FOSTERING THE ADOPTION OF DG AND ENERGY-EFFICIENCY ACTIONS IN AN ENERGY PLANNING STUDY

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ABSTRACT

In this paper, an optimisation procedure is proposed for evaluating the contribution of distributed generation (DG) production and energy-efficiency (EE) actions. A linear programming methodology based on Energy Flow Optimisation Model (EFOM) is adopted, detailing the primary energy sources exploitation, power and heat generation, emissions and end-use sectors. The model outline is enhanced in order to include the description of DG technologies and EE measures. In particular, a detailed description of the electric power grid is carried out, considering a subdivision in various voltage levels of electricity production and energy demand. Moreover, economic subsidies are taken into account to analyse the potential exploitation of DG and EE technologies. The methodology, aiming to reduce environmental impact and economic efforts, provides feasible generation settlements between large-scale generation and DG, and optimal diffusion of EE technologies. The proposed methodology is applied to a realistic energy system.

INTRODUCTION

The distributed generation (DG) concept is more and more studied with extended aims of finding a more efficient and less pollutant way of generating and supplying energy. Various factors prevent investments in DG from occurring. Among these, there are subsidies for conventional forms of energy, high initial and transaction costs, lack of fuel-price risk assessment, lack of skills or information, poor market acceptance. These factors put DG at an economic disadvantage relative to other forms of energy.

Moreover, energy uses are below the maximum efficiency of current technologies and lower than the optimum economic level. Barriers to the diffusion of energy-efficiency (EE) actions are lack of information to end-users, non-inclusion in prices of externality, tariff structure disregarding marginal costs, bounded rationality, etc..

Recently, many policies have been adopted in industrialized countries to compensate for DG high capital costs. Among these policies, additional subsidies are provided for renewable energy in the form of tax credits or investment incentives, special pricing and power-purchasing rules are set for electricity production coming from renewable energy sources (RES) and transaction costs are lowered [1][2].

Renewable energy obligation systems also referred to as renewables portfolio standards (RPSs), have recently been implemented in Australia, USA, Europe, and Japan. Many of these policies are supported by a Tradable Renewable Energy Certificate (TREC) system.

Since 2002, in UK an obligation system on electricity suppliers has been adopted, to ensure that a minimum part of the sold power comes from RES. The obligation level started at 3% of electricity supplied in 2002/2003 and rises to 10.4% in 2010/2011. Electricity suppliers have to surrender TRECs, or pay a penalty to comply with the legislation [3]. The Italian system intends to promote renewable installations, by imposing a quota obligation on the global electricity generation, starting from 2% at 2002, increasing of 0.35% every year until 2006 and meant to be extended until 2012. The mechanism includes TRECs, assigned to eligible production plants. The part of the target not covered by suppliers is granted by the electric system operator, so that no penalty is provided.

At the same time, energy saving programmes have been implemented in order to support the diffusion of EE actions in end-users. This is the case of mandatory energy saving targets imposed in Italy and in the UK, involving electricity and gas retailers. In Italy a system of White Certificates has been provided, whereas the UK scheme only considers bilateral exchanges of savings and targets. In both cases, energy distributors that do not meet their target, estimated according to their market share, have to pay penalties.

Moreover, both policies aiming to spread DG and EE technologies are involved into the general strategy to cut greenhouse gas emissions [4][5].

To this purpose, analytical tools for evaluating the contribution of DG technologies and EE actions need to be developed in an energy planning study. In this work, the penetration level of the DG and of EE actions and the conditions to promote their use are studied when an energy planning is carried out. In compliance with limits on environmental impact of energy production, feasible scenarios over the next 10 years are analysed, taking into account the characteristic and availability of energy sources and technologies for energy generation and consumption. The energy planning optimisation procedure adopted in [6] is considered. The procedure follows the modular structure of the *Energy Flow Optimisation Method (EFOM)* [7]. In this work, the methodology is extended in order to investigate the economics of DG as an alternative to centralized energy production and to analyse the contribution of EE measures to the reduction of the energy demand. In particular, economic incentives able to lighten relevant costs are considered for fostering DG spreading and EE actions penetration.

The effectiveness of the approach is proven by carrying out simulations on a suitable energy system.

MODEL FORMULATION

The developed energy planning procedure can be reduced to the following optimisation problem:

$$\begin{cases} max\ \boldsymbol{f}'\cdot \boldsymbol{x} \\ \boldsymbol{A_{eq}}\cdot \boldsymbol{x} = \boldsymbol{b_{eq}} \\ \boldsymbol{A_{ineq}}\cdot \boldsymbol{x} \le \boldsymbol{b_{ineq}} \end{cases} \quad (1)$$

where $\boldsymbol{x}$ is the state variable vector, $\boldsymbol{f}'\cdot \boldsymbol{x}$ is the objective function, subject to equality constraints $\boldsymbol{A_{eq}}\cdot \boldsymbol{x} = \boldsymbol{b_{eq}}$ and inequality constraints $\boldsymbol{A_{ineq}}\cdot \boldsymbol{x} \le \boldsymbol{b_{ineq}}$.

The state variable vector $\boldsymbol{x}$ contains the new generation capacity to be installed and the energy productions of the energy conversion options, power flows through the electric grid, industrial steam production levels, EE installations in the end-use sectors and the corresponding energy saving.

