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# Modelling the 2020 Greek electricity system using Plexos


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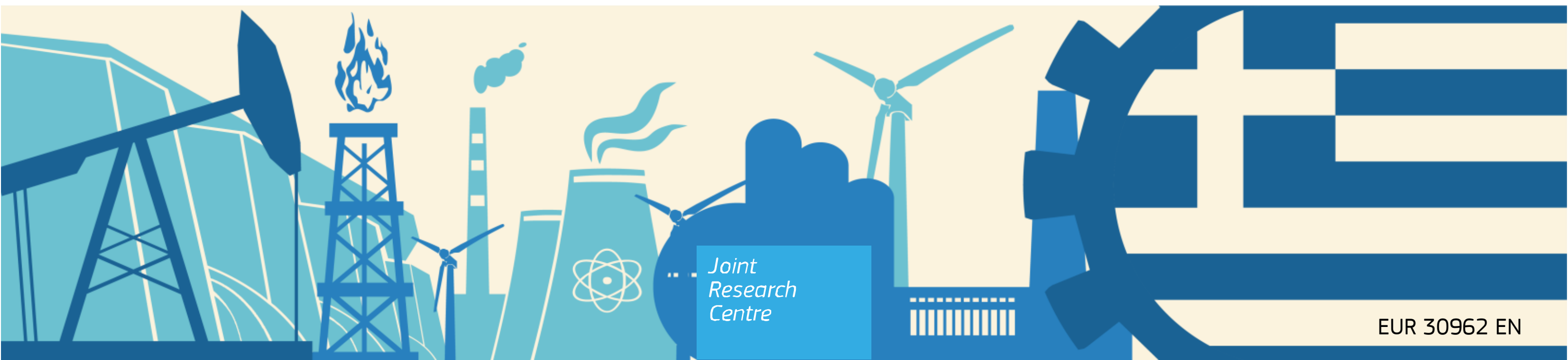


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# Contents

## Abstract

The Joint Research Centre (JRC) of the European Commission has recently undertaken several research activities related to natural gas and electricity sector coupling. These activities are framed within the Regulation (EU) No 2017/1938 concerning measures to safeguard the security of gas supply and encompass various operational and policy challenges such as the identification of critical gas-fired power plants in interconnected natural gas and electricity systems as well as the elaboration of risk assessments in joint energy networks. In this context, Greece has been identified as a suitable country to carry out such assessments because of its high interdependency between natural gas and electric infrastructure. The Greek high-pressure natural gas network model is currently up-to-date and has been previously used in other technical activities to perform national and regional risk assessments. For this reason, this report mainly provides an overview of the Greek 400-kV electric grid model.

Specifically, this report presents publicly-available data including transmission, demand and generation data to build up an electricity system model for Greece in 2020 by using the commercial software Plexos. The report describes the electricity grid model, which accounts for the 400-kV transmission lines only, technical characteristics of fossil-fuel power plants and renewable generating units, and cross-border flows and capacities with neighbouring countries. The Greek natural gas system including transmission, demand and cross-border entry points is also described for the sake of completeness. In addition, the impact of the COVID-19 outbreak on the Greek electricity demand compared to previous years is briefly analysed. The integrated natural gas and electricity system model of Greece can be used to identify and analyse the critical gas-fired power plants under various disruption scenarios. The model may be also used for conducting national or regional risk assessments wherein the gas-electricity interactions play an important role.

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# 1 Introduction

The Joint Research Centre (JRC) of the European Commission has recently undertaken several research activities related to natural gas and electricity sector coupling under the Regulation (EU) No 2017/1938 concerning measures to safeguard the security of gas supply. These activities are mainly focused on the identification of critical gas-fired power plants (GFPPs) within the elaboration of risk assessments of interconnected natural gas and electricity networks. These assessments are more appropriate in countries or areas in which there exists a high interdependency between the natural gas and electric infrastructure. Greece has been identified as a suitable country to perform such studies given its high gas-electricity interdependency. In (Jung et al., 2021), the energy-balance-based compound indicator for the degree of dependency of the electricity sector on the gas sector is 42.6 % for Greece in 2018, being one of the 5 highest values at EU level.

Greece is a European country with an area of around 132 000 $km^2$. It shares borders with four countries: Albania, North Macedonia, Bulgaria, and Turkey. The land area consists of the large peninsulas of the Peloponnese and Attica, the northern mainland, and over 2 000 islands covering more than one-fifth of the territory. The key institutions (IEA, 2017) related to the electricity sector are the following:

- The *Ministry of Environment and Energy* is responsible for environment, energy, and climate change policy within the government. Within the ministry, the Directorate for Energy is responsible for energy policy and energy statistics.
- The *Regulatory Authority for Energy* (RAE) is an independent authority with financial and administrative independence for all energy markets. It has gained direct powers over time, including the right of a consenting opinion for the National Gas and Electricity Grid Operation Code, the Power Exchanges Code, and the Gas and Power Distribution Network Operation Code. RAE also approves methodologies and details for the implementation of operation codes and is responsible for licensing, market control, and supervision.
- The *Public Power Corporation S.A.* (PPC)[1] is a majority state-owned vertically integrated electricity company, which holds assets in lignite mines, power generation, transmission, and distribution. PPC's power generation capacity accounted for about 68 % of the total installed capacity in Greece in 2016. The *Independent Power Transmission Operator* (ADMIE) and the Hellenic Electricity Distribution Network Operator (HEDNO) were created as two 100 % subsidiaries of PPC in 2012.
- The *Independent Power Transmission Operator* (ADMIE)[2], also known as IPTO, is the owner and operator of the *Hellenic Electricity Transmission System* (HETS), in accordance with the provisions of Law 4001/2011 the requirements in the Grid Code and the HETS operation license. Its mission is the operation, control, maintenance and development of the HETS while ensuring the country's supply with electricity in an adequate, safe, efficient and reliable manner. IPTO is also in charge of the operation of the electricity market for transactions outside the day-ahead scheduling in accordance with the principles of transparency, equality and free competition.

The Greek high-pressure natural gas network model is currently up-to-date and has been previously used in other technical activities to perform national and regional risk assessments. However, the model for the Greek electricity network needs to be revisited and updated to the latest developments in the electricity sector. Data for the electricity system model can be found in various sources:

- Platts' database[3], which provides electric power market data.
- ADMIE, which is the Greek electricity system operator[4].
- JRC-PPDB, which stands for JRC Power Plant DataBase (Kanellopoulos et al., 2017). This database contains a more detailed and coherent, albeit still incomplete, dataset of European power plants[5].
- ENTSO-E, which is the European Network of Transmission System Operators for Electricity, publishes electricity generation, transmission, and consumption data for the pan-European market through its transparency platform[6].

[1] https://www.dei.gr/en/i-dei/i-etairia/omilos-dei-ae/dei-ae.
[2] https://www.admie.gr/en/company/about-us.
[3] https://www.spglobal.com/platts/en.
[4] https://www.admie.gr/en/company/about-us.
[5] https://zenodo.org/record/3349843#.YVWx_OdS-F4.

— TYNDP, which stands for Ten-Year Network Development Plan, provides techno-economic data for future energy pathways (ENTSO-E and ENTSOG, 2019).

— ETRI (Energy Technology Reference Indicator) provides independent cost and performance characteristics of the present and future European energy technology portfolio (Carlsson et al., 2014). The operation and maintenance costs for all type of generators of the Greek power system come from this reference. Although it is outdated, the assumptions on these costs might still be valid.

— HAEE, which stands for the Hellenic Association for Energy Economics (HAEE, 2019).

— DESFA, which is the Greek gas transmission system operator[7].

The model described in this report will be used to identify and analyse the critical gas-fired power plants under various disruption scenarios. National or regional risk assessments in countries with high interdependent gas and electricity sectors may also benefit from this model to analyse the operation in normal and stressed conditions.

This report is organised as follows. Section 2 presents the main characteristics of the short-term electricity model implemented in Plexos. Sections 3-7 describe the electricity system model including the model for the 400-kV electricity grid of Greece, the electricity demand, the thermal and renewable power plants, as well as the cross-border interconnections. Section 8 presents various economic- and emission-related data for the electricity system. Section 9 gives an overview of the Greek natural gas system: topology, gas demand, and cross-border entry points. Section 10 compares the results from the resulting Plexos' model with the 2020 historical figures. Section 11 contains the conclusions of the report. Finally, Annex 1 provides the heat input function of the gas-fired power plants of Greece, Annex 2 summarises the data sources, and Annex 3 includes complementary figures for the validation of the Plexos' model.

[6] https://transparency.entsoe.eu/.

[7] https://www.desfa.gr/.

## 2 Modelling the energy system in Plexos

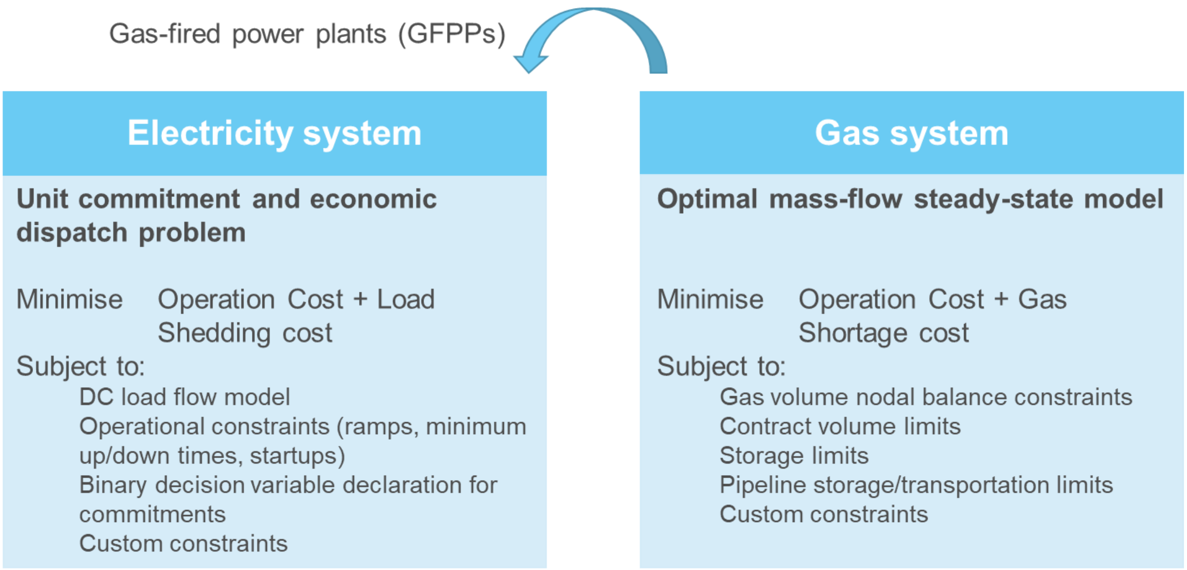
The software Plexos[8] is a powerful commercial software for modelling energy systems and commonly used by industry and organisations around the world. In this report, a day-ahead optimisation model of the Greek electricity system is implemented in Plexos. This electricity system model is jointly optimised along with the Greek natural gas system model given the high interdependency between natural gas and electric infrastructure in Greece.  The electricity system is modelled as an economic dispatch and unit commitment problem, whereas the gas system is characterised with a mass-flow steady-state model. We assume hourly time steps for both models. Figure 1 shows the objective function and typical constraints modelled in each system.

The aim of the electricity system is to satisfy the electricity demand at the least operation cost. To do that, a DC load flow model is used in the unit commitment and economic dispatch model of Plexos. Operational, technical, and economic constraints are also included in the problem formulation: line capacity limits, generation scheduling constraints to model ramp rates, minimum up and down times, start-ups, production limits, and binary scheduling decisions.

Likewise, the main goal of the natural gas system is to satisfy the conventional gas demand (industrial consumers and city gate stations) as well as gas for electricity production at minimum operating cost. In Plexos, a mass-flow steady-state model is used to represent the operation of the natural gas network. Operational and technical constraints are also accounted for: gas volume nodal balance constraints, pipeline transport and maximum production limits, and external injections in the liquefied natural gas (LNG) facility (i.e. arrival of cargoes). Although this is not the case for the Greek system, other constraints such as gas storage chronological constraints can be easily added into the formulation.

The gas-electricity interaction is covered by the dependency of the power system on gas by linking the gas offtake for electricity production to the corresponding GFPP.

Figure 1. Joint natural gas and electricity model in Plexos.




Source: JRC.

The resulting model is thus characterised as a mixed-integer linear programming problem and it is built in Plexos 8.1. This model could help analyse the short-term operation of these networks, explore the consequences of gas disruptions or electricity outages, or, for example, identify the critical GFPPs in integrated natural gas and electricity networks.

[8] https://energyexemplar.com/

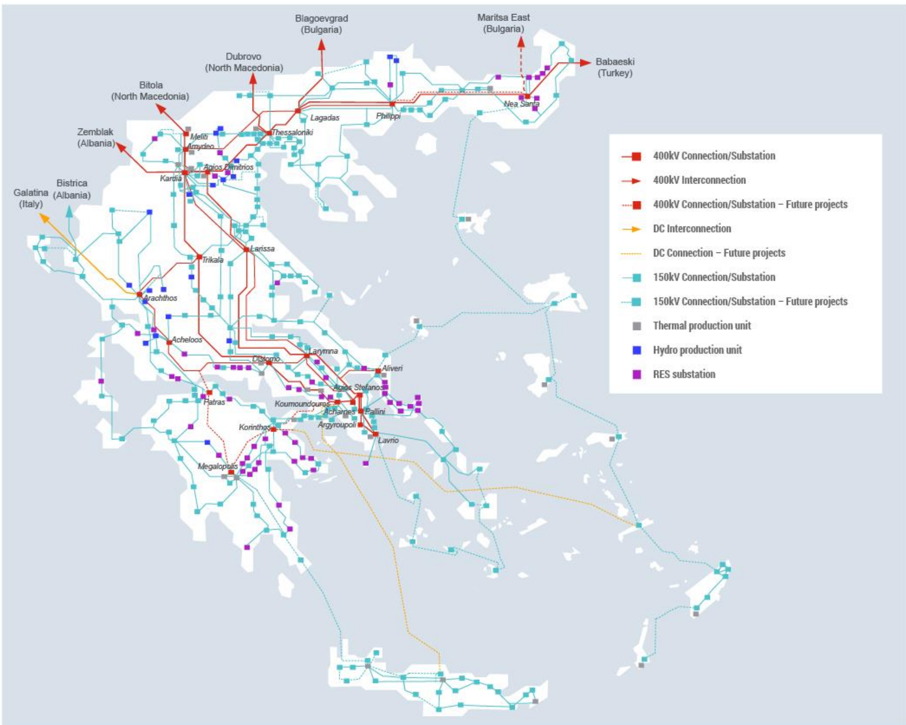
## 3 Greek electricity transmission network

The Greek power transmission system consists of around 12 000 km of transmission lines, including 400 kV alternating current (AC) and direct current (DC), 150 kV and 66 kV lines and cables, plus 361 substations and 68 transformers[9]. Around 23 % of the total length corresponds to 400 kV AC transmission lines, whereas 76 % is attributed to 150 kV AC lines. The backbone of the transmission system are the 400 kV AC lines connecting the north of the country to the Athens and Thessaloniki areas. Figure 2 shows a simplified network of the Greek electricity system. A more detailed electricity network can be found in the website of the Greek transmission system operator IPTO. According to the TYNDP for the period 2022-2031[10], there will be new interconnections and storage projects:

- Reinforcement of transnational interconnections with Bulgaria, Italy, Albania, and North Macedonia.
- Installation of battery systems in Naxos, with a capacity of 7 to 10 MW and a completion schedule within 2022.
- Increased penetration of renewable energy sources.

In addition, there are plans for intercontinental interconnector projects such as the EUROASIA interconnector, which is currently listed in the list of projects of common interest[11]. The EUROASIA interconnector consists of a 500 kV DC underwater electric cable with a total length around 1 500 km and an expected capacity of 2 000 MW. This project will allow the interconnection of the electricity transmission networks of Israel, Cyprus and Greece[12]. Another project under consideration is the Greece-Africa Power (GAP) interconnector which would link the electricity grids of Egypt and Greece at the island of Crete[13]. Apart from interconnections and storage projects, there is a plan for the phase-out of all lignite power plants by 2025[14].

Figure 2. Simplified network of the Greek electricity system.

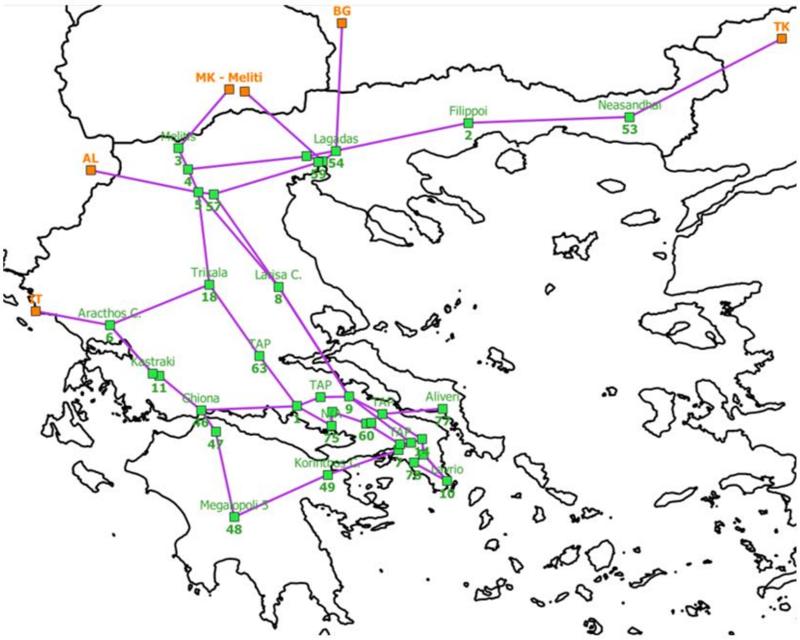



Source: ADMIE.

