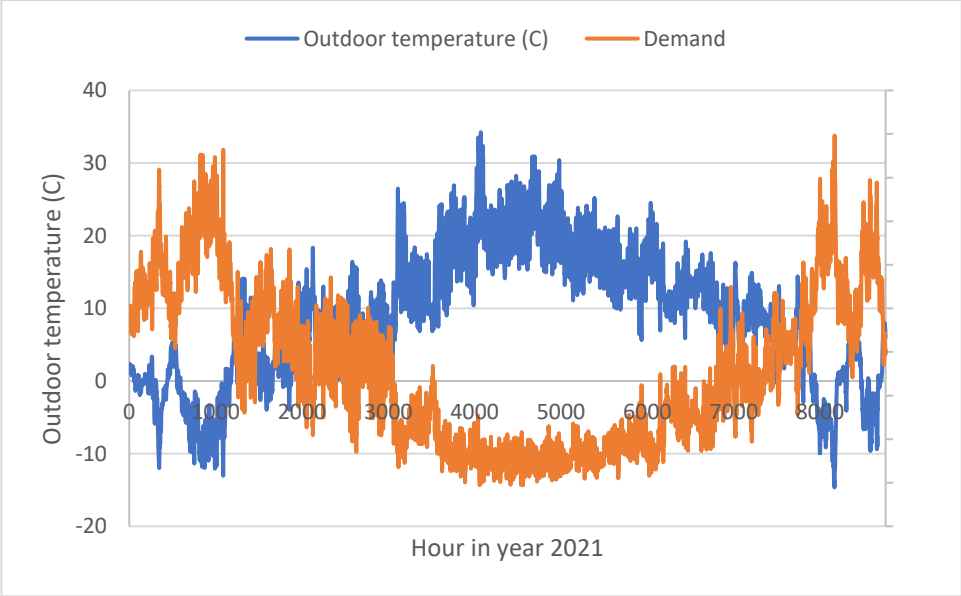


Figure 4. Historical hourly heat demand and outdoor temperature of Linköping in 2021 [17]

2 Data forecasts for Spain

2.1 Review of existing forecasting tools

For Spain, the open-access commercial model openTEPES [18] is selected as a forecasting tool. Developed by Universidad Pontificia Comillas departing from the TEPES model (Transmission Expansion Planning for an Electric System), the energy planning model aims to minimise the total cost of a large-scale electric system at a tactical level.

Its objective function considers both the capital expenses (generation, storage and transmission investment costs) and the expected variable operation costs (e.g., generation emissions, fuels, labor and maintenance, ramp rates). The model also considers the reliability-related costs due to energy not supplied (ENS).

As a forecasting tool and decision support system, openTEPES can define the optimal generation and expansion plans that satisfy several attributes simultaneously. To carry out the forecast scenarios for this study, simulations are used that determine the necessary investment in the storage and generation capacity of the Spanish electricity system while discarding further transmission investment costs [19]. The network costs represent a small share of the total transition costs.
OpenTEPES was created in Python 3.7.4 and Pyomo 5.6.6 and uses a .csv format for its inputs and outputs. By default, it uses Gurobi 8.1. as a mixed-integer programming (MIP) solver.

2.2 Data collection for 2030 and 2050

2.2.1 2030 forecast scenario

In order to determine the 2030 pricing scenario for the Spanish electric system, a single-node system is assumed. The following assumptions apply to this model:

- All involved transmission lines have an infinite interconnection capacity.
- No energy trading between international borders happens (worst-case scenario).
- Spanish electricity system is considered as an isolated, energy-autonomous territory.

Two storage investment scenarios are simulated:

1. The first one is solved to obtain the storage investment needed to supply a low hydrological year (18.01 TWh, corresponding to 2017). This is done to determine the need for investments in a dry-year scenario.
2. The second one represents an average hydrological year (29.61 TWh, corresponding to 2015). This scenario determines the average operation and resulting costs, prices and emissions.

All input data related to energy generation is taken from the Spanish National energy and climate plan (NECP) [20], a plan issued by the Spanish Government to achieve a reduction of 23% of 1990´s greenhouse gas emissions by 2030.

The most relevant input data is listed below based on [19]:

- The total energy demand for 2030 is 263 TWh/year, with the peak demand being 47,768 MWh.
- Installed capacity by generation source is listed in Table 4:

Table 4. Expected Spanish installed capacity in 2030

Source	Capacity [MW]	
Wind	48550	31%
Solar PV	38404	25%
CCGT	24560	16%
Hydro (+PSH)	24140	16%
Solar thermal	7300	5%
Cogeneration	3980	2%
Nuclear	3050	2%
Batteries	2500	2%
Biomass + biogas	1730	1%

- Hydropower reserves: maximum = 14.2 TWh, minimum = 4.3 TWh.
- Storage technologies: batteries (2500 MW) and Pumped Storage Hydro (PSH)(12,748 MW).
- Demand side management (DSM) hypothesis:
    - Commercial and industrial demand: 10% manageable, with a maximum displacement period of 1 hour.
    - Residential demand: 24% manageable.
- Electric mobility demand: 11.2 TWh/year.
- Carbon emissions price: 100 – 150 €/tCO2[1]
- The natural gas price is 37.8 €/MWh (thermal) and 64.95 €/MWh (electric). This means that the considered Combined-Cycle Gas Turbine (CCGT) power plant efficiency is 58.2%.
- Energy Not Served (ENS) expected cost: 6000 €/MWh.

Once the input data and the program's constraints are defined, the simulations are run, and openTEPES' minimum-cost solution is determined. The results obtained should reflect the "normal" operation of the Spanish electric system under the conditions specified in the NECP.

