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Modelling Renewable Energy Policies in an Integrated Renewable-Conventional Generation Planning Framework

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ABSTRACT

In recent decades, the welfare of human being is seriously threatened by climate change. As a result, numerous energy regulations have been put in place to encourage the expansion of investments in renewable energy. In this context, open questions remain regarding the impacts that these policies may have on generation expansion planning (GEP). This paper addresses this issue by applying three of the most widely adopted energy strategies, namely quota obligation, feed-in tariffs, and emission trade system, to the GEP problem, resulting in an integrated renewable-conventional generation expansion planning (IRCGEP) model with a properly modified cost function and extra constraints. To achieve this aim, first, the IRCGEP model is solved using general algebraic modeling system from a generation company (GENCO) perspective. Afterwards, according to the obtained optimized expansion strategies, the policies impact on the social welfare terms including consumer surplus, GENCO profit, and environmental damages cost are investigated, while they are included on the Bergson-Samuelson social welfare function. Moreover, to assess the financing mechanism effect of the policies on consumer surplus, a suitable attribute known as the "virtual price" is put forth. Numerical studies shed light on the reactions of investment decisions and the social welfare to the energy policies.

Nomenclature

Indices

i	Index that is based on the planning horizon's years.
j	Index that is based on the individuals of utilities in the society.
k	Index corresponding to the number of units pertaining to each technology in operation in each year.
m	Segment index for linearized emission model.
t	Index corresponding to a generation technology available for planning.
u	Index corresponding to a demand period in each year (peak, off-peak or valley).

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Parameters

$A_i^{CO_2}$	Allowed amount of CO2 emission in year i (t/year).
C_t	A unit's Capacity based on technology t (MW).
$\underline{Em}_t$	Lower cap on the emission of tth technology.
EL_i^u	Demand curve elasticity for period u in year i.
$e_{t,m}$	Slope of mth segment in linearized emission curve.
$\hbar_t$	Utilization (use) hours per year related to technology t.
$I_{i,t}$	Cost of installation for a generation unit of technology t in the ith year (M€/MW).
I^{tot}	Available budget in present day for planning (M€/MW).
$\overline{n}_{i,t}$	Maximum number of units from technology *t* that can be installed in year i.
$NS_{i,t,k}$	The piece-wise linearized emission curve's number of segments belonging to k-th unit of technology type t in year i.
N^Y	The planning horizon's number of years.
$W_t^{\max}$	The maximum number of units from technology t that could be installed.
r	Discount rate.
Q_i^u	Demand corresponding to period u in year i (MW).
SCC_i	Social cost of carbon in year i (€/t).
$x_{t,m}$	Generation of segment m in linearized emission curve related to technology t (MW).
ω^u	Time duration of demand period u (h).
τ_j	Commodity of jth individual in society.
$\upsilon_{i,t}$	Generation cost of technology t in year i (€/MWh).
$\Pi_{i,t}^{fit}$	Sum of FIT premium of technology t and market price in the i-th year (€/MWh).
Π_i^m	Yearly average market price in year i (€/MWh).
Π_i^{gc}	Green certificate's price in the ith year (€/MWh).
Π_i^{er}	CO2 emission right price in the ith year (€/t).

Variables

a_i^u	The intercept where the quantity demanded is zero in demand curve of period u (€/MWh) in year i.
b_i^u	Slope of demand curve corresponding to the demand period u in year i (€/MW2h).
CS_i^u	Consumer surplus in demand period u in year i (M€).
E_i^d	The sold total energy in the ith year (MWh).
$Em_{i,t,k}$	Emission amount of k-th unit pertaining to technology t in operation in year i (t/h).
$n_{i,t}$	Number of units of type t in operation in year i.
$P_{i,t,k}^{new}$	Power generated by k-th new added unit from technology type t in year i (MW).
$P_{i,t,k}^{ex}$	Rated power of the k-th existing unit belonging to technology t in operation in year i (MW).
VP_i	Obtained virtual price for year i (€/MWh).
$\vartheta_i^s\,(\vartheta_i^b)$	The sold (bought) green certificates in year i (MWh).
$\partial_i^s\,(\partial_i^b)$	The sold (bought) emission rights in year i (t).
$\Gamma_i^{CO_2}$	Total emitted CO2 in year i (t/year).

Sets

S_i^{ex}	Set of existing units in the i-th year.
S_i^{new}	Set of new units in the i-th year.
S_i^{ren}	Set of renewable-based units in the i-th year.
S_i^{therm}	Set of nuclear and fossil fuelled thermal (conventional) units in operation in year i.

1. Introduction

The issue of choosing the best technology, size, location, and timing for the building of new plants has historically been addressed through generation expansion planning (GEP), which also makes sure that the installed capacity is sufficient to satisfy the anticipated demand growth. [1].

The importance of environmental protection has increased globally in response to the restructuring of the electricity sector. One of the primary greenhouse gases (GHG) contributing to global warming and climate change is carbon dioxide (CO2). The combustion of fossil fuels plays the main role in the generation of CO_2 in the atmosphere. Many countries are committed to the Kyoto Protocol and aimed for significant reduction in GHG emissions within the next decades [2]. In this regard, deploying renewable energy sources (RES) is the most practical way to lessen reliance on fossil fuel resources and address the issue of climate change. Beside "decarbonization" aspect, "energy security" and "expanding energy access" can be also treated as other aspects driving countries to promote RES with respect to the inevitable nature of demand for electricity and its growth [3]-[5].

High intermittency, investment costs, uncertainty, and excessively long return-on-investment periods are the main characteristics connected to the lack of appropriate maturity of these generation technologies in power industry, despite the benefits of RES penetration that have been listed. [6]. As a result, many energy policies have been implemented over the past few decades in numerous jurisdictions worldwide in an effort to convince generation firms (GENCOs) to invest in green generation technology. Policy makers view these programmes as the solution to a variety of socioeconomic issues, including the human-caused global warming, dependence on fossil fuels, and a lack of innovation in the power sector. [7]. Quota obligations with tradable green certificate, Feed-in-tariff (FIT), and tender schemes are included some of the most applied policies for fostering RSE. In addition to these regulations, the Emission Trading System (ETS) and carbon tax, both of which are considered CO2 emission mitigation measures and are primarily intended to discourage the use of fossil fuels, also serve as a covert inducement for the penetration of renewable energy sources [8].

Numerous studies addressing various policy and environmental regulation effects on the GEP problem have been reported recently. The literature suggests a variety of goals, including lowering emissions in the power sector by only taking into account emission limits during long-term generation planning [9]-[12], evaluating the impacts of the policies on promoting the use of RES in issues with expansion planning [13]-[15], analysing other solutions for emission mitigation in the GEP context, such as demand-side management, CO_2 capture technologies, clean coal fuel or nuclear generation units [16]-[19], and designing efficient policies for simulating the investment in RES for a long period of time [20]. Recent studies evaluate the effectiveness of various incentive schemes based on their capacity to meet a renewable portfolio standard and combat climate change in the GEP framework [21]-[22].