[9] https://www.admie.gr/en/grid/description/asset-management-data.
[10] https://www.admie.gr/en/nea/deltia-typoy/new-interconnections-and-storage-projects-iptos-tyndp-2022-2031.
[11] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0389&from=en.
[12] https://tyndp.entsoe.eu/tyndp2018/projects/projects/219.
[13] https://tyndp2020-project-platform.azurewebsites.net/projectsheets/transmission/1048.
[14] https://www.euractiv.com/section/climate-environment/news/greece-confirms-last-coal-plant-will-be-shut-in-2025/.

The proposed electricity grid model considers only the 400-kV electricity network, for the sake of simplicity. The backbone of the topology is based on data from previous limited distribution JRC reports (Cakir Erdener et al., 2015), the Platts' database[15], and the maps provided by the Greek transmission system operator (ADMIE). Although manual checking is extremely time-consuming, it was often required. Figure 3 shows a snapshot of the final 400-kV electricity network model. In total, there are 42 electrical buses, of which 33 corresponds to demand buses and 6 to cross-border interconnectors. Note that the expansion of 400 kV system to the Peloponnese has been already added into the network. The new GFPP Megalopoli V is in full operation (operates up to 500 MW under special status according to Law 4533/2018) and significant capacity is expected to be added from new renewable energy sources. Therefore, buses 47, 48 and 49 have been added to the transmission network, but demand has not been assigned to them yet. The modelling of the electricity demand is further discussed in the next section. The thermal and hydro power plants are connected to the closest buses and the renewable power plants are aggregated per region (see Sections 5 and 6, respectively).

Figure 3. The proposed Greek 400-kV electricity transmission grid in the Plexos' model.




Source: JRC.

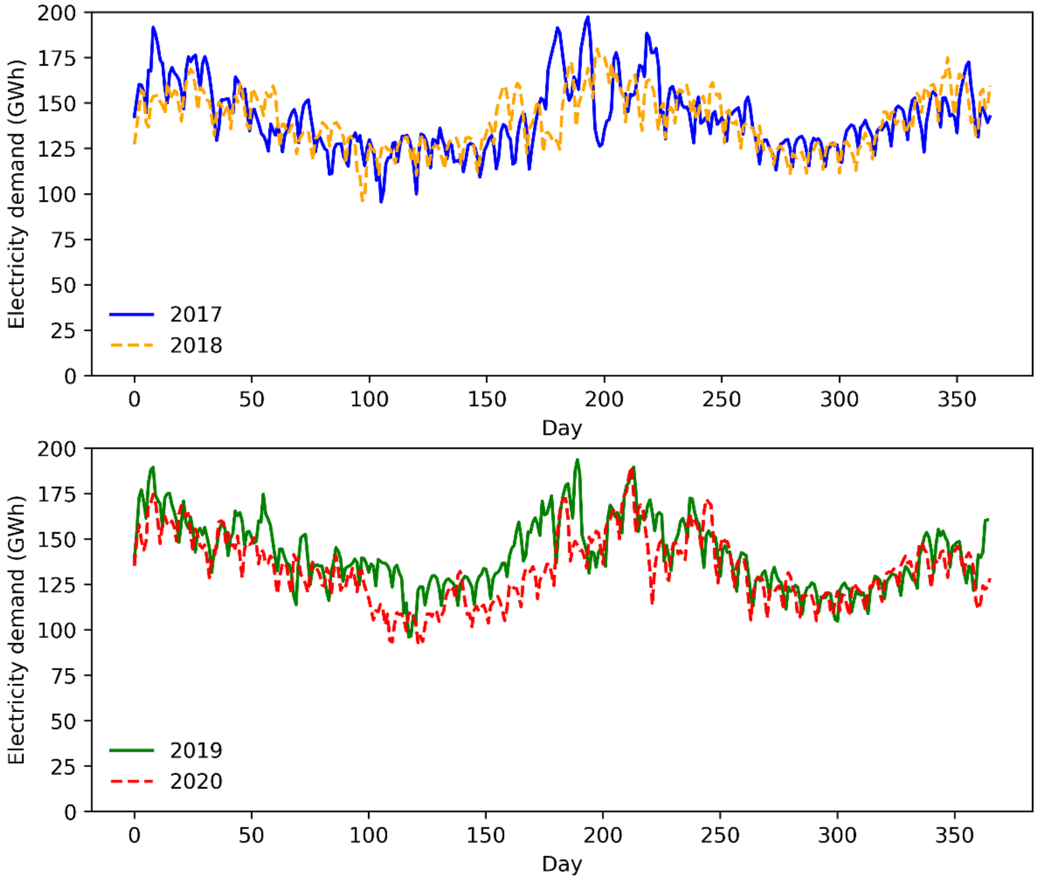
Three parameters are used to define the transmission lines in Plexos: the transmission line capacity and the values of resistance and reactance in per unit (p.u.). We assume that the transmission line capacity is 500 MW for single-circuit transmission lines and 1 000 MW for double-circuit lines (Lioutas et al., 2007). Generic values of the resistance and reactance are adopted and are equal to 0.000074 and 0.0006 p.u./km, respectively.

[15] https://www.spglobal.com/platts/en.

# 4 Electricity demand

The COVID-19 outbreak had an impact on the global energy demand in the year 2020. Figure 4 shows the daily electricity demand in Greece for the years 2017-2020 in order to compare the figures in 2020 with those in pre-COVID years. Table 1 presents the peak electricity demand values for these four years. The Greek Government decreed a lockdown that went into effect on 14 March 2020 and lasted for 45 days until 4 May 2020. We can clearly observe a reduction in the electricity demand over this period (days 73-118 in the bottom plot of Figure 4) with respect to the values in 2019. After the lift of the lockdown, there is also a reduction in the electricity demand which cannot be directly attributed to the coronavirus pandemic. As pointed out in (Lalas et al., 2021), the Greek Government imposed a second full lockdown on 7 November 2020, including a strict night curfew. The lockdown was partially lifted on 11 January 2021. However, the effect of the second lockdown was milder than the first one since its impact on the electricity demand is less obvious in Figure 4. As a consequence of both lockdowns, the annual electricity demand in 2020 decreased to 48.9 TWh, i.e., a reduction of 5.4 % with respect to the annual demand in 2019 (51.7 TWh).

Figure 4. Daily electricity demand in Greece for the years 2017-2020.




Source: ENTSO-E, JRC's analysis.

Table 1 shows some descriptive statistics for the aforementioned years. The total electricity demand remains stable during pre-COVID years. As expected, the hourly peak electricity demand happened in July for the years 2017-2020, and the peak in 2020 decreased by 2 % with respect to that in 2019.

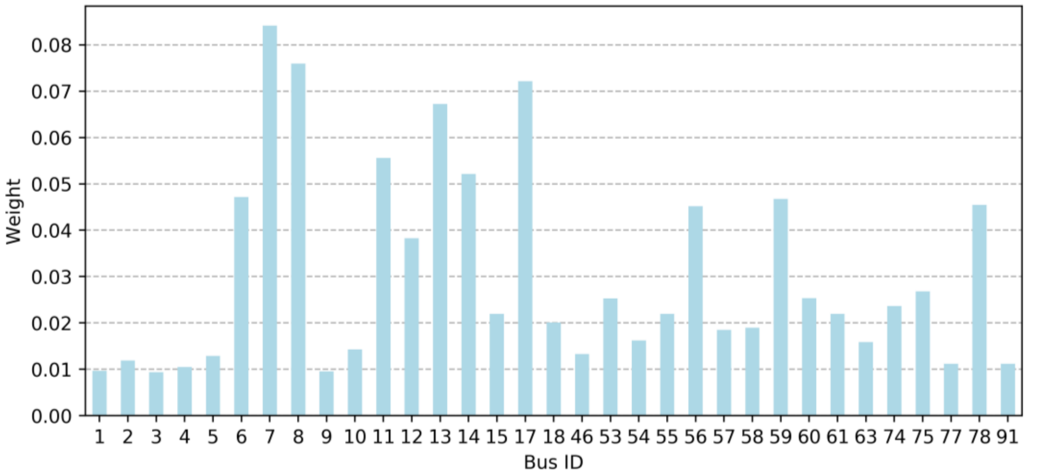
Table 1. Greek electricity demand statistics for the years 2017-2020.

| Year | Mean (MW) | Minimum (MW) | Maximum (MW) | Total (TWh) |
|---|---|---|---|---|
| **2017** | 5889.1 | 3295 | 9715 | 51.6 |
| **2018** | 5847.6 | 3340 | 9112 | 51.2 |
| **2019** | 5900.1 | 3344 | 9701 | 51.7 |
| **2020** | 5564.1 | 3010 | 9510 | 48.9 |

Source: ENTSO-E, JRC's analysis.

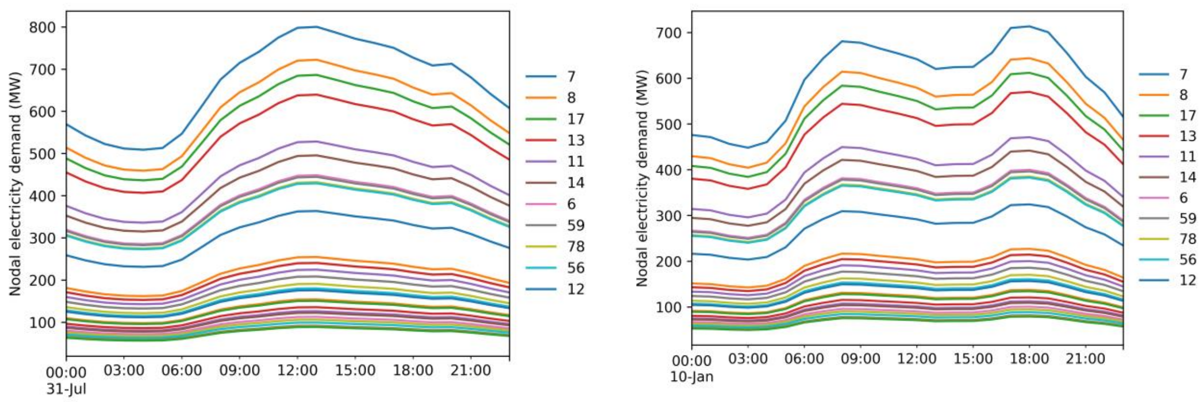
In Plexos, we model the electricity demand deterministically. The electricity consumption of the year 2020 (and of previous years) can be found in the ENTSO-E transparency platform[16]. In total, we assume 33 demand buses and the total hourly demand is geographically distributed based on the weighting factors provided in Figure 5. The highest demand weights are found in the Attica region (IDs 7, 13, 14, 78), Thessaloniki (IDs 17 and 59), Larisa (ID 8), and west of Greece (IDs 6, 11). For the sake of simplicity, we assume constant weights along the year. As an example, Figure 6 illustrates the nodal electricity demand for both the peak electricity demand day and the peak gas demand day, which, in total, amounts to 189.9 GWh and 170.8 GWh, respectively.

Figure 5. Weights for estimating the nodal electricity demand.




Source: (Cakir Erdener et al., 2015) , JRC's analysis.

Figure 6. Nodal electricity demand for the peak electricity day (left plot) and peak gas day (right plot). Note that the legend is only shown for the eleven buses with the highest demand.



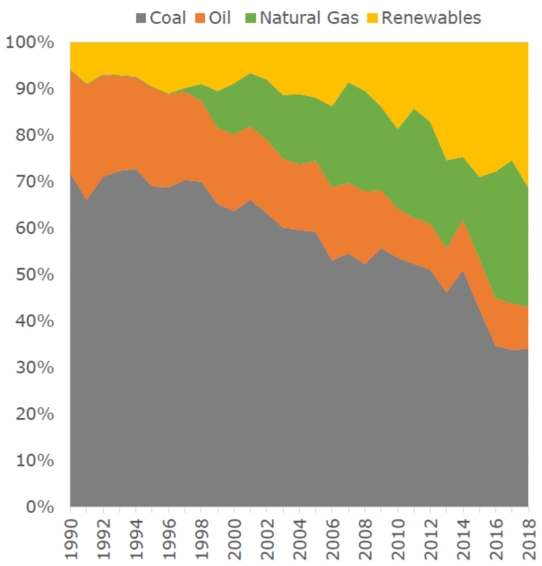

Source: ENTSO-E and (Cakir Erdener et al., 2015) , JRC's analysis.

16 https://transparency.entsoe.eu/.

# 5 Electricity generation fleet

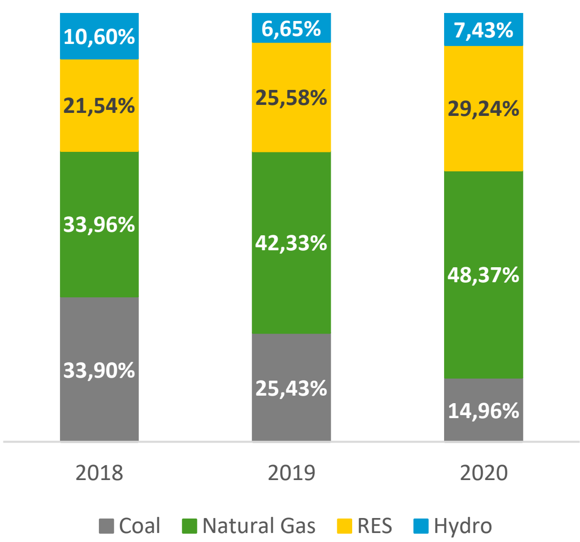
Historically electricity generation in Greece has relied mainly on fossil fuels, as can be seen in Figure 7 and Figure 8. Figure 7 shows the evolution of the electricity generation up to 2017. Note that the x-axis shows data until the beginning of 2018, but data for this year are excluded. Figure 8 compares the share of electricity generation in the last three years 2018-2020. The electricity generation has evolved over time by shifting from a fossil-fuel paradigm towards a more renewable-based paradigm. In 1990, more than 80 % of the total electricity generation was produced by fossil fuels. In contrast, in 2020, the share of renewable energy sources was greater than one third of the total generation. We can also observe the increased use of natural gas to produce electricity which provides almost half the electricity generation in 2020. There is an obvious decline of the electricity produced by oil and lignite. Oil-based generation is completely phased out from 2018 onwards and the share of electricity production from lignite-fuelled power pants has been decreased from 34 % in 2018 to 15 % in 2020.

Figure 7. Gross electricity generation by fuel (%) for years 1990-2018.




Source: (HAEE, 2020)

Figure 8. Gross electricity generation by fuel (%) for years 2018-2020.




Source: (HAEE, 2020) and ENTSO-E, JRC's analysis.

Table 2 shows the installed capacity in the Greek electricity system model. These figures come from various sources: the ENTSO-E transparency platform, the JRC-PPDB (Kanellopoulos et al., 2017), the Hellenic Association for Energy Economics (HAEE, 2019), and our own assumptions. The total installed capacity is 17 752 MW, of which 32 % corresponds to GFPPs, 28 % to solar and wind generating units, 22 % to lignite-fuelled power plants, and 18 % to hydro units including hydro pumped storage, hydro run-of-river and poundage, and hydro water reservoir. Mismatches with respect to ENTSO-E figures can be found in the installed capacity of GFPPs because of two reasons: (i) the upgrade of Protergia GFPP[17], also known as Agios Nikolaos, has been already included, thus resulting in a total installed capacity of 1 258.7 MW, and (ii) the installed capacity of Megalopoli V has been kept to 500 MW because the 400-kV network expansion of the Peloponnese Peninsula was not still implemented in the first semester of 2020. In addition, figures for solar and wind installed capacity are underestimated due to lack of available disaggregated data. In the following sections, we provide a more detailed overview of each of the technologies involved in the electricity mix.

Table 2. Installed capacity in the Greek electricity system considered in the Plexos' model.

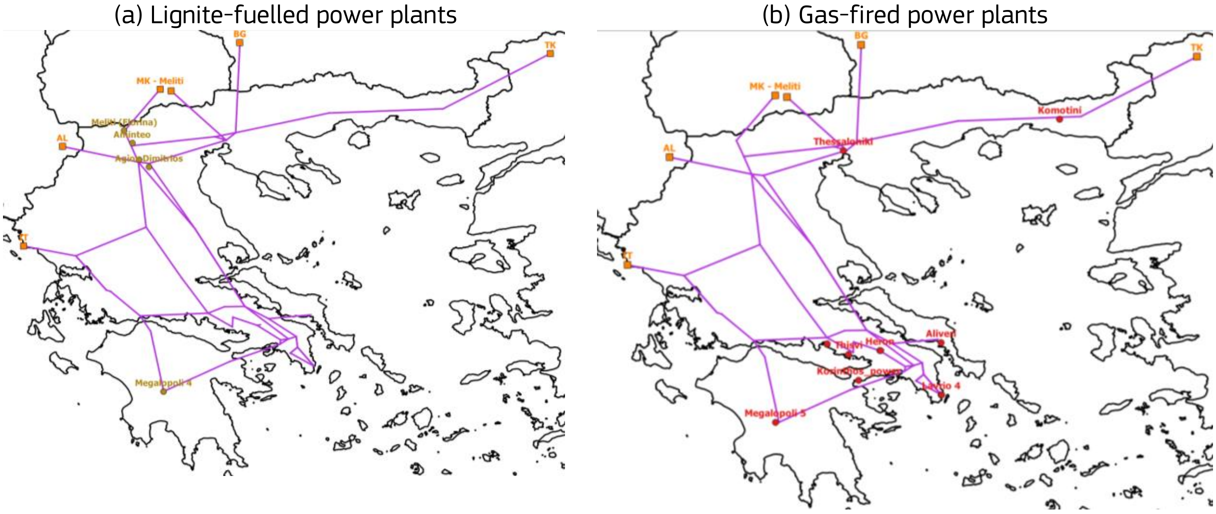
| Fuel type | Installed capacity (MW) |
|---|---|
| Fossil Brown coal/Lignite | 3905 |
| Fossil Gas | 5721.7 |
| Hydro Pumped Storage | 699 |
| Hydro Run-of-river and poundage | 69 |
| Hydro Water Reservoir | 2404 |
| Solar | 2148 |
| Wind | 2828 |

Source: ENTSO-E, (HAEE, 2019), JRC-PPDB (Kanellopoulos et al., 2017), JRC's analysis.