Simulation operation results:

- Calculated demand: 267.5 TWh/year
- Electricity generation mix is listed in Table 5

[1] The underlying assumptions by the Spanish government of 100 €/tCO2, as published in [19], might not reflect the most recent decisions to revise the EU ETS and the introduction of the CBAM, as announced by the Council of the European Union in December 2022. Hence, a more aggressive CO2 price scenario of 150 €/tCO2 by 2030 might be more likely (SEE ECOLOGIC SOURCE FROM COMMENT: https://forms.ecologic.eu/ariadne-ets-webinar).

Table 5. Expected Spanish generation mix in 2030

Source	Generation [GWh]	
Wind	114934	40%
Solar PV	52773	19%
Hydro (+PSH)	28941	10%
CCGT	22423	8%
Nuclear	22034	8%
Cogeneration	18398	6%
Solar thermal	13294	5%
Biomass + biogas	12088	4%

- Storage capacity:
  - Batteries: 385 MW
  - PSH: 1263 MW
- Surplus of renewable electricity production: 29,633 GWh/year
- Emissions production: 15.77 $MtCO_2$

Economic results:

- Total generation costs: 2089 M€
- Investment costs: 74 M€
- Emissions cost: 1577 M€
- Marginal energy price: 68.77 €/MWh
- Monotonous price curves (energy and reserves):

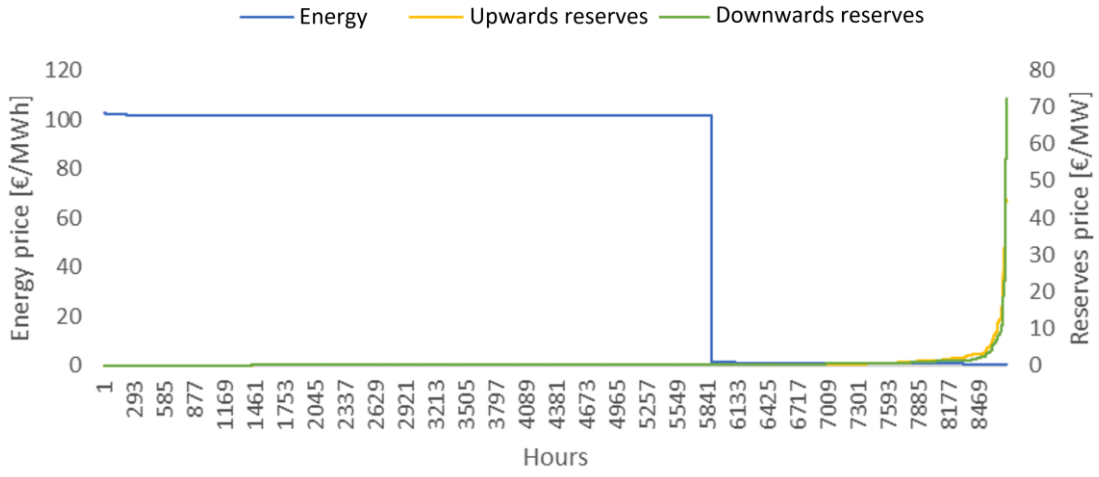


Figure 5. Monotonous price curves (energy and reserves) for the 2030 Spanish electric system (forecast)

Figure 5 shows how, under the model conditions, the marginal energy price is defined by the generation costs of the combined cycle power plants during 5800 hours. In the remaining hours, however, the marginal price is practically zero, as they are determined by the surplus renewable energy. The model optimizes hydro resources, the opportunity cost is the water value, only when there

is no storage capacity water may be spilled. Thus, the average energy price in the 2030´s Spanish electric system results in 68.77 €/MWh.

Regarding the reserve prices, both upwards and downwards reserves have a price lower than 1 €/MW during the first 7800 hours. The maximum downward reserve price is 45.16 €/MW, and 72.40 €/MW in the upwards case. Thus, the average reserve prices are 0.56 €/MW for downwards and 0.48 €/MW for upwards.

2.2.2 2050 forecast scenario

The 2050 data would be obtained using the same methodology as for 2030. Currently, the Spanish government is updating the scenarios, and for Bio-FlexGen Deliverable 3.6 these data will be updated accordingly.

2.2.3 Ancillary services price forecast

As for the forecast of the ancillary services markets, the forecasted day-ahead (DA) market prices and the historical relation between wholesale prices and each of the ancillary service price are used. For this purpose, market prices for different Spanish electricity submarkets for 2021 will be used as shown in Figure 6.

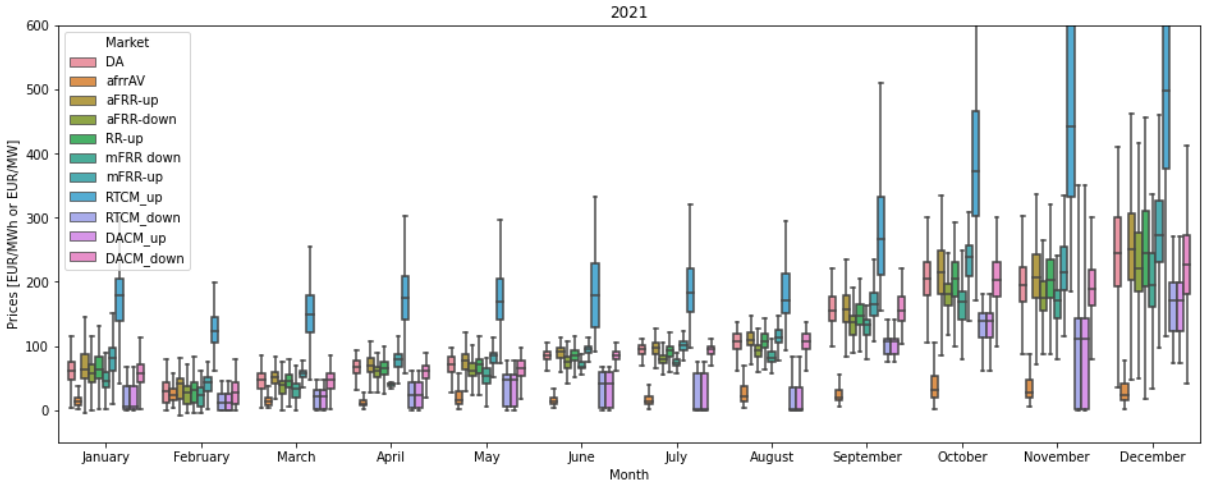


Figure 6: Comparison of all procurement prices in 2021 for Spain.