Significant impacts that energy policies can have on various issues such as investment decisions, RES deployment, environmental issues, and consumers' welfare, a subject that has been less noticed till now, are resulted in a need for more accurate economic analyses of the policies from an extensive perspective, i.e. the social welfare (SW). In the present paper, a comprehensive study is presented for exploring the impacts that different policies may have on the social welfare in the context of GEP problem faced by a GENCO. To achieve this aim, first, the most popular policies are included into a long-term generation planning problem, resulting in formation of an integrated renewable-conventional generation expansion planning (IRCGEP) model. The IRCGEP is modelled in the General Algebraic Modelling System (GAMS) environment and solved in several scenarios as a mix-integer non-linear programming (MINLP) problem by one of the popular GAMS MINLP solvers, i.e. BARON. The effects of each policy on social welfare are then examined in relation to the resulting optimised expansion strategies, with GENCO profit, consumer surplus, and environmental damage cost being modelled as the social welfare terms on the Bergson-Samuelson SW function. The social cost of carbon (SCC) criterion, which represents the economic damages associated with CO2 emission, is used in this framework to assess the cost of environmental damages resulting from power sector emissions [23]. Furthermore, an appropriate price index, the so-called virtual price (VP), is presented to assess the consumer surplus affected by the policies in which the RES subsidies are financed on the consumers. The main contributions of this work are:

- Proposing a policy-based GEP model
- Investigating the impacts of RES promotion measures on electricity end-users.

After presenting Introduction part, the rest of this paper is organized as follows: The most popular energy policies are briefly reviewed in section 2. Section 3 describes the proposed hierarchy to investigate the social welfare reactions to the policies. Obtained results from numerical studies are conducted in section 4 jointly with an in-depth discussion of the policy implications. Finally, conclusion is given in section 5.

2. Policies for RES Promotion and CO_2 Mitigation

There are a few widely adopted strategies adopted for emission reduction or RES deployment. These strategies are mainly in the form of certificates, tax reliefs, and purchase agreements that can be classified as either quantity-based or price-based schemes. As a result of these strategies, GENCOs are motivated to invest in RES. The most applied policy employed is feed-in-tariff incentive which is a price-based measure [6]. In actuality, the FIT system is a fixed premium in which an environmental premium (bonus) unique to a technology is paid to RES generators in addition to the standard electricity price. This premium is required by a regulator and is guaranteed for a number of years (up to 20 years). The cost of the premiums is financed on the consumers [7]. Quota obligations which are based on tradable green certificates (TGC) are generation-oriented capacity-based (quantity-based) instruments. For each unit of electricity produced (green electricity), certified RES-based units gain tradable green certificates. The energy generated by these units is sold on the electricity market at the market price. to ensure that the desired green electricity is generated and to finance the additional cost of producing green electricity, electricity supply companies are obliged by the regulatory authority to purchase a certain number of green certificates from renewable energy generators according to a fixed percentage, or quota, of their total electrical energy production. GENCOs, then, pass the certificates to some form of regulatory authority to demonstrate their compliance with their regulatory obligations [13].

To battle climate change, beside the policies for promoting the RES, the EU has agreed on an ambitious target for 2020 in which greenhouse gas emissions shall be reduced by 20 percent compared to 1990 emissions levels. The EU strategy to attain this target rests on a portfolio of policy instruments, out of which the ETS is outstanding. This mechanism is designed as a classic ''cap and trade'' system. A quantity-based measure, the ETS operates by allocation and trading of emission rights (ER). One ER gives the right to emit one ton of CO_2. An absolute quantity limit or cap on the amount of CO_2 that can be emitted is established by the regulatory authority. The allowances are then distributed to the installation in the scheme in an amount equal to the cap, thus limiting total emission to that level. The ERs can be traded in a specific market in which the seller is rewarded for having reduced emissions, while the buyer actually pays a charge for polluting [22].

3. Problem Formulation

The presented hierarchy to assess the social welfare affected by planned expansion strategies under considered policies is generally shown in Fig. 1. As shown in Fig. 1, the GEP problem based on solving the proposed IRCGEP model is considered as the first step; thus, multiple scenarios are simulated with respect to the required information including, market price, available candidate technology types and energy policies data. Accordingly, in step #2, the whole amount of energy generated by both renewable and conventional units of the GENCO generation mix, additional cost derived from the RES subsidies for consumers, and the GENCO profit are obtained, while the IRCGEP model is implemented in the GAMS. Base on the additional cost and energy market price, the virtual price is determined in step #3. In this step, the total amount of emission is also determined with respect to the existing and new fossil fuel-fired units scheduled in the GENCO generation mix. Regarding the difference in the energy demand behaviour (peak, off-peak and valley) during a year, three linear demand curves with different elasticity are employed to consumer surplus computation in step #4. Moreover, the environmental damages cost is also addressed using the SCC criteria in this step. Ultimately, description of how the SW reacts to the policies is achieved in step #5 with respect to the results yield from previous steps. Detailed explanations about formulation of different components of the hierarchy are described in the following subsections.

3.1. Bergson-Samuelson Social Welfare Function

In economic theory, social welfare is originally defined by the Bergson–Samuelson SW function as follows [24]:

$$Social\,Welfare = SW\{\kappa_j(\tau_j)\} \qquad \forall j \in \{1,2,...,n\} \tag{1}$$

where τ_j κ_j and are commodity allocation for individual *j and* the utility function, respectively. It can be observed that the social welfare is a function of the utility of all the individuals in the society. Utility is a measure of the satisfaction gained by consuming good and services. Thereafter, SW is modified by economists to refer to the well-being or benefit of various groups, such as producers and customers in the electricity market [25]. Here, referring to (1), the GENCO profit, consumer surplus, and environmental damages cost (as a negative term) are considered as the SW terms and presented as follow.

$$\begin{cases} \kappa_1(\tau_1) \triangleq GENCO\ profit \\ \kappa_2(\tau_2) \triangleq Consumer\ surplus \\ \kappa_3(\tau_3) \triangleq Environmental\ damages\ cost \end{cases} \tag{2}$$

In the Bergson-Samuelson SW function, the utility functions of all groups are linearly added. Accordingly, here, the social welfare function is characterized as the total Net Present Worth (NPW) of the considered terms and is expressed as:

$$SW = \sum_{i=1}^{N^Y} (1+r)^{1-i} \left[\left(U_i^{G_1} + U_i^{G_2} - U_i^{G_3} \right) + U_i^C - U_i^D \right] \tag{3}$$

where $U_i^{G_1}$ (M€) is the GENCO profit yield from energy sold at the market price, $U_i^{G_2}$ (M€) is its benefit/cost derived from the energy policies; $U_i^{G_3}$ (M€) represents the GENCO investment cost in *i*-th year of planning horizon; U_i^C (M€) indicates the surplus obtained by the consumers from energy consumption in year *i*, and U_i^D (M€) denotes the environmental damages cost due to CO_2 emitted by the GENCO generation mix in relevant year.