## 5.1 Thermal power plants

The technical characteristics of the thermal power plants including coal and natural gas-fired generating units are shown in Table 3. This table provides the installed capacity, the minimum power output, the corresponding heat rate at nominal capacity, the minimum up and down times, and the ramp-up and ramp-down rates. Figure 9 provides the locations of the thermal power plants. The lignite-fuelled power plants are mainly located in Western Macedonia, while most of the GFPPs are concentrated in the Attica region.

Figure 9. Location of lignite-fuelled power plants (a) and GFPPs (b) in the Plexos' model.




Source: Platts, JRC-PPDB (Kanellopoulos et al., 2017), JRC's analysis.

[17] https://energypress.eu/damco-energys-ccgt-capacity-boost-to-840-mw-approved-by-rae/.

Table 3. Technical features of the Greek thermal power plants[18].

| Name | Fuel type | Technology [19] | Installed capacity (MW) | Min stable level (MW) | Heat Rate (GJ/MWh) | Min Up Time (h) | Min Down Time (h) | Ramp-up rate (MW/min) | Ramp-down rate (MW/min) |
|---|---|---|---|---|---|---|---|---|---|
| AG_DIMITRIOS1 | Fossil Brown coal/Lignite | - | 1456.0 | 786.2 | 12.0 | 6 | 3 | 14.6 | 20.4 |
| AMYNDEO1 | Fossil Brown coal/Lignite | - | 546.0 | 294.8 | 12.4 | 6 | 3 | 11.0 | 7.6 |
| KARDIA1 | Fossil Brown coal/Lignite | - | 1103.0 | 595.6 | 13.3 | 6 | 3 | 2.6 | 15.4 |
| MEGALOPOLI3 | Fossil Brown coal/Lignite | - | 255.0 | 137.7 | 10.9 | 6 | 3 | 4.0 | 3.6 |
| MEGALOPOLI4 | Fossil Brown coal/Lignite | - | 256.0 | 138.2 | 10.9 | 6 | 3 | 4.4 | 3.6 |
| MELITI | Fossil Brown coal/Lignite | - | 289.0 | 156.1 | 9.7 | 6 | 3 | 0.3 | 4.0 |
| ALIVERI5 | Fossil Gas | CC | 417.0 | 128.4 | 6.8 | 3 | 1 | 6.6 | 5.8 |
| KOMOTINI | Fossil Gas | CC | 472.0 | 145.4 | 7.5 | 3 | 1 | 5.0 | 6.6 |
| LAVRIO4 | Fossil Gas | CC | 550.0 | 169.4 | 7.8 | 3 | 1 | 6.6 | 7.7 |
| LAVRIO5 | Fossil Gas | CC | 378.0 | 126.6 | 6.9 | 1 | 1 | 4.2 | 4.9 |
| ELPEDISON_THESS | Fossil Gas | CC | 400.0 | 134.0 | 6.9 | 1 | 1 | 4.2 | 5.2 |
| HERON1 | Fossil Gas | OC | 147.0 | 20.4 | 10.3 | 1 | 2 | 0.7 | 1.9 |
| HERON_CC | Fossil Gas | CC | 422.0 | 130.0 | 6.5 | 3 | 1 | 0.2 | 5.9 |
| ALOUMINIO | Fossil Gas | CC | 334.0 | 111.9 | 7.8 | 1 | 1 | 4.1 | 4.3 |
| KORINTHOS_POWER | Fossil Gas | CC | 433.0 | 133.4 | 6.9 | 3 | 1 | 3.6 | 6.1 |
| ELPEDISON_THISVI | Fossil Gas | CC | 410.0 | 126.3 | 6.7 | 3 | 1 | 1.8 | 5.7 |
| PROTERGIA_CC | Fossil Gas | CC | 1258.7 | 387.7 | 6.5 | 3 | 1 | 1.8 | 17.6 |
| MEGALOPOLI_V | Fossil Gas | CC | 500.0 | 154.0 | 6.5 | 3 | 1 | 1.4 | 7.0 |

Source: JRC-PPDB (Kanellopoulos et al., 2017), JRC's analysis.

## 5.2 Heat input function of gas-fired power plants

Heat rate is the inverse of the efficiency of the thermal power plants, i.e., it shows how many GJ of fuel are needed to generate one MWh of electricity. Heat rate in Table 3 only provides the efficiency at nominal capacity, however more complex models could be defined to account for the relationship between the fuel consumed at the power plant and its electricity produced.

In this work, rather than using the values shown in Table 3, we have opted to modelling quadratic or linear heat input functions of GFPPs, which are derived based on their corresponding natural gas offtake and electricity production quantities provided by DESFA and ENTSO-E, respectively. Both time series can be found on an hourly basis. Let $h_t$ and $p_t$ be the gas consumed and the electricity produced by the gas-fired power plant at time period $t$, respectively. Then, the heat input function can be expressed as follows:

$$h_t = ap_t^2 + bp_t + c \tag{1}$$

where $a$, $b$, and $c$ are the quadratic, linear and constant coefficients of the heat input function, in that order. These coefficients are estimated by using non-linear least squares regression. In particular, we apply one built-in method provided by the open-source software package SciPy[20]. In order to obtain convex heat curves, we further impose the quadratic coefficient to be greater than or equal to 0. The estimated coefficients can be found in Table 4 and Annex 1 provides the fitting curves along with the actual hourly data for each GFPP. Note that the derivative of the heat input function with respect to the power production is the heat rate function and can be written as $2ap_t + b$.

[18] The labels of the columns are defined in the list of definitions at the end of this document.
[19] In Table 3, CC stands for 'combined cycle' and OC for 'open cycle'.
[20] https://www.scipy.org/.

Table 4. Estimated coefficients of the heat input function of the gas-fired generators.

| Name | a (GJ/MWh$^2$) | b (GJ/MWh) | c (GJ/h) |
|---|---|---|---|
| **Aliveri 5** | 0 | 5.76 | 420.7 |
| **Alouminio** | 0.00447 | 6.35 | 601.8 |
| **Elpedison Thess** | 0.00288 | 4.26 | 680.0 |
| **Elpedison Thisvi** | 0.00138 | 5.29 | 503.4 |
| **Heron** | 0 | 8.25 | 228.2 |
| **Heron CC** | 0 | 6.11 | 371.2 |
| **Komotini** | 0 | 7.39 | 211.8 |
| **Korinthos Power** | 0 | 5.91 | 453.9 |
| **Lavrio** | 0 | 7.58 | 156.7 |
| **Megalopoli V** | 0.00001 | 6.57 | 374.9 |
| **Protergia CC** | 0 | 6.21 | 342.4 |

Source: JRC.

## 5.3 Fuel-switching capabilities of gas-fired power plants

Greece can use fuel switching to respond to natural gas supply disruptions. The GFPPs may switch from natural gas to alternative fuels (e.g. oil), but not all of them are equipped with dual-fuel capabilities. As previously mentioned, the total installed capacity of gas-fired generators amounts to approximately 6 000 MW including the new extension of 826 MW of Protergia GFPP[21]. Four companies own the fleet of GFPPs: 33.3 % of the total installed capacity belongs to Mytilineos S.A., 13.5 % to Elpedison S.A., 43.7 % to PPC S.A., and 9.5 % to Heron Thermoelectric S.A. & Heron II Voiotias S.A. Five GFPPs (Elpedison Thess, Elpedison Thisvi, Heron, Komotini, and Lavrio IV), which represent one third of the total gas-fired installed capacity, are equipped with dual-fuel capabilities. Due to the paramount importance of the fuel-switching capabilities, a questionnaire was sent to RAE, and subsequently distributed to the companies operating the GFPPs, in order to obtain an updated view of the technical data and further details about these capabilities (if any) of the GFPPs.

The core of the survey was organised in five tables whose contents are provided below:

- Basic information about GFPPs.
  - Name of the GFPP.
  - Installed net capacity of the power plant (MW).
  - Fuel switching availability (YES/NO).
  - Name of the electricity node where GFPP is connected to.
  - Coordinates of GFPP (latitude, longitude).
  - Coordinates of the connection point of the GFPPs to the transmission grid (if different from above)
- Technical characteristics of GFPPs.
  - Minimum stable level (% with respect to the installed net capacity).
  - Ramp up/down (%/min). Percentage should be expressed with respect to the installed net capacity.
  - Minimum up/down time (min).
  - Net electric efficiency.
- Information about fuel-switching capabilities of the GFPPs.
  - Type of back-up fuel.
  - Is the fuel stored on-site? If yes, how much is typically stored on-site at all times?

[21] https://energypress.eu/damco-energys-ccgt-capacity-boost-to-840-mw-approved-by-rae/.

- Available capacity in case back-up fuel is used (MW).
- Maximum volume of back-up fuel stored on-site (TJ).
- How long does it take to start running the power plant under replacement fuel after stopping burning gas? (hours)

— Technical characteristics of GFPPs working on replacement fuel.

- Minimum stable level (% with respect to the installed net capacity).
- Ramp up/down (%/min). Percentage should be expressed with respect to the installed net capacity.
- Minimum up/down time (min).
- Net electric efficiency.

— Additional information about fuel-switching capabilities. In this table, additional information was required to understand the particularities of GFPPs with dual-fuel availability based on the license issued for operating the facility. For instance, any additional requirements to use alternative fuel or the ability to ship it to the site when running out of alternative fuel when facing longer crises. The following questions were explicitly asked:

- Is there any well-designed plan to provide continuous supply of replacement fuel after the exhaustion of the replacement fuel stored on site?
- If such a plan exists, what is the rate of replenishment of the fuel stocks and what daily operating profile can it support in an extended period?
- Is there any other limiting condition of non-technical nature that could affect the availability of the unit to operate with the secondary fuel for longer periods?
- What is the availability or mean time between failures (MTBF) of the secondary fuel system based on your operational testing?

All relevant stakeholders reacted quickly to the request and responses were received relatively soon, before the end of March 2021. Due to confidentiality reasons, the responses cannot be publicly disseminated and, within the JRC, this has been summarised in a limited distribution addendum (Fernández-Blanco Carramolino et al., 2021).

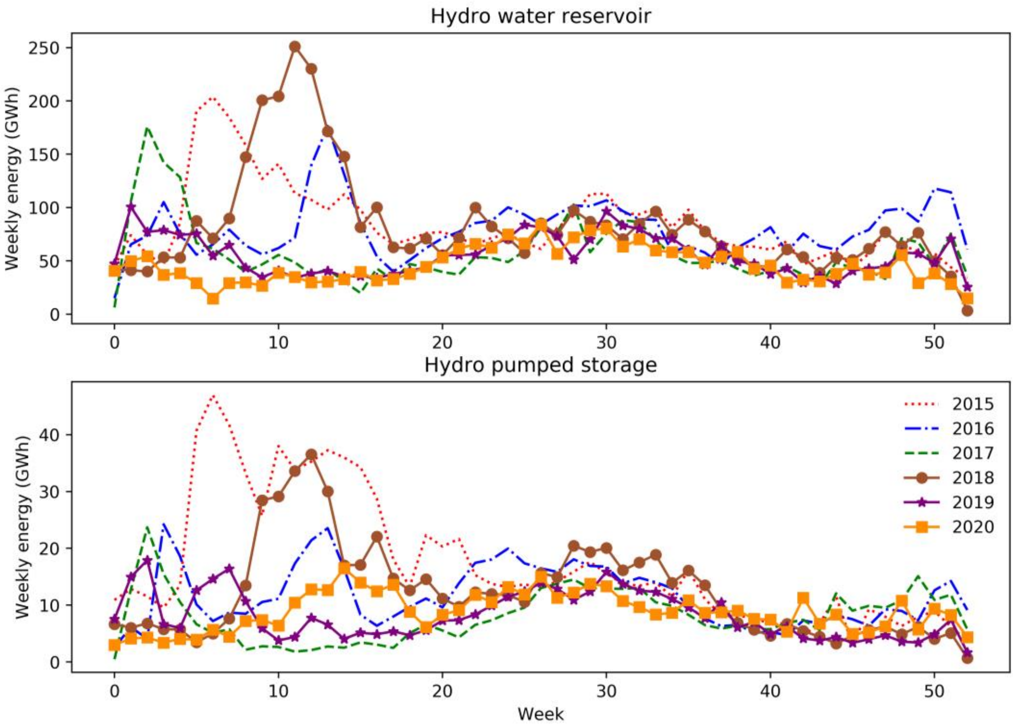
The information included in Plexos to model the fuel-switching capabilities is the maximum volume of back-up fuel stored on-site and the corresponding de-rated capacity in case alternative fuel is used for the GFPPs with dual-fuel availability.

# 6 Renewable power plants

## 6.1 Hydropower plants

Hydropower is a weather-dependent energy which relies on the water cycle. In Greece, hydropower installed capacity has remained unchanged since 2015 according to the ENTSO-E transparency platform[22]. Hydroelectricity's share of total Greek electricity generation varied around 7-10 % in the latest three years (see Figure 8). Figure 10 depicts the weekly energy generation of hydro water reservoir units and hydro pumped storage units from 2015 until 2020 in Greece. Energy produced by hydropower resources is in general greater during winter and spring but it depends on the water availability. For instance, year 2020 could be considered a dry hydrological year. This figure could also give us an idea about the uncertainty ranges of the energy generated by hydropower plants at any moment of the year, being more uncertain during winter time.

Figure 10. Weekly energy generation of hydro water reservoir and hydro pumped storage units from 2015 until 2020.




Source: ENTSO-E, JRC's analysis.

Hydro reservoir units and pumped-storage hydropower units are modelled as energy-constrained generators, which is the approach with the lowest level of complexity in Plexos. In other words, energy constraints can be included in the simulations for the hydro generators in order to approximate the availability of water. Table 5 shows the technical characteristics of the Greek hydro generating units: installed capacity, minimum power output, minimum up and down times, and ramp-up and –down rates. Figure 11 shows the approximate locations of the hydropower generating units in the Greek system. The coordinates of these power plants may not be accurate and are located to the closest electrical bus where we assume the unit is connected to.

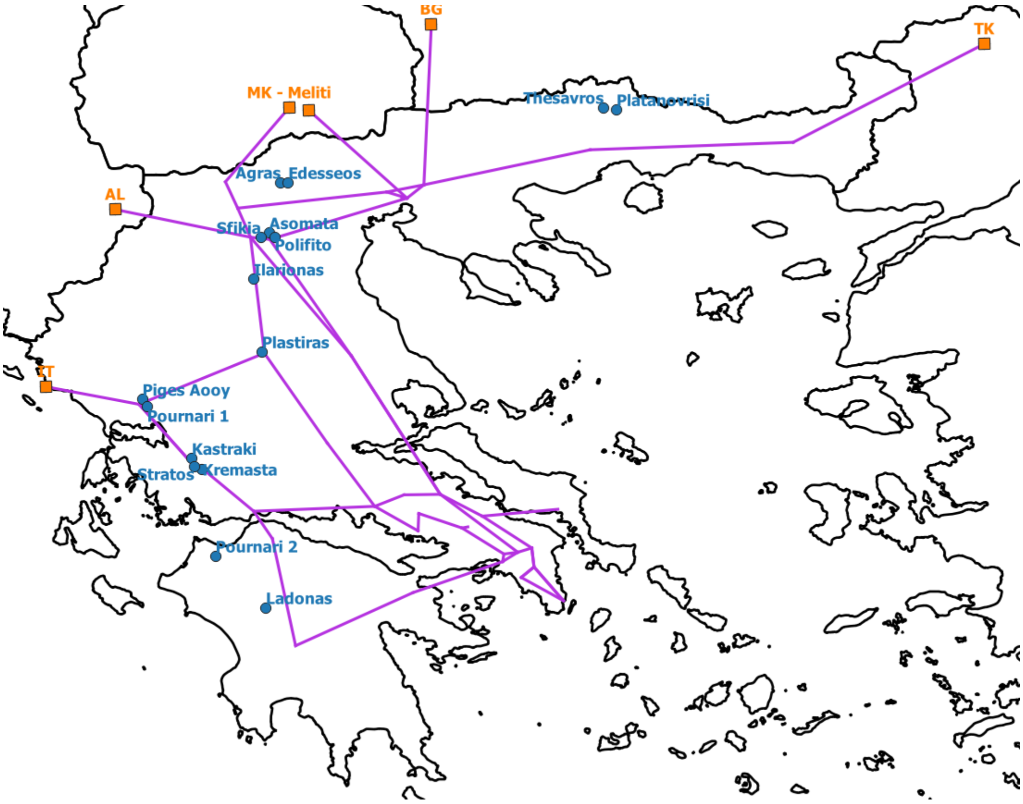
[22] https://transparency.entsoe.eu/dashboard/show.

Table 5. Technical features of the Greek hydro generating units.

| Name | Fuel type | Installed capacity (MW) | Min stable level (MW) | Min Up Time (h) | Min Down Time (h) | Ramp-up rate (MW/min) | Ramp-down rate (MW/min) |
|---|---|---|---|---|---|---|---|
| SFIKIA | Hydro Pumped Storage | 315.0 | 24.6 | 1 | 1 | 7.5 | 4.7 |
| THESAVROS1 | Hydro Pumped Storage | 384.0 | 46.5 | 1 | 1 | 1.1 | 5.8 |
| AGRAS | Hydro Run-of-river and poundage | 50.0 | 10.0 | 5 | 1 | 5.6 | 0.8 |
| EDESSAIOS | Hydro Run-of-river and poundage | 19.0 | 3.8 | 5 | 1 | 4.5 | 0.3 |
| ASOMATA | Hydro Water Reservoir | 108.0 | 22.8 | 1 | 1 | 3.6 | 1.5 |
| KASTRAKI | Hydro Water Reservoir | 320.0 | 39.7 | 1 | 1 | 4.0 | 4.5 |
| KREMASTA | Hydro Water Reservoir | 437.0 | 22.7 | 1 | 1 | 6.1 | 5.7 |
| P_AOOU | Hydro Water Reservoir | 210.0 | 26.0 | 1 | 1 | 4.7 | 2.9 |
| PLASTIRAS | Hydro Water Reservoir | 130.0 | 27.4 | 1 | 1 | 6.1 | 1.8 |
| POLYFYTO | Hydro Water Reservoir | 375.0 | 46.5 | 1 | 1 | 5.7 | 5.3 |
| POURNARI1 | Hydro Water Reservoir | 300.0 | 37.2 | 1 | 1 | 17.3 | 4.2 |
| STRATOS1 | Hydro Water Reservoir | 150.0 | 31.7 | 1 | 1 | 4.4 | 2.1 |
| ILARIONAS | Hydro Water Reservoir | 154.0 | 19.1 | 1 | 1 | 3.9 | 2.2 |
| PLATANOVRYSI | Hydro Water Reservoir | 116.0 | 24.5 | 1 | 1 | 7.7 | 1.6 |
| LADONAS | Hydro Water Reservoir | 70.0 | 14.8 | 1 | 1 | 4.4 | 1.0 |
| POURNARI2 | Hydro Water Reservoir | 34.0 | 7.2 | 1 | 1 | 12.7 | 0.5 |

Source: JRC-PPDB (Kanellopoulos et al., 2017).