In Figure 6 The y-axis has been capped at 600 EUR/MW for better readability. Note that mFRR up and down are only procured in up- and down-regulated hours, respectively; the hours with no procurement (corresponding to zero revenue) in these markets are not included in the box plots. The following abbreviations are used: DA congestion management market (DA CM) and real-time congestion management market (RT CM), Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR), manual Frequency Restoration Reserves (mFRR) and Replacement Reserves (RR). "Up" means Upward, and "Down" downward direction.

2.3 Hydrogen demand forecast

The prospective emergence of a hydrogen economy is a global development driven by the need to drastically reduce emissions stemming from the use of fossil energy carriers. However, due to the

differences in local resource availability, the role of hydrogen always needs to be analysed in a domestic context.

Like other European economies, Spain is highly dependent on fossil fuel imports to meet today's energy demand. Hence, today´s hydrogen demand, mainly stemming from the refining and fertiliser industry, is met by hydrogen produced from imported natural gas. The main import routes are seven Liquified Natural Gas (LNG) regasification terminals [21], one of which has been mothballed since its construction in 2012 but will be fired up in early 2023 [22]. Additionally, the country receives imports from Algeria via a subsea pipeline system and is well connected with Portugal. The Iberian Peninsula remains weakly interconnected with France. As such, producing "blue" hydrogen from natural gas by capturing resulting emissions and storing them underground would imply a continuation of primary energy imports from Northern Africa and via its regasification terminals.

Spain is in a unique position when it comes to the production of electricity-based "green" hydrogen in Europe. In contrast to other EU countries, Spain can be characterised by its high availability of land with excellent solar radiation and wind potentials that could allow the country to generate significantly more renewable energy than is needed for its transition to a climate-neutral economy. A closer look at national hydrogen strategies shows that countries like Germany acknowledge their dependence on hydrogen imports to transform their economy while remaining relatively neutral on the production method for low-emission hydrogen. On the other hand, Spain focuses on "green" hydrogen, which could potentially be exported in the long run [23].

Hydrogen demand forecast scenarios, analysed in the following, are understood to be green hydrogen scenarios that reflect the potentially beneficial position of Spain to integrate hydrogen into its national energy mix.

2.3.1 Methods

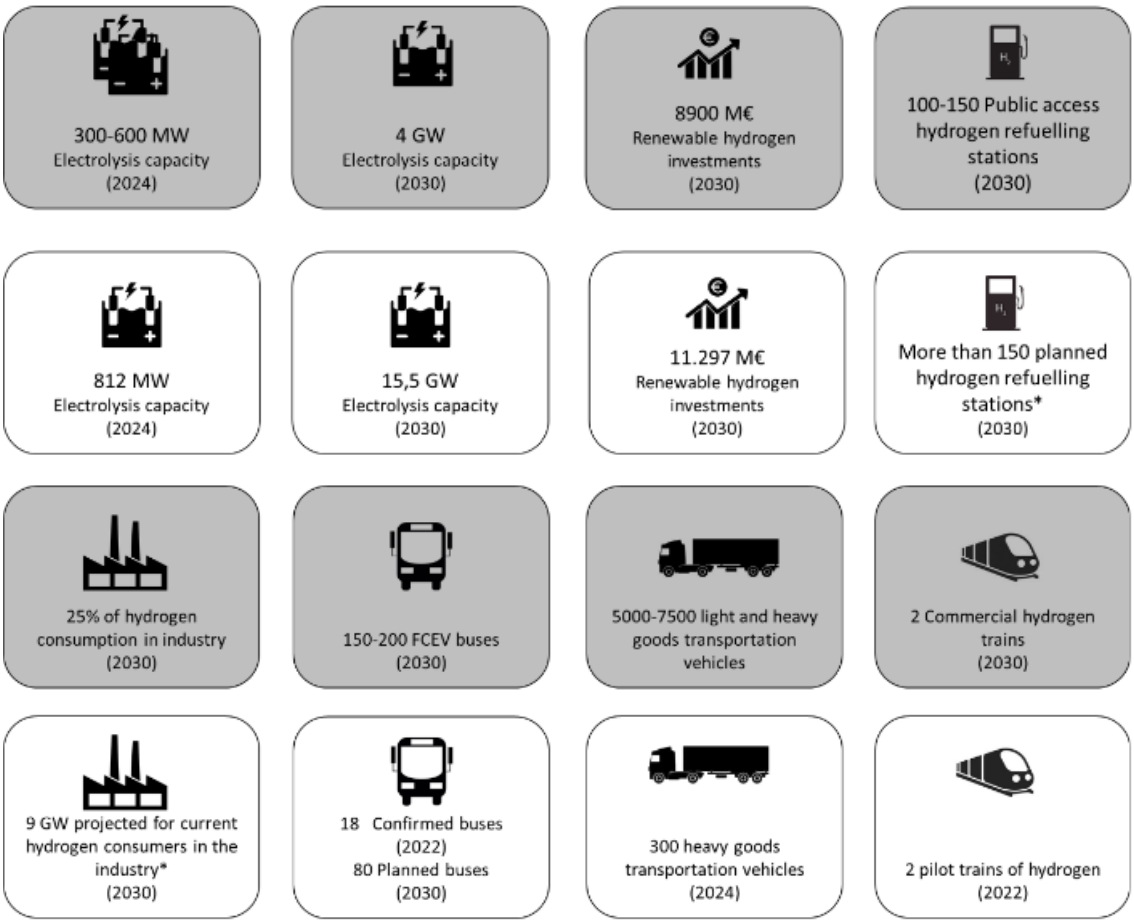
The following section contain different demand scenarios for hydrogen in 2030 and 2050. The main references for this analysis are the Spanish national hydrogen roadmap "Hoja de ruta de hidrógeno: una apuesta por el hidrógeno renovable" [24], published by the Spanish Ministry for the Ecological Transition and the Demographic Challenge in October 2020, and the annual report of the Chair for Low Carbon Hydrogen Studies at the Pontifical University Comillas on the current state of the hydrogen sector in Spain, published in October 2022 [25]. The analysis of long-term scenarios focuses on the impact of different potential decarbonisation trends on the Spanish energy mix, departing from the national energy balance as of 2018.

