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Price Signal of Tradable Guarantees of Origin for Hedging Risk of Renewable Energy Sources Investments

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ABSTRACT

The risk of renewable energy sources (RES) investments in several European Union (EU) countries is offset by site-specific compensation, resulted by competitive auctions according the EU state aid guidelines for energy for the period 2014-2020. However, this scheme of incentivizing RES will probably be replaced, inheriting risk for RES investments. A potential market-based scheme could be the introduction of tradable guarantees of origin (GOs). This paper uses an integrated model, integrating the optimal power systems expansion planning problem with the unit commitment problem, which performs the simulation of the day-ahead electricity market. The model is used for the expansion of the Greek power system, identifying the RES capacity mix per technology type. The model estimates the new RES capacity, the evolution of the day-ahead price and the levelized cost of avoided energy. This enables the identification of the remuneration of RES producers from the wholesale market and the premium required for covering their levelized cost of electricity. The estimation of this premium provides insights on the price signals of tradable GOs, which could offset the risk of RES investments. The paper finally discusses the GOs' status and challenges, towards becoming the preferred policy for RES promotion.

Keywords: Renewable Energy Sources, Guarantees of Origin, Risk, Power System Expansion Planning, Feed-in-Tariff, State Aid Guidelines
JEL Classifications: Q4, Q42

1. INTRODUCTION

The European Union (EU), in its 2020 strategy, has set binding legislation (EU Package, 2009) to ensure the EU meets its three key climate and energy targets for the year 2020: 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewable energy sources (RES), and 20% improvement in energy efficiency. The targets were set by EU leaders in 2007 and enacted in legislation in 2009 (EU Package, 2009). Towards meeting the RES targets, the EU realizes that, "their implementation may not always result in the most efficient market outcome and under certain conditions state aid can be an appropriate instrument to contribute to the achievement of the union objectives and related national targets" (EC, 2014). Therefore, according to the guidelines for state aid for environmental protection and energy for the period 2014-2020, the EU allows subsidies to RES, under the condition that - since first January 2017 - a competitive bidding process, on the basis of clear, transparent and non-discriminatory criteria, takes place for supporting RES investments. These guidelines are consistent with that objective and will ensure the transition to a cost-effective delivery through market-based mechanisms, such as auctioning or competitive bidding process open to all RES producers.

The levelized cost of electricity for RES is decreasing rapidly, as shown in a recent paper (Žiković and Gržeta, 2017), which provides insights on the competitiveness of RES on the liberalized electricity market in the South Eastern Europe countries. The final target for the European energy policy, expected to be implemented for the period between 2020 and 2030, is that RES will become grid-competitive and therefore penetrate in the market without subsidy and priority in dispatching, as well without any exemption from balancing responsibilities. Therefore, the abolition/replacement of existing support schemes is expecting to inherit risk on RES investments, which could be alleviated by the incorporation of supplementary market-based schemes, such as the tradable green certificates (TGC). Tradable certificates are measures that are already applied, either related to RES projects

(Girish et al., 2015), which present renewable energy certificate trading through power exchanges in India, or energy efficiency projects (Di Foggia, 2016), which examine the effectiveness of energy efficiency certificates as drivers for industrial energy efficiency projects.

Towards, meeting the RES targets, each EU member state implements its long-term energy planning, identifying the penetration level of each RES technology for the different sectors that RES are used. The power sector is the most critical, not only for the RES targets, but also for ambitious emissions reductions (Dagoumas and Barker, 2010). The main mechanism for the promotion of RES are the feed-in-tariff (FIT) schemes and the TGCs or Green Certificates system. The latter together with the electricity disclosure aim to provide consumers with relevant information about the generated electricity. Ringel (2006) examined the race between FIT and TGC in the EU, which finally resulted in favour of the FIT scheme. The main reason is that FIT scheme alleviates the risk for investments. Lemming (2003) examined the financial risks for green electricity investors and producers in a TGC market, identifying two critical risk factors: Fluctuations in production, i.e., volume risk and imperfect information about supply and demand. Kildegaard (2008) examined the risk of over-investment and the role of long-term contracts in green certificate markets. The paper demonstrates that in a TGC scheme characterized by high fixed- and low marginal-cost technologies, reliance on the spot market poses an asymmetric risk of over-investment and capital losses to investors. This will lead to the emergence of long-term certificate contracts, facing two major challenges: (i) The liquidity of the certificate spot market; (ii) cost-reducing competition between technology vintages.

Klessmann (2009) examined the evolution of flexibility mechanisms for achieving European 2020 renewable energy targets. They conclude that free or restricted certificate trade based on guarantees of origins (GOs) – as proposed earlier by the European Commission – is not a viable option due to some “knockout” criteria, despite other potential advantages. Koltsaklis et al. (2017) examined the impact of renewables on flexibility schemes, towards identifying the volumes of flexibility needs depending on the penetration level of RES, as well as the remuneration of the flexibility services. Verbruggen and Lauber (2012) provided an assessment of the performance of renewable electricity support instruments, namely FITs and TGC, based on the criteria of efficacy, efficiency, equity and institutional feasibility. The paper concludes that FIT are superior in addressing the renewables’ diversity and in promoting innovation. Moreover, FITs put transition burdens on incumbents and stimulate independent producers. Raadal et al. (2012) examined the interaction between electricity disclosure and TGCs. The paper concludes that electricity disclosure may create a customer-driven demand for renewable electricity, which can supplement the TGC system. In the long-term, GOs may thus influence the decisions made by investors in renewable energy.