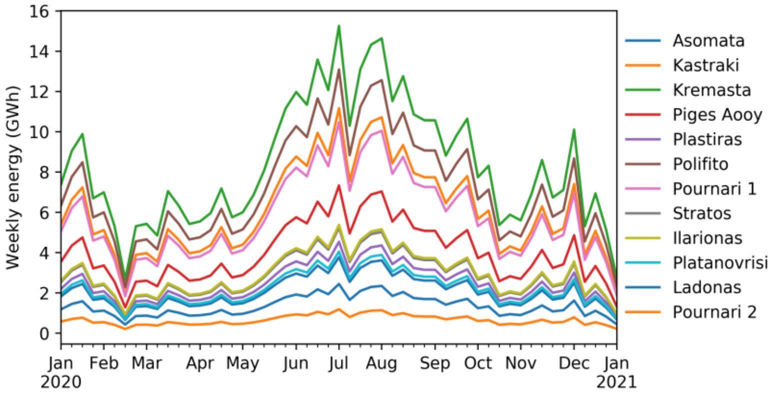
Figure 11. Location of the hydro generating units in the Plexos' model.




Source: JRC.

For the hydro reservoir units, we limit the energy generation per week to the observed values in the year 2020. Maximum weekly energy values can be derived from the hourly aggregated data that can be found in the ENTSO-E transparency platform. We assume that the weekly energy values for individual plants are scaled down according to the installed capacity of the power plant.

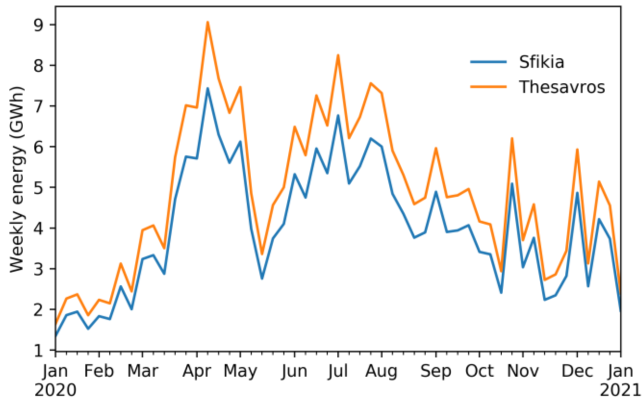
Figure 12. Weekly energy values for hydro reservoir units in the Plexos' model.




Source: ENTSO-E, JRC's analysis.

The pumped-storage hydropower units are modelled by using a generic generator class and two storage objects to model the upper and lower reservoir of the storage system. To do that, we need to define two additional parameters compared to the hydro reservoir generators, namely the pump efficiency and pump load. Due to lack of data, we assume that the pump efficiency is 80 % and the pump load is equal to the installed capacity of the power plant. Additionally, we model minimum energy generation constraints to impose the utilisation rates of the pumped-storage units during 2020, which can be seen in Figure 13.

Figure 13. Weekly energy values for pumped-storage hydropower units in the Plexos' model.




Source: ENTSO-E, JRC's analysis.

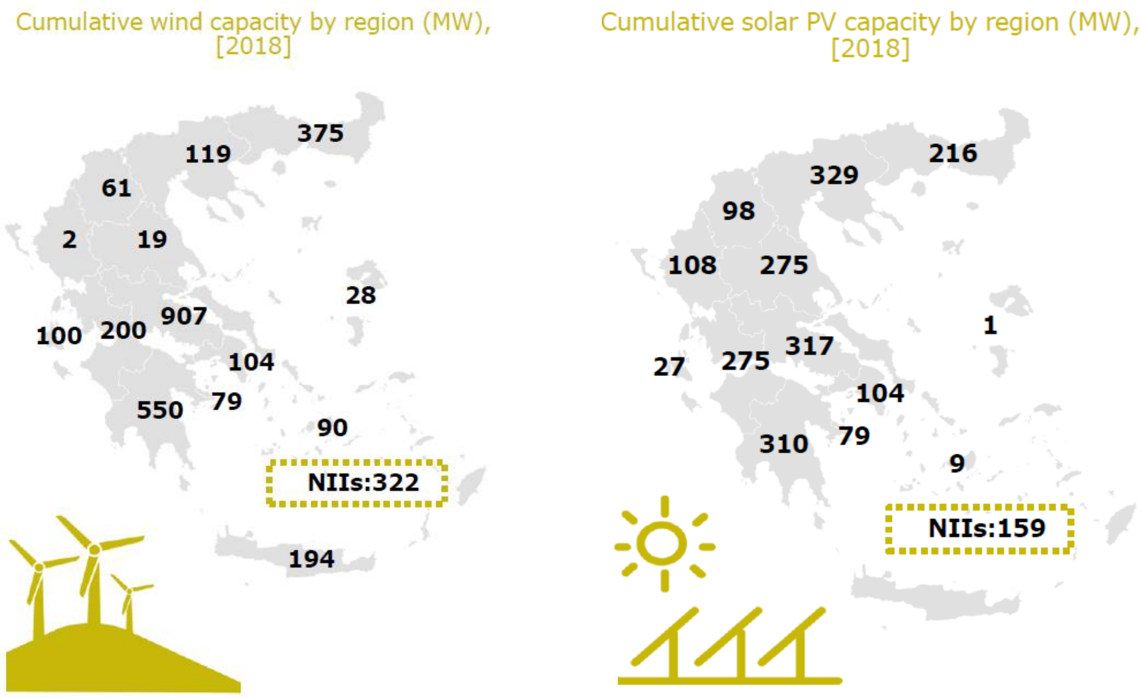
Finally, run-of-river generators are assumed to work at 30 % of their corresponding rated capacity due to lack of data in the ENTSO-E transparency platform. However, this can be easily fine-tuned.

## 6.2 Wind and photovoltaic generating units

Wind and photovoltaic generating units are modelled deterministically in Plexos, i.e., we assume that the renewable production is known in advance and therefore we neglect the stochastic nature of the renewable energy sources. The total installed capacity for PV and wind generating units, amounts to 2 148 and 2 828 MW, respectively, without accounting for the capacity in the non-interconnected islands (NIIs). We aggregate the renewable generating units at NUTS 2 level. The most up-to-date data can be found in Figure 14 (HAEE, 2019), although these values have increased in the last couple of years. For the sake of simplicity, we aggregate the capacity of North and South Aegean in the Crete region, and the one in Epirus and Ionian

Islands is accumulated in Western Greece. This gives rise to the installed capacity provided in Table 6. The location of each cluster can be seen in Figure 15.

Figure 14. Cumulative wind and solar installed capacity at NUTS2 level in 2018.



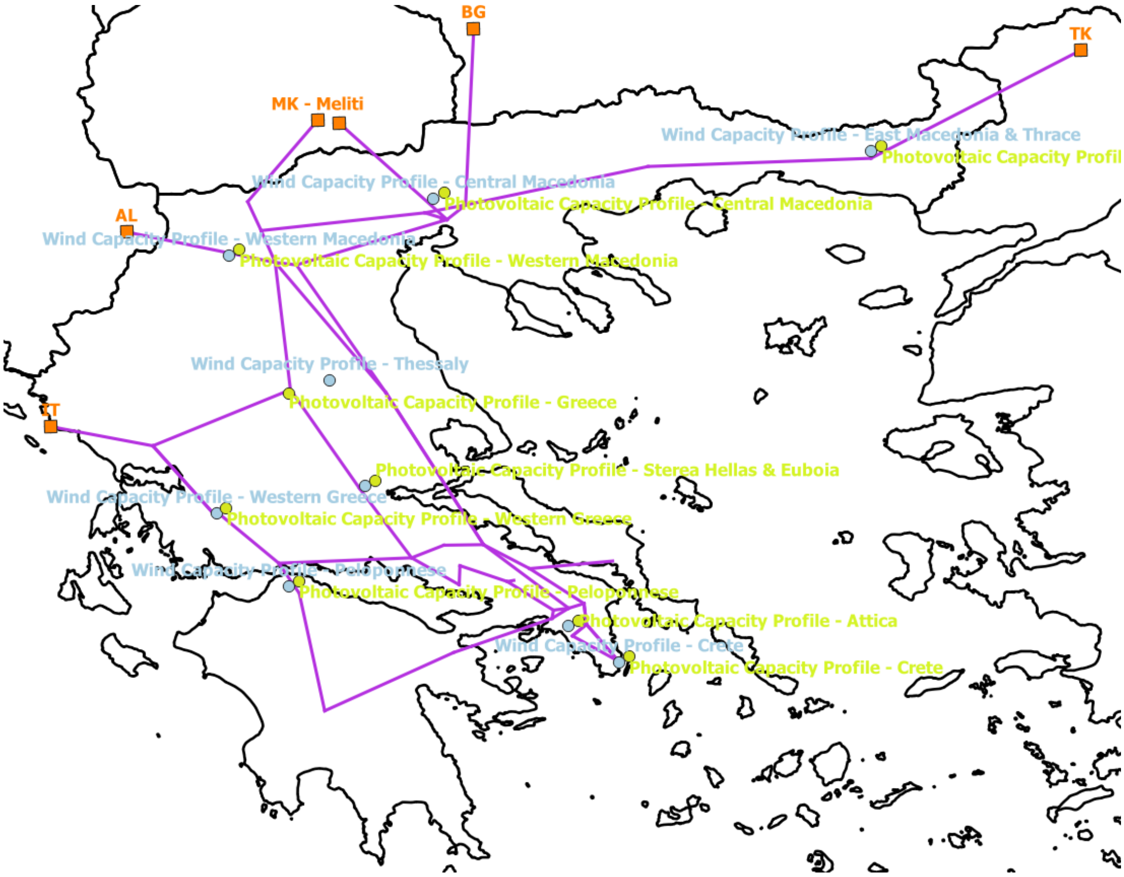

Source: (HAEE, 2019)

Table 6. Renewable (wind and solar) installed capacity.

| Name | Fuel type | Installed capacity (MW) |
|---|---|---|
| Photovoltaic Capacity Profile - Greece | Solar | 275 |
| PV - Attica | Solar | 183 |
| PV - Central Macedonia | Solar | 329 |
| PV - Crete | Solar | 10 |
| PV - Peloponnese | Solar | 310 |
| PV - Sterea Hellas & Euboia | Solar | 317 |
| PV - Western Greece | Solar | 410 |
| PV - Western Macedonia | Solar | 98 |
| PV- East Macedonia & Thrace | Solar | 216 |
| Wind Capacity Profile - Attica | Wind | 183 |
| Wind Capacity Profile - Central Macedonia | Wind | 119 |
| Wind Capacity Profile - Crete | Wind | 312 |
| Wind Capacity Profile - East Macedonia & Thrace | Wind | 375 |
| Wind Capacity Profile - Peloponnese | Wind | 550 |
| Wind Capacity Profile - Sterea Hellas & Euboia | Wind | 907 |
| Wind Capacity Profile - Thessaly | Wind | 19 |
| Wind Capacity Profile - Western Greece | Wind | 302 |
| Wind Capacity Profile - Western Macedonia | Wind | 61 |

Source: (HAEE, 2019).

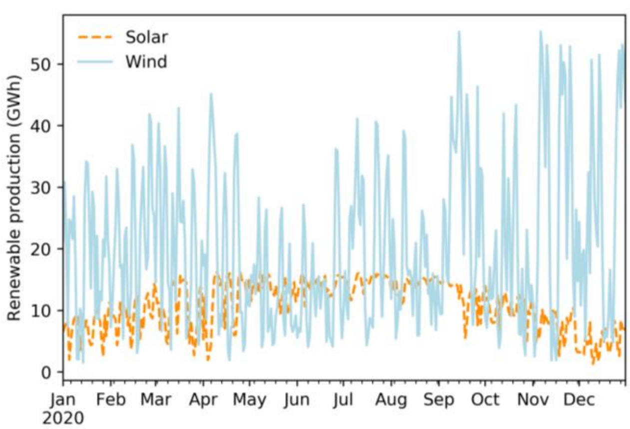
Figure 15. Location of the aggregated wind and solar generating units in the Plexos' model.




Source: Platts, (HAEE, 2019), JRC's analysis.

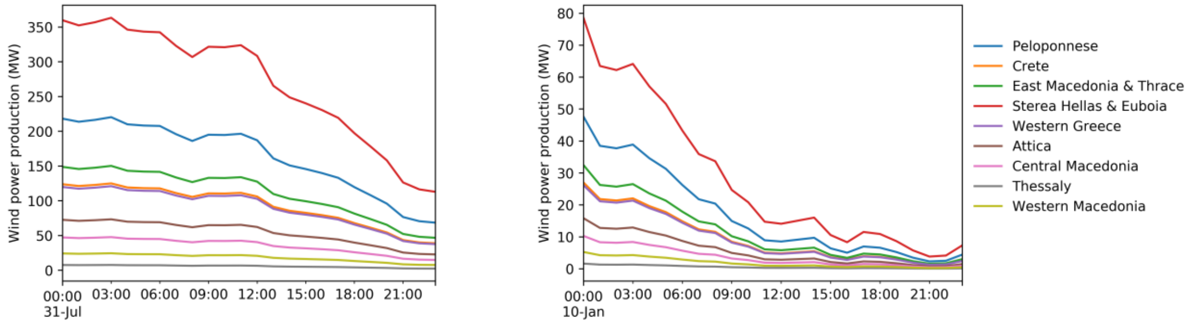
In the Plexos' model, we assume the hourly renewable generation provided by the ENTSO-E transparency platform, whose daily values are shown in Figure 16. In 2020, both solar and wind energy sources produced 11.4 TWh, which represented almost 30 % of the total electricity generation. The corresponding annual capacity factors for the aggregated solar and wind power plants in 2020 were 20 % and 31 %, respectively. The wind generation availability factor in each cluster is assumed equal to the total wind generation profile divided by the total wind installed capacity. Likewise, the solar generation availability factor in each cluster is assumed equal to the solar generation profile divided by the accumulated solar installed capacity. As an example, Figure 17 shows the wind generation profiles of each cluster for the peak electricity and gas days, while Figure 18 shows the solar generation profiles of each cluster for the same days.

Figure 16. Daily solar and wind production in Greece in 2020.



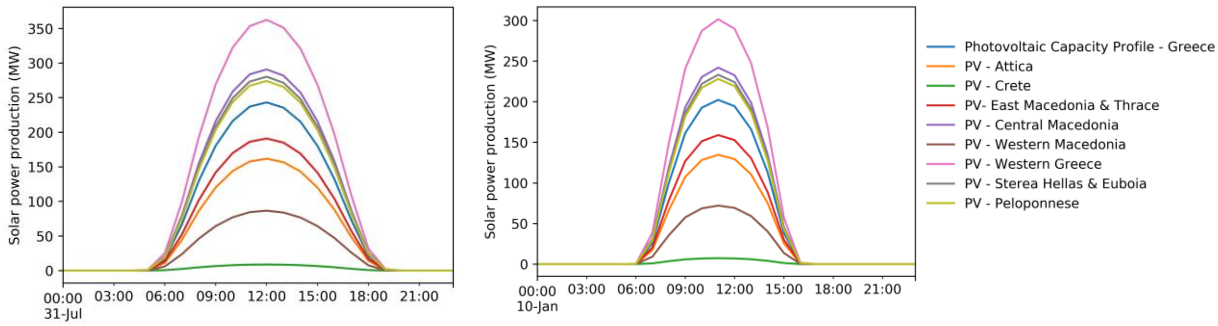

Source: ENTSO-E, JRC's analysis.

Figure 17. Wind power production for the peak electricity day (left plot) and peak gas day (right plot). Note that the scales of the y-axes are different.




Source: ENTSO-E, JRC's analysis.

Figure 18. Solar power production for the peak electricity day (left plot) and peak gas day (right plot). Note that the scales of the y-axes are different.

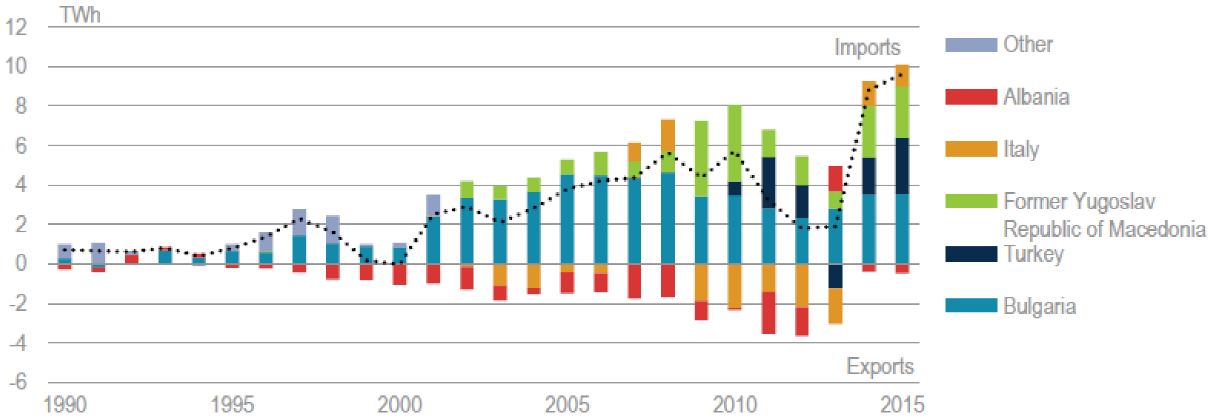



Source: ENTSO-E, JRC's analysis.