2.3.2 Analysis

2030:

Until 2030, the national hydrogen roadmap foresees a growth from electrolyser capacity to 4GW with 300-600 MW installed by 2024. Depending on the operational mode, the average load factor of the installed capacity might vary. If operating at 50% of their nameplate capacity, annual hydrogen production in Spain would be 17,500 GWh by 2030, doubling to 35,000 GWh if continuous operation near 100% capacity is assumed. The Spanish NECP [26] foresees a total energy demand of approximately 1200 TWh per year in 2030. Hence, the contribution of hydrogen to the total energy mix would be between 1.5 and 3.0%.

As shown in Figure 7, currently announced projects in the national context sum 15.5 GW of capacity to be installed by 2030 with 812 MW already in service by 2024. Suppose all these projects will be realised or an equivalent amount of capacity will be installed by 2030. In that case, the contribution of hydrogen in the energy mix could increase by 388% compared to the values stated in the national hydrogen roadmap, equivalent to 5.8 and 11.6% of the total energy demand stated by the NECP.
About 60% of all announced projects address industrial hydrogen consumption (9 GW). However, very little information about ongoing and expected projects to ramp up other hydrogen end-uses is available, especially in the transport sector (Figure 7). The delayed emergence of hydrogen as transport fuel might significantly reduce the expected hydrogen demand and the need for installed electrolyser capacity.



* It is not specified how many will be of public access.
* It is impossible to compare the 25% of hydrogen to be consumed in the industry with current projects. A comparison with the projected electrolysis capacity for current hydrogen consumers (refining, fertilisers, and methanol) is included.

Figure 7: Roadmap objectives according to the Spanish government (grey) and hydrogen project projections (white) according to the Chair of Low Carbon Hydrogen Studies

2050:

The future Spanish energy mix will be the result of many internal and external factors that impact the transition towards a net-zero emission economy by 2050. Departing from total national energy

consumption of 1090 GWh in 2018 [27], the energy balance in 2050 might be impacted as follows, based on the underlying assumptions of the NCEP for 2030:

- Improved energy efficiency of 1.5% per year in the industrial sector combined with increased consumption by 1.3% per year due to economic growth.
- Annual demand reduction of 1.5% per year in the transport sector due to more efficient energy use (electrification) and behaviour change.
- Annual demand reduction of 1.0% in the residential and service sector due to energy efficiency measures.

These assumptions would lead to a total final end-user energy demand reduction by 37.5% by 2050 compared to 2018. However, given the use of hydrogen in high-temperature industrial applications such as for steel making, the chemical industry, glass, and ceramics production, a substantial ramp-up of electricity generation for green hydrogen production would be needed. Hydrogen consumption of 250 TWh in the industrial sector, representing 37% of the total energy demand, would imply a doubling of today´s electricity generation. Hydrogen might also play an important role in the transport sector for terrestrial, maritime and aviation. Additionally, Spain might be an important exporter of hydrogen to other European countries, given that estimates for cost-competitive renewable electricity production potential exceed prospected demand [28]. For example, it is estimated that Germany might have to import 250 to 400 TWh if moving towards a hydrogen-based economy in 2050, with sourcing from the Iberian peninsula expected to be the most economically viable option [29]. Hence, the required hydrogen production capacity could imply a far greater increase in renewable generation capacity.

2.3.3 Results

The emergence of a hydrogen economy is subject to countless uncertainties. Hence, exact demand estimations are only valid given a very limited set of strict assumptions about future end-use applications. Figure 8 Figure 8 sketches a potential spectrum of hydrogen generation scenarios in the national context. The bounds for the 2030 scenario are defined by capacity targets stated in the NCEP and the capacities announced publicly for planned projects. For 2050, the industrial demand projection based on the assumptions stated in section 2.3.2 is used as a lower bound, while the upper bound is represented by a triplication of demand justified by hydrogen use in road transport and exports to central-European partners. Combined, these scenarios describe a solution space for exponentially increasing hydrogen demand until 2050.

