Techno-economic assessment of replacement options for Ptolemaida V

REPORT

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enervis

CONTENTS

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Executive Summary

Greece's lignite phase-out until 2028 will require the new Ptolemaida V lignite plant to be replaced or retrofitted.

In light of Greece's planned lignite phase-out until 2028, the not fully constructed Ptolemaida V (P5) lignite plant will have to be replaced with alternative technologies or retrofitted. This study aims to estimate the levelized cost of electricity ("LCOE") and effects on employment of four (4) replacement options, namely Carbon Capture and Storage (CCS), biomass, fossil gas and thermal energy storage coupled with renewable energy ("replacement options").

Replacement options are characterized by uncertainties regarding their cost-development. Therefore, a range of scenarios and sensitivities were analysed.

Two scenarios for CO_2 prices were considered, one based on the Greek National Energy and Climate Plan (NECP) and a more ambitious one from the European Commission's Impact Assessment that achieves a greenhouse gas emission reduction of 55 %, compared to 1990, until 2030. The latter is, nevertheless, less ambitious than recent predictions (BloombergNEF, 2020) for the current decade and for the same 55% greenhouse gas emissions reduction target, where CO_2 prices are expected to surpass 40 €/t in 2023, 50 €/t by 2028 and reach almost 80 €/t by 2030. On the other hand, the NECP scenario we considered does not take into account the imminent revision of the EU-ETS directive to comply with the ambitious 55% greenhouse gas emission reduction target for 2030 and can to some extent be viewed as unrealistic. To account for uncertainties in the development of fuel prices, a variation of fuel price scenarios was used. For fossil gas the NECP projection as well as the European Union's Joint Research Center (JRC) projection from the EU Heat Road Map were compared. Since the NECP lacks a projection for biomass costs, only the JRC projections were considered.

Renewables in combination with a thermal storage are the only emission-free technology to reach cost parity with fossil gas and biomass retrofits.

Among the scoped technologies, the thermal storage plant is a fully emission-free technology that allows for leveraging increasingly cost-efficient renewables at a large scale. Its economic viability will depend on the evolution of investment costs for wind turbines and photovoltaics. Under the assumptions that were made for the cost of renewables, the corresponding costs of the thermal energy storage option were found to be only slightly above those of other technologies for the unrealistically conservative NECP scenario. However, ***under the ambitious CO_2 price scenario, thermal energy storages could become the cheapest replacement option for Ptolemaida V***.

CCS is the most expensive technology across all scenarios.

CCS is unlikely to become an economically viable solution. This is especially the case for a high CO_2 price scenario at a state-of-the-art CO_2 capture rate, in which the LCOE becomes significantly higher than that for all other alternatives. The costs are shown to be the highest among all technologies, for both the reference case as well as more optimistic cost estimates.

Biomass retrofits and CCGT plants are the cheapest option for conservative CO_2 scenarios.

Biomass co-firing at a low rate (10 %) or a retrofit to a gas-CCGT plant may be the potentially cheapest technologies under the scenario, where CO_2 prices evolve as assumed in the current Greek NECP. Their high emissions and remaining dependence on fossil fuels make them a less sustainable and economically attractive alternative in the medium to long term for the more realistic, scenario on the evolution of CO_2 prices found in the European Commission's Impact Assessment.

A thermal storage combined with renewables provides the highest employment potential. For gas and biomass, local employment is likely to be significantly reduced.

A complete switch to biomass or a retrofit to a gas-CCGT plant would lead to the loss of over 500 mining jobs in the region. Fuel handling for biomass and fossil gas is likely to generate jobs outside the region of Western Macedonia. The thermal energy storage solution system combined with an appropriately sized renewable energy system could potentially fully substitute the jobs related to the lignite operation of the P5 plant and provides the overall highest employment potential compared to other options.

1 Introduction & Background

Introduction

In alignment with global efforts to mitigate carbon dioxide emissions, the Greek government, in 2019, announced the complete phase-out of all operating lignite and coal power plants until the year 2028. The decommissioning of lignite-fired units raises the question, which alternatives would be the most economically viable, ensure sustainable and secure energy supply, and create and sustain jobs in the energy sector.

The new Ptolemaida V (P5) lignite power plant in the Greek region of Western Macedonia, which is still under construction and planned to be commissioned before 2023, is the most prominent example for the abovementioned challenges. With a total investment of about 1.4 bn € and only 6 full years of planned operation as a lignite plant, the challenge of finding viable alternatives for replacing P5 arises.

In this light, ClientEarth and The Green Tank asked enervis energy advisors GmbH to conduct a study. The goal of the study is to quantify and analyze the levelized costs of electricity, emissions and implications for regional employment for chosen alternative technologies for the planned P5 power plant.

Objectives

The objective of this study is the estimation of the levelized cost of electricity (LCOE) for different replacement options for the planned P5 power unit. To this end, four technologies of interest were considered and investigated under varying carbon and fuel price scenarios, as well as technology-specific sensitivities: Carbon Capture and Storage (CCS), retrofits to burn biomass or fossil gas with combined-cycle gas turbines (CCGT) and thermal energy storage coupled with renewable energy. Additionally, the total CO_2 emissions and implications for direct employment for each of the respective technologies are estimated. An assessment of technical feasibility is not within the scope of this study and will have to be conducted more extensively for technologies of interest.

2 Scoping of Replacement Options

Within the scope of this study, four key technologies were analysed. The technologies subject to the assessment are briefly described in this section.

Lignite power plants can be replaced or retrofitted with numerous technologies.

Existing lignite power units can be adjusted in multiple ways in order to reduce the emission intensity of the plant. Options for such adjustments include fuel switches (e.g. to biomass or fossil gas), as well as additions of further units (carbon capture & storage). Alternatively, energy storage options that utilize the existing steam cycle can be considered.

The lignite plant can be retrofitted to capture, transport and store the emitted CO_2.

The possibility of capturing and storing the CO_2 emitted by burning fossil fuels has received increasing attention in the energy industry in recent years. The Public Power Corporation (PPC) of Greece has investigated the possibility of retrofitting P5 to incorporate CCS (PPC Thermal Projects Engineering and Construction Department, 2011), and P5 has been constructed to be CCS-ready. Similar projects have been implemented at coal power plants in the U.S. (Petra Nova) and Canada (Boundary Dam). The assessment in this study is based on existing data by PPC as well as on the case of the Petra Nova plant.

Biomass could serve as a potential replacement fuel, allowing the plant to be operated similarly as before.

Replacing the fuel for the power plant either partially (co-firing) or completely with biomass, can help mitigate emissions at coal or lignite power plants. Biomass retrofits offer the advantage of utilizing most of the existing power plants equipment, mainly due to pulverized lignite-fired boilers having suitable geometries for the combustion of biomass pellets. Therefore, maintaining the efficiency and net power output is possible when switching the fuel. In this study, the assessment is being conducted for two cases, a 10 % co-firing scenario and a 100 % fuel switch from lignite to biomass.

CCGT plants allow for a higher flexibility, high efficiency and lower emissions.

Being a mature technology, CCGT power plants offer the advantage of a lower carbon intensity than lignite plants combined with a higher operational flexibility. However, their costs are still dependent on the evolution of CO_2 prices. They are not eligible for funding under the recently concluded Just Transition Fund Regulations; they are also not included in the EU's Sustainable Taxonomy Regulation and are not consistent with the EU's climate neutrality objective. In terms of the technical feasibility, retrofitting lignite plants of such scale is unlikely to be economical, due to both the need for over-dimensioning the gas turbines, as well as the differences in boiler geometries for lignite and gas. For the case of repowering old coal and lignite plants, a case can thus be made for building new CCGT units at the existing location of the power plant (see section 3.2). A similar project is currently in planning for the Drax Power Station. (Drax Power, 2019)

Thermal storage coupled with renewable energy generation offer a 100 % carbon-free solution.

As a fourth option, this study investigates the potential costs of retrofitting the P5 plants to use the molten salt thermal energy storage technology. The plant would be powered by renewable energy sources and be able to operate as a baseload plant. Such retrofits have not been applied to existing coal or lignite plants yet but are currently under investigation for RWE's lignite plants in the Rhenish lignite region.

3 Methodology & Framework

In this section the applied methodology for assessing the levelized costs of electricity (LCOE) for each technology is introduced. Additionally, an overview of key techno-economic assumptions and scenarios is presented.

3.1 LCOE Methodology

LCOE are used as measure for comparing the economic viability of different technologies.

The cost-efficiency of different electricity generation technologies can be compared by using the Levelized Cost of Electricity (LCOE) as a measure. The LCOE averages lifetime costs of producing electricity using a given technology. The LCOE represent the average generation costs of a plant over the energy that is expected to be generated during its lifetime. Generally, there are different ways of computing the LCOE.

The assumptions regarding the LCOE computation in this study were the following:

- A constant energy production & efficiency of power plants throughout all years of technical lifetime
- Varying CO_2 prices depending on the scenario
- Varying fuel prices depending on the scenario
- The overall cost is weighted with an annuity factor, calculated with the weighted average cost of capital (WACC), which is assumed to be constant at 7 %.
- Prices and costs from all years were converted to € 2019.

