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Transmission Expansion and Electricity Trade: A Case Study of the Greek Power System

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ABSTRACT

The integration of European electricity markets, through the market coupling process, can create significant efficiency gains in terms of social welfare to European consumers and industries. The market coupling process is anticipated to more efficiently utilize the generation and transmission activities, reducing the requirements of large idle generation capacity. This paper uses an optimization-based methodological framework to address the problem of the optimal planning of a power system at an annual level in competitive and volatile power markets, under dynamic formulation of the strategy employed by all market participants. The model is used for a scenario-based transmission expansion of the Greek power system with neighboring power systems in Southeast Europe, identifying its impact on a series of operational and economic aspects. The model determines the optimal power generation mix in each scenario, the electricity trade with the neighboring countries, the evolution of the system marginal price and the resulting environmental impact. This enables the identification of the remuneration of all types of producers from the wholesale market through a detailed calculation of all the relevant cost components. The proposed approach can provide useful insights on the optimal portfolio determination by potential investors at a national and/or regional level, highlighting potential risks and appropriate price signals on critical infrastructure projects under real electricity market operating conditions.

Keywords: CO_2 Emissions, Electricity Trade, Power Market Dynamics, Power Generation Mix, Transmission Expansion
JEL Classifications: Q43, Q47

1. INTRODUCTION

The main objectives of the EU energy policy are affordability, climate change, and security of supply (de Menezes and Houllier, 2015). The expansion of interconnection and transmission capacity in Europe is of great significance, since it has the ability to facilitate the optimal utilization of variable renewable energy generation, alleviating the impacts of daily and seasonal demand peaks, as well as to mitigate the requirements for new generation capacity to cover increasing energy demand inside the regions (IEA, 2016; Koltsaklis et al., 2013). The ever-increasing market integration over large regions is of great significance for utilizing the benefits of smoothing out the variations and forecast errors associated with variable renewable energy and dynamic loads. In that context, power markets have largely been designed with the objective of enabling cross-border electricity trading (IEA, 2017). A recent study confirmed the benefits of market coupling in terms of welfare, as well as of generation adequacy (Ringler et al., 2017). Oseni and Pollitt (2016) presented a comparative analysis, based on four international case studies, of key factors that exert influence on regional market integration, underlining all the necessary preconditions, institutional arrangements and timetabling for its successful implementation. Within that context, there is an ever-increasing penetration of renewable energy into the power systems in order for each country to comply with its declared national environmental targets. de Groot et al. (2017) investigated the impacts of increased penetration of variable renewable energy on the energy efficiency and full load hours of fossil fuel-fired power plants in the EU, while Coester et al. (2018) proposed a new market design for the German power market in order for the conventional power units to optimally adapt in market conditions with increasing amounts of renewable energy, satisfying simultaneously the efficient market operation (security of power supply, improved power units' profitability) and the further penetration of renewables in the power mix. Pattupara and Kannan (2016) assessed through the examination of a set of scenarios with the cross-border Swiss TIMES electricity model, the long-term development of the Swiss power system and its neighboring countries under various policy objectives, including nuclear phase-out and CO_2 emissions mitigation. The results reveal that increased cross-border interconnection capacities can play a vital role in that transition. Examining also the Swiss power system, Osorio and van Ackere (2016) studied the effects of a nuclear phase-out on the Swiss power system, focusing on the resulting security of supply and capacity adequacy, while Dujardin et al. (2017) assessed the interactions among photovoltaic, wind energy and storage hydropower in a fully renewable Swiss power system when considering nuclear power phase-out. In addition, Das et al. (2018) examined through scenarios possible pathways of the power system of Bangladesh. Their findings suggest that the concurrent consideration of high power imports and high share of renewables can lower the power supply cost, as well as maintain the system's energy security through diversification of utilized fuel sources. Moreover, Norvaiša and Galinis (2016) applied the MESSAGE modelling tool to assess the future pathways of the Lithuanian power system, characterized by one of the highest electricity imports share to its consumption, in an effort to combine the competitive power prices provided by electricity imports, with improved security of supply provided by domestic installed power capacity. Also, Bompard et al. (2017) implemented an analysis to study the current and future perspectives of the electricity independence of the Baltic States, in terms of adequacy, security, and economic factor (electricity price). The findings emphasize the importance of additional grid investments for the maintenance of high security level of power supply in the future.