3.2. IRCGEP Model

From a GENCO viewpoint, a comprehensive model for generation planning under different regimes related to the policies is proposed with respect to the logical constraints that are required to be accounted for to properly model the GEP problem and the policies. The resultant model, i.e. IRCGEP, gives rise to a large-scale mixed integer nonlinear programming problem. In the presented framework, the decision-making of the GENCO with objective of maximizing profit during a N^Y year optimization horizon depends on different terms such as market price, characteristics of candidate technologies, type of applied energy policy, present day budget and etc. According to these terms, the formulation of the IRCGEP model is presented in the following:

- *Objective Function*

Based upon the GENCO investment and operational decisions affected by different energy policies implementation, the the GEP problem's objective function is presented by (4)-(8) as follows:

$$Max \left\{ \sum_{i=1}^{N^Y} (1+r)^{1-i} \left(U_i^{G_1} + U_i^{G_2} - U_i^{G_3} \right) \right\} \tag{4}$$

$$U_i^{G_1} = \varPi_i^m E_i^d - \sum_{t \in S_i^{ex}} \sum_{k=1}^{n_{i-1,t}} \upsilon_{i,t} P_{i,t,k}^{ex} \hbar_t - \sum_{t \in S_i^{new}} \sum_{k=1}^{q_{i,t}} \upsilon_{i,t} P_{i,t,k}^{new} \hbar_t \tag{5}$$

$$U_i^{G_2} = \sum_{t \in S_i^{ren}} \sum_{k=1}^{n_{i,t}} \varPi_{i,t}^{fit} P_{i,t,k}^{ex} \hbar_t + \varPi_i^{gc} (\vartheta_i^s - \vartheta_i^b) + \varPi_i^{er} (\partial_i^s - \partial_i^b) \tag{6}$$

$$U_i^{G_3} = \sum_{t \in S_i^{new}} I_{i,t} C_t q_{i,t} \tag{7}$$

$$q_{i,t} = \max\left\{0, n_{i,t} - n_{i-1,t}\right\} \tag{8}$$

According to the (4), the objective function comprises the gain's NPW obtained from the difference between costs and incomes. Rate *r* is used to discount all future cash flows including both outgoing and incoming. Expenditures include the operating costs derived from both existing and new added units, capital investment, the purchase of emission rights in emission trading scheme as well as green certificates in quota regime. Energy sold at the price Π_i^m in the market and implemented policies result in revenue for the GENCO. The latter terms are represented by (5) and (6), respectively. Equation (7) determines the investment cost of the GENCO related to each planning interval. Here, it is assumed that the investment cost of new addition capacities, i.e. $I_{i,t}C_t$, is paid when the unit comes to operation, that is when the integer variable $n_{i,t}$ increases. To pursue this aim, the integer variable $q_{i,t}$ is defined by (8); this variable represents the number of generation units of type *t* that start to operate during the *i*-th planning year.

Regarding FIT implementing mechanism, the net GENCO revenue yield from this scheme is obtained by the first term of (6). Other incomes from support schemes can be provided by the sale of green certificates and CO_2 emission rights, at prices Π_i^{gc} and Π_i^{er}, respectively. In order to follow the quota compliance in quota mechanism, the GENCO either should buy a certain number of TGC from certified RES-based units or invests in renewable technologies. Hence, the GENCO can obtain two revenues; one from the sale of green electrical energy at the market price and the other from the sale of green certificates, if it decides to invest in RES-based technologies. The latter is presented by the second term of (6) while the third term models trading mechanism of ETS system with respect to the number of emission rights bought/sold by the GENCO. Regarding the defined objective function terms, required logical constraints are considered in the following.

- *Energy Balance Constraint*

Equality constraints provided by Eq. (9), one for each interval, show the balance between energy produced by all existing and new added units and energy sold at the electricity market. It should be noted that for both existing and new plants, the product of the obtained optimum generation rate and relevant utilization hours is resulted in the amount of produced energy. The utilization hour parameter takes into account forced outages, scheduled maintenance, and, regarding non-dispatchable sources, the volatility of the energy resources. Here, indeed, the uncertainties related to the operation of each generation technology are addressed by considering a minimum value for operation hours per year as the utilization hour parameter. On the basis of historical data pertaining to running units using the same technology, this metric can be calibrated. [13].

$$E_i^d = \sum_{t\in S_i^{ex}} \sum_{k=1}^{n_{i-1,t}} P_{i,t,k}^{ex} \hbar_t + \sum_{t\in S_i^{new}} \sum_{k=1}^{q_{i,t}} P_{i,t,k}^{new} \hbar_t \tag{9}$$

- *Construction's Limitation*

The time of construction of the generating units which is proportional to their types, restricts the number of units selected to build during a planning interval. This constraint is considered as the constructions' limitation by (10). Also, the upper bounds related to the maximum number of units that can be installed for each technology during the whole expansion horizon are established by (11) as follows.

$$0\le n_{i,t} \le \bar{n}_{i,t} \tag{10}$$

$$0\le \sum_{i=1}^{N^Y} n_{i,t} \le W_t^{\max} \tag{11}$$

- *Budget Constraint*

The budget constraint presented by (12) sets an upper limit on total investments that can be made by the GENCO over the whole planning horizon. When discounted values are used, as in (12), it is possible to compare investments made at various points in the future in relation to the present day budget., i.e. I^{tot}.

$$\sum_{i=1}^{N^Y} (1+r)^{1-i} \left(\sum_{t\in S_i^{new}} I_{i,t}\, C_t\, q_{i,t} \right) \le I^{tot} \tag{12}$$

- *Quota Obligation Constraint*

As mentioned in section II, under quota regime, a specific fraction of yearly GENCO produced electricity should be supplied by RES-based units. Accordingly, to ensure that the quota compliance is followed by the GENCO, an equality constraint provided by (13) is considered here with respect to the TGC mechanism. Moreover, non-negativity constraints for traded green certificates are established by (14).

$$\sum_{t\in S_i^{therm}} \sum_{k=1}^{n_{i,t}} \delta_i P_{i,t,k}^{ex} \hbar_t = \sum_{t\in S_i^{ren}} \sum_{k=1}^{n_{i,t}} P_{i,t,k}^{ex} \hbar_t + \vartheta_i^b - \vartheta_i^s \tag{13}$$

$$\vartheta_i^s \ge 0,\ \vartheta_i^b \ge 0 \tag{14}$$

Regarding (13), for each planning intervals, a share δ_i of the generation from thermal units must be balanced by the green certificates bought at the market ϑ_i^b and/or produced by certified RES-based units existing in the GENCO generation mix. On the other hand, after following the quota compliance, the extra certificates ϑ_i^s may be profitably sold at the market.