The LCOE are calculated based on an "annuity method".

The LCOE were then calculated with the annuity method by applying the following equation[1] (Fraunhofer ISE, 2018):

$$LCOE = \frac{(I_0 + \sum_{t=0}^{n} \frac{A_t}{(1+r)^t}) * ANF}{\sum_{t=0}^{n} \frac{M_t}{n}}$$

For each technology, the LCOE was computed in real terms as of 2019 ("€ 2019"). The underlying assumptions for every technology will briefly be explained in the following sections.

[1] With I0= initial investment, At = Operational costs (including fuel and emission costs). ANF= annuity factor, Mt = energy output per year)

3.2 Techno-economic assumptions

General assumptions

The general assumptions made for all technologies are defined as follows:

- The overall lifetime of the technologies was set to 30 years (2023 – 2053). For Wind and PV, a lifetime of 20 years was assumed.
- The initial investment cost of P5 are assumed to be fully paid off at the beginning of the observation period. For each technology the new investment cost required for the retrofit and/or for additional units as well as the plants operational costs are considered.
- The P5 technical parameters (see table 1), such as the electrical efficiency, capacity and power output, were used for the retrofit options when suitable and the corresponding values were taken from documents presented by PPC.

The official P5 data is used as reference for defining the dimensions of the replacement technologies.

Since the dimension of the original steam turbine as well as the operational costs associated with the power plant are relevant to various replacement technologies, the official P5 data was used for defining the dimensions of the replacement technologies in accordance with the planned power output. Table 1 summarizes the corresponding data for P5 from PPC (PPC, 2013) and the NECP (Greek Ministry of the Environment and Energy , 2019).

Table 1- Techno-economic parameters of the P5 lignite unit

Parameter	Unit	Value
OPEX fix	€ / kW /a	35[2]
Carbon intensity	t CO_2 / MWh_{el}	1.05 [4]
Gross capacity	MW_{el}	660
Efficiency	% / 100	0.415[3]
Annual energy output	TWh	4.54

The following table provides an overview of key cost-related parameters for each technology. It is followed by a description of sources used and assumptions made for calculating the final costs for each technology:

[2] Based on PPC press release (PPC, 2013)

[3] Based on PPC presentation (PPC, 2013)

The cost-related parameters are based on existing retrofit projects and relevant literature.

Table 2- Overview of technology-related parameters

	CAPEX power	CAPEX storage	O&M fix	O&M var[4]	Lifetime
Technology	**€/kW**	**€ / kWh**	**€/kW/a**	**€/ kWh**	**a**
CCS - capture[5]	975 / 1260	-	5%	0	30
CCS- pipeline[6]	120	-	1.7	0	30
CCS- storage[7]	205	-	5.9	0	30
Biomass[8]	310 / 440	-	35	0.0054	30
CCGT[9]	390	-	22	0.004	30
PV	505	-	2%	0	20
Wind[10]	1063	-	2%	0	20
Storage	-	112[11]	35	0	30[12]

The LCOE of a CCS retrofit are assessed under two different investment costs.

The cost of CCS was analysed under two different CAPEX-assumptions- for the estimate PPC (PPC Thermal Projects Engineering and Construction Department, 2011) and for investment costs based on the Petra Nova power plant (U.S. Energy Information Administration, 2017). The CAPEX for the transportation and storage within Greece are based on PPC's assessment in both cases. The costs are added for the total investment required for the plant. Since the CCS plant will be added to the lignite unit, the total operational costs would equal to the sum of the CCS operational costs and the power plant operational costs. The investment cost is assumed to scale with the capture rate, with the base vales (table 2) being based on a 30 % total capture rate.[13]

[4] The variable operational expenditures are based on auxiliary consumptions and do not contain the fuel costs. In the case of biomass, the value is equal to the lignite power plant (Germany Energy Agency, 2011). For CCGT and estimation from Fraunhofer ISE is used (Fraunhofer ISE, 2018).

[5] The investment costs of 975 €/kW are based on PPC's estimate for retrofitting the plant (PPC Thermal Projects Engineering and Construction Department, 2011). The total investment for the Petra Nova CCS plant was 1 bn USD for a plant of 654 MW (U.S. Energy Information Administration, 2017). The value of 1529 USD / kW was then converted by using a 10-year average USD-EUR exchange rate (Euro Dollar Exchange Rate, 2020). The O&M assumption of 5% is based on PPC's estimate (PPC Thermal Projects Engineering and Construction Department, 2011)

[6] CCS Pipeline values based on PPC (PPC Thermal Projects Engineering and Construction Department, 2011). Investment cost based on yearly total investments of € 2.65 Mio. The operational cost contains the pipeline as well the compressor station costs. The additional case of ship transportation, as examined by PPC, is not considered in this study.

[7] CCS Pipeline values based on PPC (PPC Thermal Projects Engineering and Construction Department, 2011). Investment cost based on yearly total investments of € 2.65 Mio. The operational cost contains the pipeline as well the compressor station costs. The additional case of ship transportation, as examined by PPC, is not considered in this study.

[8] CAPEX based on a Dena estimate for the 10% co-firing (Germany Energy Agency, 2011) and on the Drax power unit for the 100% case. The O&M cost are assumed to be equal to the plant operating with lignite as main fuel.

[9] CAPEX based on the newly planned Mytilineos SA CCGT unit at Agios Nikolaos (European Investment Bank, 2020), O&M value are based on Fraunhofer ISE (Fraunhofer ISE, 2018).

[10] Wind and PV values are based on the NECP (Greek Ministry of the Environment and Energy , 2019). For the year 2023, in which replacement system would be commissioned, obtained through interpolation between 2020 and 2025

[11] Based on an assessment by DLR (DLR, 2019)

[12] This study assumes that the cost of electricity from renewables is constant and level with the LCOE throughout the lifetime of the storage. The value used is the LCOE based on a lifetime of 20 years. The simplified approach is motivated by the decreasing investment costs of renewables and the lower impact of future payments on the present value as calculated by the underlying LCOE method. The change in LCOE under consideration of a further future one-time investment after 20 years is assumed to be negligible, if the PV and Wind plants can be operated for further 20 years after re-investment.

[13] The PPC study assumes a capture rate of 90 % and a specific investment of 950 € / kW. The case of Petra Nova shows the investment costs for a capturing (slipstream with a 240 MW capture plant) to be significantly higher for a total plant capture rate of 30 %. This study therefore assumes that the PPC investment costs would realistically be required for a total plant capture rate of 30 % rather than 90 %. For all subsequent capture rates up until 90 %, the investment cost is scaled in accordance with the additional MW required for the capture plant.

A CCS retrofit will result in a decrease in power output and efficiency

Additionally, the decrease in efficiency and net power output were adjusted in accordance to the PPC estimate (PPC Thermal Projects Engineering and Construction Department, 2011). According to the corresponding study the plant's power output would decrease to 537 MW with the net efficiency decreasing down to 30.1% (PPC Thermal Projects Engineering and Construction Department, 2011). The efficiency decrease was assumed to be constant for all capture rates between 30 and 90 %. Furthermore, the plant's load factor was assumed to remain unchanged after a CCS retrofit.

Two scenarios based on different biomass shares were considered.

In order to assess the LCOE of a fuel switch to biomass, two cases were considered: one corresponding to a 10% biomass-90% lignite co-firing scenario, and one for a full 100% fuel switch from lignite to biomass. The estimates of the German Energy Agency for the investment costs in the case of 10% co-firing with biomass were used (Germany Energy Agency, 2011). For the 100% retrofit, the investment costs for the Drax Power Unit in the United Kingdom were assumed, where instead of co-firing a complete repowering has been performed (Drax Power, 2018)[14]. The repowering requires larger adjustments such as the change of classifiers in the mills and fire and explosions suppression systems for the new conveyor and storage systems of the biomass plant. Therefore, the required investment is also higher.

The biomass-based production is assumed to be emission-free.

The efficiency and power output of the power plant were assumed to remain unchanged after the fuel switch to biomass. An energy density of 5.42 kWh/kg for the wood pellets (European Biomass Association, 2017) was assumed. For biomass, carbon neutrality was assumed, i.e. no indirect emissions from the transportation are considered. The total lifecycle emissions of the biomass pellets were therefore negligible.

A new CCGT unit, based on current investment costs is assumed.

Since the technical feasibility of retrofitting a lignite plant of such a large size to fossil gas is questionable[15] (DBI Gas- und Umwelttechnik GmbH, 2017), a total replacement of the P5 unit with a CCGT plant was assumed. The investment costs that were used, were based on the newly planned power plant at Agios Nikolaos (European Investment Bank, 2020), amounting to a total of 390 €/kW.

The yearly full-load hours vary between 4000 h and 6000 h.

An efficiency of 63% as well as an emission factor of 0.32 t CO2 / MWh according to the planned unit is used. The operational costs were assessed based on a study on LCOE of different technologies by Fraunhofer ISE (Fraunhofer ISE, 2018). An installed capacity of 660 MW and three different load factors (4000 Full Load Hours (FLH), 5000 FLH and 6000 FLH) were considered.