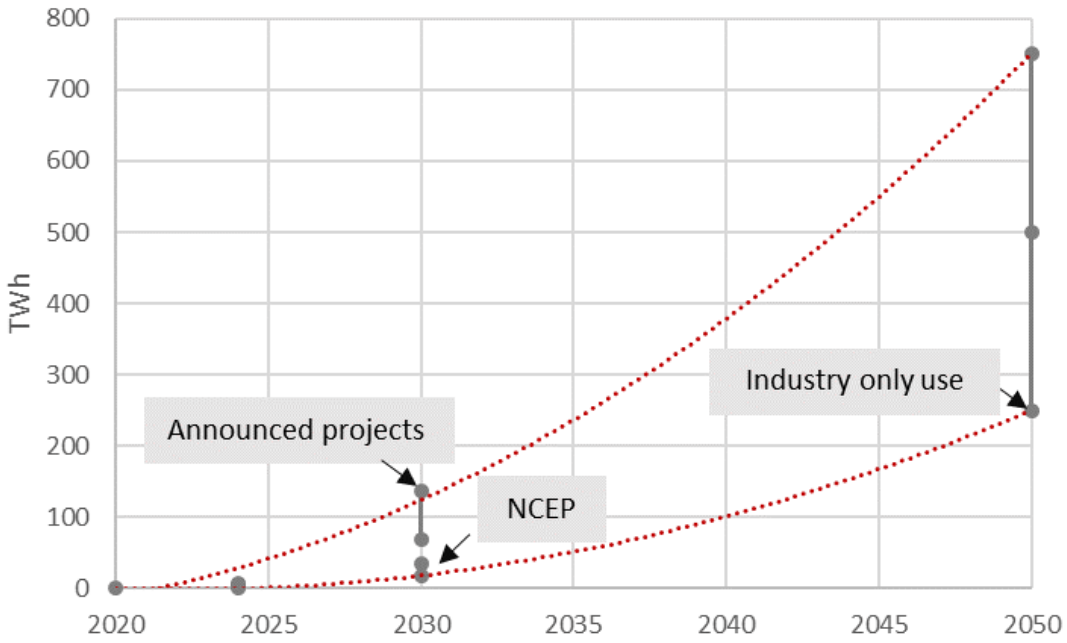


Figure 8: Hydrogen production scenarios for Spain until 2050. Own elaboration

2.4 Biomass price forecast

Biomass is a potentially sustainable renewable energy source that may play a prominent role in transitioning towards climate-neutral energy systems. However, several of its characteristics make it more difficult to evaluate its future cost and availability for a Bio-flexGen cogeneration plant. First, biomass is a rather broad term for a wide range of heterogeneous biogenic matter that can be used energetically. Depending on its composition, it has different energetic content and combustion characteristics. The most standardised form of biomass is ENplus A1 pellets that comply with the ISO. 17225-2 for solid biomass. Developed in 2011, ENplus A1 is commonly referred to for benchmarking prices, and there is an increasingly global trading volume for ENPlus A1 conform compliant biomass of nearly 14 million tonnes in 2021 [30].

The variety and heterogeneity of biomass sources also mean that there is no central marketplace. Biomass prices for comparable products might differ significantly across different regions and countries, given that biomass availability depends greatly on access to local, sustainable biomass sources. To be sustainable, biomass production must not be in conflict with or substitute other conventional end uses of these biobased resources. Hence, biomass prices are also subject to constrained availability. Biomass is a feasible option to reduce emissions for many high-temperature processes in industry. It represents the only source of non-fossil carbon that can potentially be emitted to the atmosphere without increasing atmospheric carbon concentration. Hence, demand is expected to surpass availability in the future. This supply-demand gap in the European Union is estimated to be as big as 40-70 % by 2050 [31]. In light of this perspective on biomass cost and availability, the following analysis of price scenarios is based on the potential drivers of biomass prices in the EU.

2.4.1 Method

Our analysis is based on historic price data for biomass in Spain. We contrast this data from various sources, such as data published by the Spanish Institute for Diversification and Saving of Energy (IDAE), the Spanish biomass association (AVEBIOM) and the publicly available data from the market data provider Argus Media. We contrast this data with historic natural gas TTF[2] gas prices and reflect on emission pricing. Based on this analysis, we present factors that might influence biomass prices and help construct future price scenarios in the Spanish context.

2.4.2 Analysis

Figure 9 presents an overview of historic biomass prices in €/kWh presented by various providers in the Spanish context. ENplus A1 pellets are the principal benchmark for biomass pricing (dark green). Due to the lack of a single market authority, quarterly bulk pellet prices differ significantly across various sources, which can vary by more than 30%. However, excluding price peaks due to the ongoing energy crisis since mid-2021, each source only reports a maximum price variation of 21.1% from Q1 2014 until Q2 2021.

Since the first energy price shocks due to the energy crisis in Q3 2021, it can be noted that ENPlus A1 pellet prices in Spain have increased by 72.8% from Q3 2021 until Q2 2022 (AVEBIOM) or 86.4% from Q3 2021 until Q3 2022 (Argus Media). At the same time, the prices for other biomass sources, such as olive oil pits, have only experienced minor price changes (+16.5%). However, in 2022 observed price peaks for ENPlus A1 pellets in Spain remained significantly below natural gas prices after price parity between biomass and TTF natural prices was reached in Q3 2021. However, at least in Spain, which tends to have higher biomass prices than other EU regions [32], the price trend has not been reversed. Biomass futures in the North Western European Markets, Baltics and Portugal have been declining for Q3 2022.

The price shocks since Q3 2021 are relatively recent. Hence, only operators with the technical ability to switch between fuels can benefit from lower energetic prices for pellets to operate their processes. However, if natural gas prices remain relatively high for longer, it would incentivise investments in bio-combustion technologies to replace natural gas as the main energy source. Note that electricity prices correlate with natural gas prices in most European countries, though this correlation is weaker in Spain than in other electricity markets [33].

[2] TTF (Title Transfer Facility) gas prices are the reference natural gas prices for the European market.