The aim of this paper is to examine the price signals of GOs that would hedge the risk of RES investors. The robust quantification of such price signals, requires the development and use of detailed modelling approaches. This paper uses a systematic and analytical model that integrates two distinct problems:

i. The power systems expansion planning (PSEP) problem, which identifies the optimal type of energy technologies, the capacity expansion, location, and time construction of new power generation plants that will be commissioned based on a mixed-integer optimization framework that considers techno-economic and environmental criteria, and
ii. The unit commitment (UC) problem, which determines the units that will operate in the day-ahead electricity market based on an optimization approach that considers their variable costs, their bidding strategy, the ancillary services, and other technical criteria required by the transmission system operator (TSO).

The complete PSEP problem is a large-scale highly constrained mixed integer non-linear programming problem. Due to the complexity of the problem, researchers have developed more simplified versions of the overall problem utilizing various exact and approximate optimization methods (e.g., mathematical programming, evolutionary programming, and heuristics) (Koltsaklis et al., 2014; Chen et al., 2010). Concerning the Greek Power System, Bakirtzis et al. (2012), proposed an MILP model for the solution of the centralized generation expansion planning (GEP) problem, considering mid-term scheduling. They evaluated their model in the Greek energy system and conducted also sensitivity analysis for the evaluation of the effect of demand, fuel and CO_2 prices on the GEP decisions. Georgiou et al. (2011) examined the effect of islands’ interconnection to the mainland system on the development of RES in the Greek Power Sector. Kagiannas et al. (2004) presented a survey from monopoly to competition, concerning the power system. Rentizelas et al. (2012) presented a LP model for the long-term power systems expansion and their model was applied on the Greek Power Sector. A sensitivity analysis was also implemented to investigate the influence of several uncertain parameters, including the CO_2 emissions allowance price, the interest rate, the investment and operational cost, as well as the fuel cost. However, the risk of RES investments in the Greek Power System has not also been examined thoroughly.

Therefore, the paper contributes to the relevant literature on the provision of price signals of tradable GOs that would hedge the risk of RES investors, per technology type. The main contributions and the novel features of our work include: (i) Mid-term power system expansion planning for identification the RES capacity per technology type, (ii) identification of levelized system marginal price (LSMP) and of levelized cost of avoided energy (LACE) per RES technology type, (iii) identification of remuneration of RES producers from the wholesale market, and (iv) provision of price signals on GOs prices that hedge risk of RES investments, compared to unit-based FITs, specified by competitive auctions, and (v) discusses the status and challenges for GOs towards becoming the preferred RES promotion policy.

The manuscript is organized as follows. Section 2 presents the problem statement and the methodology adopted. In Section 3, a real case study concerning the RES penetration in Greece is presented. Section 4 discusses critically the results of the case study, while Section 5 discusses the current status of GOS and its challenges for becoming a preferred RES promotion policy. Finally, Section 6 draws upon some concluding remarks.

2. PROBLEM STATEMENT AND FORMULATION

Methodologically, the current work uses an integrated model, combining a power system expansion planning model with a UC model, based on recent work (Koltsaklis et al., 2014; 2016). The problem to be addressed in this work is concerned with the risk hedging of RES investors, under unit-based FITs and tradable GOs. The problem under consideration is formally defined in terms of the following items:

- The integrated model identifies the power capacity expansion of each type of power generation technology during each time period, the electricity production of each type of power generation technology in each zone and time interval, the optimal locations of new power plants, the quantity of energy resources used by each power generation technology in each location (zone), as well as the quantity of energy resources transported among the zones.
- The integrated model determines the optimal scheduling plan and the system marginal price (SMP) for each time period. The power system's requirements include: (i) electricity demand requirements, (ii) primary-up reserve requirements, (iii) secondary-up and secondary-down reserve requirements, (iv) fast secondary-up and fast secondary-down reserve, and (v) tertiary reserve requirements in each time period.
- The integrated model estimates the RES capacity and energy mix, as well as the LACE. The latter, together with the LSMP, identify the remuneration of RES producers from the wholesale market. Moreover, it identifies the premium required for hedging the RES investments. This premium is a price signal for tradable GOs that could replace the unit-based FITs, resulted from a competitive auctioning mechanism, according to the EU guidelines for state aid for environmental protection and energy for the period 2014-2020.