At a regional level, Abrell and Rausch (2016) developed a general equilibrium model and an electricity dispatch model to assess the impacts of transmission expansion and renewable energy penetration in Europe. One key finding is that transmission expansion can lead to noticeable gains in terms of electricity trading, which has also positive correlation with significant renewable penetration. In the same frame of reference, Martínez-Anido et al. (2013a) conducted a techno-economic analysis of the implications of North African electricity imports on the European and the Italian power systems in 2030, resulting in a decrease in European power prices, and highlighting Italy's potential of becoming a regional energy hub. At a European level, Martínez-Anido et al. (2013b) assessed the effects of cross-border power transmission capacity investments on annual dispatch costs, wind and solar energy curtailment, CO_2 emissions, hydro storage utilization and on security of supply, in terms of energy not served. Lopez et al. (2018) presented an analysis to study the effects of the electricity trading on global carbon emissions. According to the results provided, the European region offset approximately 10.3 $MtCO_2$ between 1990 and 2014 due to electricity trading, due namely clean power exports from a series of countries. However, some countries report an increase in their emissions due to electricity exports, which even outweighed the respective increases due to population grown, highlighting the need for careful and coordinated planning at a regional level. Torriti (2014) focused on the key determinants of power trading among the European power systems, and concluded that privatization has the potential to enhance power flows and transactions in most cases, transforming national markets into a continental "supergrid" for Europe. Finally, Lilliestam (2014) examined the vulnerability to terrorist attacks in European electricity decarburization scenarios, and also compared renewable electricity imports to gas imports. According to the findings, the vulnerability of both gas and electricity imports is low, but electricity imports are characterized by higher vulnerability than gas imports given their fewer possibilities for storage and the need for uninterruptible electricity demand balance.

This paper makes use of a systematic and detailed mixed integer linear programming model to address the problem of determining the optimal annual energy mix of a given power system (Koltsaklis and Nazos, 2017), focusing on the impacts of the interconnections' transmission expansion on the resulting energy mix, the cross-border electricity trade, and other economic aspects of a specific power system. The aim of this paper is to assess the impact of several scenarios of transmission capacities on a series of operational and economic aspects of a given power system including: (1) The optimal power generation mix, (2) The electricity trade, (3) the annual weighted average system marginal price, (4) the environmental impact in terms of CO_2 emissions, and (5) the supply cost.

Therefore, the paper contributes to the relevant literature on the quantification of the impacts of different transmission capacities among interconnected power systems on a series of power systems operational and economic aspects. The key contributions and the prominent features of our work include: (1) Mid-term power system expansion planning for identification of its impact on the power system, (2) identification of remuneration of all types of producers from the wholesale market, and (3) provision of price signals on potential investors for the optimal determination of their generation portfolio.

The remainder of the paper is organized as follows: Section 2 defines the key aspects of the applied mathematical model, while Section 3 introduces the case study description. Section 4 provides a critical discussion of the results obtained from the model execution, and finally Section 5 draws upon some concluding remarks.

2. MATERIALS AND METHODS

The problem to be addressed in this work deals with a scenario-based transmission expansion planning of a given power system, investigating its impact on a series of operational, economic, and environmental aspects. The current work makes use of a mixed integer linear programming model for the optimal energy planning of a power system, combined with the dynamic formulation and adaptation of the strategy applied by all the market participants in the market operation (Koltsaklis and Nazos, 2017). In this work the considered time period is 1 year, and 12 representative days are employed (with a 24-h profile), in order to capture the variability and the seasonality characterizing the renewables penetration and the electricity demand. The transmission expansion planning is taken into consideration through the incorporation of relevant scenarios, namely they do not constitute decision variables. The objective function of the integrated model, as described in a previous work (Koltsaklis and Nazos, 2017), concerns the minimization of the total operational cost of the studied power system at an annual period. Therefore, the model's objective function includes: (1) Marginal production cost of thermal power units incorporating fuel cost, variable operating and maintenance cost, and CO_2 emission allowances cost, (2) Operational hydro production cost, (3) electricity imports cost, (4) electricity exports revenues, and (5) pumping load revenues, as represented by Equation (1).