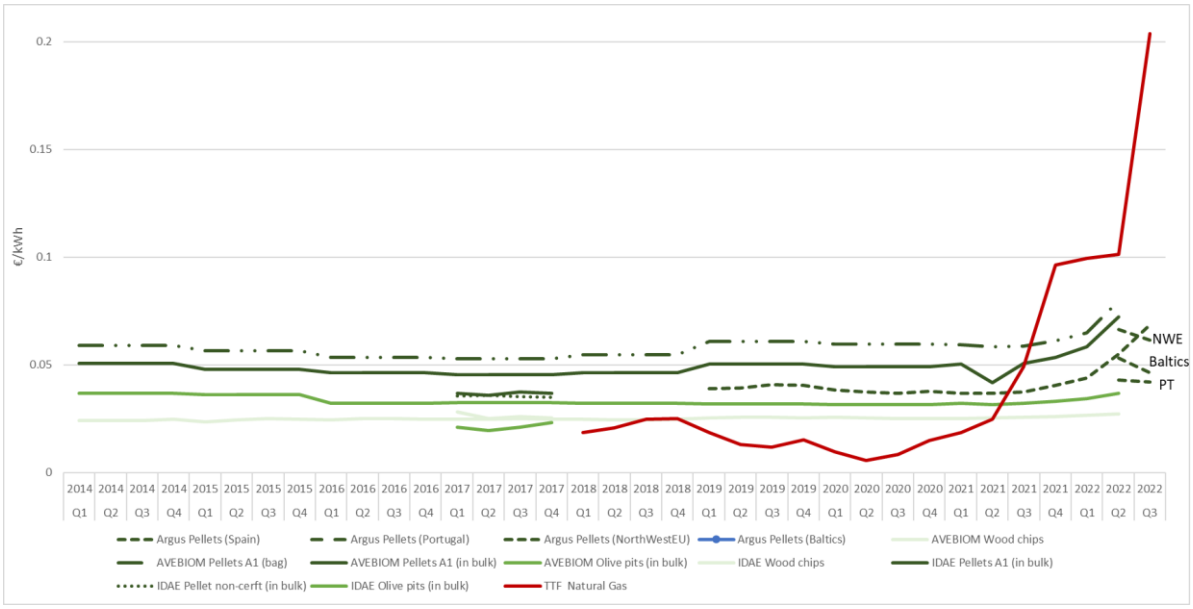


Figure 9: Historic quarterly biomass prices in Spain compared to TTF natural gas prices and pellet prices from other EU regions

Another price driver for biomass is the price for CO2 emission certificates on the EU ETS, potentially increasing the cost of using conventional fossil energy sources. Historic data only indicates one price peak that may be linked to increasing CO2 prices. CO2 prices have been low between Q1 2014 and Q4 2017, hovering around 5 €/tCO2. However, since early 2018 the CO2 EU ETS price has increased steadily, surpassing 26 €/tCO2 by the end of 2018, fluctuating mostly between 25 and 30 €/tCO2 in 2019. Over the same period, the pellet price in Spain increased by approximately 10% by the end of 2018 and remained at this level until a price dip during the COVID pandemic. While this correlation is not strong, long-run biomass prices might be impacted by higher CO2 prices that increase the cost of using conventional fuels.

2.4.3 Results

Spain's relatively stable historic biomass prices can only serve as a baseline for future biomass price scenarios. Given the scarcity of biomass resources and the long-term perspective to use biomass as a substitute for fossil energy sources, we have to see biomass prices in light of future natural gas and CO2 prices. We, therefore, suggest applying average historic ENPlus pellet prices as minimum baseline prices for biomass in Spain. For scenarios that foresee a combination of natural gas and CO2 prices that exceeds the historic average biomass pellet price of 44.69 €/MWh, the biomass price shall be indexed against the energy use cost (CO2 + natural gas) for industry (Figure 10).

In case other biomass sources than pellets are expected to be used in Bio-FlexGen cogeneration plants, the following price adjustment factors based on historic price differences in Spain (Q1 2014 until Q2 2021) according to data published by AVEBIOM will be applied:

Olive Pits: - 30.7% compared to ENPlus A1 pellets
Wood Chips: - 48.1% compared to ENPlus A1 pellets