[14] For both the fixed and variable operational costs, equal costs to the P5 costs without mining were assumed (PPC, 2013).

[15] The case of retrofitting the power plant for the usage of fossil gas, i.e. replacing the existing boiler and adding a gas turbine is unlikely to be feasible. Power plants of smaller scale (< 400 MW) can be suitable for such retrofits, while large lignite producing units would have over-dimensioned steam turbines for CCGT retrofits as well as large existing lignite-supply infrastructures, making an operation with fossil gas uneconomical. (DBI Gas- und Umwelttechnik GmbH, 2017). This technology, unlike the others, is therefore not to be thought of as a retrofit but instead as a construction of

The cost of renewable energy is assessed using NECP as well as current tariffs.

The LCOE of Wind and PV that were needed for the calculations of the thermal energy storage option were calculated based on the projection of the Greek NECP (Greek Ministry of the Environment and Energy , 2019). O&M costs of 2% and a lifetime of 20 years were assumed for both cases. An average FLH of 1500h for PV and 2000h for Wind for the Kozani region (MERRA-2, 2016) were used. Note that this is a conservative assumption for the FLH of PV. PPC estimates that their 230MW planned PV unit in Western Macedonia will produce 390GWh annually which corresponds to approximately 1700 FLH (Energypress, 2020). For a second more conservative assessment, the more expensive tariffs that apply today (2020) according to the Greek Regulatory Authority for Energy (Regulatory Authority for Energy, 2020) were also used instead of the LCOE predicted by the Greek NECP.

The dimension of the thermal energy storage system was chosen in accordance to the plant's gross power.

For the case of converting P5 to a thermal energy storage facility, an installation cost of 112 €/kWh[16] and 10 hours of storage time was assumed, based on an assessment by DLR (DLR, 2019). The total storage capacity, given by the storage time and power output of the steam turbine was taken to be to 660 MW*10h = 6600 MWh. The system's overall efficiency was computed by assuming a 95% thermal storage efficiency and a 41.5% steam turbine efficiency, resulting in a total of 39.4% overall efficiency.

3.3 Scenarios and sensitivities

Scenario analysis mitigates uncertainty-related risks in cost-assessment

With P5 being an unfinished power plant, planned to be commissioned by late 2022 or early 2023, and costs of electricity highly dependent on the future evolution of EU-ETS emission allowance and fuel prices, the LCOE were estimated under different scenarios. The analysis of different scenarios provides the possibility of assessing different future policies and varying techno-economic parameters, thus resulting in a more robust assessment. An overview of the core scenarios and sensitivities is given in figure 1.

[16] This value is based on an assessment by DLR. It contains construction, electric heating and salt costs. The salt costs are based on a conventional solar salt $NaNO_3$ / KNO_3 mixture. Since such retrofits have not been applied to other lignite power plants yet, a feasibility study would need to be conducted to assess the exact composition requirements and thus costs for a thermal storage system at the P5 unit.

The LCOE are computed for two main carbon price scenarios and additional technology-specific sensitivities.

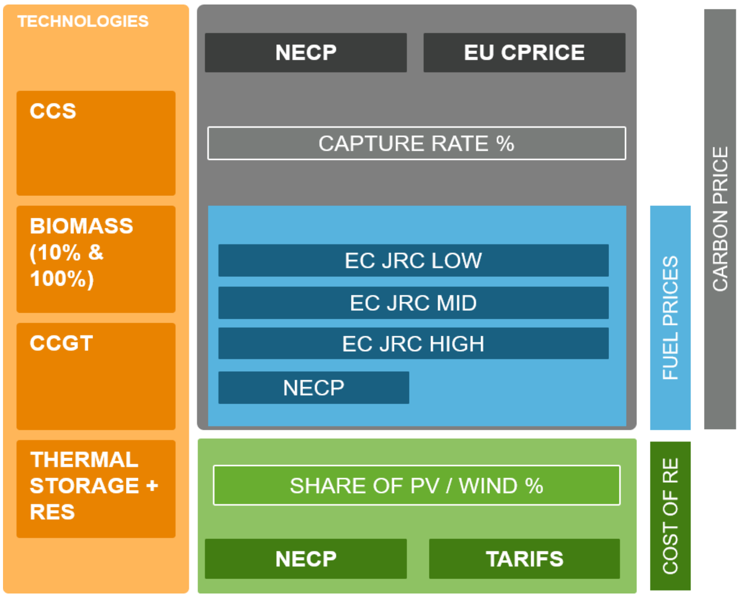

Figure 1- Scenario overview

For this study two CO_2 price scenarios were considered, as depicted in the below figure:

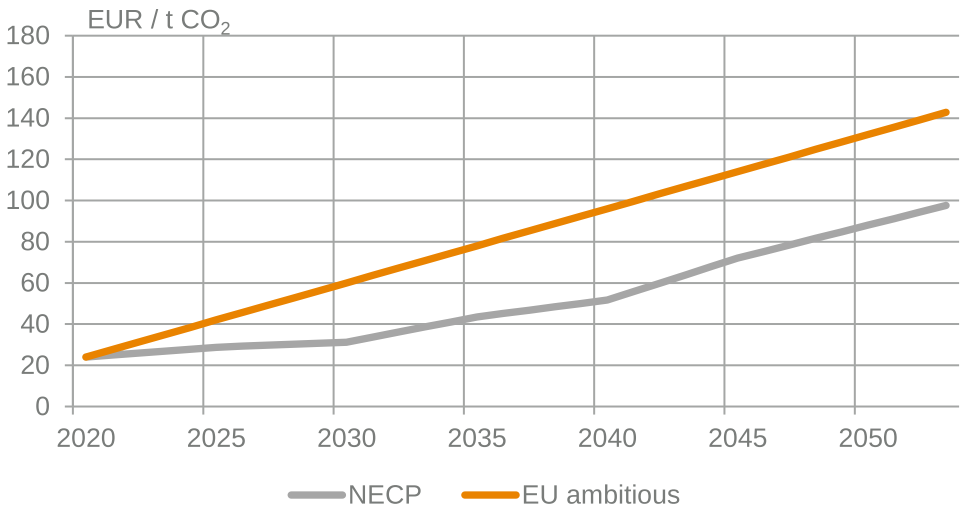

Figure 2- carbon price scenarios

The main CO_2 scenario is based on the Greek NECP

Baseline (NECP): A conservative estimation on the future development of EU-ETS carbon prices, based on the Greek NECP. This scenario serves as the baseline scenario and aligns with the current energy policies of the Greek government. It assumes a CO_2 price of 32 € / t in the year 2030, increasing to 88 € / t in the year 2050.

In the ambitious scenario a high CO_2 price of 60 €/t for 2030 is reached.

EU CPRICE scenario (Ambitious): A more ambitious carbon price scenario from the European Commissions Impact Assessment (European Commission, 2020) that achieves a GHG emissions reduction of 55 % compared to 1990 until 2030, assuming a carbon price of 60 €/ t in the year 2030[17].

[17] Values after 2030 are computed by linear extrapolation

Recent predictions indicate an even steeper increase in CO_2 prices than what is assumed in the Ambitious scenario.

Further values were computed through linear extrapolation. Since the CO_2 price projection in the baseline (NECP) scenario is more conservative, the ambitious scenario is used to put the values found into a greater context of possible changes in political framework. However, note that the more ambitious of the two scenarios we considered is less ambitious than the recent predictions of BloombergNEF (BloombergNEF, 2020) for the current decade and for the same 55% greenhouse gas emissions reduction target, where CO_2 prices are expected to surpass 40 €/t in 2023, 50 €/t by 2028 and reach almost 80 €/t by 2030.

In addition to the main scenarios, technology-specific sensitivities are considered for each scenario.

In addition to the two main carbon price scenarios, several technology-specific sensitivities were considered:

- Fossil gas prices based on projections by the NECP as well the JRC as used in the EU Heat Road Map until 2050 (Aalborg University, 2018), are depicted in figure 3.
- Biomass prices (relevant to Biomass retrofit) are depicted in figure 4
- The values of the LCOE for the renewables providing the electricity for the thermal energy storage system were based on the projections of the Greek NECP projections (Greek Ministry of the Environment and Energy , 2019) as well as on current (2020) tariffs for PV and Wind (Regulatory Authority for Energy, 2020).

The development of fossil gas prices is based on the NECP and additionally on the EU Heat Road Map projections.