The objective function of the integrated model, as described in our recent work (Koltsaklis et al., 2016) is based on the short-term market operation, namely the minimization of the total operational cost of the studied power system at a daily period. Therefore, the model's objective function includes: (i) Marginal production cost of the power units incorporating fuel cost, variable operating and maintenance cost, and CO_2 emission allowances cost, (ii) power imports cost, (iii) power exports revenues, (iv) pumping load revenues, (v) units' shut-down cost, and (vi) reserves provision cost, as represented by Equation (1). The objective function differentiates from the previous work (Koltsaklis et al., 2016) in the period it examines. Therefore, in the following equation, each time period $t \in T$ belongs to the period 2017-2020, for which the integrated model finds the optimum overall energy system cost.

$$\text{Min Cost}^{\text{period}} = \overbrace{\sum_{u\in(U^{hth}\cap U^{z})}\sum_{z\in Z}\sum_{b\in B}\sum_{t\in T}\left(CB_{u,z,b,t}\bullet PEO_{u,z,b,t}\bullet L_{z,t}\right)}^{\text{Marginal production cost}}+$$
$$\overbrace{\sum_{n\in N^{z}}\sum_{z\in Z}\sum_{b\in B}\sum_{t\in T}\left(ICB_{n,z,b,t}\bullet IEO_{n,z,b,t}\bullet L_{z,t}\right)}^{\text{Power imports cost}}-$$
$$\overbrace{\sum_{n\in N^{z}}\sum_{z\in Z}\sum_{b\in B}\sum_{t\in T}\left(ECB_{n,z,b,t}\bullet EEO_{n,z,b,t}\right)}^{\text{Power exports revenues}}-$$
$$\overbrace{\sum_{e\in E^{z}}\sum_{z\in Z}\sum_{b\in B}\sum_{t\in T}\left(PMCB^{pum}_{e,z,b,t}\bullet PMEO_{e,z,b,t}\right)}^{\text{Pumping load revenues}}+\overbrace{\sum_{u\in U^{hth}}\sum_{t\in T}\left(x^{sd}_{u,t}\bullet SDC_{u}\right)}^{\text{Shut-down cost}}$$
$$+\overbrace{\sum_{u\in U^{hth}}\sum_{z\in Z}\sum_{t\in T}\left[\left(PR^{up}_{u,z,t}\bullet PRO_{u,z,t}\right)+\left(SR^{up}_{u,z,t}+SR^{down}_{u,z,t}\right)\bullet SRO_{u,z,t}\right]}^{\text{Reserves provision cost}}+ \quad (1)$$

The minimization of the objective function leads to the estimation of the $SMP_{s,t}$ 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 represents the determination of SMP, as the crossroad of aggregate Supply and Demand curves. The technical and operational constraints of the model are described in equations (2-55) of the recent work (Koltsaklis et al., 2016).

The model estimates for each RES technology type the LSMP, for each RES unit $u \in U^{res}$, fuel type $f \in F$, zone $z \in Z$ and time period $t \in T$.

$$LSMP_{f,t} = \sum_{u\in U}\sum_{z\in Z}\frac{\left(SMP_{t} * CB_{u,f,z,t}\right)}{CB_{u,f,z,t}} \quad \forall\ u \in U^{res},\ f \in F,\ z \in Z,\ t \in T \quad (2)$$

Similarly, the model estimates the LACE, which in fact uses the updated SMP, when no RES are considered in the day-ahead market. This updated SMP, is represented in this paper with the variable avoided cost of electricity, in order to be consistent with the terminology used in the literature (EIA, 2016). Moreover, the levelized cost of electricity (LCOE) is estimated for each RES unit $u \in U^{res}$, fuel type $f \in F$, zone $z \in Z$ and time period $t \in T$.

$$LACE_{f,t} = \sum_{u\in U}\sum_{z\in Z}\frac{\left(ACE_{t} * CB_{u,f,z,t}\right)}{CB_{u,f,z,t}} \quad \forall\ u \in U^{res},\ f \in F,\ z \in Z,\ t \in T \quad (3)$$

$$LCOE_{f,t} = \sum_{u\in U}\sum_{z\in Z}\frac{\left(LCOE_{u,f,z,t} * CB_{u,f,z,t}\right)}{CB_{u,f,z,t}} \quad \forall\ u \in U^{res},\ f \in F,\ z \in Z,\ t \in T \quad (4)$$

Variable RACE, represents the difference between the LSMP and LACE variables, as shown in equation (5). This variable is the actual cost of the wholesale market, that the retailers avoid, because of the RES penetration.

$$RACE_{f,t} = LACE_{f,t} - LSMP_{f,t}\ \forall f \in F, t \in T \tag{5}$$

The final aim of the paper is to estimate the price signal of the tradable GOs, represented here as GO, again for each RES type. This variable is equal the difference between the LCOE and LACE variables, as shown in equation (6).

$$GO_{f,t} = LCOE_{f,t} - LACE_{f,t}\ \forall f \in F, t \in T \tag{6}$$

$$GO_t = \sum_{t \in T} GO_{f,t}\quad \forall f \in F \tag{7}$$

3. DESCRIPTION OF CASE STUDY

The inter-zonal Greek Power System including the interconnected system (mainland), i.e., the North and the South subsystem, is taken into account. Those subsystems are divided into two and three zones respectively. The Greek Power System has interconnections with the systems of five countries (Albania, Bulgaria, FYROM, Turkey, and Italy). The latest available monthly energy report of LAGIE of June 2017, reports 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 4.7 GW, and 16 hydroelectric units whose capacity equals 3.2 GW. With regard to the installed capacity of renewables in the interconnected power system, this include 2.1 GW of wind turbines, 2.4 GW of photovoltaics, 100.1 MW of high-efficiency combined heat and power units, 60.5 MW of biomass units, and 229.3 MW of small hydroelectric units in total.