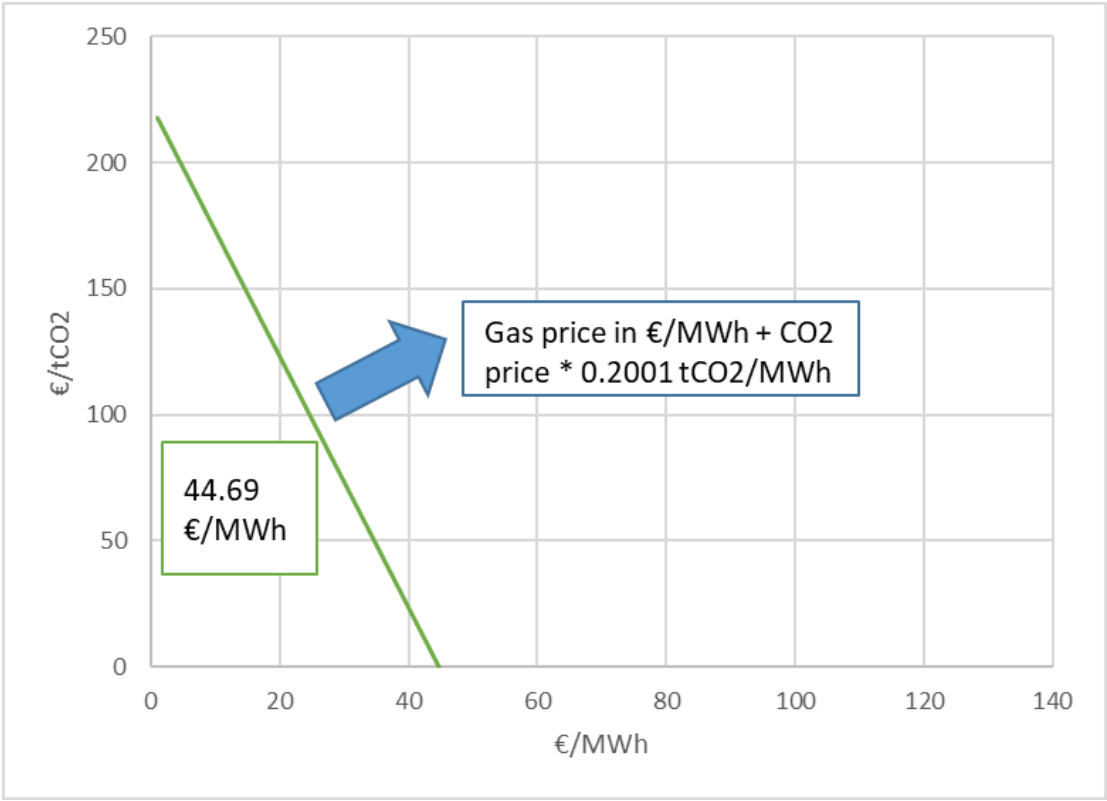


Figure 10: Biomass price scenarios for Spain

3 Conclusion

Expectations for Sweden's future electricity demand have increased sharply. Adjusting the energy system to zero net emissions of greenhouse gases requires expanding electrification. There are different uncertainty factors in the future such as the impact of electricity-based hydrogen and efficiency potential. Changes in the power system are happening more and more quickly. Some production capacity is closed, and large consumers wish to connect to the electricity grid, but grid expansion takes a long time. In order to capture the development, SVK has developed four scenarios for long-term market analysis that are varied in electricity demand and production mix. The scenarios identify the most robust action to meet the needs. In all scenarios demand increases and there are different expansions of different production capacities. In all scenarios, 35 historical weather years have been used to simulate spot market price and different unit productions for 2035 and 2045. Input data for optimization models of Swedish use cases in WP4 are derived considering the average of 35 weather years data. This means that for all simulated data for the years 2035 and 2045, the average of 35 weather years is considered. In all scenarios, one biomass price has been applied for the simulated year. Biomass prices for years 2035 and 2045 in the analysis are assumed to be 26.1 €/MW and 27.3 €/MW, respectively. However, considering possible increase of long-term biomass prices due to the gap between demand and adequacy of biomass in Europe, biomass price scenarios can be studied by additional sensitivity analysis for optimization model.

Overall, the scenarios represent a changed power system compared to today, where the challenges are to ensure that the power system is sustainable, safe and cost-effective. The long-term market analysis provides an overall picture for future transmission, expansion and needs for flexible production in different scenarios. For example, in the two scenarios with greatly increased electricity demand in the north of Sweden, trade flows through SE2 and SE1 are limited during a large part of the simulated hours. In the scenario with high electrification, the analyses of power adequacy show that Sweden becomes completely dependent on flexible electricity use and imports from neighbouring countries during busy hours.

The electricity demand in Spain is expected to grow significantly to foster the decarbonisation of the energy sector, especially for transportation, heating and industrial processes. Higher electricity demand must be met by new generation capacity. Given that the Iberian peninsula will remain an energy island with little connectivity to the rest of central Europe, all additional demand will be met by an increased share of renewable energy generation. Since the potential additions in hydropower capacity are limited and nuclear capacity is to be phased out, technologies like the Bio-FlexGen CHP plant can help to ensure enough system flexibility. For the 2030 horizon, Bio-FlexGen CHP would have to compete with gas power plants and energy storage as a flexibility provider, and for the 2050 horizon Bio-FlexGen CHP would primarily compete with other energy storage options such as batteries.

A key factor for the competitiveness of Bio-FlexGen CHP in the electricity system is the expected cost for biomass. Here, we assume that the scarcity of available biomass in Spain will link its long-term price to the cost of alternatively consuming natural gas. Since scenarios for 2030 and 2050 will reflect different natural gas price and CO2 price scenarios, we can hereby define the framework conditions that make biomass CHP competitive for the Spanish case.

High shares of volatile renewable generation and the expectation of highly fluctuating electricity prices might create a business case for hydrogen generation and combustion with Bio-FlexGen CHP instead of using biomass. Given the wide range of potential hydrogen adoption scenarios due to the high level of uncertainty regarding the future development of a national hydrogen network, it is assumed that hydrogen would originate from an on-site electrolyser producing green hydrogen in instances of renewable electricity oversupply. Hence, exploring the business case for hydrogen combustion with Bio-FlexGen CHP under the premise of future electricity price fluctuations is key for evaluating its economic viability.

References

[1] J. Contreras, R. Espinola, F. J. Nogales, and A. J. Conejo, "ARIMA models to predict next-day electricity prices," *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 1014–1020, Aug. 2003, doi: 10.1109/TPWRS.2002.804943.

[2] M. Shafie-khah, M. P. Moghaddam, and M. K. Sheikh-El-Eslami, "Price forecasting of day-ahead electricity markets using a hybrid forecast method," *Energy Convers. Manag.*, vol. 52, no. 5, pp. 2165–2169, May 2011, doi: 10.1016/j.enconman.2010.10.047.

[3] O. B. Fosso, A. Gjelsvik, A. Haugstad, B. Mo, and I. Wangensteen, "Generation scheduling in a deregulated system. The Norwegian case," *IEEE Trans. Power Syst.*, vol. 14, no. 1, pp. 75–81, 1999, doi: 10.1109/59.744487.

[4] J. P. S. Catalão, S. J. P. S. Mariano, V. M. F. Mendes, and L. A. F. M. Ferreira, "Short-term electricity prices forecasting in a competitive market: A neural network approach," *Electr. Power Syst. Res.*, vol. 77, no. 10, pp. 1297–1304, Aug. 2007, doi: 10.1016/j.epsr.2006.09.022.

[5] F. J. Nogales and A. J. Conejo, "Electricity price forecasting through transfer function models," *J. Oper. Res. Soc.*, vol. 57, no. 4, pp. 350–356, Apr. 2006, doi: 10.1057/palgrave.jors.2601995.

[6] N. Amjady and M. Hemmati, "Day-ahead price forecasting of electricity markets by a hybrid intelligent system," *Eur. Trans. Electr. Power*, vol. 19, no. 1, pp. 89–102, Jan. 2009, doi: 10.1002/etep.242.

[7] "SVENSKA KRAFTNÄT." https://www.svk.se/ (accessed Dec. 14, 2022).