- *Emission Trading Constraint*

Based upon the emission trading mechanism, the total CO_2 emitted by both existing and new scheduled fossil fuel-fired power plants in year *i* must be equal to the allowance (cap), $A_i^{CO_2}$, that is total number of emission rights established by the regulating authority on the basis of the GENCO fossil fueled units in the relevant year. Hence, (15) is considered here to complete the implementation of emission trading policy with respect to the number of bought/sold emission rights modeled by the third term of (6). Non-negativity constraints for traded emission rights are established by (16).

$$\Gamma_i^{CO_2} + \partial_i^s - \partial_i^b = A_i^{CO_2} \tag{15}$$

$$\partial_i^s \ge 0,\ \partial_i^b \ge 0 \tag{16}$$

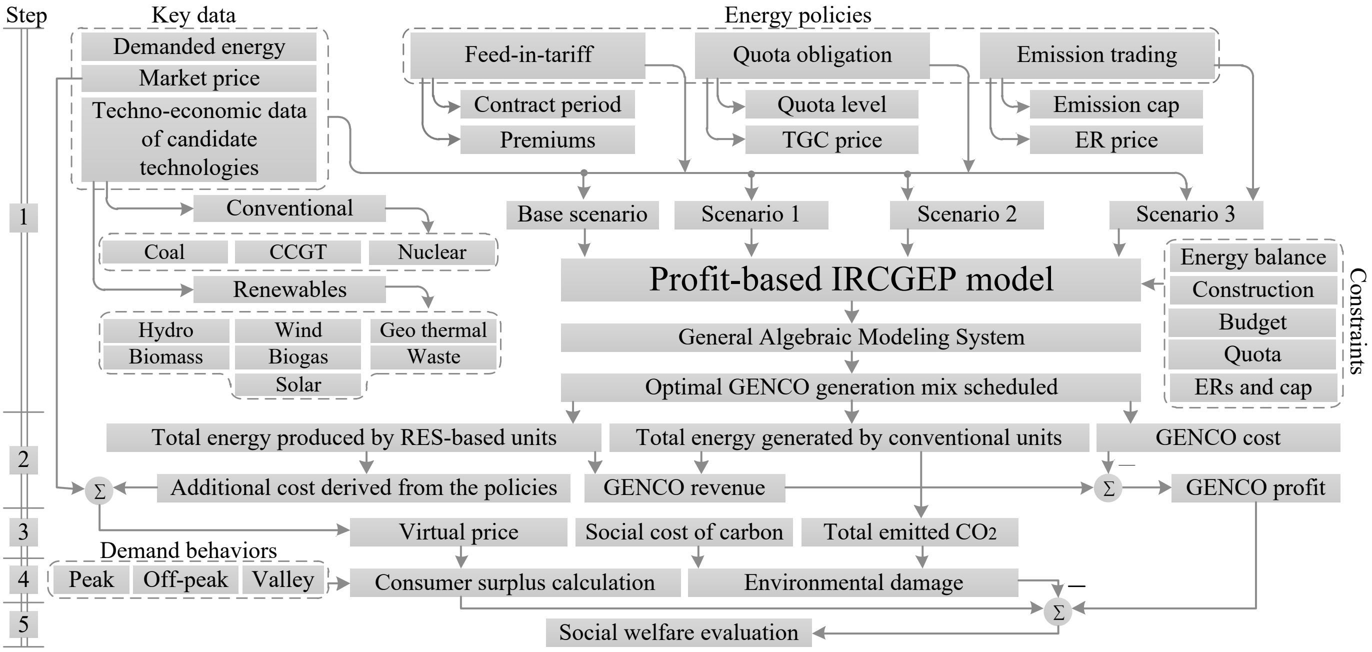

Fig.1. Proposed framework to investigate energy policies impact on generation expansion planning

According to (15), constraint enforcement may be obtained by buying emission rights ∂_i^b at the relevant market regarding the emission amount. Even in this case, surplus emission rights ∂_i^s may be sold. In this study, to estimate the amount of released CO_2 from existing and new scheduled fossil fuel-fired units in year i an exponential-polynomial emission model [26] is considered as follow:

$$Em_{i,t,k} = \alpha_t + \beta_t P^{ex}_{i,t,k} + \lambda_t (P^{ex}_{i,t,k})^2 + \mu_t \exp(\eta_t P^{ex}_{i,t,k}) \qquad (17)$$

where α_t (t/h), β_t (t/MWh), λ_t (t/MW^{2}h), μ_t (t/h), and η_t (1/MW) are the emission coefficients of fossil fuel-fried units belonging to technology t. The emission function in (17) can be accurately approximated by a set of piecewise blocks [27]. For practical purposes, the piecewise linear form is indistinguishable from the nonlinear model if enough segments are used. The analytic representation of this linear approximation can be formulated as:

$$Em^{Lin}_{i,t,k} = \underline{Em}_t + \sum_{m=1}^{NS_{i,t,k}} x_{t,m}\, e_{t,m} \qquad (18)$$

where $Em^{Lin}_{i,t,k}$ is obtained emission amount in ton per year from piecewise linear form of emission model belonging to technology t in year i. Ultimately, regarding the number of fossil fuel-fired units from technology type t in year i and relevant utilization hour parameters, the whole yearly amount of CO_2 emission can be determined by (19) as follows:

$$\Gamma^{CO_2}_i = \sum_{t\in S_i^{therm}} \sum_{k=1}^{n_{i,t}} Em^{Lin}_{i,t,k}\, \hbar_t \qquad (19)$$

3.3. Virtual Price

In this section, to better appreciate the impacts that FIT, quota and emission trading policies may have on the consumer surplus, a new categorization of the policies is provided. According to the policies implementing mechanism mentioned in section II, ETS and quota systems can be classified in the same category while the expenditures derived from purchasing ERs and green certificates are covered by the electricity supply companies, resulting in producer surplus reduction. In contrast, in FIT system categorized as another category, the cost derived from premiums is financed on the consumers. Therefore, feed-in-tariff mechanism poses a threat to the consumer surplus that can be significant from the social welfare point of view. To assess consumer surplus affected by the GENCO investment decision under FIT regime, an appropriate criterion is required to model the effect of RES subsidies on the cost actually paid by the consumers for every unit of consumed energy. To pursue this aim, the virtual price index is proposed in this study. Regarding the whole FIT incentives received by the GENCO during each planning interval, the VP is formulated by (20) as follows.

$$VP_i = \Pi^m_i + \frac{\sum_{t\in S_i^{ren}} \sum_{k=1}^{n_{i,t}} \Pi^{fit}_{i,t} P^{ex}_{i,t,k}\, \hbar_t}{E^d_i} \qquad (20)$$

According to (20), the VP accounts for the premiums pertaining to the FIT mechanism, market price, and total energy produced by the GENCO generation mix scheduled in year i. In other words, the VP embraces the average of total cost paid for every unit of purchased energy with respect to the renewable penetration rate units under FIT regime.