# 7 Cross-border interconnections

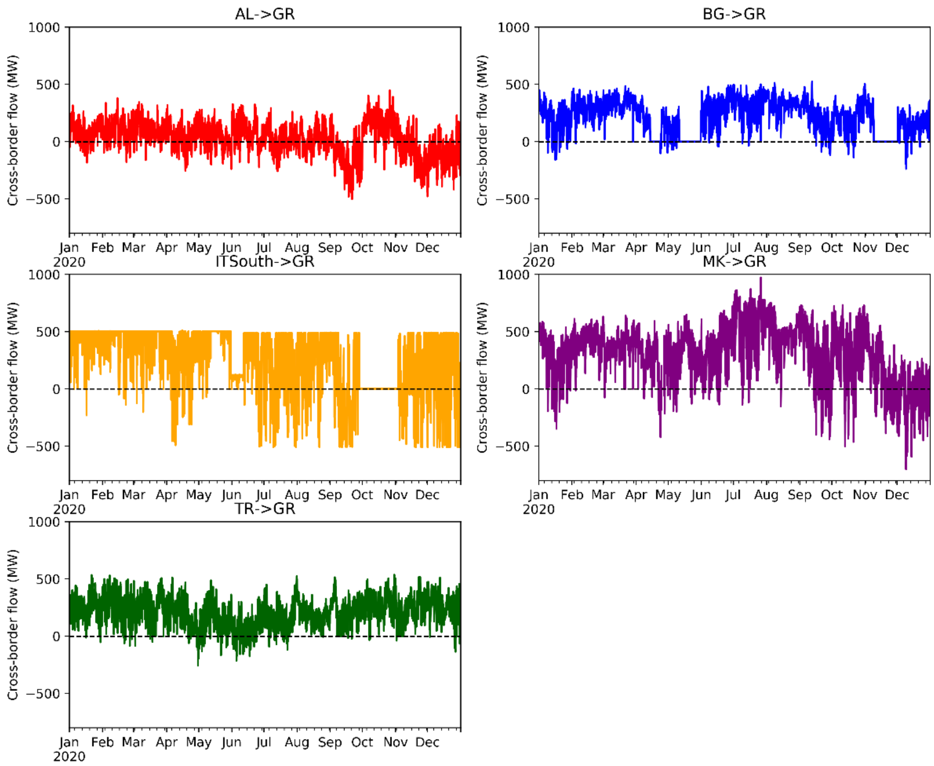
Greece shares electric borders with five countries: Bulgaria (1 line of 400 kV), North Macedonia (2 lines of 400 kV), Albania (1 line of 400 kV and 1 line of 150 kV), Italy (1 HVDC line of 400 kV) and Turkey (1 HVDC line of 400 kV). As can be seen in Figure 19, the electricity trade has become increasingly active in the last decade, being Greece a net importer of electricity. Figure 20 represents the evolution of the cross-border flows with the five countries in 2020. Positive values are electricity imports while negative values represent electricity exports. Accumulated figures are shown in Figure 21. Almost 56 % of all imports (9.6 TWh) come from Italy and North Macedonia, while the remaining is imported from Bulgaria, Turkey and, to a lesser degree, Albania. Electricity exports from Greece amounts only to 0.9 TWh during the year 2020 and Greece exports electricity mainly to Albania (43 %), Italy (35 %) and North Macedonia (19 %).

Figure 19. Electricity imports and exports by source for years 1990-2015.



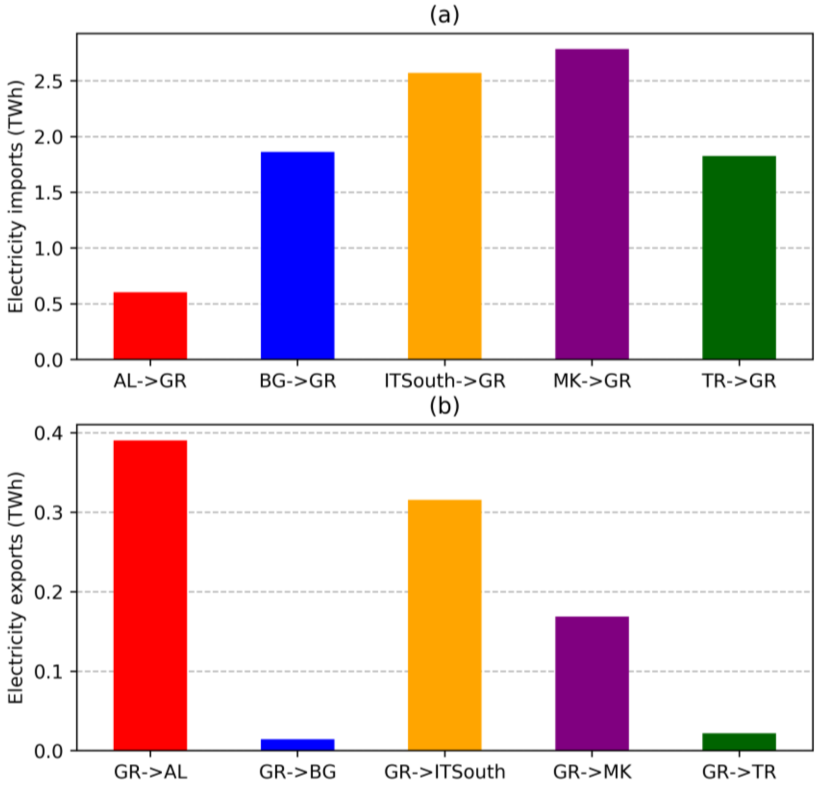

Source: (IEA, 2017)

Figure 20. Cross-border electricity flows in Greece in the year 2020.




Source: ENTSO-E, JRC's analysis.

Figure 21. Electricity imports (a) and exports (b) in Greece in 2020.




Source: ENTSO-E, JRC's analysis.

The cross-border imports (CBIs) can be modelled as dummy generators in Plexos, wherein the maximum capacity and the import prices are required. In Table 7, the second column provides the 99 percentile of the transmission trading capacity time series provided by the ENTSO-E transparency platform. The 99 percentile is considered in order to avoid outliers. The third column shows the values assumed in the model for the maximum capacity of the corresponding generator object. Note, however, that two cross-border interconnections are considered in the border with North Macedonia, as can be seen in Figure 3. The same transmission power capacity is assumed for each interconnection with North Macedonia, i.e., 380 MW each. The cross-border exports are also accounted for in the model while ensuring that, for each interconnection, the imports and exports do not occur simultaneously.

Table 7. Transmission power capacity for the cross-border interconnections in the Greek electricity system.

| Cross-border interconnections | Transmission trading capacity ENTSO-E data in 2020 (MW)[23] | Transmission power capacity (MW) |
|---|---|---|
| **Greece - Albania** | 295.0 | 300 |
| **Greece - Bulgaria** | 460.2 | 500 |
| **Greece - Italy** | 505.0 | 500 |
| **Greece – North Macedonia** | 758.0 | 760 |
| **Greece - Turkey** | 468 | 500 |

Source: ENTSO-E, JRC's analysis.

[23] This is the 99 percentile of transmission trading capacity provided by the transparency platform of ENTSO-E.

# 8 Economic- and emission-related data for the electricity system model

Fuel price for lignite is set to 1.1 €/GJ, as assumed in the TYNDP scenarios (ENTSO-E and ENTSOG, 2019). Fuel price for natural gas is not required to be defined in Plexos when running an integrated electricity and gas model. Regarding the emission-related data, the emission factors for lignite and natural gas are considered, respectively, equal to 0.262 and 0.1125 $tCO_2$/GJ (Hernández et al., 2019). The carbon price is set to 19.7 €/$tCO_2$, as assumed in the National Trends scenario in Figure 34 of the TYNDP 2020 report (ENTSO-E and ENTSOG, 2019). The carbon price needs to be updated for conducting studies in 2021 or analyses in future energy scenarios since this price is expected to increase. Finally, operation and maintenance (O&M) costs for all type of generators are provided in Table 8 based on the Energy Technology Reference Indicator (ETRI) report (Carlsson et al., 2014).

Table 8. Operation and maintenance costs per type of fuel.

| Fuel type | O&M cost (€/MWh) |
|---|---|
| Gas | 2 |
| Lignite | 4.5 |
| Hydro | 3 |
| Hydro run-of-river | 5 |

Source: ETRI (Carlsson et al., 2014).

# 9 Greek natural gas system

This section describes the Greek natural gas system including the natural gas network, natural gas demand, and cross-border entry points. Modelling assumptions and data used for the simulations are described in each section.

## 9.1 Natural gas network

The Greek transmission network[24] consists of 512 km of high pressure trunk pipeline with a design pressure of 70 bar-g and 953.2 km of additional transmission branches. The transmission system extends from the Greek-Bulgarian border at Promachonas to Attica. The transmission branches connect the trunk transmission pipeline with the regions of Eastern Macedonia, Thrace, Thessaloniki, Platy, Volos, Trikala, Oinofyta, Antikyra, Aliveri, Korinthos, Megalopoli, Thisvi and Attica, supplying them with gas. Figure 22 shows the high-pressure natural gas transportation network of Greece.

The natural gas transmission system transports gas from the Greek-Bulgarian border (upstream TSO BULGARTRANSGAZ) and the Greek-Turkish border (upstream TSO BOTAS) to consumers in continental Greece and it consists of the following elements:

- The main gas transmission pipeline and its branches;
- The Border Metering Stations at Sidirokastro, near Serrers and at Kipi, near Evros River;
- The Compression Station at Nea Mesimvria, Thessaloniki;
- The Natural Gas Metering and Regulating Stations;
- The Natural Gas Control and Dispatching Centers at Patima Magoulas near Athens and at Nea Mesimvria near Thessaloniki;
- The Operation and Maintenance Centers of Sidirokastro Border Station, Northern Greece, Eastern Greece, Central Greece and Southern Greece; and
- The Remote Control and Communication System.

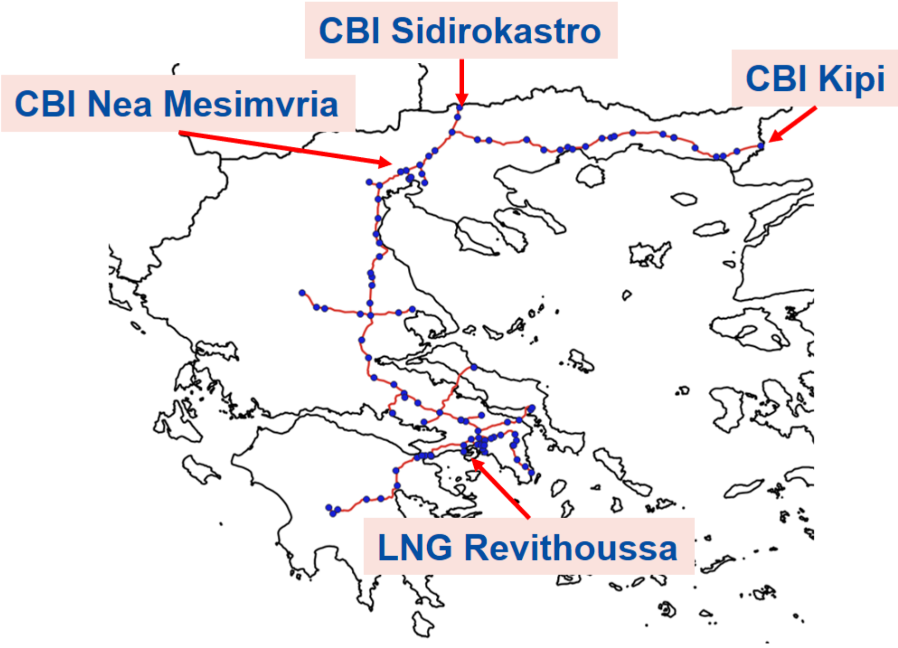
[24] https://www.desfa.gr/en/national-natural-gas-system/transmission.

Figure 22. High-pressure natural gas transportation network of Greece.


Source: DESFA.

The model in Plexos also represents the high-pressure natural gas network of Greece consisting of 112 gas nodes and 112 gas pipelines (see Figure 23). There are four entry points to the Greek natural gas network: Sidirokastro (Greek-Bulgarian border), Kipi (Greek-Turkish border), Nea Mesimvria (link between the Greek gas network to the Trans Adriatic Pipeline – TAP, not included in this model), and the LNG terminal, which is installed at Revithoussa island at Megara (located in the Attica region, southern Greece). In total, we consider 46 gas offtakes, of which 27 corresponds to city gate stations, 8 to industrial consumers, and 11 are linked to GFPPs. Note also that gas could flow from Greece to Bulgaria through Sidirokastro in reverse flow mode.

Figure 23. Greek natural gas network considered in the Plexos' model.




Source: JRC.

## 9.2 Natural gas demand

The natural gas demand has increased in the years 2019 and 2020 by 10 % and 14 %, respectively. This growth in the natural gas consumption is due to an increase of the gas for electricity production, as can be seen in Table 9. In 2020, there is also a noticeable increase of the gas demand for industrial purposes compared to previous years. Overall, the gas offtake for city gate stations represents a 20 % of the total gas consumption regardless of the year, while the share of gas for electricity production varies between 60-70 %.

Table 9. Natural gas demand (TWh) per type of consumer for years 2017-2020 and the first two months of 2021.

| Year | Distribution | Gas-fired power plants | Industrial | Cross-border exports | Total |
|---|---|---|---|---|---|
| **2017** | 10.4 | 35.8 | 6 | 0 | 52.2 |
| **2018** | 10.2 | 33.2 | 7.1 | 0 | 50.4 |
| **2019** | 11.1 | 37.4 | 6.8 | 0.2 | 55.5 |
| **2020** | 11.7 | 41 | 10.4 | 0.3 | 63.4 |
| **2021 (Jan-Feb)** | 3.7 | 6.1 | 2 | 0 | 11.8 |

Source: DESFA, JRC's analysis.

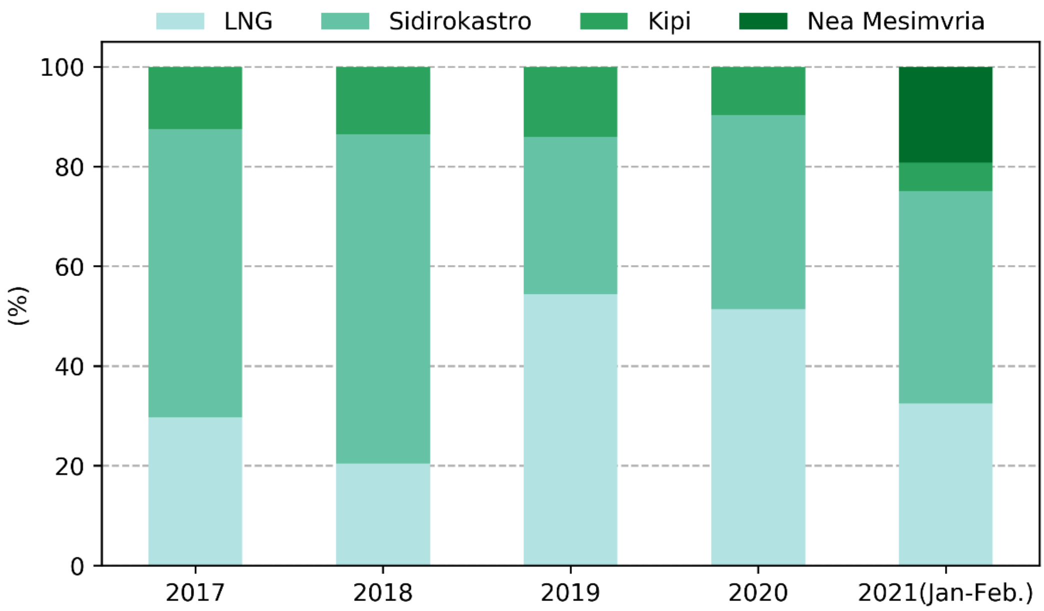
In Plexos, we model the natural gas demand deterministically. For validation purposes, we use the natural gas consumption of the year 2020, which can be found disaggregated in DESFA's website. As stated previously, we assume 11 gas offtakes for GFPPs, 8 big industrial consumers, and 27 city gate stations.

## 9.3 Entry points

The Greek natural gas network transports gas to consumers connected to the natural gas system in the Greek mainland from three entry points: Sidirokastro (Greek-Bulgarian border), Kipi (Greek-Turkish border), and the LNG terminal, which is installed at Revithoussa island at Megara (located in the Attica region, southern Greece). Upcoming infrastructure projects will increase security of gas supply in Greece and will transform Greece to a natural gas hub (HAEE, 2020). The interconnection point at Nea Mesimvria linking the Greek natural gas network to TAP has been completed and ready for commercial operations since the 21st of December 2020[25]. The TAP route will bring natural gas from Azerbaijan to Europe.

Figure 24 represents the share of gas delivered by each entry point for the period spanning from 2017 until February 2021. In the last two years, the LNG terminal supplies more than half of the total gas imported to the Greek natural gas system, representing 55 % and 51 % for years 2019 and 2020, respectively. This has been possible due to the storage capacity expansion of the LNG terminal. At the end of 2020, the new entry point of Nea Mesimvria was operational and it represents almost one fifth of the total imports in the first two months of 2021. The new upgrade in the LNG facility at Revithoussa made possible the flow of gas from Greece to Bulgaria in 2019 and 2020, however it represented a small share of the total gas demand, 0.3 % and 0.4 %, respectively.

Figure 24. Import entry points (%) for years 2017-2020 and first two months of 2021.




Source: DESFA, JRC's analysis.

The technical capacities of the cross-border entry points are shown in Table 10 in GWh/d and TJ/h. These capacities in TJ/h are used in the Plexos' model. LNG data is described in next section 9.3.1.