Concerning RES, 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 wind farms and photovoltaics respectively.

Moreover, the model assumes that the candidate RES, especially the wind and solar plants, have different values of LCOE depending on the site. This curve of LCOE per cumulative capacity is reported in Figure 4.

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. The implementation of the model determines the needs for new capacity per technology, based on assumptions on critical variables. Table 1 present the assumptions on the evolution of the fuel and CO_2 price over the period 2017-2020, while Table 2 presents the assumptions on the techno-economic data of candidate new power generation units. The latter assumptions are based on the relevant considerations used by the Hellenic Ministry of Environment and Energy (HP, 2016) in the public consultation of a new legislation for RES.

The main operational and economic characteristics of the installed units are available in our previous contribution (Koltsaklis et al., 2016). These data include: (i) Representative ramp rates, maximum contribution in primary, secondary, spinning and non-spinning tertiary reserve per technology type, (ii) representative power outputs in different operational stages (automatic generation control, soak phase, dispatch phase) per technology type, (iii) representative

Figure 1: Determination of the system marginal price, as the crossroad of aggregate supply and demand curves (€/MWh)

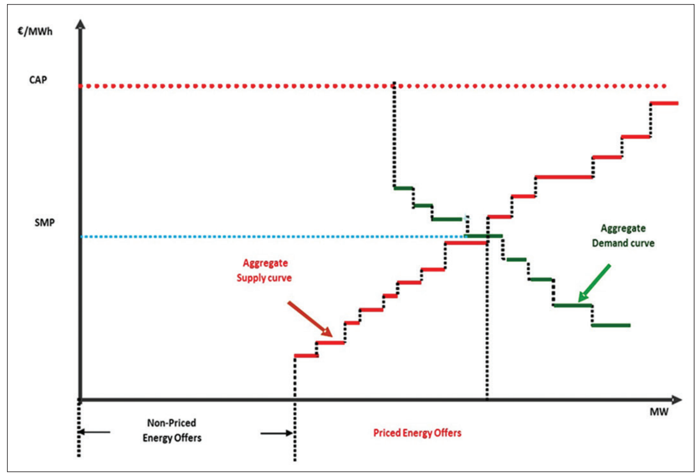


Figure 2: Average hourly capacity factor of photovoltaics for each month (%)

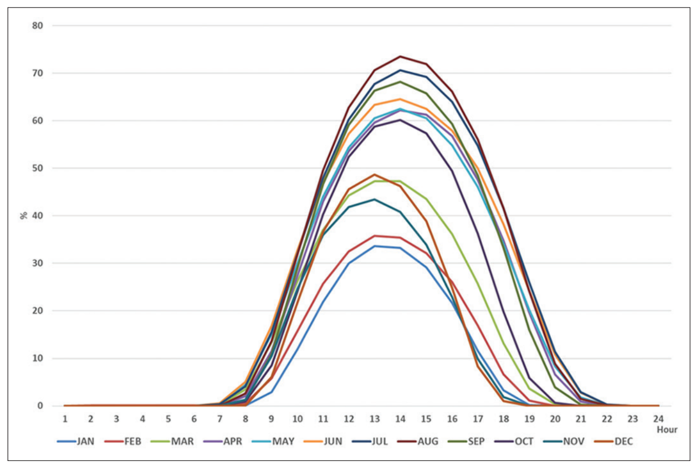
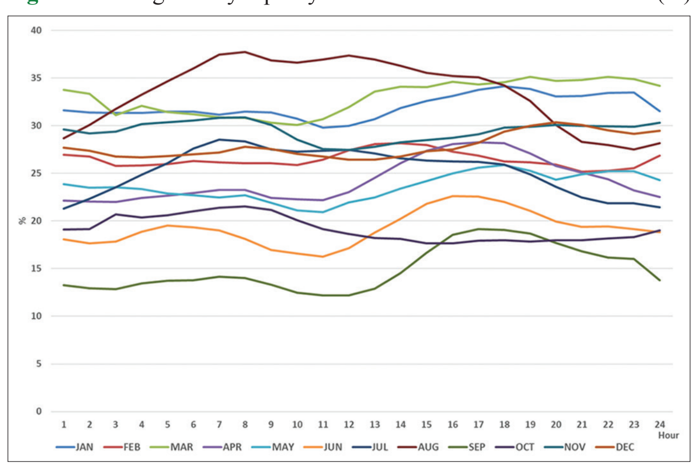


Figure 3: Average hourly capacity factor of wind farms for each month (%)



CO_2 emission factor per capacity block and technology type, (iv) representative non-operational time intervals before each representative unit's transition to the next standby condition and shut-down cost, and (v) representative synchronization (per start-up type), soak (per start-up type), desynchronization, minimum up and down time per technology type.

Considering the overcapacity of the Greek interconnected system, the model estimates that about 1 GW of new RES investments will be installed for the needs of the system stability, i.e. meeting reserve requirements. However, we assume that the relevant Ministry of Environment and Energy will identify more ambitious targets for RES penetration, as part of the overall GHG mitigation effort. Similar plans that have been elaborated in the past (YPEKA, 2010; YPEKA, 2012), have identified the needs for installation of 7 and 10 GW respectively of RES capacity up to 2020. Considering that already almost 5 GW of RES are installed in the Greek system, we assume that further 2.1 GW will be installed by 2020, consisting of 1 GW of wind, 1 GW of solar and 100 MW of biomass capacity. Table 3 provides the penetration of this capacity per RES technology type, over the period 2017-2020.