3.4. Consumer Surplus

Price and demand are related in economic theory through a function known as the demand curve. The demand curve function makes the assumption that the quantity of customer demand decreases as price increases. Consumer surplus is also described as the financial gain made by consumers as a result of the discrepancy between their willingness to pay and their actual price. Under this circumstance, an increase in price results in consumer surplus reduction as consumer decrease the consumption willingly to a less quantity. Consumer reaction to price changes is known as the price elasticity of demand that is a measure used in economics to show the responsiveness, or elasticity, of the quantity demanded of a good or service to a change in its price [24]. In this study, the most commonly used shape of demand curve, i.e. linear form, is employed to consumer surplus evaluation. Moreover, corresponding to the different behaviour of demand during a year, pertaining to the peak, off-peak and valley periods, different elasticity are considered. Figure 2 illustrates three linear demand curves with respect to the different price elasticity. According to Fig. 2, the relationship between the market price and the power demand in each demand period takes a linear form [5] as:

$$\Pi_i^u(Q) = a_i^u - b_i^u Q_i^u \tag{21}$$

where the parameter $a_i^u > 0$ (€/MWh) represent the intercept where the quantity demanded is zero in the demand carve of demand period u in year i; the parameter $-b_i^u < 0$ (€/MW^2 h) is the slope of demand curve for demand period u in the relevant year and represents that there is a negative relationship between demanded power and market price. Given the price elasticity of demand EL_i^u for demand period u, the slope of relevant demand curve in year i can be obtained as [24]:

$$b_i^u = \frac{1}{EL_i^u} \cdot \frac{\Pi_i^m}{Q_i^u} \tag{22}$$

Given the slope of demand curve for each demand period u in year i, the relevant demand curve function, i.e. $\Pi_i^u(Q)$, is obtained. Therefore, the size of consumer's surplus for time period u can be calculated by examining the area below the demand function and above the price as follows [24]:

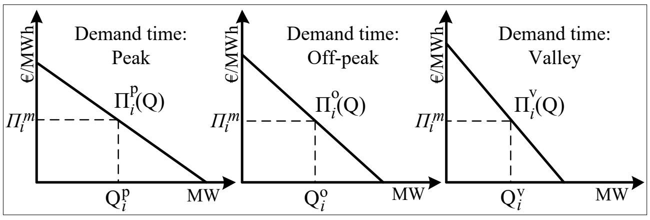

Fig. 2. Linear demand curves pertaining to the different demand behaviours.

$$CS_i^u = \omega^u \left[\int_0^{Q_i^u} \Pi_i^u(Q)\, dQ - \Pi_i^m \cdot Q_i^u \right] \tag{23}$$

where ω^u (h/year) is the duration of demand period u. Consequently, the whole surplus of consumers corresponding to the each planning interval can be obtained by (24). Similarly, consumer surplus at virtual price can be also determined through (21)-(24).

$$U_i^C = \sum_u CS_i^u \tag{24}$$

3.5. Environmental Damages Cost

Due to the complexity and potential impacts of global climate change, numerous regulations and policies have been introduced. The economic costs (social costs) of climate change are gaining attention in the policy debate, which has historically concentrated on the costs of mitigation. The agencies seeking to incorporate climate change considerations in rules and regulations often rely on a cost-benefit analysis, weighing the cost of curbing emissions against the expected damages from every ton of CO_2 that goes into the atmosphere, a value known as the social cost of carbon. In other words, the SCC is the marginal damage cost of carbon emission, estimated as the net present value of climate change impacts over an extended time period caused by an additional unit of CO_2 emitted into the atmosphere today [23]. In this study, regarding the whole released CO_2 by yearly GENCO generation mix, the environmental damages cost is estimated using the SCC as follow:

$$U_i^D = \Gamma_i^{CO_2} \cdot SCC_i \tag{25}$$

4. Numerical Study

Relevant simulations of the GEP problem are performed in the GAMS software package [28]. To solve the MINLP-based IRCGEP model, large-scale BARON 7.2.5 optimization solver is applied. As a popular GAMS solver for solving MINLP problems, BARON is based on deterministic global optimization algorithms of the branch-and-bound type, which are guaranteed to provide global optimal under fairly general assumptions. All the test results were performed in a 2.66-GHz Intel Core 2 personal computer under the Windows 7 operating system.

4.1. Test System Description

The proposed framework of the IRCGEP problem was applied to a test system with reference to the Italian system for a 20-year optimization horizon (from 2024 to 2043). The base year is 2014 and the existing capacity of the GENCO amounts to about 6300 MW comprising five types generating unit. The most relevant data of the GENCO generation arrangement related to the base year is presented in Table I. Initial data of the test system including market price as well as techno-economic data of candidate technologies are adopted from [13]. Other input data such as energy policies data, price elasticity of demand, duration of each demand period, and projected social cost of carbon are taken from [6], [7], [29], [30], and [23]; the rest is estimated using different sources. Generation technology options for capacity additions include: coal-fired, CCGT, nuclear units and a variety of RES-based units. The main techno-economic information of the candidate generation technologies is provided in Table II.

To investigate the impacts that each policy, i.e. FIT, quota, or ETS, can have on the GENCO investment decisions as well as SW terms, one GEP scenario is simulated corresponding to each policy, resulting in three different scenarios denoted by S2, S3 and S4. Furthermore, to better appreciate these impacts, a base case scenario, i.e. S1, is also simulated in which none of the policies is assumed. To allow the simulation of four aforementioned policy-based scenarios, the IRCGEP model is sufficiently general with respect to both cost and revenue that can be derived from the policies.

4.2. Simulation Results

In this section, the social welfare terms are obtained and evaluated in accordance with the mentioned steps in section III. Hence, first, the generation expansion planning scenarios are solved from a GENCO perspective. Obtained results comprise the expansion strategies planned by the GENCO and the energy generation behaviour of both conventional and renewable units. Regarding the GEP results, the emission amount of the scheduled generation mix in each year is also determined. In addition, the surplus of consumers is computed at both the market and virtual prices. Then, the effect of each considered energy policy on the social welfare is investigated, while the relevant terms are determined for every defined scenario. For the sake of simplicity, the price of energy at the market is considered as an average price varied linearly from 91.62 €/MWh (year 2024) to 117.75 €/MWh (year 2043).