Min Cost^{total}

$$\overbrace{\sum_{(i,s)\in I^{th,S}}\sum_{f}\sum_{m}\sum_{t}(bp_{i,f,m,t}.INL_{s,m,t}.THOF_{i,f,m,t}.Dur_{m})}^{Operational\ thermal\ production\ cost}+$$

$$\overbrace{\sum_{(i,s)\in I^{h,S}}\sum_{f}\sum_{m}\sum_{t}(bp_{i,f,m,t}.INL_{s,m,t}.HOF_{i,f,m,t}.Dur_{m})}^{Operational\ hydro\ production\ cost}+$$

$$\overbrace{\sum_{(int,s)\in INT^{imp,S}}\sum_{f}\sum_{m}\sum_{t}(bim_{int,f,m,t}.INL_{s,m,t}.IMOF_{inf,f,m,t}.Dur_{m})}^{Electricity\ imports\ cost}-$$

$$\overbrace{\sum_{int\in INT^{exp}}\sum_{f}\sum_{m}\sum_{t}(bex_{int,f,m,t}.EXBD_{int,f,m,t}.Dur_{m})}^{Electricity\ exports\ revenues}-$$

$$\overbrace{\sum_{pm}\sum_{f}\sum_{m}\sum_{t}(bp_{pm,f,m,t}.PMBD_{pm,f,m,t}.Dur_{m})}^{Pumping\ revenues} \tag{1}$$

The minimization of the objective function leads to the estimation of the system's marginal price which is defined as "the price that all electricity suppliers (e.g., producers, importers) are going to be paid and all power load representatives (e.g., exporters, large consumers) are going to pay" (Koltsaklis et al., 2016).

Figure 1 depicts the calculation of the system's marginal price, as the crossroad of aggregated Supply and Demand curves. A detailed description of the technical and operational constraints of the proposed model can be found in equations (1-55) and (M1-M13) of a recent work (Koltsaklis and Nazos, 2017). The main aim of the present work is to examine the influence of the interconnection capacities with the neighboring power systems on the operational and economic decisions variables. For convenience purposes, the energy demand balance is also presented here as equations (2).

$$\overbrace{\sum_{(i,s)\in I^{ht,S}}\sum_{f}(bp_{i,f,m,t}.INL_{s,m,t})}^{Hydrothermal\ power\ supply}+\overbrace{\sum_{(int,s)\in I^{imp,s}}\sum_{f}(bim_{int,f,m,t}.INL_{s,m,t})}^{Electricity\ imports}-$$

$$\overbrace{\sum_{int\in I^{exp}}\sum_{f}bex_{int,f,m,t}}^{Electricity\ exports}+\overbrace{\sum_{(i,s)\in I^{h,S}}\sum_{f}(P^{fix}_{i,m,t}.INL_{s,m,t})}^{Non-priced\ hydro\ power\ supply}+\forall_{m,t} \tag{2}$$

$$\overbrace{\sum_{(i,s)\in I^{rn,S}}\sum_{f}(P^{fix}_{i,m,t}.INL_{s,m,t})}^{Non-priced\ renewables\ power\ supply}=\overbrace{Dem_{m,t}}^{Power\ load}+\overbrace{\sum_{pm}\sum_{f}bp_{pm,f,m,t}}^{Electricity\ imports}$$

Equations (2) define the energy demand balance of the studied power system. More specifically, net power injection (taking into account power losses) from all power generating units, plus net electricity imports to each subsystem, must satisfy the electricity demand of each subsystem and the pumping load.

3. CASE STUDY DESCRIPTION

The inter-zonal Greek power system including the interconnected system (mainland), i.e. the North and the South subsystems, is taken into consideration. Those subsystems are divided into two and three zones respectively, in order to accurately reflect the spatial characteristics of the studied power system. The Greek power system has interconnections with the power systems of five neighboring Southeast European countries (Albania, Bulgaria, FYROM, Turkey, and Italy). Table 1 summarizes the main techno-economic data of each technology type in the Greek power system, including the installed capacity, the optimal efficiency, the CO_2 emission factor, as well as the raw material and maintenance cost per technology type.

Regarding the installed power generating capacity, there are fourteen lignite-fired units with a total capacity of 3.9 GW, fourteen natural-gas fired (both natural gas combined cycle and natural gas open cycle units) power plants with a cumulative capacity of 4.8 GW, and sixteen hydroelectric units whose capacity equals 3.1 GW. With regard to the installed capacity of renewables in the interconnected power system, this include around 2 GW of wind turbines, 2.45 GW of photovoltaics, 50 MW of high-efficiency combined heat and power units, 60 MW of biomass units, and 235 MW of small hydroelectric units in total. It can be also observed that natural gas-fired units are characterized by higher thermal efficiencies when compared to those of lignite-fired units, as well as they have lower carbon impact than the lignite-fired ones. With regard to the raw material and maintenance costs, they are