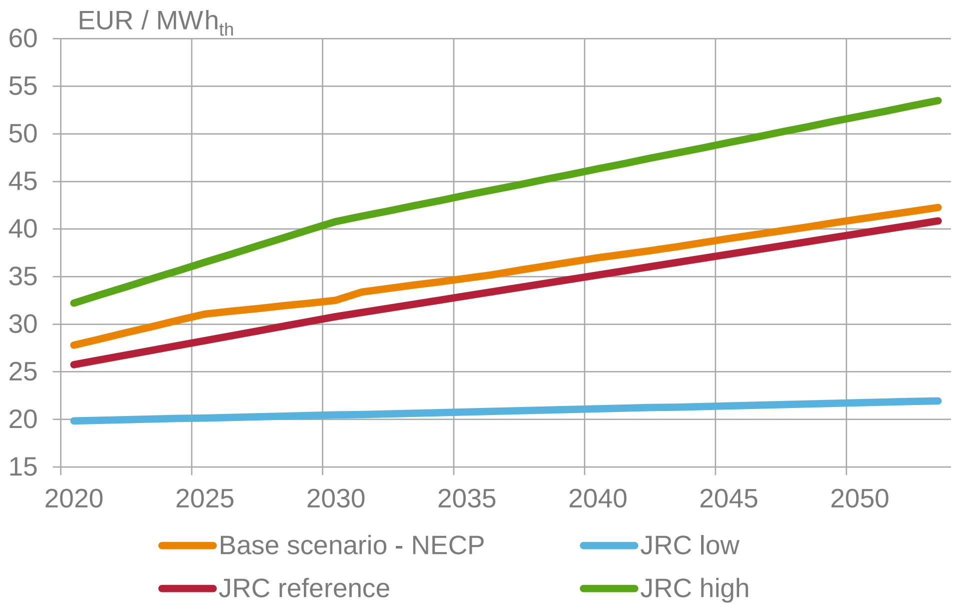

Figure 3- Fossil gas prices under different scenarios

Biomass pellet prices based on the EU Heat Road Maps projections for Greece.

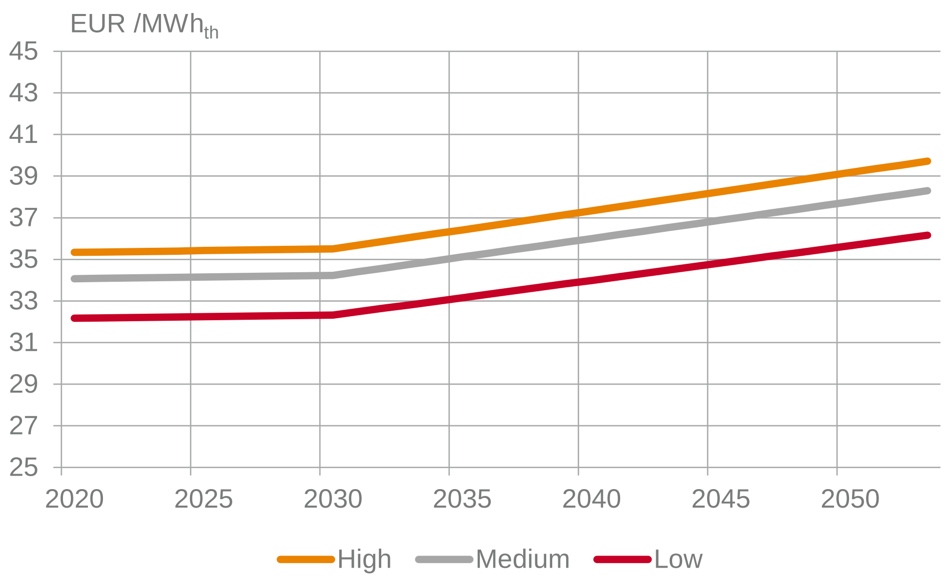

Figure 4- Pellet cost development

Further technology-specific sensitivities help assess the LCOE under uncertain technological developments.

In addition to the carbon and fuel prices, additional technology-specific sensitivities were used:

- Carbon capture rate (relevant to CCS) ranging from 30% up to 90%[18]
- Two different CAPEX for the cases of CCS and Biomass
- Load factor of the CCGT plant (4000 – 6000 FLH)
- Co-firing rate of the biomass-lignite plant (10 % and 100 %)
- Share of PV and Wind electricity generation used as input in the thermal storage

[18] It is uncertain which rates will be achieved in future CCS technology. The total plant's capture rate is 33% in the case of Petra Nova. 90% capture can be achieved with current technology on a smaller scale (200-300 MW).

4 Technology-specific results

4.1 CCS retrofit

The LCOE of a CCS plant including transportation and storage would amount to 12.8 ct/kWh in the NECP scenario.

The LCOE of a CCS-retrofit including capturing, transporting and storing the carbon dioxide are depicted in figure 5. An LCOE of 12.8 ct/kWh for CO_2 prices in the conservative NECP scenario, and 15.8 ct/kWh in the ambitious scenario (CPRICE) were computed. Notice that the LCOE for the NECP scenario increases only slightly with increasing CO_2 capture rates. Increasing the CO_2 capture rate decreases the CO_2 costs, but the corresponding cost reduction is counter-balanced by the additional investment costs which are necessary for a higher CO_2 capture rate.

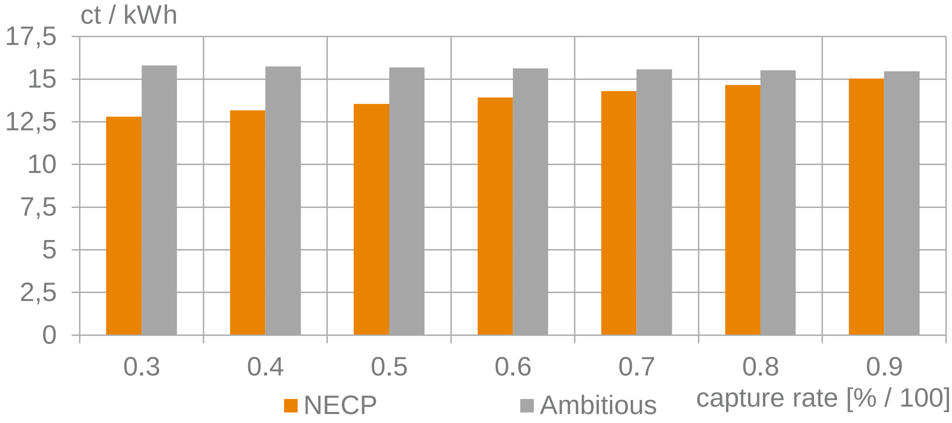

Figure 5- LCOE for a CCS retrofit

The total initial investment for CCS range between 0.94 and 1.1 bn € for a 30 % total capture rate.

For a 30% CO_2 capture rate, applying Petra Nova's specific investment costs for the CCS system, a would require an initial investment of about 1.1 bn € for P5. In the case of PPC's estimate for a CCS retrofit (PPC Thermal Projects Engineering and Construction Department, 2011)the costs would amount to 0.94 bn € in 2019 prices.

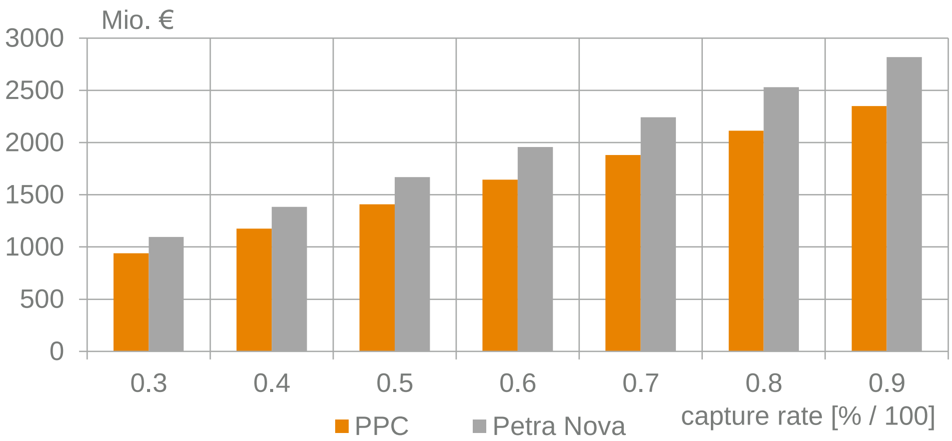

Figure 6- total investment costs for CCS

Being dependent on lignite, the overall emissions of the power plant would amount to 3.7 Mt CO_2 annually for a 30 % CO_2 capture rate.

Depending on the assumed CO_2 capture rate, the annual CO_2 emissions could be reduced down to 0.53 Mio t CO_2 per year. In the base scenario of a total plant capture rate of 30 % (Petra Nova), the total emissions would amount to 3.7 Mio. t CO_2. This comparatively high value, is due to the decrease in efficiency of the plant. It would lead to a higher required amount of lignite per unit of electricity produced. This in turn implies that a significant reduction in CO_2 emissions would require a much higher carbon capture rate for the entire plant. High capture rates, if feasible on such a scale[19] would require a significantly higher initial investment. For a 90 % capture rate this investment would exceed by far the initial power plant costs of 1.4 bn €, reaching up to 2.8 bn €, taking into account the entire infrastructure with transportation and storage within Greece.