Having assumed 5000 M€ as the upper limit on the present-day budget of the GENCO I^{tot} and a 5% discount rate, the results obtained from the GEP scenarios are summarized in Table III with respect to the number of new added units and their start up years. For ease of reference, assigned numbers to the type of candidate technologies (see Table II) are used in Table III instead of their full name. Furthermore, in this table, number of new added RES-based units in each scenario has been shown by shaded boxes. This makes it easier to understand the policies impact on RES promotion. More detailed explanations about obtained results are elaborated in the following.

TABLE I. Existing Plant Date [13]

Gen. Techn	Total capacity MW	Generated energy GWh	Emission t/year
Coal	740	4440	2009000
CCGT	4256	21280	4001200
Oil	740	3200	1350951
On-shore wind	340	1300	–
Small hydro	280	480	–

TABLE II. New plant Date [13, 17]

No.	Gen. Techn	C_t MW	$\hbar_t$ H/year	$\upsilon_{i,t}$ €/MWh	$I_{i,t}$ M€/MW
1	Coal	600	6000	33.96	1
2	CCGT	400	5000	72.46	0.47
3	Nuclear	1200	7800	13.95	2.5
4	Small Hydro	10	3400	19.67	3
5	Mini Hydro	1	3900	40.86	0.5
6	On-shore wind	100	1700	44.79	1.2
7	Off-shore wind	100	2700	60.57	2.8
8	Geo thermal	100	7700	32.82	3.5
9	Biomass	20	6100	46.74	2.35
10	Biogas	10	4200	27.36	1.5
11	Waste	50	5000	58.31	4
12	Photov. solar	1	1400	83.53	4
13	Thermal solar	10	2000	72.41	5

For comparison proposes, the scenario S1 is simulated regardless of the policies. To achieve this aim, the prices of green certificates Π_i^{gc} and emission allowances Π_i^{er} as well as the premiums of the FIT $\Pi_{i,t}^{fit}$ are set to zero from the IRCGEP model. Hence, the decision making of the GENCO is simply based upon the economic reflections. As Table III shows, the investment decisions of the GENCO through S1 result in adding two coal-fired, four CCGT, and one nuclear power plants to the conventional type units of the base year. Among available candidate renewable technologies, only two biogas units are selected to invest, indicating that the GENCO has not much willingness for investing in RES-based units. Hence, it can be seen that the non-renewable generation technologies are more convenient than RES-based ones, while investment decisions are only made on the basis of economic measurements. Moreover, the need for energy policies in terms of support schemes for RES deployment can also be deduced from the results.

The effect of the FIT mechanism on the expansion strategies is examined by second scenario, i.e. S2. To achieve this aim, different premiums are assigned to the new scheduled RES-based units with respect to their technology type. Here, it is assumed that each new added renewable unit receives its relevant premium from the startup year to the end of optimization horizon. Regarding the second scenario results summarized in Table III and start up years of new RES-based scheduled units, we observe that three small hydro units for periods of 20, 20 and 18 years, five units belonging to the on-shore wind for periods of 20, 19, 19, 18 and 18 years, three biogas technologies for periods of 19, 19, and 18 years, and ultimately four thermal solar units for 20, 19, 18 and 18-year periods are received predefined premiums; four aforementioned generation technologies are granted a feed-in tariff of 42.71 €/MWh, 42.75 €/MWh, 73.1 €/MWh, and 280 €/MWh, respectively.

The impact of quota obligation system combined with TGC on expansion strategies is investigated by simulating scenario S3. The RES quota, δ_i, is assumed to vary linearly from 9% in year 2024 to over 22% in year 2043. A linear trend is also considered for the annual green certificates reference price ranging from 88.38 €/MWh (year 2024) to 62.25 €/MWh (year 2043). Regarding the provided summary of new added units through scenario S3 in Table III, it can be seen that implementing the quota obligation system could play a significant role in commissioning of a wider range of RES based technologies so that four small hydro, four on-shore wind, one geothermal, four biomass, and six biogas generation units are scheduled during the optimization horizon. Comparing the GEP results obtained from S2 and S3 reveals that the quota mechanism can be more effective in RES deployment than FIT system. This can be derived from the obligation should be met by the GENCO in quota regime, while in the FIT no obligation or coercive measure exists. Evaluating the ETS impact on the GEP problem is accomplished by forth scenario, i.e. S4. In this scenario, the value of emission allowance established by the regulatory authority is assumed to be 7.6 Mt/year at the beginning of the optimization horizon; this value is decreased by a 2% yearly during the planning horizon. A piecewise linear behaviour is considered for the price of CO_2 on the ETS market. For each ton of emission, this price is assumed to be 19.34 € in year 2024, 30.78 € (as first break point) in year 2033, and 38.18 € (as second break point) at the end of expansion horizon.

TABLE III

OBTAINED GENERATION EXPANSION PLANNING RESULTS FROM DIFFERENT SCENARIOS

	Generation expansion planning scenarios																								
	S1				S2							S3								S4					
	Without policies				Under FIT regime							Under quota regime								Under ETS regime					
Techn. No. / Year	1	2	3	10	1	2	3	4	6	10	13	1	2	3	4	6	8	9	10	2	3	6	8	9	10
2024	0	1	0	0	0	1	0	2	1	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0
2025	0	1	0	0	0	0	0	0	2	2	1	0	1	0	0	2	0	1	0	0	1	1	0	0	0
2026	0	0	0	0	0	1	0	1	2	1	2	0	0	1	0	0	1	0	1	1	0	0	0	0	0
2027	0	0	1	0	0	0	1	0	0	0	0	0	0	0	2	1	0	1	1	0	0	0	0	0	0
2029	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	1	0	0	0	0	1
2030	1	0	0	0	0	1	0	0	0	0	0	1	0	0	2	0	0	0	1	1	0	0	0	0	0
2032	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2033	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0
2034	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
2035	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
Total units	2	4	1	2	2	3	1	3	5	3	4	2	3	1	4	4	1	4	6	4	1	2	1	1	1