Figure 1: Determination of the SMP, as the crossroad of aggregate Supply and Demand curves (€/MWh)

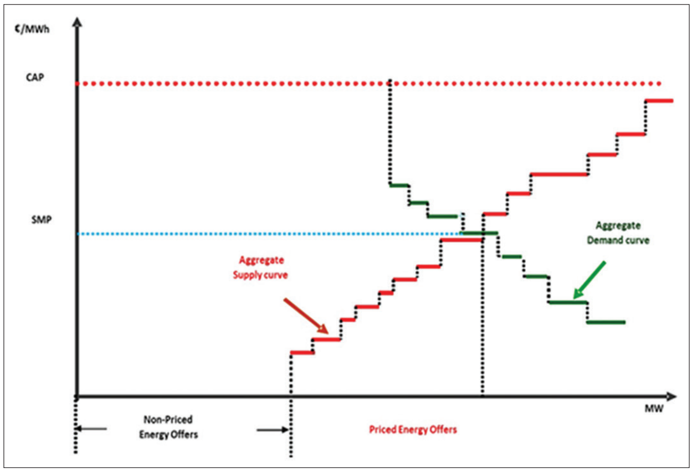


Table 1: Main techno-economic data of each technology type

Technology type	Capacity (MW)	Optimal efficiency (%)	CO_2 emission factor (tCO_2/MWh)	Raw material cost (€/MWh)	Maintenance cost (€/MWh)
Lignite	3912	28-35	1.2-1.8	1.0-1.9	0.45-0.81
Natural gas	4800	40-60	0.37-0.53	1.1-1.3	0.48-0.54
Large hydroelectric	3117	-	-	-	-
Wind	2050	-	-	-	-
Photovoltaics	2450	-	-	-	-
Small hydroelectric	235	-	-	-	-
Biomass	60	-	-	-	-
Combined heat and power	50	-	-	-	-

similar in both technology types. Concerning the renewable energy technologies, the model uses historical data of existing plants and estimates the average hourly capacity factor per technology type. Figures 2 and 3 present the average hourly capacity factor for each month in percentage terms (%), of photovoltaics and small hydroelectric units respectively.

When it comes to other cost assumptions, lignite fuel cost is considered to be between 10 and 22 €/t, depending on the specific lignite-fired unit, while the natural gas fuel cost is in the range of 0.26-0.28 €/m^3. The CO_2 emission allowances cost amounts to 5 €/tCO_2, while the electricity demand equals around 51 TWh at an annual base. With regard to the interconnection of the Greek power system, Table 2 summarizes the main techno-economic data of the interconnections of the Greek power system, including the yearly average available reference capacity, and the yearly average price of each interconnection.

The determination of the energy planning requires the implementation of energy system modelling for the whole energy system. Therefore, the above-mentioned model is useful in providing insights of the power sector, as part of an overall energy system modelling approach. Based on the reference values of the yearly average capacity (Base Case), a sensitivity analysis has been conducted in order to examine the influences of the available capacity on several operational, economic, and environmental decisions. More specifically, 10 cases have been examined (Case 1-Case 10), in which the available capacity from each interconnection increases successively by 10% in each case, in relation with the initial level. As a consequence, in the last case (Case 10), the available capacity from each interconnection increases by 100% in comparison with its initial value, namely it has doubled.

4. RESULTS AND DISCUSSION

The problem is solved to global optimality using the ILOG CPLEX 12.6.0.0 solver incorporated in the general algebraic modelling system tool (GAMS) (GAMS, 2017). An integrality gap of 0% was imposed.

Table 2: Main techno-economic data of the interconnections of the Greek power system

Type	Yearly average capacity (MW)	Yearly average price (€/MWh)
Imports from Bulgaria	400	40
Imports from Albania & FYROM	600	40
Imports from Italy	500	42
Imports from Turkey	134	38
Exports to Bulgaria	400	48
Exports to Albania & FYROM	600	49
Exports to Italy	500	50
Exports to Turkey	216	51

Figure 2: Hourly availability factor of photovoltaic units in each representative day of each month (%)