Table 10. Technical capacities of the cross-border entry points to the Greek natural gas system.

| Entry point | Technical capacity (GWh/d) | Technical capacity (TJ/h) |
|---|---|---|
| Sidirokastro | 122.6 | 18.4 |
| Kipi | 48.6 | 7.3 |
| Nea Mesimvria | 53.4 | 8.0 |

Source: DESFA.

### 9.3.1 Liquefied natural gas facility

The Revithoussa LNG terminal is located in southern Greece (Agia Triada), in the gulf of Pachi at Megara, 45 km west of Athens. This is the only LNG terminal in Greece that receives periodically LNG cargoes, stores the gas temporarily, and regasifies LNG and supplies the natural gas transmission system[26]. As stated by DESFA, the LNG terminal is an important energy asset for Greece, providing security of energy supply, operational flexibility in the transmission system and increased capability to meet peak gas demand. Currently, its storage capacity is 225 000 $m^3$ LNG and its sustained maximum sendout rate is 0.812 $Mm^3/h$ in normal conditions (0℃ and 1 bar-g).

[25] https://www.desfa.gr/en/announcements/nngs-users-information/diasyndesh-tap-desfa-xronodiagramma-enarjhs.
[26] https://www.desfa.gr/en/national-natural-gas-system/lng-facility.

DESFA has made significant investments in the energy infrastructure to enhance the reliability and uninterrupted operation of the natural gas system. In October 2007 and December 2018, the 1st and 2nd upgrading phases of the LNG terminal were completed respectively, ensuring an increased storage capacity of the terminal from 130 000 to 225 000 $m^3$ LNG and an increased LNG regasification capacity. Thanks to the storage capacity expansion, the diversification of LNG suppliers has also been increased, as can be seen in Table 11, thus increasing the energy security of supply. In 2018, LNG was delivered mainly by three countries: Algeria, Qatar and USA. In 2019, the number of suppliers was substantially increased and LNG came from 10 countries and the 70 % of the total LNG was delivered by Algeria, Norway, Qatar and Nigeria.

Table 11. LNG imports by Greece at Revithoussa LNG terminal in $Mm^3$ (2016-2019).

| LNG Origin: | 2016 | 2017 | 2018 | 2019 | (%) 2019 |
|---|---|---|---|---|---|
| Algeria | 671,677 | 1,185,933 | 796,266 | 513,098 | 19% |
| Norway | 77,975 | 50,313 | 0 | 514,449 | 19% |
| Egypt | 0 | 0 | 0 | 244,241 | 9% |
| Nigeria | 0 | 0 | 0 | 409,093 | 15% |
| Trinidad | 0 | 0 | 0 | 24,319 | 1% |
| Qatar | 0 | 158,858 | 79,963 | 483,373 | 18% |
| USA | 0 | 0 | 95,883 | 217,837 | 8% |
| France | 0 | 0 | 0 | 85,640 | 3% |
| Netherlands | 0 | 0 | 0 | 78,975 | 3% |
| Angola | 0 | 0 | 0 | 85,471 | 3% |
| Total: | **749,652** | **1,395,104** | **972,112** | **2,656,497** | **100%** |

Source: (RAE, 2020).

Table 12 provides the technical parameters of the LNG terminal in the Plexos' model. For converting volumetric units in normal conditions to energy units, we assume a gross calorific value (GCV) equal to the average value over the period from 01 January 2020 until 11 April 2021, which results in 11.374 $kWh/Nm^3$. The daily GCV can be downloaded from ENTSO-G transparency platform[27] for the corresponding LNG entry point. In addition, we also assume that $1m^3$ LNG is equal to 570 $m^3N$. Gas Infrastructure Europe (GIE), which is the association representing the interests of European gas infrastructure operators, makes available historical values of LNG inventory and sendout rates per day. Figure 25 illustrates the evolution of the LNG inventory throughout the year 2020. From these data, we can derive the initial volume of the LNG storage at the beginning of 2020, which is the year used for validation purposes, and a daily minimum bound of around 1150 TJ to avoid a complete discharge of the LNG storage. By using the LNG inventory and sendout rate, daily external injections can be computed in order to model the arrival of LNG cargoes. The daily values are distributed evenly throughout the 24 hours of the day. The total external injections amounted to 115 000 TJ in 2020.

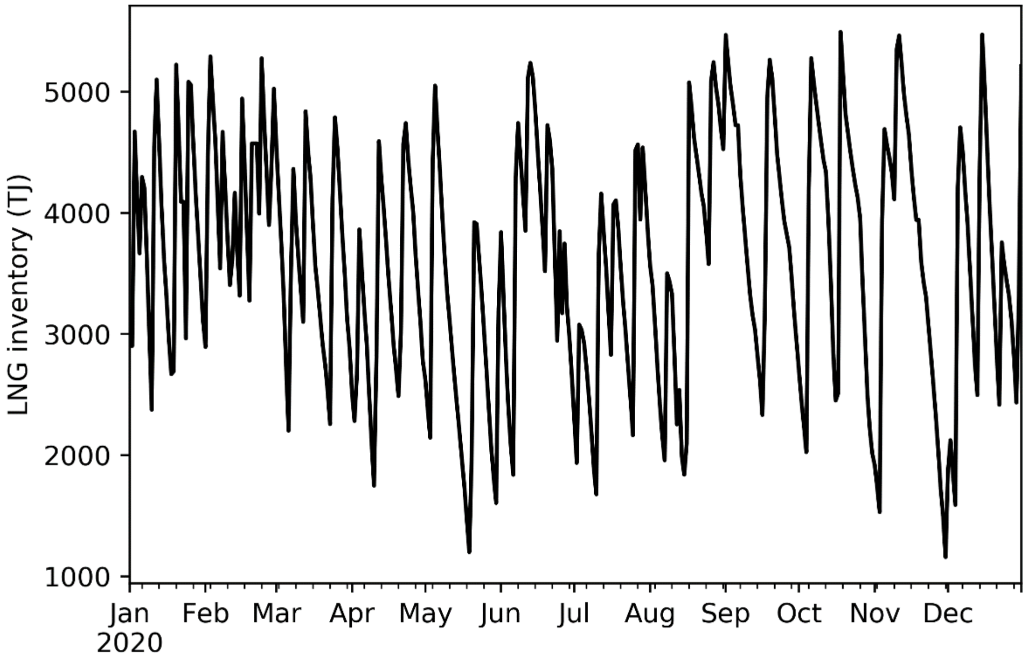
Table 12. Technical parameters of the LNG terminal.

| Parameter in Plexos | Value | Source |
|---|---|---|
| Maximum volume (TJ) | 5250.0 | DESFA |
| Maximum production per hour (TJ/h) | 33.25 | DESFA |
| Initial volume (TJ) at the beginning of 2020 | 2902.5 | GIE |
| Minimum volume per day (TJ/d) | 1150.0 | GIE |

Source: JRC.

[27] https://transparency.entsog.eu.

Figure 25. LNG inventory in the year 2020.




Source: GIE, JRC's analysis.

### 9.3.2 Economic data for entry points

The cross-border imports and LNG facility are modelled in Plexos by means of the "Gas Field" object, which requires essentially technical parameters to define the amount of gas that can be delivered to the natural gas network as well as production costs. The IHS Markit database[28] provides the monthly LNG import prices for Greece since 2010. Given the lack of import prices for the cross-border imports, we initially assume these LNG import prices as production costs for all CBIs. Subsequently, the production costs have been adjusted in the calibration phase and the resulting average values are shown in Table 13.

[28] https://ihsmarkit.com/products/data-information-services.html.

# 10 Validation of the Plexos' model

The year 2020 has been used for validating the model due to two main reasons. First, it is the year with the most up-to-date natural gas and electricity infrastructures for which data is available. Second, the electricity demand remained within acceptable operational limits compared to previous years despite the measures implemented due to the COVID-19 outbreak. The short-term operation of a joint natural gas and electricity system is run every day with hourly time periods and a 4-hour look-ahead window. We run the relaxed optimisation problem, i.e. binary variables are treated as continuous variables. The relaxed problem takes usually around three minutes to run a whole year. To adjust the model as much as possible to the figures in 2020, we adopt the following assumptions in the electricity system:

— Installed capacity of Protergia GFPP has not been upgraded yet. Thus its installed capacity is kept at 432.7 MW.

— Installed capacity of Megalopoli V is limited to 500 MW during the first 5 months of the year since the 400-kV network expansion of the Peloponnese Peninsula was not still implemented in the first semester of 2020. The capacity from June onwards is increased to 845 MW.

— Agios Dimitrios 5 is unavailable from 1 August 2020 until end of the year and Heron CC is scheduled off from 1 September 2020 until the end of the year, as can be checked in ENTSO-E transparency platform.

— Alouminio GFPP is kept at least at minimum power output for the whole year, which is the general behaviour observed during the year 2020.

From the natural gas system point of view, Nea Mesimvria entry point is considered unavailable.

The Plexos' model has been calibrated by means of various economic parameters. On the one hand, prices for the electricity imports and carbon price of $CO_2$ emissions have been modified in the electricity system. On the other hand, gas pipeline flow charges and average production costs for the natural gas imports via Kipi and Sidirokastron entry points as well as the LNG facility of Revithoussa have been adjusted in the natural gas system. The values for these parameters can be found in Table 13. The production costs for the entry points are fine-tuned so that the annual electricity generation of GFPPs and lignite-fired generating units as well as the annual gas deliveries through the three natural gas entry points are adjusted to the 2020 figures.

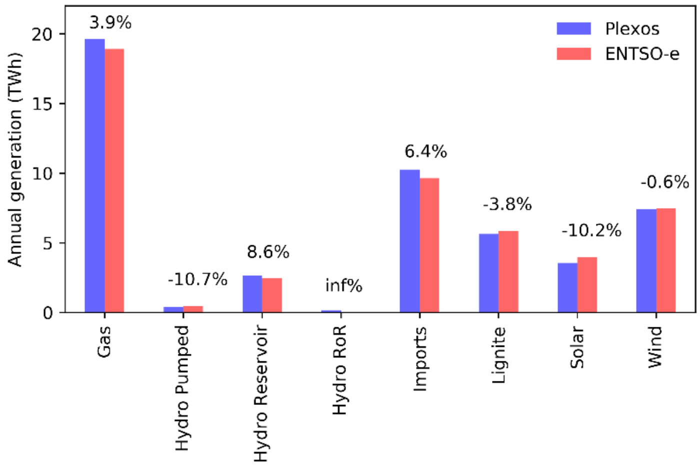
Table 13. Adjusted economic parameters to calibrate the Plexos' model.

| **Parameter** | | **Value** | **Units** |
|---|---|---|---|
| Carbon emission price | | 18.7 | €/ton $CO_2$ |
| Pipeline flow charge | | 0.21 | €/GJ |
| Fuel price for electricity imports | | 70.0 | €/GJ |
| Average production costs | Sidirokastro | 3.04 | €/GJ |
| | Kipi | 3.66 | €/GJ |
| | Revithoussa | 5.41 | €/GJ |

Source: JRC.

Figure 26 compares the results of the annual electricity generation for all fuel types (gas, hydro, lignite, solar, and wind) with the actual values provided by the ENTSO-E transparency platform. Also, annual electricity imports are included in the figure. Annual electricity generation of the fleet of gas, coal and wind generating units are well-adjusted to the values observed during 2020, i.e., the relative error is kept below 5 %. The largest relative errors are caused by the hydro pumped storage units and photovoltaic units (10 %), which are compensated by the increase in gas-fired power plants, imports, and hydro reservoir generating units during that year. The solar generation is unexpectedly lower than the actual figure in 2020, which means that there is a 10 % of solar curtailment. The reason of this curtailment relies on the underlying assumption of aggregating the solar generation at NUTS 2 level. This may cause an oversupply during certain periods of time, thus leading to the congestion of the 400-kV electricity network.

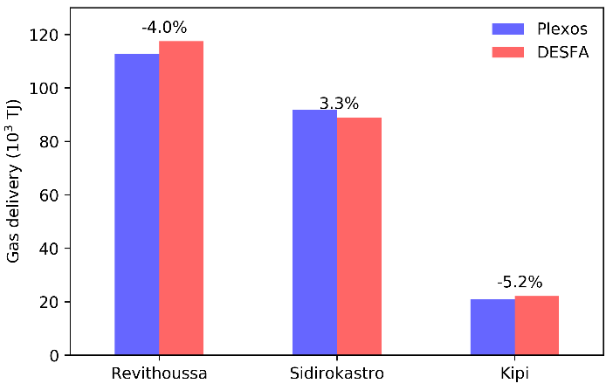
Figure 26. Annual electricity generation per fuel type and electricity imports. Comparison of the results from the Plexos' model with actual figures (ENTSO-E). The relative error in % is shown on top of each pair of bars.




Source: JRC.

Likewise, the annual gas deliveries for the three entry points of the Greek natural gas system are compared in Figure 27 against the actual values provided by DESFA, the natural gas transmission system operator of Greece. Bearing in mind that the natural gas demand for industrial customers and city gate stations is identical to the values in 2020, the natural gas offtake for electricity production computed by Plexos is slightly lower than the one given by DESFA. The main reason for this mismatch relies on the modelling of the heat rates of the GFPPs. Although we estimated quadratic or linear heat input functions from observed data, the heat rates vary considerably with the power output of the power plant and the previous operating conditions. In addition, other events may have led to the scheduling of less efficient GFPPs during certain periods of time, e.g. planned or unplanned outages, and thus leading to a higher gas consumption to produce the same amount of electricity.

Figure 27. Annual natural gas delivery for all entry points. Comparison of the results from the Plexos' model with actual figures (DESFA). The relative error in % is shown on top of each pair of bars.




Source: JRC.

All in all, the errors are within acceptable limits taking into account the underlying modelling assumptions. The relative error of the annual electricity generation per fuel type is kept below 11 % and that of the natural gas delivery at entry points is kept below 6 %. Annex 3 provides complementary figures such as the daily electricity generation profiles for thermal and hydro power plants, daily natural gas deliveries at all entry points, and the volume of gas at the Revithoussa LNG facility.

# 11 Conclusions

The current modelling research activities carried out by the Joint Research Centre of the European Commission in line with Regulation (EU) No 2017/1938 concerning measures to safeguard the security of gas supply comprise the identification of critical gas-fired power plants and the elaboration of risk assessments in interconnected natural gas and electricity systems. Greece has been identified as a suitable country to conduct such assessments due to the high interdependency between its electricity and natural gas sectors.

This report is focused on the description of the Greek electricity system model implemented in the software Plexos including the underlying modelling assumptions. Part of the data comes from publicly available sources, however other data rely on strong assumptions or on sensitive information which cannot be disseminated in this publicly-available report. The Greek natural gas system comprising the high-pressure natural gas network, the gas demand, and the cross-border entry points is also described. The results from the short-term operation of the Greek integrated electricity and natural gas system model are compared with the 2020 historical figures in order to validate the resulting Plexos' model.

The resulting model can be used to identify and analyse the critical gas-fired power plants under various disruption scenarios. Moreover, other studies can be conducted with the current model, e.g. national or regional risk assessments in countries with high interdependent gas and electricity sectors, in which the operation of the electricity system could be analysed in normal and stressed conditions.

The Greek electricity model could be further enhanced as follows:

- Weights for the nodal electricity demand can be recomputed based on the actual population of the corresponding geographical areas due to the lack of disaggregated electricity demand.
- Renewable installed capacity could be updated to current figures. However, regional values (NUTS 2 level) cannot be found for the last two years. In addition, it is crucial to account for the spatial variability of renewable generation which may be significant among different regions.
- Modelling of the hydrological topology may be included along with the electricity network. However, this would require additional input data such as energy or volumetric inflows.
- Planned and unplanned outages of thermal power plants could be also added to the model in order to refine the modelling results.

As a final recommendation, the Greek electricity system model, as with any other model, needs to be frequently revisited and updated to the latest infrastructure developments. In addition, reporting such updates is of great interest for maintaining a working model that can be readily used for future techno-economic analyses.