Figure 4: Evolution of the levelized cost of electricity for solar and wind investments (€/MWh)

Table 1: Assumptions on fuel and CO_2 price evolution over the period 2017-2020

Year	2017	2018	2019	2020
Lignite price (in €/tonne)	15	15	15	15
Brent crude oil price (in $/barrel)	51.9	55.0	57.5	60.0
Biomass price (in €/MWh of fuel)	15	15	15	15
CO_2 price (€/tonne CO_2)	5	5	5	5

4. RESULTS

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 Development Corporation). An integrality gap of 0% was imposed.

The integrated model provides the energy mix of the Greek Interconnected Power System, over the period of 2017-2020, as shown in Table 4. The situation where the Greek market is dominated by lignite generation is challenged, by the evolution of competitive natural gas units, with oil-linked fuel supply contracts, competitive imports, mainly from trading with the north borders but also from the Italian market, and the RES that inject in the power system, having dispatch priority and almost zero marginal cost. Those four "energy carriers" are taking almost similar shares to the energy mix for the examined period 2017-2020. Therefore, the participation in the Greek Market, is not strongly related to the ownership of lignite-fired units, as their competitiveness is now challenged by alternative sources. However, ownership of lignite units from other market participants, besides the Public Power Corporation, enables the creating of symmetrical portfolios among market participants and therefore enhance competition as well as hedging in case of sharp fluctuations of crude oil or CO_2 prices.

The competition of all those "energy carriers' is also depicted in smoothing the curve of the day-ahead prices. It has to be mentioned, that the Greek day-ahead market -for the time being- is organized as a mandatory pool. In order to clear the market, the market operator collects all the offers/bids and determines aggregate sale and purchase curves, by sorting the sale offers according to increasing prices, and the purchase bids in the inverse order, as shown in Figure 1. The cross-road of those curves concerns the SMP. Considering, that the RES do not inject the same volume of energy for each time period, we estimate the LSMP for each technology. Moreover, over the last years, an increasing number of researchers and policy makers (IEA, 2016) consider the ACE, which refers to the SMP without considering the injection for RES. Similarly, if we estimate the weighted average of the ACE for each RES technology type, we estimate the LACE.

The integrated model estimates the evolution of the average, over the period 2017-2020, SMP and ACE, for each hour of a 24-h period in €/MWh. The ACE is increased by about 6 €/MWh, compared to the SMP, when considering all RES units, both the existing units and the new installations. However, there is a fluctuation among time periods, is in the range of 3.1-9.8 €/MWh. This is attributed

Table 2: Assumptions on the techno-economic data of candidate new power generation units

Power unit	Capacity factor (%)	CO_2 content (tCO_2/MWh)	Fixed O and M cost (€/MW)	Variable O and M cost (€/MWh)	Investment cost (€/MW)	Commissioning time (years)
Lignite	85	0.85	21,653.8	2.500	1,600,000	4
Natural gas CCGT	90	0.35	9,200.0	3.500	700,000	3
Large hydro	30	-	10,715.4	1.915	2,000,000	7
Wind	25	-	23,830.8	0.000	1,250,000	1
Solar	17	-	9,184.6	0.000	925,000	1
Biomass	90	-	50,684.6	5.276	2,650,000	3
Geothermal	90	-	129,484.6	0.000	4,400,000	4

O and M: Operating and maintenance

Table 3: Evolution of cumulative RES investments over the period 2017-2020 (MW)

Energy	2017	2018	2019	2020
Solar	250	500	750	1000
Wind	400	500	700	1000
Biomass	25	50	75	100

RES: Renewable energy sources

Table 4: Evolution of energy mix over the period 2017-2020 (TWh)

Energy	2017	2018	2019	2020
Natural gas	12.76	13.01	13.24	14.06
Lignite	15.24	15.28	14.89	15.09
Hydro	4.40	4.40	4.40	4.40
RES	9.91	10.30	11.04	12.04
Net imports	10.31	10.69	10.97	11.70
Total demand	52.62	53.69	54.51	58.13

RES: Renewable energy sources

to the fact that the RES availability is not flat among time periods, as shown from the capacity factors of RES usage, presented in Figures 3 and 4. Therefore, this leads to different SMP and ACE for each technology type, based on the energy they produce for each time period. The weighted average of those SMP and ACE curves, on the relevant energy the RES units injected, provide the LSMP and ACE, estimated by equations (2 and 3). Similarly, equation (4) estimates the levelized COE per technology type.

Figure 6 presents the comparison between the LCOE, the LSMP and the LACE, price signal of GOs and RACE over the period 2017-2020 for solar, wind and biomass investments. All those figures are expressed in €/MWh. RACE, which represents the revenues of the retailers from the RES penetration in the wholesale market, is calculated from equation (5), while GO, which indicates the price signal of the tradeable GO to hedge the risk of RES investors, is estimated from equations (6 and 7). This figure provides a clear price signal on the level of required GO, that would attract similar RES investments and replace the unit-based FITs. Moreover, it provides a decomposition of the remuneration of a RES producer from the different market elements.