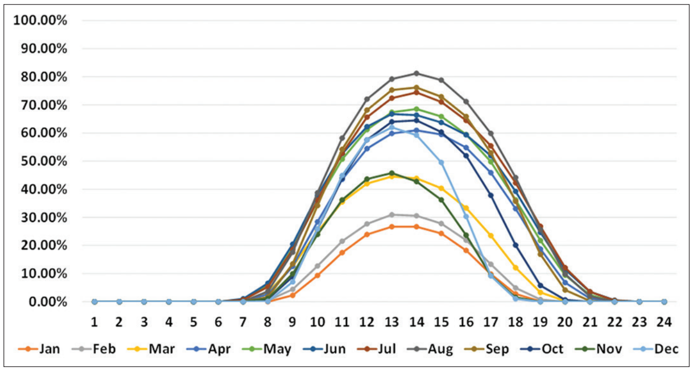
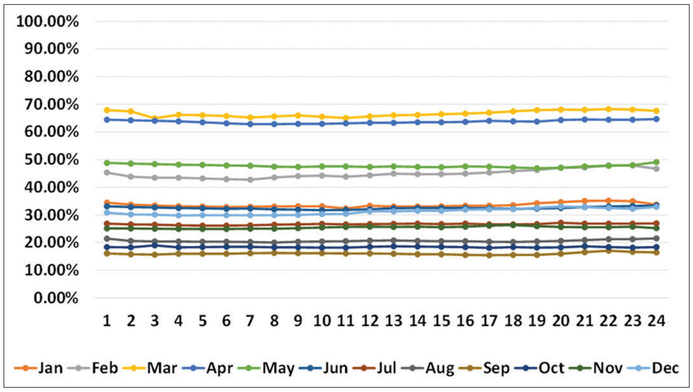


Figure 3: Hourly availability factor of small hydroelectric units in each representative day of each month (%)



4.1. Electricity Production Mix

Figure 4 depicts the energy balance of the studied power system in each Case. The results underscore the increasing role that electricity trade plays in the power demand satisfaction, since net imports, namely electricity imports minus exports, are characterized by an increase of 74.4% between base case and case 10. More specifically, they amount to 7.7 TWh in base case, 10.3 TWh in Case 4, rise to 12 TWh in Case 7, and they finally reach 13.4 TWh in Case 10. This can be explained by the increased transmission capacity with the neighboring countries and the subsequent availability of more economical amounts of electricity from those systems. Regarding the installed capacities in the Greek power system, the largest losses are reported by the natural gas-fired units, since their share decrease in the demand satisfaction equals 31% between Base Case and Case 10, or around 4 TWh in absolute terms. This can be attributed to the fact that some of the natural gas-fired units are old units, while others are less competitive in comparison with lignite-fired units, according to the assumptions made regarding their variable and fuel costs. Note also that the assumption for the CO_2 emission price is quite low, but representative of the current market conditions. Lignite-fired units report a slight decrease of around 8% between Base Case and Case 10, or around 1.3 TWh in absolute terms. Due to the cost assumptions, lignite-fired units retain their cost competitiveness in the market and they do not report significant losses. Apart from that, they are designed for base-load operation without having the ability for frequent start-ups and shut-downs, and they lack the ability for significant ramp rates. Renewables including wind turbines, photovoltaics, small hydroelectric units, biomass units, and combined heat and power units, have the same contribution in all scenarios since they are given priority when entering the system, highlighting in this way the importance of renewable energy in the Greek power mix. Finally, large hydroelectric units are characterized by a marginal decrease of around 5% between Base Case and Case 10, or around 0.26 TWh in absolute terms, comprising a conventional form of renewable energy which continues to meet a noticeable share of the power load at a national level. Its main advantage, apart from the cost competitiveness, is the significant flexibility provision to the system, since it is characterized by significant ramp rates and it can be combined with variable and intermittent renewable energy sources.

Figure 5 depicts the monthly energy balance of the studied power system. It can be observed that most of the considered technologies follow more or less the demand fluctuations, while electricity imports are characterized by the most stable profile, highlighting the relative economic competitiveness of that option. The variations also observed in the total electricity contribution from the renewable energy technologies can be also attributed to seasonal fluctuations, including the water availability for the hydroelectric units and the low availability of photovoltaics during the winter months. Natural gas-fired units, which are the most flexible thermal units of the system, having noticeable ramp-up and down limits, constitute the units that adjust their production to the contribution shifts of renewables. On the other hand, lignite-fired units are designed for base-load operation and lack the ability for frequent start-ups and shut-downs, as well as for significant production alterations.