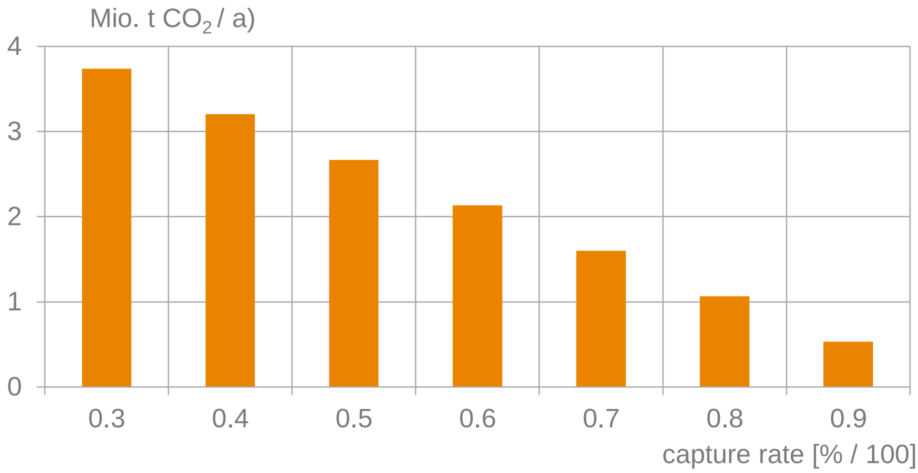

Figure 7- annual CO_2 emissions after a CCS retrofit

4.2 Conversion to a biomass plant

In the NECP scenario a 10 % co-firing retrofit has a significant cost-advantage.

This section provides an overview over key results for the costs associated with retrofitting P5 to use biomass both partially or completely as an alternative fuel to lignite. Indirect emissions associated with the processing and transportation of biomass pellets were neglected in this analysis. The main results for the costs of biomass retrofits are presented in figure 8.

The LCOE in the 10 % biomass co-firing scenario was estimated to be 7.6 ct / kWh in the case of the conservative NECP scenario for the evolution of CO_2 prices and 10.39 ct/kWh for the ambitious CO_2 price scenario. This large increase is due to the reliance of this technology on lignite as the main fuel (90%). [20] The direct emissions caused annually, assuming an equivalent load factor and capacity as for P5, would amount to 4.29 Mio t CO_2.

[19] Petra Nova reaches 90 % on a 200 MW slip stream of a plant with a total of 600 MW. The total capture rate amounts to 33%.

[20] The cost of lignite is based on a PPC press release value for lignite costs of 13.36 € / t equal to about 28.5 € / MWh_{el} (PPC, 2013)

In the ambitious scenario the cost for both technologies align, ranging between 10 and 11 ct/kWh.

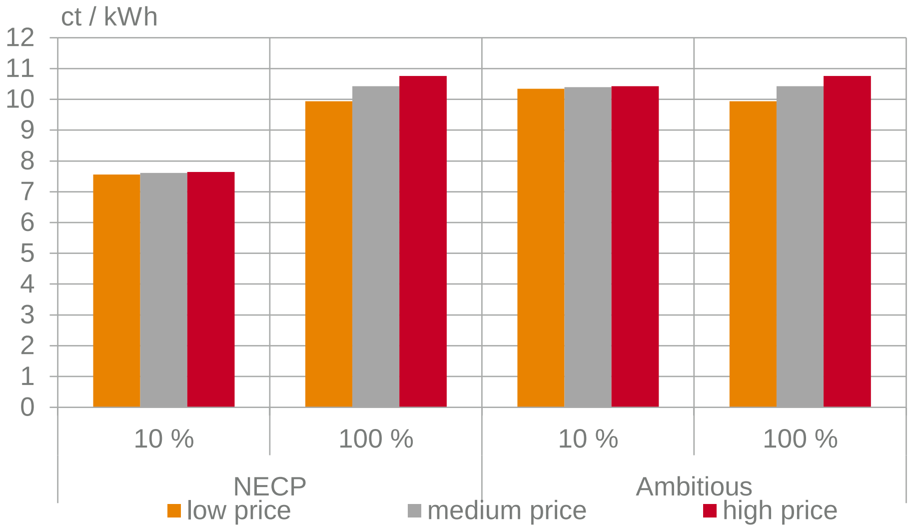

Figure 8- LCOE of Biomass retrofits

To fully decarbonise the production, a complete switch to biomass would be required. Since the power plant would operate similarly, the key cost-driver would be the significantly higher fuel costs for biomass pellets in comparison to lignite. To produce 1 MWh_{el}, the production with biomass is about four times more expensive than the lignite-based production[21]. However, under the assumption of a high CO_2 price, the LCOE in both cases will align, since biomass is considered to be carbon-neutral and excluded from ETS pricing. This would make a retrofit to 100 % biomass combustion economically viable. For biomass prices on the lower end of the cost-range, the LCOE would be as low as 9.93 ct/kWh. For higher costs this value rises to up to 10.76 ct/kWh.

High amounts of pellets are likely to require international procurement, increasing the projected costs.

In addition to using the costs as a metric, for the case of biomass, the question of fuel supply will need to be addressed by decision-makers. In order to meet the power plant's fuel demand, 0.19 to 1.9 million tons of pellets would be required yearly for the cases of 10 % co-firing and 100 % biomass, respectively. While co-firing at 10% could alternatively be done with lower quality biomass, e.g. from local agricultural residues, higher amounts for a 100 % retrofit would require the aforementioned large quantities of pellets. Such quantities would likely need to be imported due to the very large areas of land that would be required to produce such large biomass quantities, potentially leading to even higher fuel costs than those assumed in the JRC scenarios used in this study (Aalborg University, 2018).

[21] Assuming JRC-based values (Aalborg University, 2018) of an average of 35 € / MWh_{th}, or an equivalent of 85 € / MWh_{el}, assuming the efficiency of P5 at 41.5 %

4.3 Conversion to a CCGT plant

For CCGT the costs are evaluated for three dimensions.

In this section the LCOE results for the CCGT unit are presented. As described in section 3.2, three dimensions of cost-drivers were considered: CO_2 prices scenarios (NECP, Ambitious), the varying gas price scenarios (NECP, JRC low-mid-high) and varying full-load hours (4000 – 6000 h). The findings indicate a high sensitivity to fossil gas prices, a medium sensitivity to CO_2 prices, mainly due to the low emission factors of modern CCGT plants, and a minor sensitivity to the load factor (FLH) of the plant.

The LCOE range between 9.1 ct/kWh and 9.6 ct/kWh under the NECP assumptions

For the NECP-based CO_2 and gas price development (left-side, orange), values between 9.09 for 6000 FLH and 9.65 ct/kWh for 4000 FLH were found. Examining the case for the JRC scenario with high fossil gas prices, using the same NECP CO_2 price, the LCOE varies within a small range between 10.39 and 10.96 ct / kWh. The fossil gas prices have a higher impact on the LCOE than the capacity factor of the plant.

In the ambitious scenarios for the evolution of CO_2 prices and for high future gas prices, the LCOE range between 11 and 12 ct/kWh.

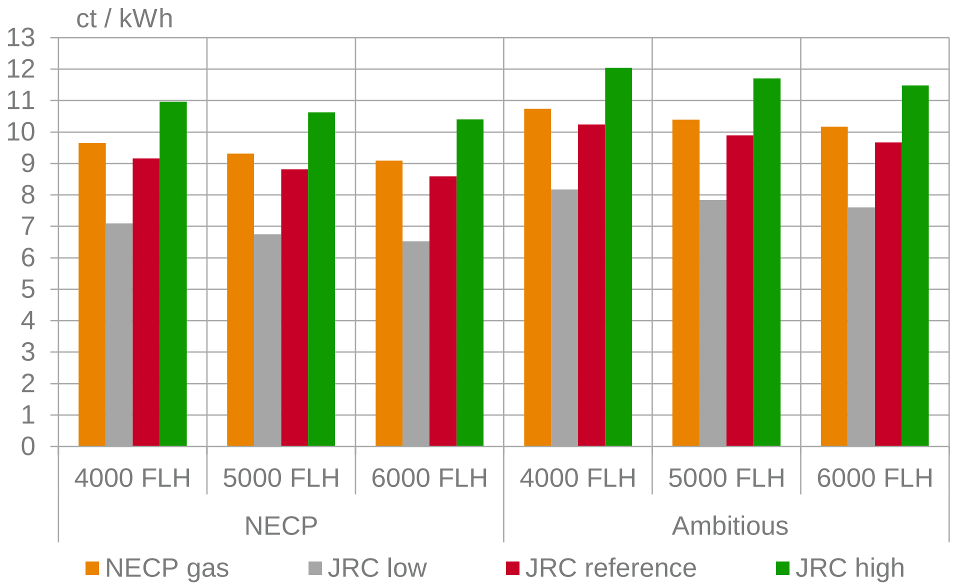

Figure 9- LCOE of CCGT replacement

The LCOE are most sensitive to fossil gas prices.

The LCOE increases by about 11 % to a range of 10.16 to 10.73 ct/kWh for the ambitious CO_2 scenario, using the same NECP gas prices. This increase for a high CO_2 price scenario can be put into comparison to the increase caused by JRC's gas price projection. For high fossil gas prices, the LCOE increases significantly, to an average of 10.6 for the NECP CO_2 price and 11.7 ct/kWh for the ambitious CO_2 price scenario.