A sensitivity analysis on the volume of new RES investments was also carried out. This in fact depicts not the RES that would enter the market based on their competitiveness, but the willingness of the policy maker to promote RES investments. Figure 7 presents the evolution of the premium in €/MWh, being equal to the difference between LCOE and LACE over the period 2017-2020, for solar, wind and biomass investments, depending on the additional RES capacity installed. The three cases, with cumulative 2100, 3100 and 4100 MW RES capacity, refers to the scenarios where 1000, 1500 and 2000 of wind and solar are installed respectively. Biomass installations are considered equal to 100 MW for all scenarios. This figure provides signals on the price of GOs that would hedge those investments. It ranges from 15 to 25 €/MWh for wind farms, from 17 to 22 €/MWh for photovoltaics, while it is at the level of 89 €/MWh for the most competitive biomass installations. Therefore, it provides the price signal for hedging RES investments, in case where the tradable

Figure 5: Evolution of the average, over the period 2017-2020, system marginal price and ACE, for each hour of 24 h period (€/MWh)

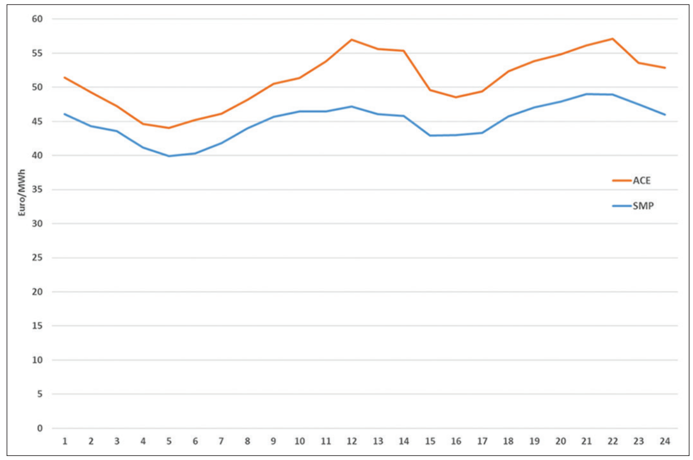


Figure 6: Comparison of levelized cost of electricity, levelized system marginal price, levelized cost of avoided energy, guarantees of origin and RACE over the period 2017-2020 for solar, wind and biomass investments (€/MWh)

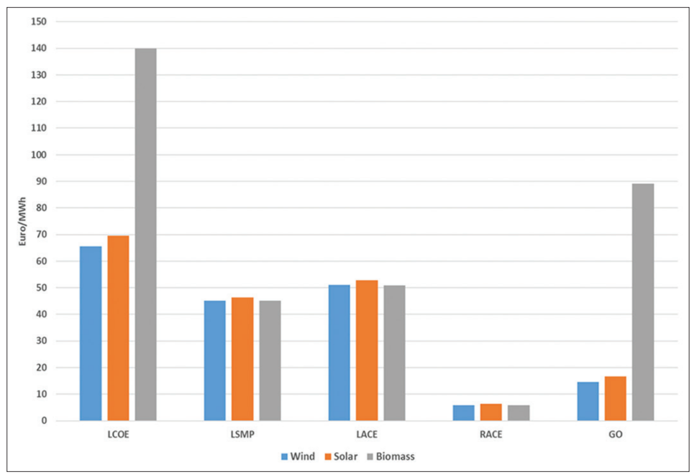
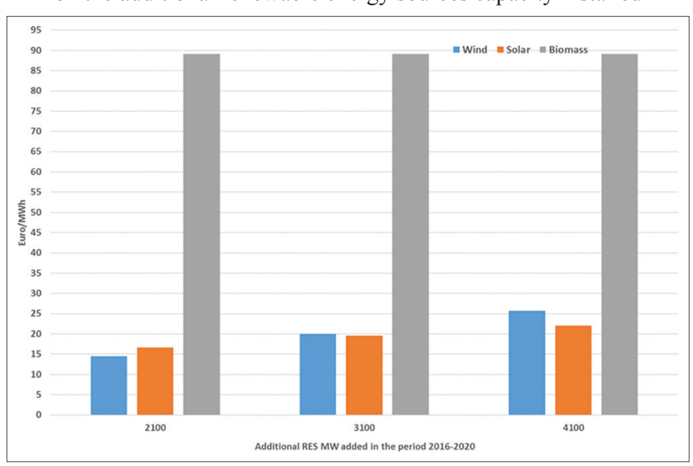


Figure 7: Evolution of the guarantees of origin, in €/MWh, over the period 2017-2020, for solar, wind and biomass investments, depending on the additional renewable energy sources capacity installed



GOs would be selected as the preferred method for the promotion of RES, instead of unit-based FITs, resulted from competitive auctions per technology type.

Considering that the highest price of GOs in the European Energy Exchange, is 0.31, 0.2 and 0.45 €/MWh for nordic hydro power, alpine hydro power and Northern Continental Europe Wind Power respectively, it derives that the GOs are far away from being considering a hedging mechanism for RES investments. However, this derives mainly from the fact, that as the RES investments were implemented with no risk through FIT schemes, there was no actual market for GOs. However, considering that the EU plans to remove any subsidy for RES investments, starting in 2021, the present paper provides useful insights on the risk of RES investments, fully depending on market dynamics.