Figure 4: Energy balance of the studied power system in each Case (GWh)

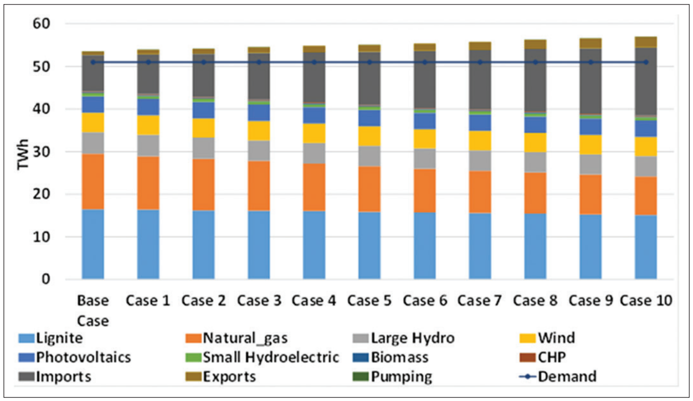


Figure 5: Monthly balance of the studied power system in the Base Case (GWh)

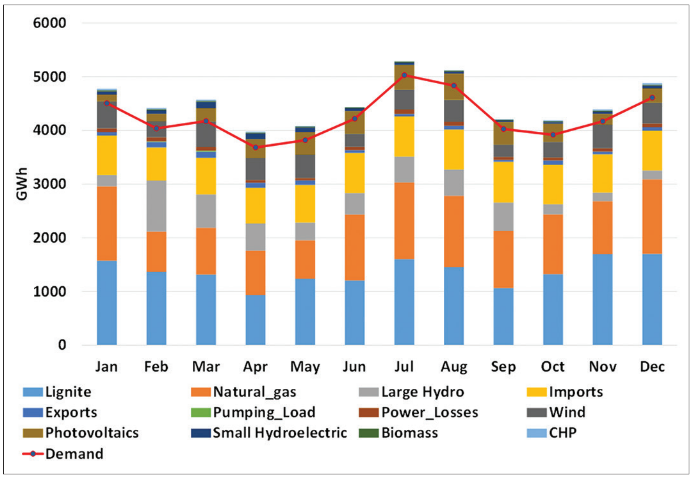
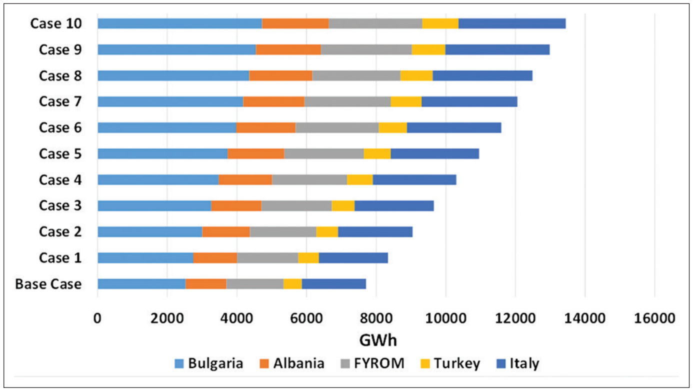


Figure 6: Annual net balance of the electricity trading activities with each interconnected country in each Case (GWh)



4.2. Electricity Trading

Figure 6 portrays the annual balance of the electricity trading activities with each interconnected country in each examined case. As can be observed from that Figure, the main trading partners of Greece are Bulgaria, FYROM and Italy. In general, Greece constitutes a net electricity importer, both as a whole and with each individual neighboring country. This is due to the fact that the production cost of the neighboring countries is lower than the corresponding of Greece. The most balanced position is reported in the case of Turkey, since the exports are comparable to the respective imports. However, the total quantities are not so significant, due to the relatively small available interconnection capacity between Greece and Turkey. Net electricity imports from Bulgaria and Italy comprise around 57% on average of Greece's electricity imports in all cases, while the remaining share is mainly met by FYROM and Albania. It is also noticeable that electricity exports increase gradually their share in comparison with electricity imports, beginning from around 10% in the Base Case, rising to 12.5% in Case 4, to 14.8% in Case 8, and finally they reach almost 16% of the corresponding electricity imports value in Case 10 at an annual level.

Figure 7 portrays the monthly balance of the electricity trading activities with each interconnected country in the Base Case. A key observation from that Figure and in connection with Figure 4, is that although the electricity demand has one of its lowest values during September, net electricity imports report their record value during that month, amounting to around 726 GWh. The main explanation for that trend is the remarkable drop reported in the electricity production coming from lignite-fired units, since several lignite-fired units are planned to shut-down during that month for their annual scheduled maintenance, and a part of their reduction is covered by electricity imports. This evolution highlights the significant flexibility provided to the power systems by electricity trading activities.