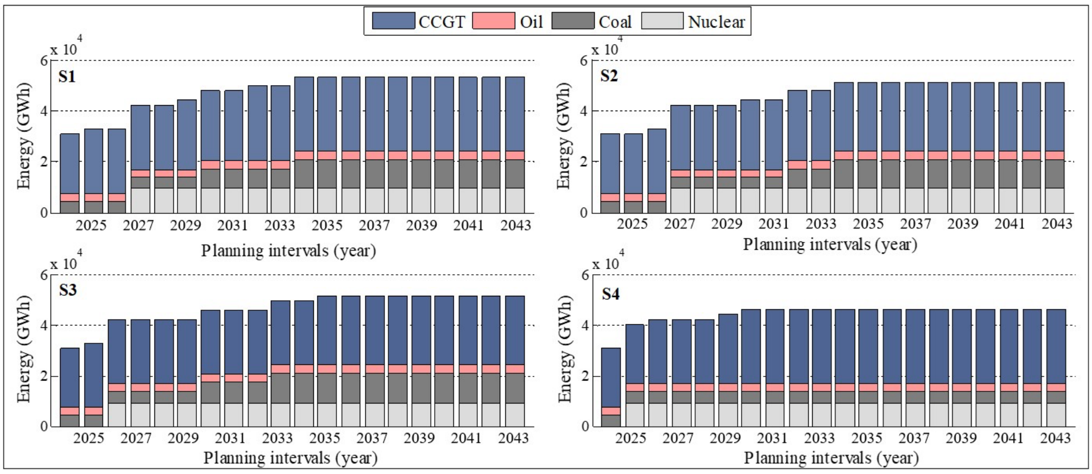

Fig. 3. Energy generation behaviours of conventional units in S1-S4.

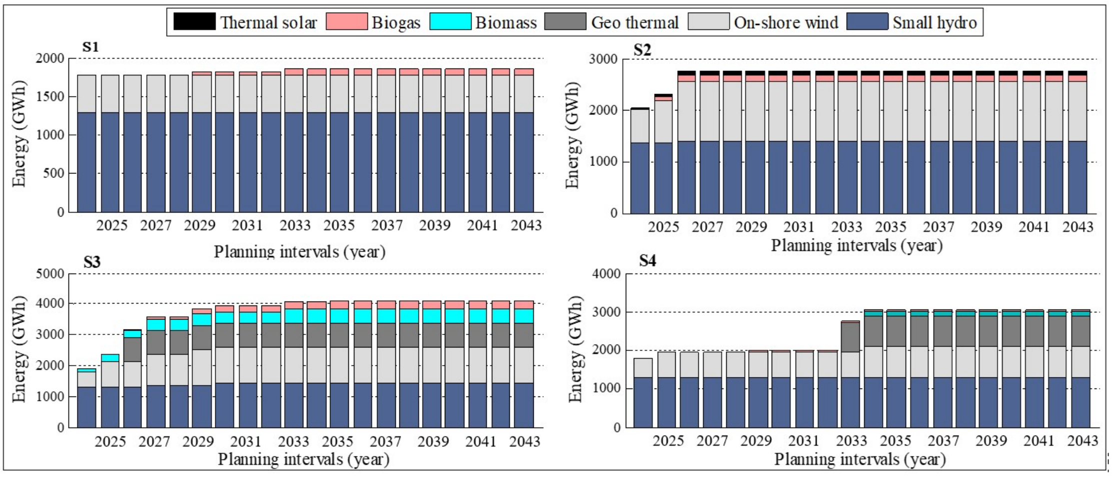

Fig. 4. Energy generation behaviours of RES-based technologies in S1-S4.

Mm ,n Regarding the S4 GEP results provided in Table III, implementing the emission trading policy in the GEP problem lead to discourage the GENCO from investing in coal-fired units due to their remarkable participation in emitting CO_2. Similar to the previous scenarios, only one nuclear generation unit is planned through S4. Despite being free from any type of atmospheric contaminants, high investment cost related to the nuclear power plants can be treated as the main reason of no more investment in them. Emission restrictions derived from ETS do not result in avoiding the investment in coal- fired units only. As a result of the emission trading policy, as Table III shows, some renewable technologies are also selected to invest including up to two on-shore wind, one geothermal, one biogas, and ultimately one biomass units.

Therefore, as can be seen, CO_2 mitigation measures can act as an indirect driver for RES penetration. Regarding the new added capacities to the existing ones, the generation behaviours of conventional and renewable units for all scenarios are illustrated in Figs. 3 and 4, respectively. In both figures, the contribution of energy produced by both existing and new plants is accounted for. As Fig 3 shows, for all scenarios, the largest energy generation contribution comes from CCGT units at the end of optimization horizon. The generation capacity of these units amounts to about 29000 (GWh) for scenarios S1 and S4 and 27000 (GWh) for scenarios S2 and S3. By comparing four generation behaviours of conventional units, the reduction in energy generation as a result of the different energy policies and allocating some budget to invest in renewable energy resources is apparent. Among the policies, the emission trading system has the most impact in reducing the energy amount generated by conventional units. However, despite the high investment cost, the role of nuclear generation remains significant according to all scenarios. Non-emission aspect and low generation cost of the nuclear power plants can be taken into account as the advantages leading to invest in them under different circumstances.

By comparing the generation behaviours of RES-based units illustrated in Fig. 4, the increase in RES penetration through scenarios S2-S4 is observable. This demonstrates the effectiveness of both incentive policies as well as emission mitigation measures in RES deployment. Regarding the generation behaviours of renewable-based units, it can be seen that the largest energy generation contribution comes from both existing and new added units belonging to the small hydro and the on-shore wind technologies through the first three scenarios. In the last scenario, i.e., S4, after existing small hydro technologies, geothermal unit has the biggest share in energy production at the end of planning horizon.

4.3. Social Welfare Analysis

Among social welfare terms, the GENCO profit is directly obtained from the GEP scenarios. Here, to investigate the impact of the policies implemented in the generation expansion planning problem on the social welfare, the rest terms, i.e. consumer surplus and the cost of environmental damages, are determined. Regarding the incentivized RES-based units scheduled in scenario S2, Table IV presents obtained virtual price VP_i and percentage difference between it and market price corresponding to each planning interval. To assess the consumer surplus at both market and virtual prices, the durations of peak, off-peak and valley type of demand periods, i.e. ω^p , ω^o and ω^v , are assumed to be 10, 14 and 28 weeks per year, respectively. Corresponding to these demand periods, three different elasticity are adopted. The considered values for the elasticity are 0.08, 0.06 and 0.05 for peak, off-peak and valley type demand curve, respectively. Accordingly, the amounts of consumer surplus at both market price and VP_i are also presented in Table IV. As Table IV demonstrates, imposing the RES subsidies pertaining to the FIT system into the consumers can have a remarkable impact on their surplus so that small changes in the cost of energy, i.e., the virtual price, significantly reduce the consumer surplus. Note that, the behaviours of consumer surplus for scenarios S1, S3 and S4 are similar in amounts and are computed at the market price.