264 Mio. € are required to construct the CCGT plant

The initial investment required for building the plant would equal to 264 Mio. € in the case of an equivalent net power as the P5 lignite plant. This low investment cost value is based on the assumptions on specific investment costs as described in section 3.2. It should be noted, that those investment costs are significantly lower than values found in literature, e.g. as estimated by Fraunhofer (Fraunhofer ISE, 2018) which are essentially double the specific cost assumed in this study.

The emissions are decreased compared to the lignite plant by up to 70% if high load factors are reached.

Depending on the annual load factor, the plants emissions would range between 0.968 and 1.452 Mt CO_2 annually. This makes the CCGT plant able to compete with high capture rate (above 80 %) CCS plants as well as low co-firing rates for biomass. Using fossil gas would, however, only be a temporary solution for the imminent lignite phase-out rather than for the long-term decarbonisation of the Greek energy system and a choice that is non-compliant with the new EU Sustainable Taxonomy Regulation.

4.4 Thermal Energy Storage

The LCOE of the storage retrofit depend on the LCOE of renewables…

The LCOE was evaluated for different shares of PV / wind in the electricity which is stored in the thermal energy system. Using the projections in the Greek NECP for the investment cost of utility scale photovoltaics of and onshore wind turbines, the power plant's LCOE would range between 9.06 ct/kWh and 10. 68 ct/kWh, with the lowest LCOE corresponding to a higher share of PV since the LCOE of PV for 2023 is significantly lower at 3.65 ct/kWh compared to 5.49 ct/kWh for wind turbines.

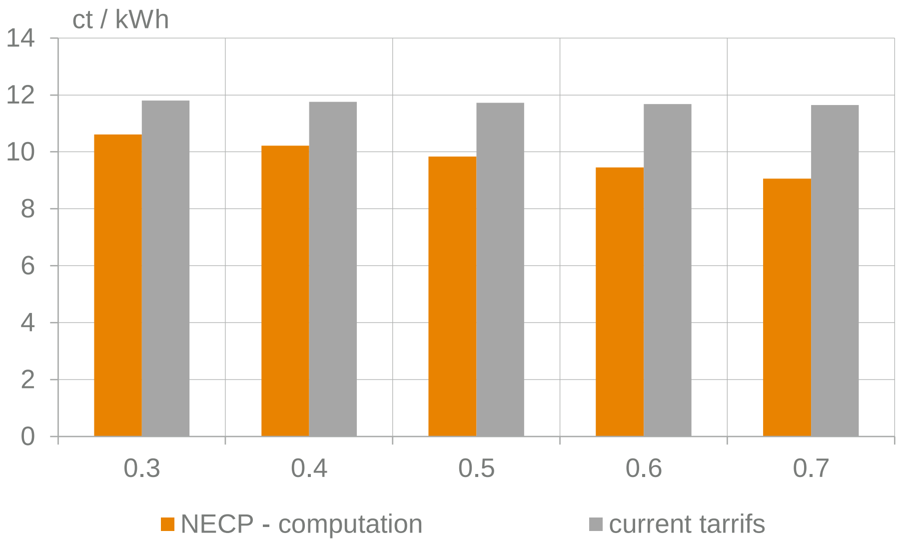

Figure 10- LCOE of thermal storage system

… under current tariffs the LCOE of the thermal storage amount to 11.7 ct/kWh.

Current tariffs for wind and PV likewise range between 5.3 and 5.6 ct/kWh- The resulting LCOE of the thermal energy storage system for current tariffs therefore exhibits a lower variance and has an average value of 11.7 ct/kWh.

… under the NECP cost projection for renewables LCOE drop to 9 ct/kWh. lower than Biomass and CCS in all scenarios.

Using the NECP projection for the construction cost of renewables, a lower average PV cost results and therefore a lower total cost for systems with a higher PV share. Assuming that for this technology, the share of PV in the generation of electricity to be stored would be 70%, in order to ensure a smooth combined feed-in profile and higher combined full-load hours, the resulting storage LCOE could be as low as 9 ct/kWh. This would render the thermal storage system cheaper than Biomass and CCS and cheaper than CCGT, for both the NECP and ambitious CO_2-price scenarios, provided that fossil gas prices evolve according to the high price scenario.

5 Comparison of replacement technologies

Across all scenarios CCGT and biomass can potentially reach the lowest LCOE

The replacement technologies are compared in figure 11 containing all values from the respective scenarios for each technology. The overall potentially lowest cost can be reached by a 10 % Biomass Retrofit and CCGT under the unrealistic NECP CO_2 price scenario and the lowest estimate for the evolution of fossil gas prices, in the case for CCGT.

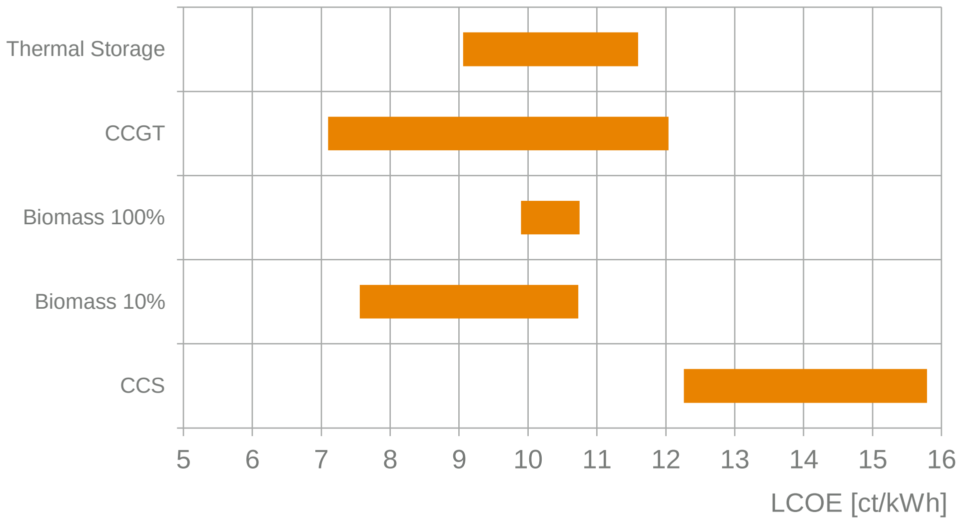

Figure 11- Comparison of LCOE

CCS is the most expensive technology, even under the moderate CO2 increase in the NECP scenario.

When considering the whole CCS system, the LCOE is signifcanty higher than for other technologies. The LCOE strongly depends on CO_2 prices, especially if only lower capture rates can be achieved. The findings therefore indicate that CCS is the least favourable replacement option in comparison to all other technologies.

Costs of a 100% biomass retrofit would mainly depend on the cost of importing biomass, Under the ambitious scenario this option can compete with CCGT.

Unlike the 10% co-firing scenario, a 100 % biomass retrofit would be more cost-intensive both in the operation in the NECP CO_2 -scenario for the evolution of CO_2 prices. The LCOE would then mainly depend on the biomass prices, which could be fairly stable in the near future, since contracts with supliers are likely to be based on fixed prices for several years. The low overall range in the LCOE of the 100% biomass case, can also be attributed to the lack of emission costs. It has to be noted however, that emissions that are caused during the processing and transportation –not considered in this study- could lead to an increase of the final costs, depending on whether or not such costs are considered in the evaluation. Lastly, even in the case of cost-parity with other technologies, the amount of biomass that has to be procured, likely internationally, might hinder the actual feasibility of this solution, since costs for shipping and transportation might further increase the operational expenditures for power generation. Such costs were not considered in this study.

Thermal Storage systems could provide the lowest cost electricity under the ambitious CO_2 scenario.

If the projections in the Greek NECP for future costs of renewable energy materialize, then the LCOE of thermal energy storage systems could drop to 9-10 ct/kWh. Under the more realistic, ambitious scenario for the evolution of CO_2 prices, this technology could become less expensive compared to both biomass and fossil gas..

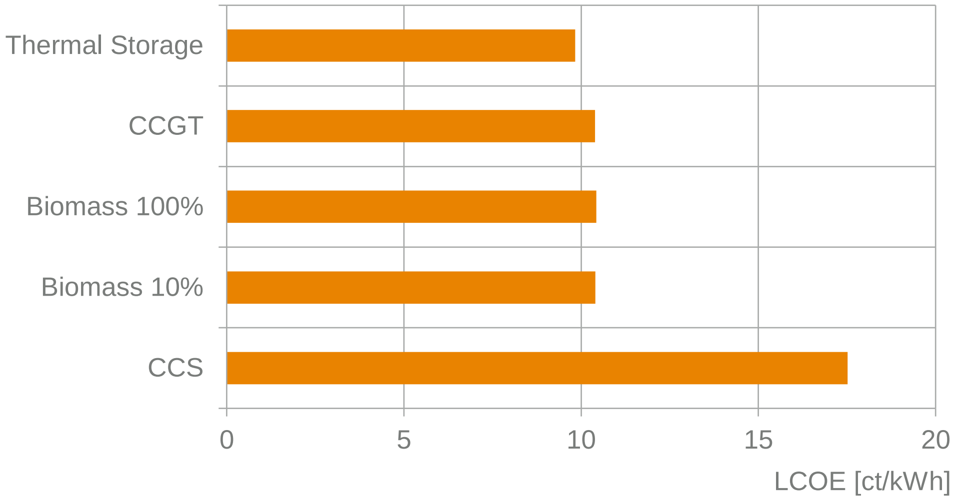

Figure 12- LCOE comparison of technologies in the ambitious CO_2 price scenario

… comparing the base case for each technology under consideration of the NECP scenario shows a 10 % biomass retrofit to achieve the lowest LCOE.