4.3. CO_2 Emissions

Figure 8 depicts the CO_2 emissions evolution at an annual level in each Case. As can be shown in that Figure, there exists a gradual decrease in the amount of the produced CO_2 emissions, which is due to the fact that part of the domestic production is gradually substituted for electricity imports from neighboring countries, from the Base Case to Case 10. More specifically, there is a 12% drop in the amount of the generated CO_2 emissions, starting from almost 30 Mt in the Base Case and reaching around 26 Mt in Case 10. If we focus on the technology origination of the CO_2 emissions, it can be observed that lignite-fired units account for the majority of those emissions, amounting to around 85.6% of the total on average in all cases, on the grounds that their carbon emission factors are in the range of 1.2-1.8 tCO_2/MWh, while the corresponding ones for natural gas-fired units are between 0.37 and 0.53 tCO_2/MWh in the Greek power system.

4.4. System's Marginal Price

Figure 9 presents the evolution of the system's marginal price at a monthly level in each Case. The increase of the available transmission capacities does not lead to a drastic decrease in the observed system's marginal price, which drops by around 1.3% between base case and Case 10. A decrease was anticipated due to the constantly increasing availability of economical electricity from the neighboring countries, which exerts downward pressure on the system's marginal price. The amount of that decrease is determined by the applied strategy of all market participants, being able to select an aggressive (as in our case, namely approaching the variable costs of the thermal units when they have that option), medium, or conservative strategy when submitting their offers/bids.

Figure 7: Monthly balance of the electricity trading activities with each interconnected country in the Base Case (GWh)

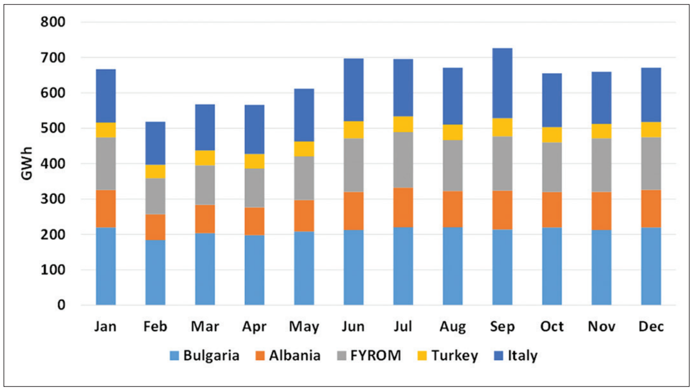


Figure 8: CO_2 emissions evolution at an annual level in each Case (Mt)

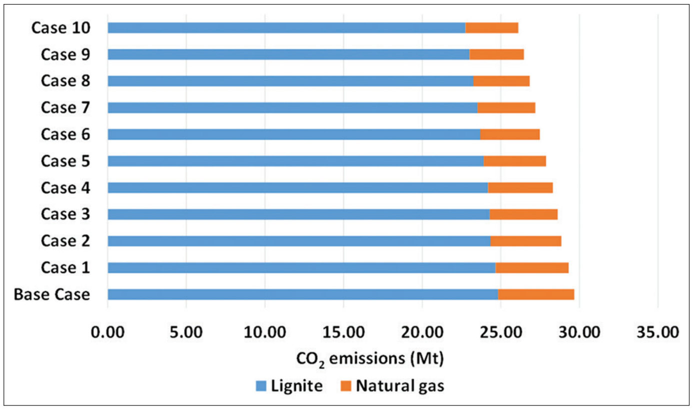
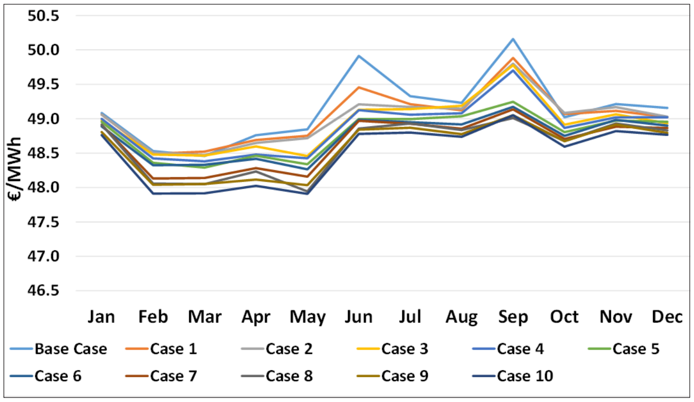