TABLE IV. CONSUMER SURPLUS AT BOTH MARKET AND VIRTUAL PRICES

N^Y year	VP_i €/MWh	$\frac{VP_i-\Pi_i^m}{\Pi_i^m}\times 100$	U_i^C at VP_i M€	U_i^C at Π_i^m M€
2024	92.098	0.5222	37379.69	37402.35
2025	94.259	1.3534	41374.50	41439.55
2026	96.391	2.1363	49378.02	49500.65
2027	97.348	1.6697	51563.96	51664.01
2028	98.728	1.6460	52308.57	52408.62
2029	100.098	1.6231	53758.56	53859.95
2030	101.431	1.5325	58313.41	58417.24
2031	102.831	1.5113	59132.07	59235.90
2032	104.122	1.3852	59958.07	60054.56
2033	105.422	1.3678	64596.82	64699.47
2034	106.703	1.2607	65459.01	65554.87
2035	108.087	1.2445	68946.79	69047.13
2036	109.455	1.2287	69836.69	69936.49
2037	110.828	1.2132	70726.19	70825.86
2038	112.203	1.1982	71615.56	71715.23
2039	113.578	1.1835	72504.92	72604.59
2040	114.953	1.1692	73394.29	73493.96
2041	116.328	1.1552	74283.65	74383.32
2042	117.704	1.1415	75173.02	75272.69
2043	119.088	1.1282	76061.71	76162.05

TABLE V . NPW OF THE SOCIAL WELFARE AND RELEVANT TERMS

NPW Values M€	Generation expansion planning scenarios			
	S1	S2	S3	S4
GENCO profit	25209	27326	26114	21854
Consumer surplus	775559	774338	775559	775559
Environmental damages	195413	187504	190931	161911
Social welfare	605355	614160	610742	635502

Based on the amount of emission released from the GENCO generation mix, the cost of environmental damages is obtained with respect to the estimated SCC. For all simulated GEP scenarios, the obtained cost corresponding to each planning interval is plotted in Fig. 5. From this figure, it is apparent that implementing the energy policies can directly/indirectly be effective in reducing emission and derived damages cost. For the sake of a fair comparison between the SW terms affected by the energy policies, the net present values of the terms are considered. These values as well as the values of the social welfare corresponding to the simulated scenarios are summarized in Table V.

As Table V demonstrates, the obtained profit in scenario S2 is greater than the ones in other scenarios. Hence, the FIT regime can be treated as the most desirable policy from the GENCO point of view as a result of the subsidies incorporated into this policy. In addition, in FIT mechanism, no coercion or obligation is placed on the GENCO; whereas, in emission trading and quota systems, the GENCO is forced to follow the RES quota and emission allowances, respectively. The effect of the policies on the consumers' welfare or environmental damages cost may be clearer when the NPW of their values are compared. As Table V shows, the NPW of the consumer surplus is decreased from 775559.6 M€ in scenarios S1, S3 and S4 to the value of 774338.6 M€ in scenario S2 because of the FIT incentives cost.

From environmental point of view, it can be seen that all of the policies have different impacts on the emission mitigation. This difference is derived from the mechanism of the policies. Hence, it is expected that the greatest impact on reducing the environmental damages cost is obtained by implementing ETS that acts based upon the direct feedback from emission amount; whereas in the other policies, i.e. quota obligation and FIT regime, promoting the RES act as an indirect factor that can contribute to the decarbonization of power sector. As Table V illustrates, implementing the energy policies decreases the environmental damages costs from 195413 M€ in scenario S1 to the values of 187504 M€, 190931, and 161911 M€ in scenarios S2, S3 and S4, respectively. Consequently, among the most popular energy policies analysed in this study, the emission trading system can be considered as the most efficient policy from environmental perspective.

Therefore, as can be seen, the measures adopted to support RES diffusion as well as reduce GHG emission can produce different impacts on the social welfare terms. To clarify the overall impact of the measures, the net present values of the social welfare are obtained by the Bergson-Samuelson SW function and illustrated in Table V. The results reveal that the energy policies cause social welfare enhancement despite the fact that the consumer/producer welfare may be reduced by implementing the policies. From Table V, we observe that the NPW of the social welfare increases from 605355 M€ in the base scenario to the values of 614160 M€, 610742 M€, and 635502 M€ in the scenarios S2, S3 and S4, respectively. From comparing these values, it can be concluded that among implemented policies in the GEP context, ETS has the most significant impact on the social welfare improvement.

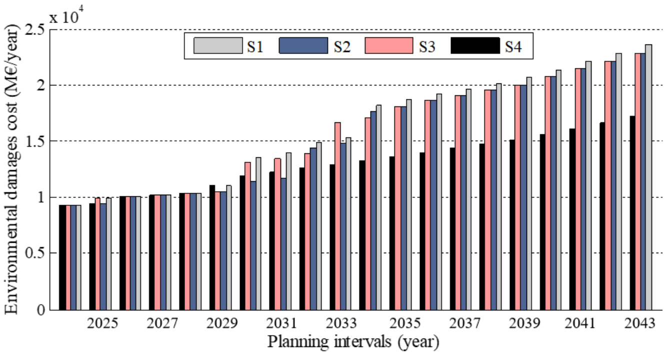

Fig. 5. Estimated cost of environmental damages through S1-S4.

5. Conclusion and Remarks

The integrated renewable-conventional GEP framework developed in this paper describes the long-term investment decisions of a GENCO in both conventional and renewable generation technologies affected by some of the most popular energy policies. FIT regime, quota obligation with tradable green certificate, and emission trading mechanism are comprised the measures implemented in the GEP problem. Consequently, a comprehensive compatible GEP model, named IRCGEP, with a suitable modified objective function and additional constraint is proposed. The IRCGEP model is formulated as a MINLP problem with real and integer mixed variables under a GAMS environment and solved by the BARON optimization solver. The generality of the model allows the simulation of multifarious scenarios with respect to the cost and/or benefits derived from the policies. The main idea of the established GEP framework is that of investigating different impacts of the policies on the social welfare terms comprising the GENCO profit, consumer surplus and the cost of environmental damages associated with the emission of the GENCO generation mix. Hence, by simulating the GEP problem through several policy-based scenarios, the social welfare terms are obtained and analysed. In this context, the virtual price index is introduced for evaluation of consumer surplus affected by the premiums of the FIT system. Combining the aforementioned terms is accomplished by the Bergson-Samuelson SW function in which all utilities are linearly added.

Obtained GEP results from a 20-year optimization horizon reveal that the policies designed to promote RES-based generation technologies as well as the measures intended to mitigate the fossil fuel emissions could affect the expansion strategies planned by a GENCO. Indeed, test results confirm the effectiveness of the policies in RES promotion as well as emission reduction and show that without energy policy implementation, few renewable generation technologies would become economically sustainable. Regarding the difference between pursued aims in the policies and their implementing mechanisms, the policies produce different impacts on the social welfare terms. The results demonstrate that among simulated measures, emission trading system can have the most significant impact on social welfare enhancement in the context of generation expansion planning.

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