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## List of abbreviations

| | |
|---|---|
| AC | Alternate current. |
| ADMIE | The independent power transmission system operator in Greece. |
| CBI | Cross-border import. |
| CC | Combined cycle. |
| DC | Direct current. |
| DESFA | The Hellenic Gas Transmission System Operator. |
| ENTSO-E | European Network of Transmission System Operators for Electricity. |
| ENTSOG | European Network of Transmission System Operators for Gas. |
| ETRI | Energy Technology Reference Indicator. |
| EU | European Union. |
| GFPP | Gas-fired power plant. |
| HEDNO | Hellenic Electricity Distribution Network Operator. |
| HETS | Hellenic Electricity Transmission System. |
| IPTO | The independent power transmission system operator in Greece. |
| JRC | Joint Research Centre. |
| LNG | Liquefied natural gas. |
| NII | Non-interconnected islands. |
| NUTS | Nomenclature of Territorial Units for Statistics. |
| OC | Open cycle. |
| PPC | Public Power Corporation S.A. |
| RAE | Regulatory Authority for Energy in Greece. |
| TYNDP | Ten-Year Network Development Plan. |

## List of definitions

| | |
|---|---|
| **Installed capacity** | Maximum output of electricity that a power plant or generating unit can produce. Installed capacity, nameplate capacity or nominal power can be used interchangeably. |
| **Minimum stable level** | Minimum output of electricity at which a power plant or generating unit can be operated stably for unlimited time. |
| **Heat rate** | Inverse of the efficiency of the thermal power plants, i.e., it shows how many GJ of fuel are needed to generate one MWh of electricity. |
| **Minimum up time** | Minimum period of time that a power plant or generating unit must remain scheduled on once it is started up. This technical limitation is to prevent the wear of generating units due to multiple start-ups and shutdowns. |
| **Minimum down time** | Minimum period of time that a power plant or generating unit must remain scheduled off once it is shut down. This technical limitation is to prevent excessive generation start-ups and shutdowns, as similarly done by the minimum up time. |
| **Ramp-up rate** | Maximum increase in power output between two consecutive periods in which a power plant or generating unit is scheduled on. For the sake of simplicity, we assume that the start-up ramp rate, which is the maximum power output that can be generated by the power plant or generating unit when the unit is started up, is equal to the ramp-up rate. |
| **Ramp-down rate** | Maximum decrease in power output between two consecutive periods in which a power plant or generating unit is scheduled on. For the sake of simplicity, we assume that the shutdown rate, which is the maximum power output that can be generated by the power plant or generating unit prior to being shut down, is equal to the ramp-down rate. |

## List of figures

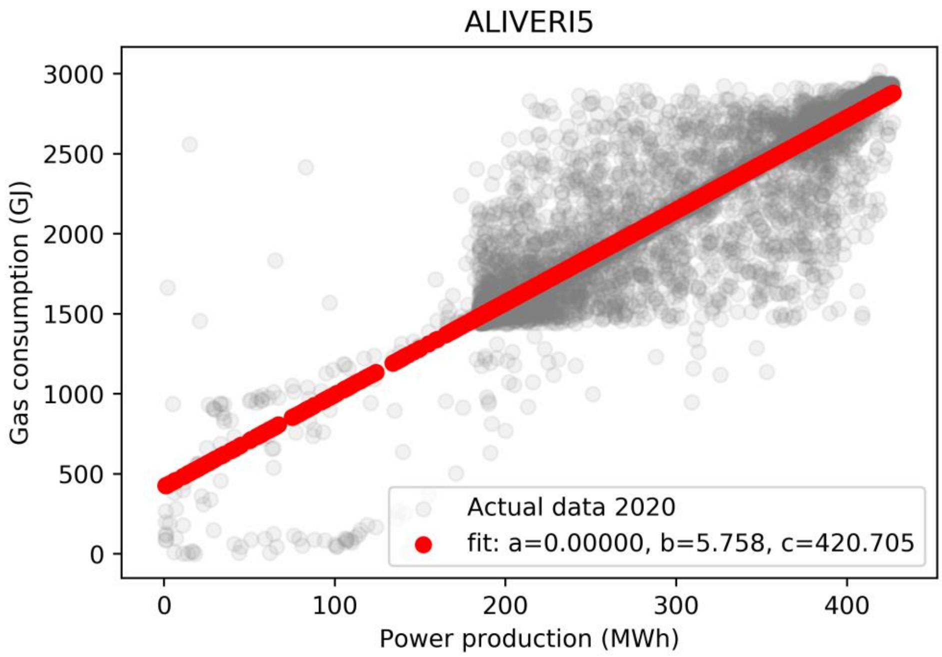
## List of tables

## Annexes

### Annex 1. Heat input function of gas-fired power plants

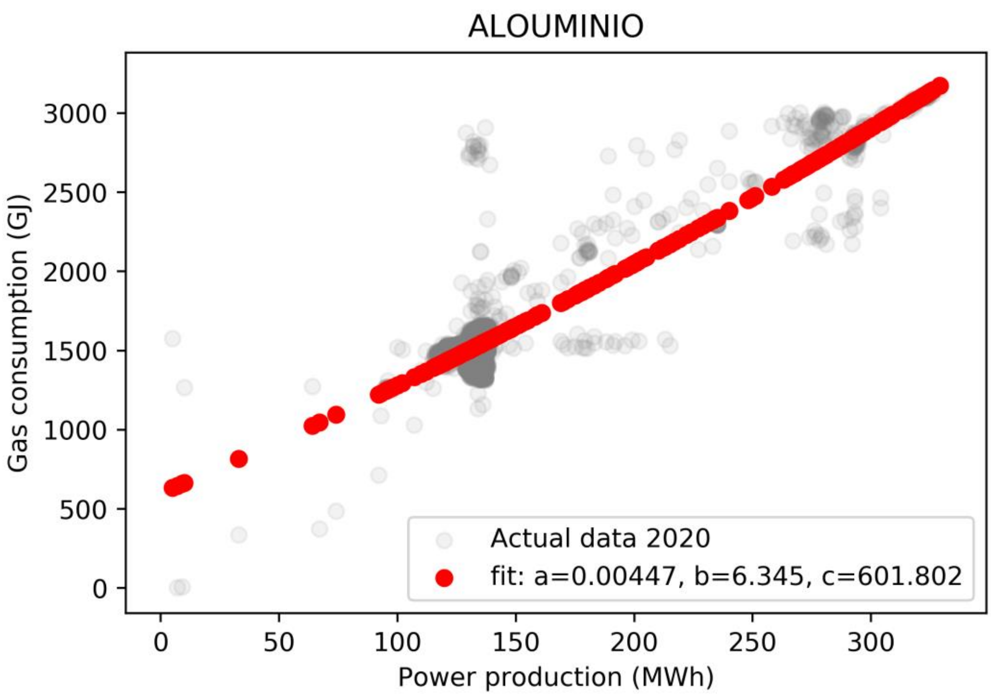
Figure 28-Figure 38 provide the fitting curve for the heat input function (in red) along with a scatter plot of the actual values of gas consumption and power production of each gas-fired power plant.

Figure 28. Heat input function of Aliveri 5.



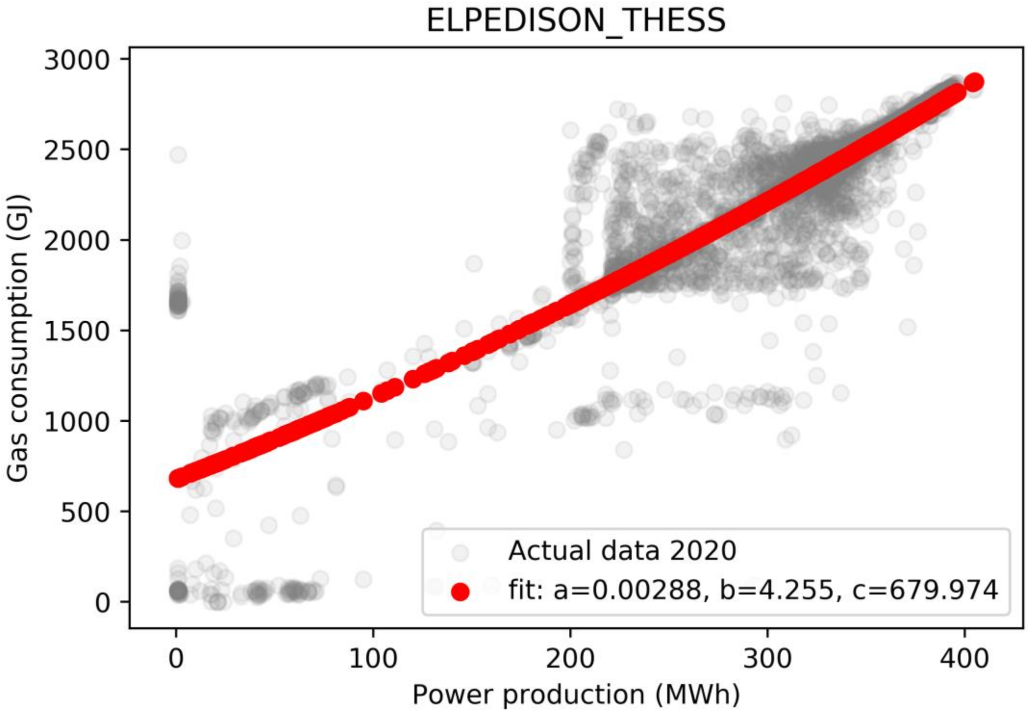

Source: JRC.

Figure 29. Heat input function of Alouminio.



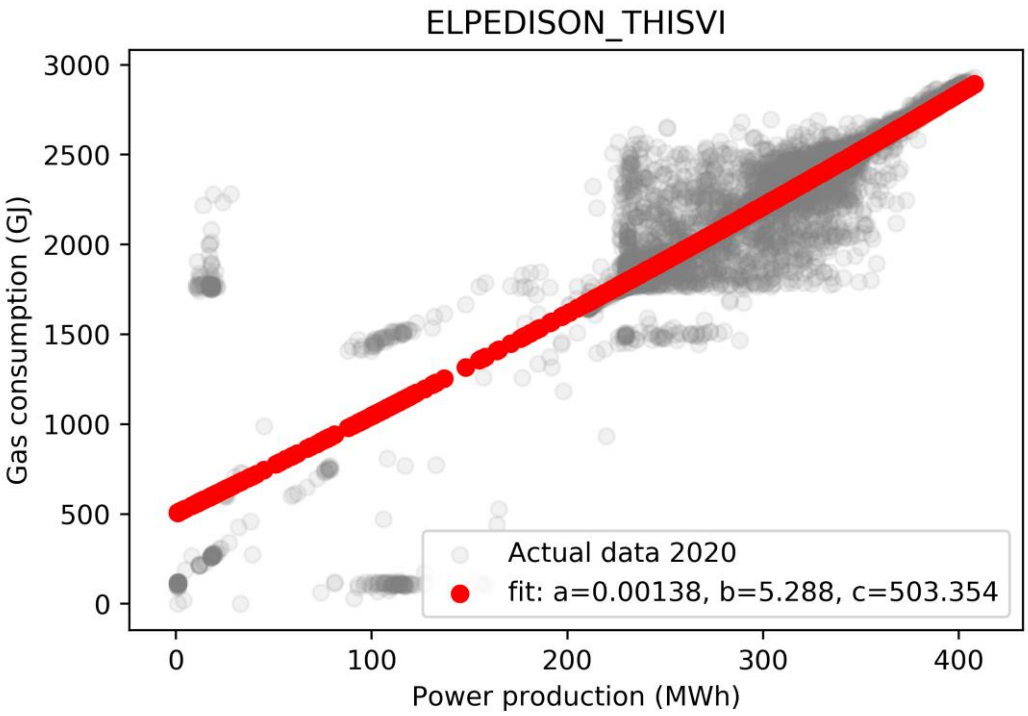

Source: JRC.

Figure 30. Heat input function of Elpedison_Thess.



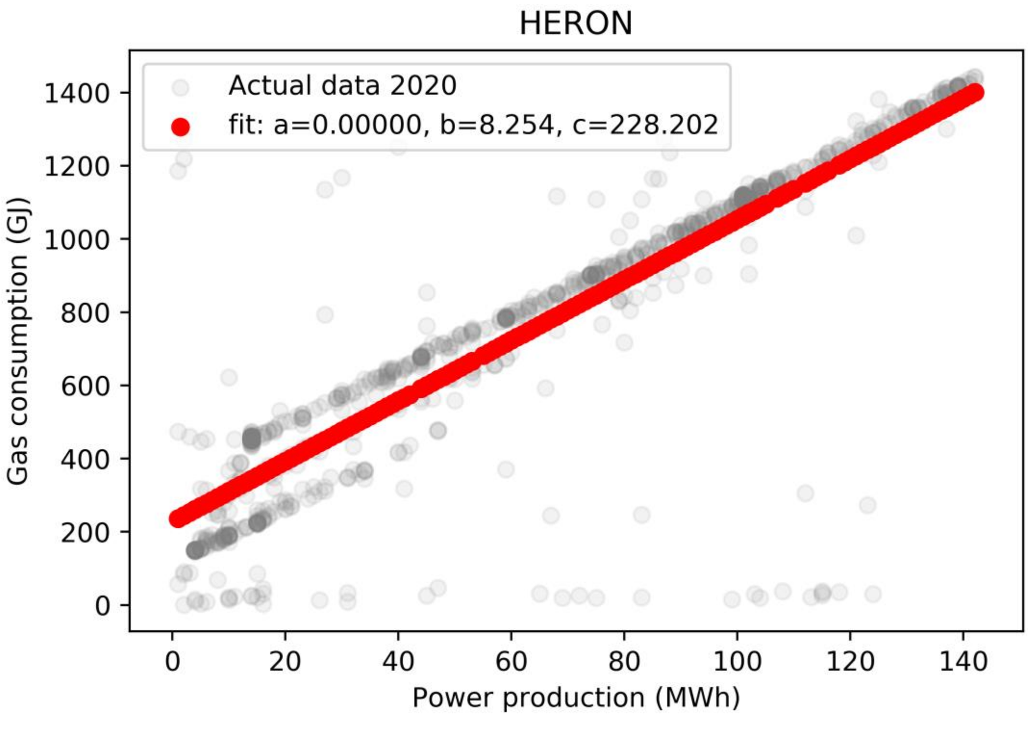

Source: JRC.

Figure 31. Heat input function of Elpedison_Thisvi.



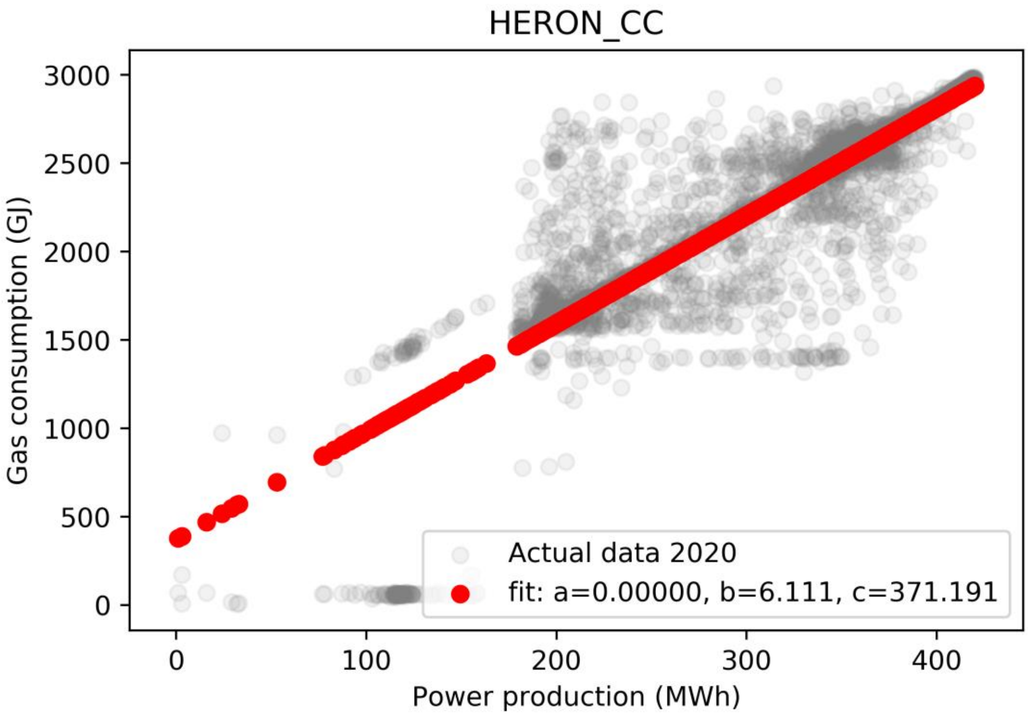

Source: JRC.

Figure 32. Heat input function of Heron.



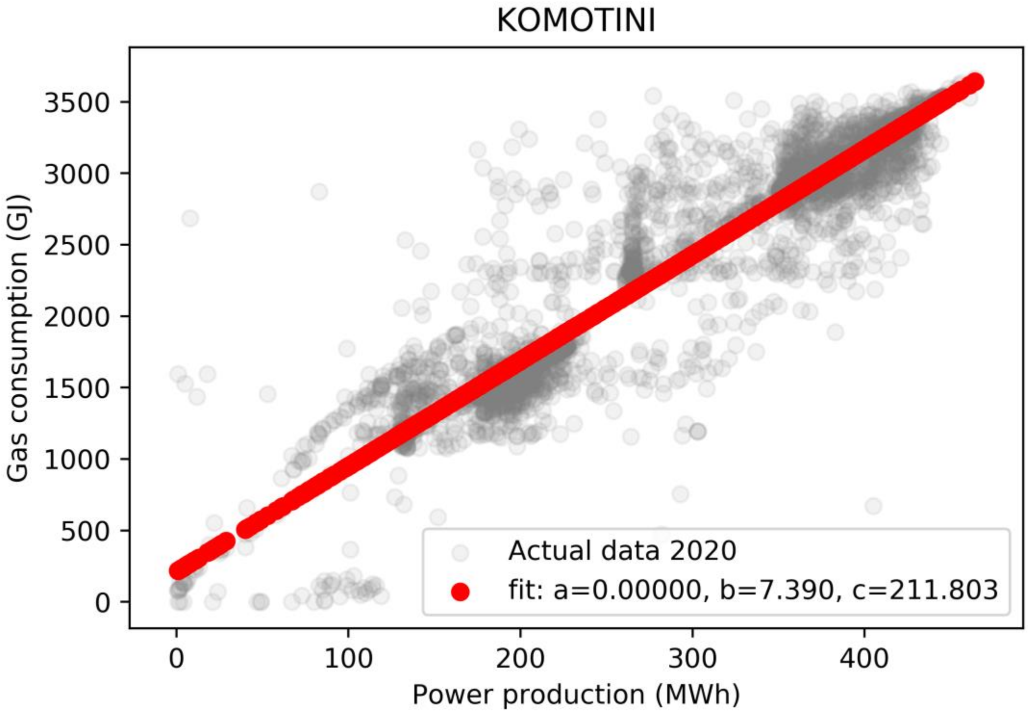

Source: JRC.

Figure 33. Heat input function of Heron CC.