Figure 9: Evolution of the system's marginal price at a monthly level in each Case (€/MWh)



4.5. Supply Cost Composition

Table 3 presents the detailed supply cost composition per technology type. The total supply cost of the power system amounts to around 2.5 billion € at annual level in all cases, with a small decrease from base case to case 10. Regarding the individual cost components, it can be seen that the cost for the remuneration of the lignite-fired comprises the dominant component in all cases, except for cases 9 and 10, where the remuneration for the implementation of electricity imports takes the lead. A significant decrease is reported in the cost for the remuneration of natural gas-fired units, being equal to around 200 million € between base case and case 10. A drastic increase is observed in the electricity imports cost and in the electricity exports revenues, in parallel with the increase in the available transmission capacities with the interconnected countries. Finally, if we individually examine the CO_2 emissions allowances costs (it is also included as a component in the total cost of the lignite and the natural gas-fired units), it is in the range of 131-148 million € in all cases, or 5.6% of the total

Table 3: Detailed supply cost composition per technology type (Million €)

Cost components	Base Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Renewables	471	470	469	469	468	467	467	466	465	465	465
Lignite	792	785	774	771	767	758	750	744	734	726	717
Natural Gas	639	613	593	569	542	519	497	480	468	452	438
Large Hydroelectric	241	241	237	232	230	229	228	227	227	226	226
Imports	413	450	489	527	564	600	637	667	698	729	759
Exports	−42	−51	−56	−66	−72	−78	−85	−94	−106	−114	−124
Pumping	−2	2	2	2	2	2	2	2	2	2	2
CO_2 emissions allowances cost	148	147	144	143	142	139	137	136	134	132	131
Total supply cost	2512	2506	2504	2501	2498	2493	2491	2487	2484	2483	2479

supply cost on average in all cases. Note also that the higher the assumed CO_2 emissions price, the higher the share of that cost component in the total supply cost.

5. CONCLUSIONS

Energy, including electricity, security is of paramount importance to the global economy. This issue is only becoming more evident as countries and regions have the decarbonization of their power sectors at the top of their agendas. The increasingly interconnected nature of power markets brings opportunities to more efficiently manage this transition process, as well as challenges, emanating from increased interdependency. Among the benefits of the large-scale increased interconnections are the balancing of mismatches in supply and demand, peak capacity savings, more effective integration of variable renewable energy, and access to remote energy resources.

This work utilizes a market-based, optimization model for the optimal operational and economic planning of a given national power system at an annual level, under uncertainty in the available interconnection capacities with its neighboring countries. The model is used for a scenario-based transmission expansion of the Greek power system with neighboring power systems in Southeast Europe, identifying its impact on a series of operational and economic aspects. The model determines the energy and capacity mix, as well as the system's marginal price, subject to a set of technical, regulatory, economic, and environmental constraints of the power system. The results highlight the huge potential for electricity trading between the Greek and the neighboring power systems in Southeast Europe, as well as the challenges for the domestic technology mix. In that context, a further penetration of renewables could exert downward pressure on the system's marginal price, which has the potential to alter, to some extent, the direction of the cross-border flows. Under the current domestic technology structure, the more the expansion of the transmission capacities, the less the electricity production coming from thermal units, mainly from natural gas-fired units but also from lignite-fired units, depending on the assumptions for the fuel and the CO_2 emission costs. The system's marginal price is also highly sensitive to the strategy adopted by all the market participants. A future influence on its determination constitutes the future bidding introduction from renewables, which, at this stage, enter the system with priority without submitting priced offers.

In general, the transmission capacity values comprise a key parameter for the future evolution of the power systems, since they can determine to a significant extent the power generating units' investments to be implemented. They can favor the operation of specific technology types, e.g., renewables and those providing increased flexibility to the system, while other types can lose their relative competitiveness, both technically and financially, such as lignite- and/or hard coal-fired units. Therefore, the investigation of their impacts is of paramount importance for a series of market participants, including strategic power producers, power suppliers and traders, as well as market and TSOs.

Future challenges include the study of both generation and transmission expansion planning, as well as the detailed examination of the power systems of the neighboring countries in order to implement an overall assessment of the development dynamics of the whole South East European region.

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