[8] K. Brunge, E. Hellström, M. Jakobsson, and E. Thornberg, "Långsiktig marknadsanalys 2021," 2019. Accessed: Dec. 14, 2022. [Online]. Available: https://www.svk.se/siteassets/om-oss/rapporter/2021/langsiktig-marknadsanalys-2021.pdf

[9] AFRY BID3, "AFRY BID3: Power Market Modelling Suite," 2022. https://afry.com/en/service/bid3-power-market-modelling

[10] SINTEF, "EMPS - multi area power-market simulator." https://www.sintef.no/en/software/emps-multi-area-power-market-simulator/

[11] Danish Energy Agency, "Ea Energy Analyses, Development of the North European power market," 2022. Accessed: Dec. 14, 2022. [Online]. Available: https://ens.dk/sites/ens.dk/files/Vindenergi/systemscenarier_ea_2022_final.pdf

[12] Energistyrelsen, "Analyseforudsætninger til energinet 2019," 2019. Accessed: Dec. 14, 2022. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/analyseforudsaetninger_til_energinet_2019.pdf

[13] Energistyrelsen, "Analyseforudsætninger til Energinet 2022 – Brændselspriser," 2022. Accessed: Dec. 14, 2022. [Online]. Available: https://ens.dk/sites/ens.dk/files/Hoeringer/af22_-_baggrundsnotat_-_braendselspriser.pdf

[14] IEA (International Energy Agency), "World Energy Outlook 2019," 2019. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2019

[15] Energistyrelsen, "Brændselspriser til 2020-fremskrivninger ," 2020. Accessed: Dec. 14, 2022. [Online]. Available: https://ens.dk/sites/ens.dk/files/Basisfremskrivning/baggrundsnotat_-_braendselspriser.pdf

[16] Material Economics, "EU biomass use in a net-zero economy," 2021. [Online]. Available: https://materialeconomics.com/latest-updates/eu-biomass-use

[17] "Tekniska verken i Linköping AB," 2021. https://www.tekniskaverken.se/om-oss/ (accessed Dec. 02, 2022).

[18] A. Ramos Galán, E. F. Álvarez Quispe, and S. Lumbreras Sancho, "OpenTEPES: Open-source transmission and generation expansion planning," 2022.

[19] J. J. Valentín Vírseda, J. P. Chaves Ávila, P. L. Llamas, and A. R. Galán, "Análisis de las necesidades de almacenamiento eléctrico de España en el horizonte 2030," *Papeles Econ. Española, N.º 174*, 2022, [Online]. Available: https://www.funcas.es/articulos/analisis-de-las-necesidades-de-almacenamiento-electrico-de-espana-en-el-horizonte-2030/

[20] G. de España, "Ministerio para la transición ecológica y el reto demográfico," *Plan Nac. Integr.*

Energía y Clima, 2020, [Online]. Available: https://www.miteco.gob.es/es/prensa/pniec.aspx
[21] K. & Spalding, “An Overview of LNG Import Terminals in Europe,” 2018. [Online]. Available: https://www.kslaw.com/attachments/000/006/010/original/LNG_in_Europe_2018_-_An_Overview_of_LNG_Import_Terminals_in_Europe.pdf?1530031152
[22] I. Esau, “Spanish LNG terminal to be fired up after nine years in mothballs,” *upstream online*, 2022. https://www.upstreamonline.com/lng/spanish-lng-terminal-to-be-fired-up-after-nine-years-in-mothballs/2-1-1256140
[23] T. Gerres, S. Serna Zuluaga, and R. Cossent, “National Hydrogen Strategies in a Global Context: Common Design Elements Across Country-Specific Visions,” 2022.
[24] V. C. del G. de España, “Hoja de ruta del hidrógeno: Una apuesta por el hidrógeno renovable,” *Minist. para la Transic. Ecológica y el Reto Demográfico (MITERD), Madrid*, 2020.
[25] S. Serna, R. Cossent, I. Figuerola-Ferretti, T. Gerres, F. J. Sanz, and I. Segarra, “Annual Report: Chair for Low Carbon Hydrogen Studies 2021-2022 - Current State of the Hydrogen Sector in Spain - Project and Regulation,” 2022. [Online]. Available: https://www.comillas.edu/images/catedras/catedra_estudios_hidrogeno/Inglés_Informe_Anual_Cátedra_Hidrógeno_FINAL_1.2_tg_ss.pdf
[26] G. de España, “PLAN NACIONAL INTEGRADO DE ENERGÍA Y CLIMA 2021--2030.” Ministerio de Fomento [Online: Available: https://www. miteco. gob. es~…, 2020.
[27] IDAE, “Balance del Consumo de energía final,” 2020. https://sieeweb.idae.es/consumofinal/bal.asp?txt=GLP&tipbal=f&rep=1
[28] J. L. G. Ortega and A. Cantero, *Renovables 2050: un informe sobre el potencial de las energ{\’\i}as renovables en la España peninsular [resum]*. Greenpeace, 2005.
[29] Fraunhofer ISI, “T45 scenarios (greenhouse gas neutral by 2045),” 2021. https://www.langfristszenarien.de/enertile-explorer-en/documents/
[30] ENplus, “ENplus - Latest Statistics,” 2022. https://www.enplus-pellets.eu/en-in/latest-statistics.html
[31] M. Economics, “EU Biomass Use in a Net-Zero Economy—A Course Correction for EU Biomass.” Material Economics Sverige AB Stockholm, Sweeden, 2021.
[32] European Pellet Coucil, “PELLET MARKET OVERVIEW,” 2017. [Online]. Available: https://epc.bioenergyeurope.org/wp-content/uploads/2017/10/FINAL-PELLET-MARKET-OVERVIEW-2017.pdf
[33] J. M. Uribe, S. Mosquera-López, and O. J. Arenas, “Assessing the relationship between electricity and natural gas prices in European markets in times of distress,” *Energy Policy*, vol. 166, p. 113018, 2022.