Under the less realistic NECP scenario for CO_2 prices a 10% biomass co-firing retrofit is the cheapest technology. The thermal storage system lies between CCGT and 100% Biomass, while CCS is signifcantly more expensive than all other alternatives.

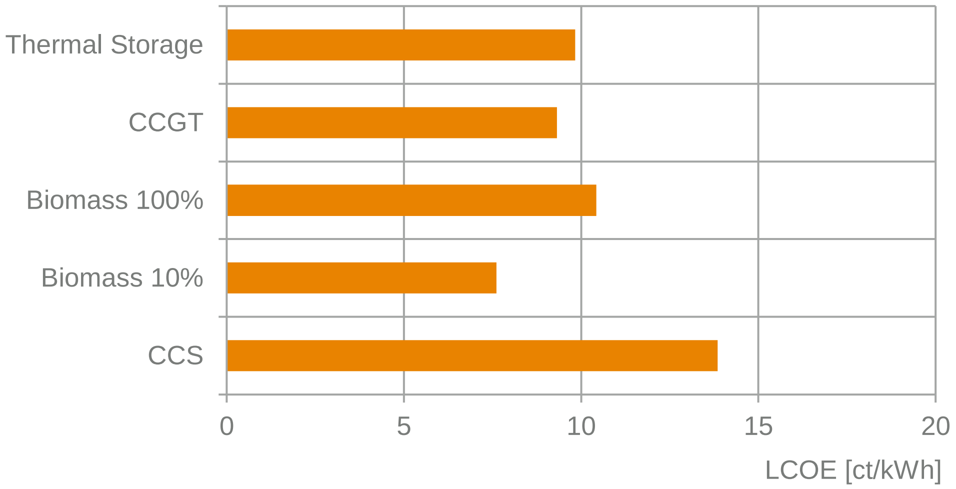

Figure 13- LCOE comparison for the NECP scenario

The emissions per technology technologies are highest for the 10 % biomass retrofit and lowest for the thermal storage

Despite its low cost under low carbon prices, a 10% biomass co-firing would cause the highest emissions out of all technologies, only barely reducing the initial emissions of the lignite-powered unit. In contrast, a CCGT plant could reduce emission to about a third. CCS would only achieve significant results if a high capture rate of 80 to 90% could be achieved for the total plant. The only carbon free alternatives are the renewables-powered thermal energy storage and the biomass plant.

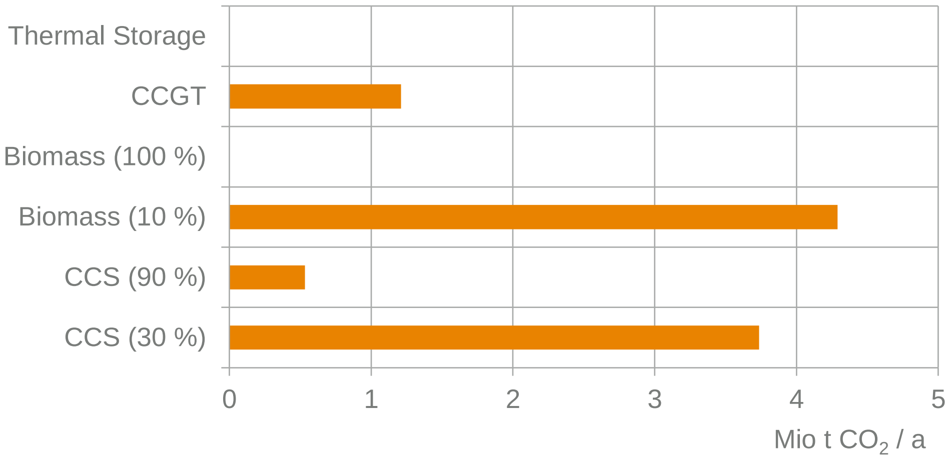

Figure 14- direct emissions of all technologies

6 Effects on employment

The region of Western Macedonia is highly dependent on jobs in the power and mining industry

Lignite and coal power plants ensure employment in many structurally weak regions of Europe. The phase-out of such power plants raises the question of the future of employment in the given regions. As such a region with a high dependence on lignite, the effects on employment in Western Macedonia are crucial for the evaluation of replacement technologies for P5, since employment is not accounted for in a LCOE-based cost assessment.

The employment effects are estimated based on technology-specific OECD employment data and regional employment in the mining sector

Within this study, the employment effects are quantified as follows: Based on current employment data in mining and at the power plants (The World Bank, 2019), an estimation for the total jobs created by P5 is made first. This value serves as a benchmark for comparison to the replacement technologies. For Biomass, Gas, PV, Wind and thermal storage, employment data from the OECD countries is used for the assessment, based on the 2020 report on Employment in the energy sector issued by the European Commission (European Commission, 2020). Since the CCS technology has only been implemented in very few power plants comparable in size to P5 a, data estimates by the Global CCS Institute are used for the estimation of employment effects (Global CCS Institute, 2020).

Direct employment factors [jobs / MW] for O&M, fuel supply, construction and manufacturing are considered.

All calculations are based on direct employment per MW for the given technology, and weighted with the installed capacity of the respective technology. Indirect employment is not being accounted for in the calculation, since such data on replacement technologies is highly uncertain. The employment is divided into mining and power plant jobs (O&M) for P5. For the replacement technologies, fuel supply (gas, biomass), O&M, and construction and manufacturing are additionally considered. Jobs for construction and manufacturing are given in job-years in the referenced literature. For all technologies, this was converted to jobs per MW based on the given construction time of 1 to 2 years on average (European Commission, 2020) to calculate the total jobs based on the installed MW of the plant. The jobs were then averaged over the lifetime of the technology.[22] Table 3 gives an overview of the main assumptions used for calculating the total direct employment for each technology.

[22] This approach only allows for a qualitative comparison, since employment also depends on qualification, and mining jobs can not necessarily be converted to jobs in the renewable sector.

Employment factors based on EU-data are used for assessing the total jobs for manufacturing, constructing, operating and maintaining and for the fuel procurement.

Table 3- Employment factors (European Commission, 2020)

Technology	Manufacturing [jobs / MW]	Construction [jobs / MW]	O&M [jobs / MW]	Fuel (jobs / PJ)
CCS	-	57 per plant[23]	0.1524	same as P5
Biomass	-	-	same as P5	29.9
CCGT	0.465	0.65	0.14	15.1
PV	6.7	6.5	0.7	-
Wind	2.35	1.6	0.3	-
Storage	2	4	0.6	-

P5 will employ approximately 832 people

Using the available 2019 values for the employment in the mines and power plants of Western Macedonia (The World Bank, 2019), a specific employment per MW of installed lignite capacities was derived. A total of 2128 jobs in the mining sector and 1161 at the power plants are equivalent to 0.9 and 0.49 jobs / MW, respectively. Applied to the installed capacity of P5 this results in around 238 full-time employees for the power plant and an estimated 594 mining jobs that will be associated to the lignite demand of the new unit, resulting in a total of 832 jobs for the P5 lignite unit.

The following figures show the employment created by each technology over its lifetime in comparison to P5. Figure 15 shows the total employment including manufacturing and construction, while figure 16 depicts the employment during the operation of the plant.

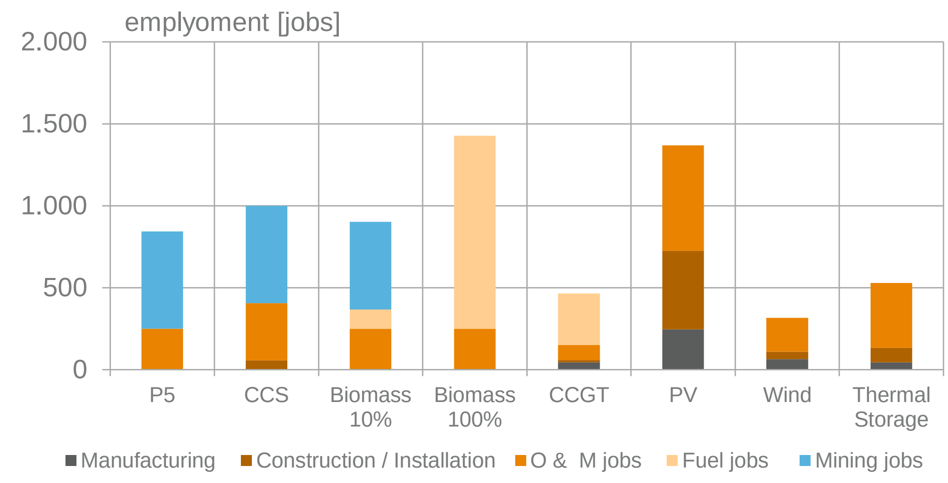

Figure 15- direct employment by technology

CCS would secure existing mining jobs

Based on data by the global CCS institute (Global CCS Institute, 2020), the CCS plant would create an additional 99 permanent jobs operating and

[23] Calculated using the value of 1700 employees per power plant over the course of 30 years of operation. No data on jobs / MW not available. (Global CCS Institute, 2020)

[24] Based on an average of 150 employees per 1 GW of power plant (Global CCS Institute, 2020)

… and create 156 new jobs.

maintaining the CO_2 capture unit. The construction of a CCS plant is estimated to require between 1700 and 2000[25] additional workers. The CCS plant would then create around 156 new jobs, while securing existing mining jobs in the regions.