5. DISCUSSION OF THE CURRENT STATUS AND THE CHALLENGES OF GOS

Risk is a crucial endogenous factor for RES producers but also for all market participants, including traders and retailers (Dagoumas et al., 2017; Dagoumas and Polemis, 2017). The above analysis provides price signal on the tradable GOs, that could offset RES investors' risk in Greece and replace the unit-based FIT scheme remunerations, as resulted from competitive auctions. However, as mentioned above, the tradable GOs or GCs are facing critical challenges, such as the liquidity of the GOs market, and the learning rates in cost reduction of competitive RES technologies, towards becoming the preferred policy tool. Concerning the latter, the fast reduction in the capital cost of RES technologies, especially the photovoltaics over the last years, as well their projections of their investments costs for the future (EIA, 2016), provide clear indication that the RES technologies are not far away from being competitive to the conventional technologies.

The second challenge is the liquidity of a GOs or GC market, as this strongly affects the pricing of such energy commodities and therefore, the decisions made by investors in renewable energy. At this point, a short description is useful to be provided on the current status of deployment of GOs in the EU member states.

A GO regime was created by the directive 2001/77/EC of the European Parliament and of the council in order to facilitate domestic or international trade in renewable electricity (i.e., proof of the green nature of the electricity), and to increase transparency in consumers' choice between renewable and non-renewable electricity. Article 5 of the directive introduces a minimum set of requirements for the GO. The GO must specify the source, date and place of production in a reliable manner; it should be mutually recognized by all member states exclusively as proof of renewably sourced electricity, and it should be reliable and accurate.

The GO can be used for a number of purposes, including claiming subsidy, i.e., a FIT or green certificate payment, supporting electricity bill energy mix "disclosure." In accordance with Article 3(6) of Directive 2003/54/EC, member states are required to implement a scheme for the disclose of the fuel mix, and to prove compliance with national renewable energy obligations. However, these applications are voluntary. Moreover, the directive 2009/28/EC on the promotion of the use of energy from renewable sources, obliges member states to create appropriate mechanisms and to establish Bodies responsible for issuing guarantee of origin for energy derived from renewable sources according to objective, transparent and non-discriminatory criteria, laid down by each member state, and specified the content of those guarantees.

Figure 8 presents the evolution of issuing of GOs by EU issuing bodies over the period 2010-2015, per energy carrier (TWh), based on data published in Association of Issuing Bodies. The majority of member states have established relevant issuing bodies, allowing RES producers to obtain relevant GOs for the energy they produce. This graph depicts the growing interest for RES, especially for hydro, wind and biomass, compared to the conventional fossil fuel production, but as well for nuclear energy, which is considered "green," concerning its GHG emissions. In year 2015, for all the EU member states, GOs have been issued for 261, 37, 22, 5 TWh of energy produced from hydro/marine, wind, biomass, and geothermal installations respectively. Concerning nuclear and fossil fuel plants, the relevant GOs are 22 and 3 TWh respectively. Therefore, as a response to the question if there is enough volume for liquid GOs market, the answer is positive, under the condition that there are not supplementary competitive mechanisms, such as the FIT schemes, that offset any motivation for trading GOs. The second major challenge is that the GO system must become obligatory and not voluntary across member states, applying the same conditions and criteria for issuing them, although the implementation of a European-wide harmonized TGC scheme for renewable electricity is not considered in advance as beneficial for all the EU Member States (Río, 2005).

6. CONCLUSIONS

The EU realizes, in the guidelines for state aid for environmental protection and energy for the period 2014-2020, that the provision of subsidies is required towards meeting its RES targets. The main mechanisms for the promotion of RES are the FIT schemes and the TGC or Green Certificates system. The FIT scheme has been the preferred mechanism, as it alleviates the risk for RES investments. The tradable GOs or GCs are facing critical challenges, such as the liquidity of the GOs market and the learning rates in the cost

Figure 8: Evolution of issuing of guarantees of origins by European Union issuing bodies over the period 2010-2015, per energy carrier (TWh), source: AIB, https://www.aib-net.org/

reduction of competitive RES technologies, towards becoming the preferred policy tool. This paper aims to examine the price signal of GOs that would hedge the risk of RES investors, and therefore influence the decisions made by investors in the renewable energy.

In order to quantify this price signal, the paper uses integrated systematic and detailed optimization model, that integrates the PSEP problem, which identifies the optimal type of energy technologies, the capacity expansion, location, and time construction of new power generation plants that will be commissioned based on a mixed-integer optimization framework that considers techno-economic and environmental criteria, with the UC problem. The latter identifies the units that will operate in the day-ahead electricity market based on an optimization approach that considers their variable costs, their bidding strategy, the ancillary services, and other technical criteria required by the TSO.

The model determines the energy and capacity mix, as well as the SMP, under the constraints of the power system and those imposed by the policy maker. The model is used for the expansion of the Greek power system, identifying the RES capacity mix per technology type. The model estimates the new RES capacity, the evolution of the day-ahead price and of the LACE. It also identifies the remuneration of RES producers from the wholesale market and the premium required for covering their LCOE, which is at the level of 15-25 €/MWh for photovoltaic and wind investments, and 90 €/MWh for biomass investments in Greece. The estimation of this premium provides insights on the price signals of tradable GOs, that could offset the risk of RES investments.