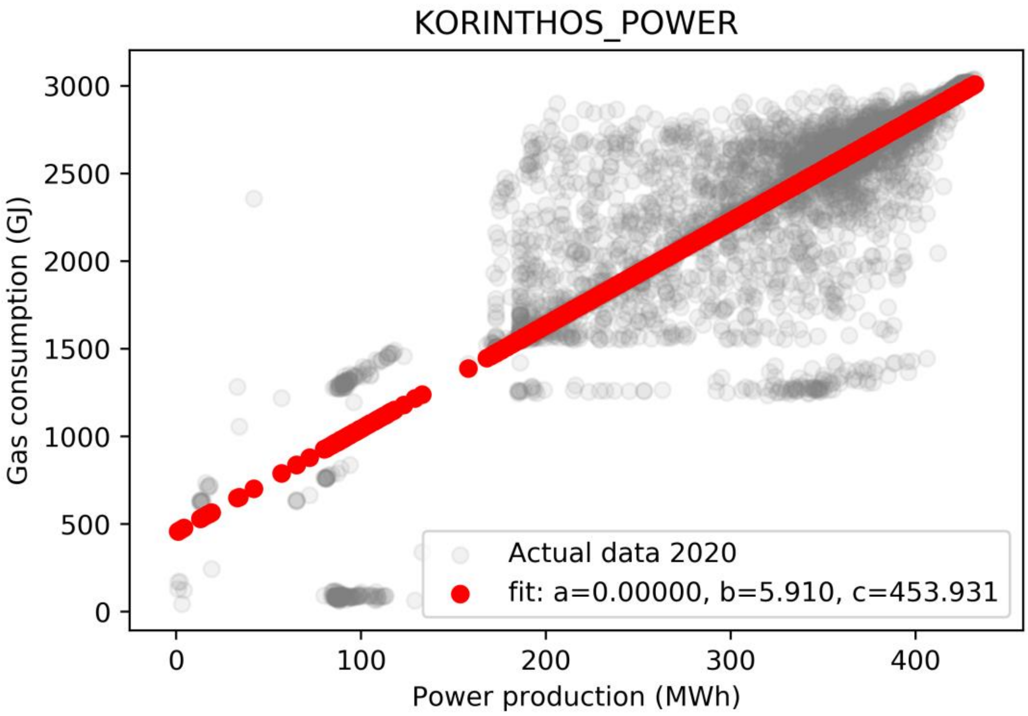

Source: JRC.

Figure 34. Heat input function of Komotini.



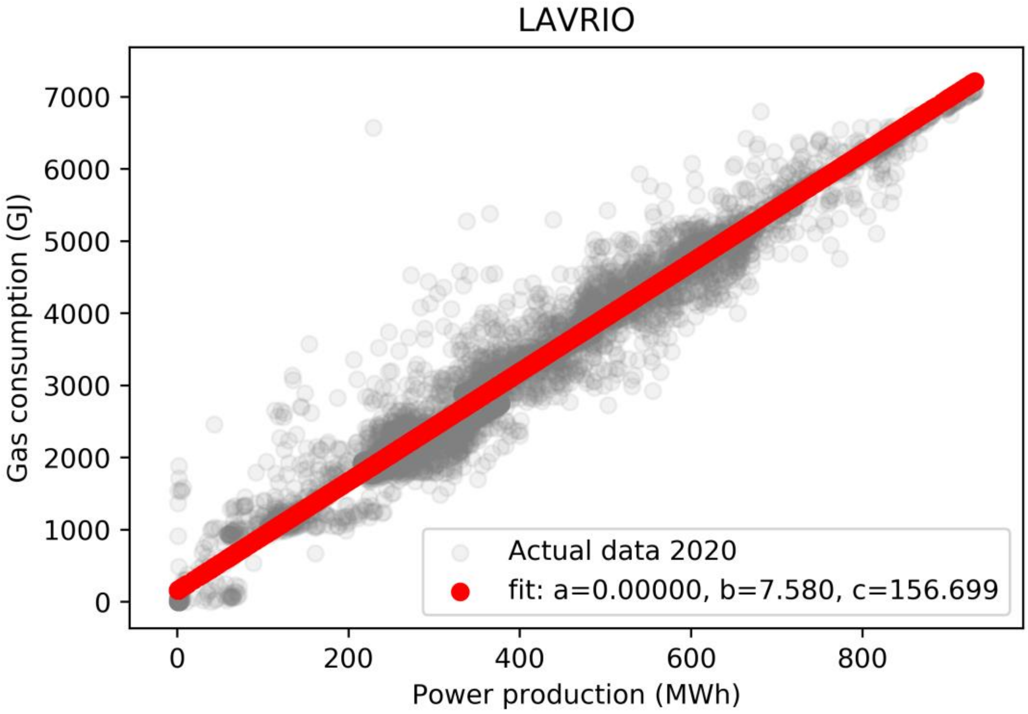

Source: JRC.

Figure 35. Heat input function of Korinthos Power.



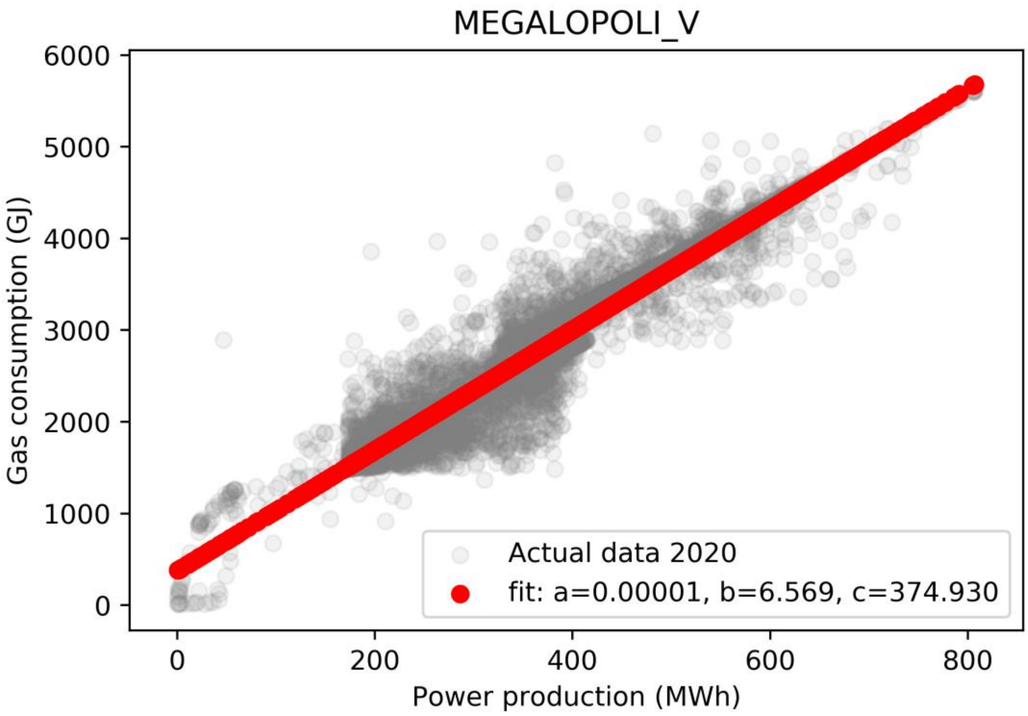

Source: JRC.

Figure 36. Heat input function of Lavrio.



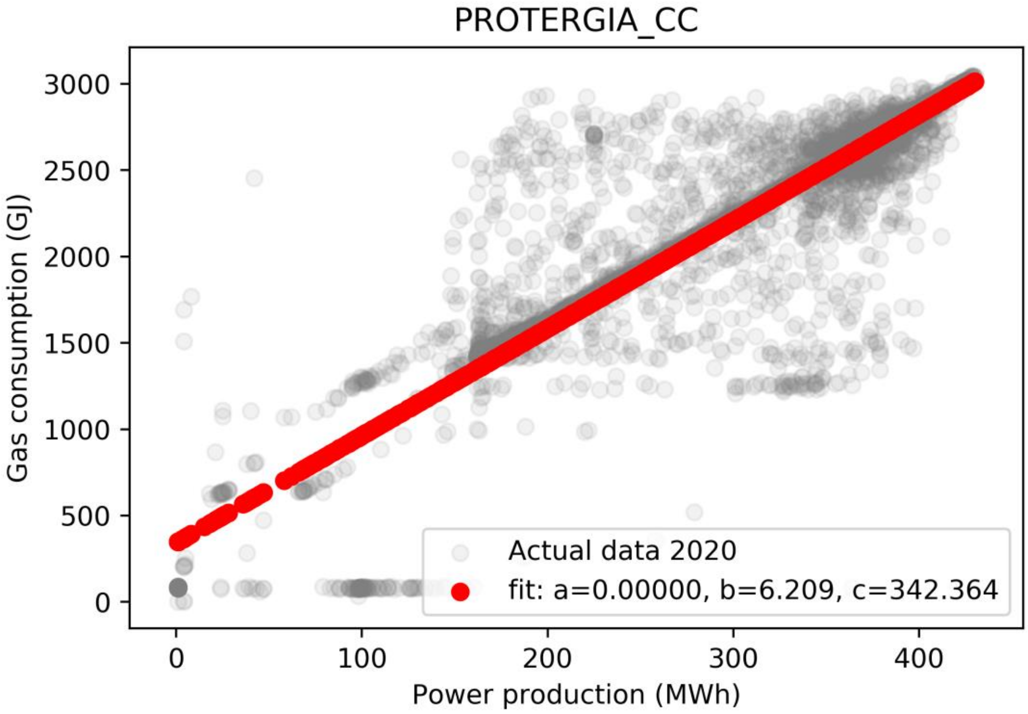

Source: JRC.

Figure 37. Heat input function of Megalopoli V.




Source: JRC.

Figure 38. Heat input function of Protergia CC.




Source: JRC.

## Annex 2. Data sources

Table 14 contains the main data sources and assumptions for the parameters used in the proposed model. The following sources of information have been used to set up the model:

- JRC: Data from previous limited distribution JRC reports (Cakir Erdener et al., 2015).
- Platts' database[29], which provides electric power market data.
- ADMIE[30].
- JRC-PPDB (Kanellopoulos et al., 2017).
- ENTSO-E, which is the European Network of Transmission System Operators for Electricity[31].
- TYNDP (ENTSO-E and ENTSOG, 2019).
- ETRI (Carlsson et al., 2014).
- HAEE (HAEE, 2019).
- DESFA[32].

Table 14. Main data sources and assumptions for the parameters used in the proposed model.

| Category | Parameter | Source | Notes |
|---|---|---|---|
| Electricity network | Reactance and resistance | JRC | Resistance and reactance are 0.000074 and 0.0006 p.u./km |
| | Topology of electricity network | Platts, ADMIE, JRC | - |
| Thermal and hydro power plants | Installed capacity | Platts, JRC-PPDB, ENTSO-E, JRC | - |
| | Heat rates of GFPPs | DESFA, ENTSO-E, JRC's analysis | Quadratic and linear heat rates are estimated |
| | Heat rates of remaining thermal plants | JRC-PPDB | - |
| | Minimum up and down times | JRC-PPDB | - |
| | Ramp rates | JRC-PPDB | - |
| | Minimum stable level | JRC-PPDB | - |
| | Fuel price lignite | TYNDP scenarios | - |
| | Operation & Maintenance costs | ETRI | - |
| | Emission factors for lignite and natural gas | (Hernández et al., 2019) | - |
| | Carbon price | TYNDP | National Trends scenario in Figure 34 of the TYNDP 2020 report. Although this parameter has been used for calibration purposes |
| Renewable generating units | Installed capacity | HAEE | Clusters at NUTS 2 level |
| | Availability factors | HAEE, ENTSO-E | -- |
| Electricity demand | Nodal electricity demand | ENTSO-E, JRC | |
| Cross-border interconnections in the electricity system | Electricity imports | ENTSO-E | 99 percentile of the transmission trading capacity |
| | Electricity exports | ENTSO-E | - |
| Gas demand | Gas demand | DESFA | - |

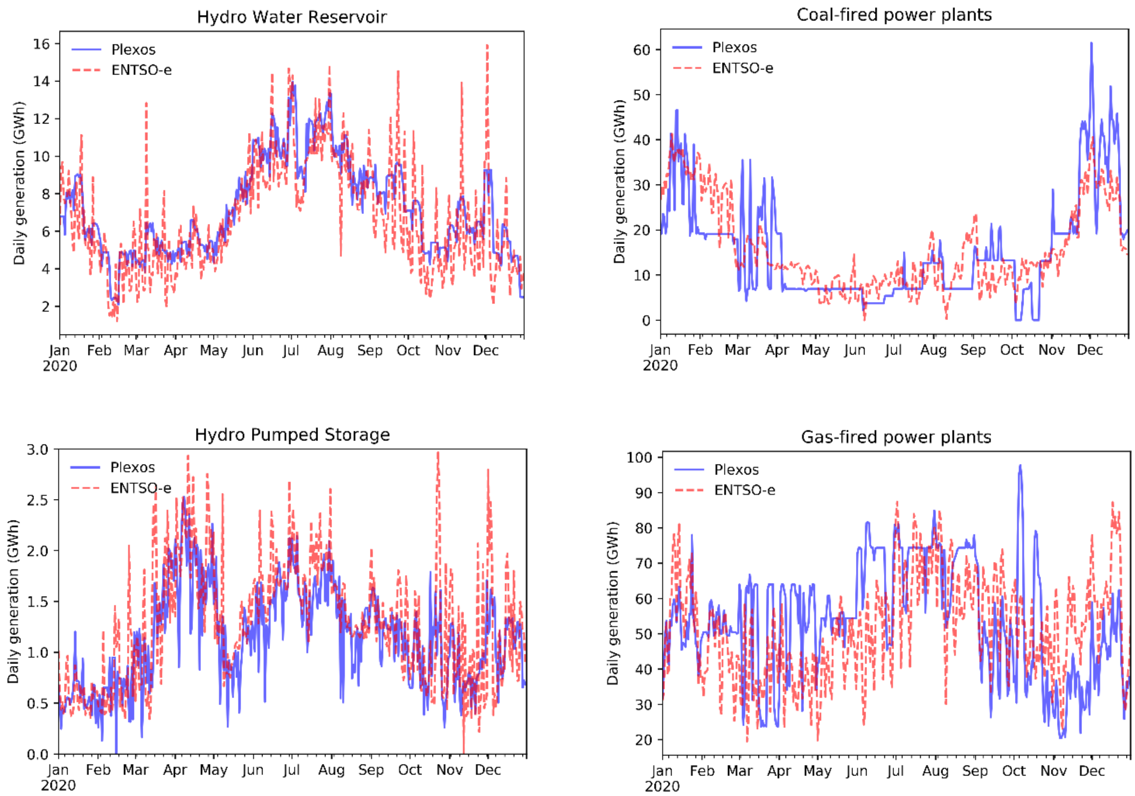
Source: JRC.

[29] https://www.spglobal.com/platts/en.
[30] https://www.admie.gr/en/company/about-us.
[31] https://transparency.entsoe.eu/.
[32] https://www.desfa.gr/.

## Annex 3. Complementary figures for the validation of the Plexos' model

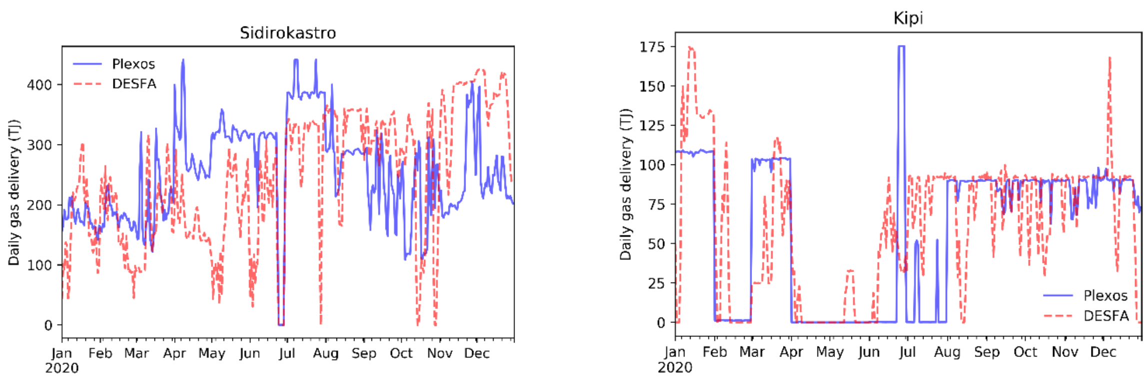
This annex provides additional figures for the validation of the Plexos' model. Daily electricity generation profiles for thermal and hydro power plants are compared with the actual generation profiles given by ENTSO-E in Figure 39. Likewise, Figure 40 compares the daily natural gas deliveries at the Sidirokastro and Kipi entry points with the actual figures provided by DESFA. In Figure 41, the daily natural gas delivery at the LNG facility and the initial volume of the LNG tank are compared with the values provided by DESFA and GIE, respectively.

Figure 39. Daily electricity generation profiles for thermal and hydro power plants. Comparison of the results from the Plexos' model with actual figures (ENTSO-E).



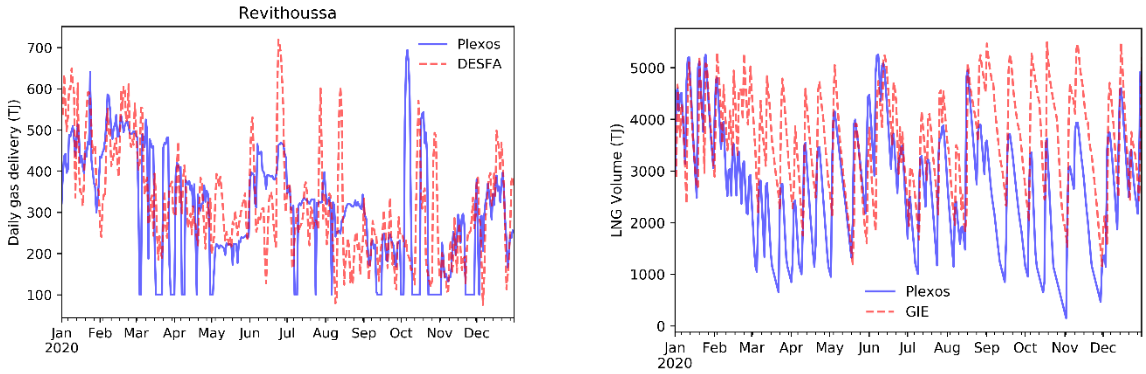

Source: JRC.

Figure 40. Daily gas delivery profiles for Sidirokastro and Kipi entry points. Comparison of the results from the Plexos' model with actual figures (DESFA).




Source: JRC.

Figure 41. Daily gas delivery profile for the LNG facility at Revithoussa (left plot) and LNG volume (right plot). Comparison of the results from the Plexos' model with actual figures (DESFA and GIE, respectively).




Source: JRC.

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