A switch to biomass would result in a loss of most mining jobs. Jobs in fuel procurement are likely to be created abroad.

A retrofit to a 10 % biomass co-firing plant results in a reduced demand for lignite as a fuel and thus a decrease in mining jobs. Simultaneously, the additional demand for biomass could create around 118 new jobs associated with the harvesting, processing and transportation of the biomass. However, such jobs are likely to be created outside of Greece, in case of international procurement for the required biomass. In a 100 % scenario, all mining jobs would be lost. However, a total of 1178 jobs in the biomass industry could emerge. In both the 10% and 100 % scenario, the same number of jobs in the power plant as in the case of the lignite plant can be expected. A complete switch to biomass would therefore cause a loss of jobs at the regional level while creating jobs on the EU-level.

Replacing P5 with a CCGT would result in a net loss of 380 direct jobs.

A CCGT plant of the assumed scale would employ an average of 92 people for its operation and maintenance. Those jobs would be created locally. Jobs associated with the handling of the fossil gas, would amount to a further 313. Unlike the O&M, the fuel handling, i.e. exploration and production as well as transportation, would be located outside the region. Overall the replacement of Ptolemaida 5 with a CCGT plant would result in a net loss of 380 direct jobs. (European Commission, 2020)

The thermal storage will secure most direct jobs in the operation and maintenance of the associated plants.

For the thermal storage and renewable energy generation the yearly average output of the P5 lignite plant was taken as reference for estimating the capacity of the PV and Wind plants that will be needed to provide electricity for the thermal energy storage facility. For a 50 % share of PV and Wind, respectively, a total of 2000 jobs will be created in the PV sector and 526 for the wind turbine installations. Additionally, the power plant and thermal storage would retain 528 jobs related to the former lignite plant.

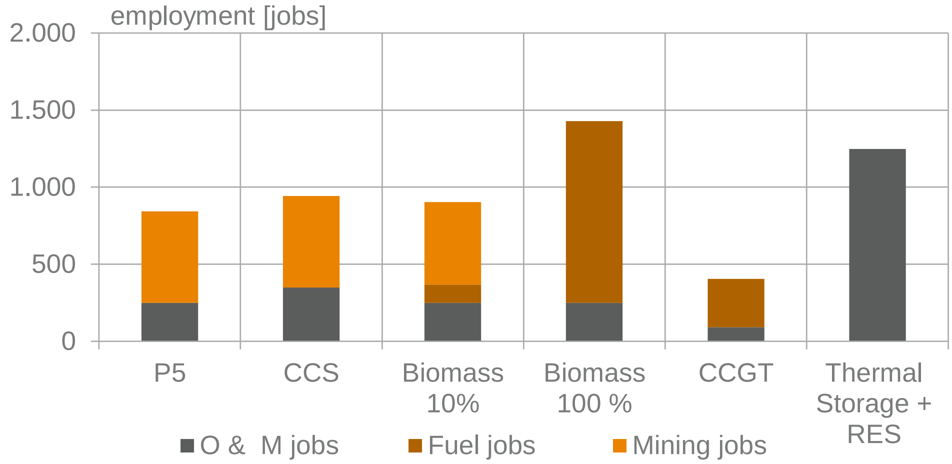

Figure 16- direct employment without construction and installation

[25] The more conservative estimate of 1700 is used in this study. The value is divided by the lifetime of 30 years, resulting in 57 jobs created on average over the course of the plant's lifetime.

Regional employment can best be ensured by CCS or a Thermal Storage though a transfer of employment from mining to the renewable sector remains questionable

In conclusion, the replacement options best suited to ensure regional employment are the CCS retrofit and the thermal storage. Both technologies will require a larger number of workers than the one of P5. While a CCS retrofit will ensure an employment in the mining sector, a thermal storage retrofit would shift employment from mining to the renewable energy sector. It is uncertain to which degree such jobs can be transferred, since qualifications required and education of the current workforce was not taken into account in this study. Jobs at the power plant, however, are likely to be ensured for both technologies, since the existing plant will be kept in operation.

Biomass and CGGT will require fewer local employees, since the procurement of fuel is likely to take place outside the region.

It is probable that both a biomass retrofit and a change to a CCGT plant will cause a loss in regional employment. This loss is mainly due to the loss in mining jobs, which can not be compensated for by biomass or fossil gas-related fuel handling jobs. Especially for the case of biomass, it is likely that a large share of the jobs will be created abroad, if pellets are to be imported.

Results for the thermal storage are sensitive to the dimensioning of renewables.

Lastly, it should be noted that in the case of the thermal energy storage system, the estimated number of jobs is mainly dependent on the system design, since the scale of installed wind turbines and PV panels determines the total number of jobs. A more precise assessment would require a feasibility and system design study, in which the exact dimensions of the storage system as well as that of th renewable energy technologies required would be assessed.

References

Aalborg University, 2018. *Heat Roadmap Europe 4 - Quantifying the impact of low-carbon heating and cooling roadmaps,* Copenhagen: Aalborg Universitetsforlag.

BloombergNEF, 2020. *EU Climate Goals Accelerate Eastern European Decarbonization.* [Online]
Available at: https://bit.ly/2LB0oX8
[Accessed January 2021].

DBI Gas- und Umwelttechnik GmbH, 2017. *Study on fossil gas retrofits for coal-fired power plants in the German energy market,* Leipzig: DBI Gas- und Umwelttechnik GmbH.

DLR, M. G., 2019. *Decarbonization and job securement by converting coal fired power plants.* Athens, s.n.

Drax Power, 2018. [Online]
Available at: https://www.drax.com/press_release/drax-moves-closer-coal-free-future-unit-four-conversion/
[Accessed November 2020].

Drax Power, 2019. [Online]
Available at: https://www.drax.com/about-us/our-projects/drax-power-station-ccgt/
[Accessed December 2020].

Energypress, 2020. *energypress.gr.* [Online]
Available at: https://energypress.gr/news/tin-anoixi-o-diagonismos-gia-proto-mega-fotovoltaiko-tis-dei-stin-ptolemaida
[Accessed January 2021].

Euro Dollar Exchange Rate, 2020. *Macrotrends.net.* [Online]
Available at: https://www.macrotrends.net/2548/euro-dollar-exchange-rate-historical-chart

European Biomass Association, 2017. *AEBIOM Statistical report,* Brussels: s.n.

European Commission, 2020. *Employment in the Energy Sector - Status Reports,* s.l.: s.n.

European Commission, 2020. *Impact Assessment - Stepping up Europe's 2030 climate ambition,* Brussels: s.n.

European Investment Bank, 2020. [Online]
Available at: https://www.eib.org/en/press/all/2020-200-eib-backs-826-mw-mytilineos-power-plant-to-support-greek-energy-transition
[Accessed December 2020].

Fraunhofer ISE, 2018. [Online]
Available at:
https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf
[Accessed November 2020].

Germany Energy Agency, 2011. *Co-firing of biomass in coal power plants - a contribution to to the energy transition?,* s.l.: s.n.

Global CCS Institute, 2020. *The value of carbon capture and storage (CCS),* s.l.: s.n.

Greek Ministry of the Environment and Energy , 2019. *National Energy and Climate Plan (NECP),* s.l.: s.n.

MERRA-2, 2016. *Average Wind and Solar profiles.* s.l.:renewables.ninja.

PPC Thermal Projects Engineering and Construction Department, 2011. *Techno-economic report for the apture-transport and storage of CO2 at the new Ptolemaida 5 lignite unit,* s.l.: s.n.

PPC, 2013. [Online]
Available at: https://bit.ly/36VnlLZ
[Accessed December 2020].

PPC, 2013. *PPC Press release - costs of lignite production.* [Online]
Available at: https://www.newsbeast.gr/files/1/2013/12/03/dei_lathidiatisias.pdf
[Accessed November 2020].

Regulatory Authority for Energy, 2020. [Online]
Available at:
http://www.rae.gr/site/file/categories_new/about_rae/factsheets/2020/maj/2707?p=file&i=0
[Accessed December 2020].

The World Bank, 2019. *A Road Map for a Managed Transition of Coal-Dependent Regions in Western Macedonia,* s.l.: s.n.

U.S. Energy Information Administration, 2017. [Online]
Available at: https://www.eia.gov/todayinenergy/detail.php?id=33552
[Accessed November 2020].

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