To sum up, the present paper contributes to the relevant literature providing a generic methodological framework on the provision of price signals of tradable GOs that would hedge the risk of RES investors, per technology type. It presents also a thorough discussion on the status and challenges for GOs towards becoming the preferred RES promotion policy. Such scheme could be introduced in several European countries, such as in South East Europe where the penetration of RES is rather low, in parallel with transmission capacities expansion and enhancement of the trading activities among the interconnected countries.

7. NOMENCLATURE

7.1. Sets

$t \in T$	Set of hours
$b \in B$	Set of blocks of the energy offer function of each hydrothermal unit
$e \in E^z$	Set of pumped storage units $e \in E$ in zone $z \in Z$
$u \in U^{hth}$	Set of hydrothermal units
$u \in U^{res}$	Set of renewable units (not including hydro units)
$u \in U^z$	Set of units $u \in U$ that are (or can be) installed in zone $z \in Z$
$n \in N^z$	Set of interconnected power systems $n \in N^z$ with zone $z \in Z$
$z \in Z$	Set of zones
$f \in F$	Set of fuel types (energy carriers)

7.2. Parameters

$PEO_{u,z,b,t}$	Priced energy offer of unit $u \in U^{hth}$ for zone $z \in Z$, block $b \in B$ and hour $t \in T$ (€/MW)
$EEP_{n,z,b,t}$	Priced energy offer for export between interconnection $n \in N$ and zone $z \in Z$, for block $b \in B$ and hour $t \in T$ (€/MW)
$IEO_{n,z,b,t}$	Priced energy offer for import between interconnection $n \in N$ and zone $z \in Z$, for block $b \in B$ and hour $t \in T$ (€/MW)
$PMEO_{e,z,b,t}$	Priced energy offer for pumped storage unit $e \in E$ for zone $z \in Z$, block $b \in B$ and hour $t \in T$ (€/MW)
$ECB_{n,z,b,t}$	Quantity of capacity block $b \in B$ for energy export between interconnection $n \in N$ and zone $z \in Z$ in hour $t \in T$ (MW)
$ICB_{n,z,b,t}$	Quantity of capacity block $b \in B$ for energy export between interconnection $n \in N$ and zone $z \in Z$ in hour $t \in T$ (MW)
$L_{z,t}$	Injection losses coefficient in zone $z \in Z$ and hour $t \in T$ (p.u.)
$PCB_{u,z,b,t}$	Power capacity block $b \in B$ of the energy offer function of unit $u \in U^{hth}$ in zone $z \in Z$ and hour $t \in T$ (MW)
$PMCB_{e,z,b,t}$	Quantity of capacity block $b \in B$ of pumped storage unit $e \in E$ in zone $z \in Z$ and hour $t \in T$ (MW)
$PRO_{u,z,t}$	Price of the primary energy offer of each unit $u \in U^{hth}$, in zone $z \in Z$ and hour $t \in T$ (€/MW)
$SRO_{u,z,t}$	Price of the secondary range energy offer of each unit $u \in U^{hth}$, in zone $z \in Z$ and hour $t \in T$ (€/MW)
SDC_u	Shut-down cost of each unit $u \in U^{hth}$ (€)
$PR^{up}_{u,z,t}$	Contribution of unit $u \in U^{hth}$ in primary-up reserve in zone $z \in Z$ and hour $t \in T$ (MW)
$SR^{Down}_{u,z,t}$	Contribution of unit $u \in U^{hth}$ in secondary-down reserve in zone $z \in Z$ and hour $t \in T$ (MW)
$SR^{UP}_{u,z,t}$	Contribution of unit $u \in U^{hth}$ in secondary-up reserve in zone $z \in Z$ and hour $t \in T$ (MW)

7.3. Continuous variables

SMP_t	System marginal price for hour $t \in T$ (€/MWh)
ACE_t	System marginal price, without considering the RES units, for hour $t \in T$ (€/MWh)
$LSMP_{f,t}$	Levelized system marginal price for fuel type $f \in F$ and hour $t \in T$ (€/MWh)
$LACE_{f,t}$	Levelized avoided cost of electricity for fuel type $f \in F$ and hour $t \in T$ (€/MWh)
$LCOE_{f,t}$	Levelized cost of electricity for fuel type $f \in F$ and hour $t \in T$ (€/MWh)
$LCOE_{u,f,z,t}$	Levelized cost of electricity for RES unit $u \in U^{res}$, fuel type $f \in F$ zone $z \in Z$ and hour $t \in T$ (€/MWh)
$RACE_{f,t}$	Avoided cost of electricity for the retailers for fuel type $f \in F$ and hour $t \in T$ (€/MWh)
$GO_{f,t}$	Price signal for tradable guarantee of origin for fuel type $f \in F$ and hour $t \in T$ (€/MWh)
GO_f	Price signal for tradable guarantee of origin for fuel type $f \in F$ over the examined period (€/MWh)

7.4. Binary variables

$\chi^{sd}_{u,t}$	1, if unit $u \in U^{hth}$ is shut-down in hour $t \in T$

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