The objective function consists in the total actualized social benefit of the energy system over the selected time horizon. It is made by two terms representing long-term suppliers' profit *SP* and customers' expense variation *CEV*.

$$\boldsymbol{f}'\cdot \boldsymbol{x} = SP + CEV \quad (2)$$

Long-term suppliers' profit is given by the difference between energy sales revenues and energy production costs. It can be represented by the following expression:

$$SP = \sum_{t=1}^{N_t}\sum_{p=1}^{N_p}\left(\pi_{t,p}\cdot\sum_{j=1}^{N_j}P_{j,t,p}\right) + -\left[\left(C_I - i_{CI}\right) + C_F + \left(C_V - i_{CV}\right) + C_E\right] \quad (3)$$

In equation (3), $\pi_{t,p}$ represents the electricity market price in the *p*-th sub-period of the *t*-th year. It is assumed to be predetermined, as all generation companies are supposed to be price-taker in the market scheme, and a suitable increasing trend is set for it. Furthermore, $P_{j,t,p}$ stands for power generation of the *j*-th generation technology in the *p*-th sub-period of the *t*-th year. The costs C_I, C_F, C_V and C_E represent respectively the total actualized investment, fixed, variable and external cost of the available generation technologies. The expressions of these terms can be found in [6]. Finally, i_{CI} and i_{CV} take into account, respectively, the total actualized incentive on capital cost and variable cost provided for DG technologies. The expressions of i_{CI} and i_{CV} are analogous to the corresponding costs C_I and C_V.

The consumers' expense variation is evaluated by comparing investment costs of EE actions and benefits from the avoided purchase of electricity due to energy saving achieved. The following expression can be assumed:

$$CEV = \sum_{t=1}^{N_t}\left[\sum_{p=1}^{N_p}\left(\pi_{t,p} + C_t^T\right)\cdot EES_{t,p} - \sum_{b=1}^{N_b}u_{b,t}\cdot\left(\Delta C_{b,t}^{EE} - i_{b,t}^{EE}\right)\right] \quad (4)$$

where C_t^T represents the additional component of the electricity tariff imposed on end-users to cover transmission costs, constant over the *t*-th year. Furthermore, $\Delta C_{b,t}^{EE}$ is the additional cost to be sustained to install a unit of the *b*-th EE measure instead of the older one, evaluated as in [8], and $i_{b,t}^{EE}$ is the capital incentive applied on the *b*-th EE technology in the *t*-th year. Finally, $EES_{t,p}$ is the electric energy saving achieved in the *p*-th sub-period of the *t*-th year by means of EE actions, installed in number of $u_{b,t}$. In the procedure, the installed EE measures are supposed to contribute to the energy saving for 10 years.

The constraints included in problem (1) can be divided into three classes: technical, structural and policy constraints.

Technical constraints include relations between installed power and peak electricity demand, upper and lower bounds imposed on yearly energy production from generation technologies. Structural constraints mainly involve energy balances between the supply side and the energy demand, for different forms of energy (electric energy, heat for civil uses, steam in industrial processes). Policy constraints involve decisions on the evolution of the energy system, such as limits on emissions of the main pollutants, limits on the exploitation of primary energy sources (oil, coal, gas, etc.), development of the energy generation options involving RES, diffusion of EE actions, electricity interchanged with neighboring systems [6].

In order to better represent the electric energy demand coming from end-use sectors at different voltage levels, a suitable scheme of the electric grid is considered, whose detailed description is illustrated in Fig. 1. In this outline, generation technologies are divided according to the voltage level at which they deliver their production into the grid. The presence of grid losses is accounted by means of suitable loss factors on power flows. Analogous factors are used for evaluating the demand from generation auxiliary services of each technology. Electric energy savings are accounted at the low voltage level. The scheme described in Fig. 1 allows the electricity balance of the system to be easily estimated.

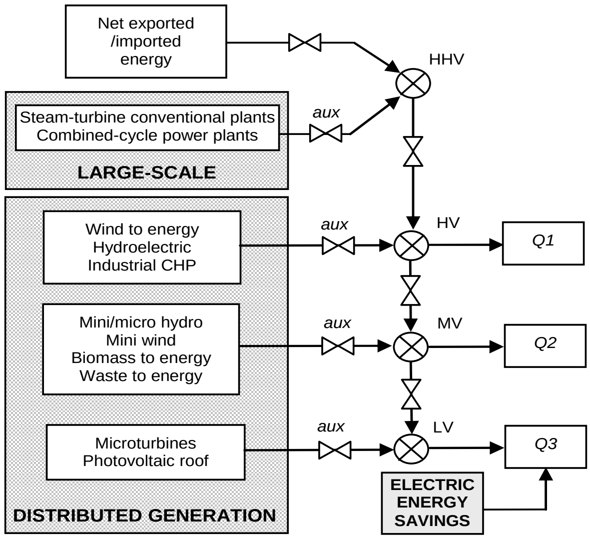

Fig. 1. Electric power grid scheme.

Table 1. Power plant installations and electricity production at the end of the planning horizon.

		Capacity [MW]						Production [GWh]					
		Initial	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Initial	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
HHV	Coal Thermoel.	2,640.0	0.0	0.0	0.0	0.0	0.0	20,210.0	10,328.0	11,664.0	9,962.0	10,449.0	10,341.0
	Oil Thermoel.	433.0	0.0	0.0	0.0	0.0	0.0	2,716.0	2,716.0	2,716.0	1,886.0	2,716.0	1,886.0
	Gas Thermoel.	20.0	0.0	0.0	0.0	0.0	0.0	28.0	0.0	0.0	0.0	0.0	0.0
	Combined Cycle	380.0	1,107.0	668.0	652.0	1,068.0	589.0	980.0	11,076.0	7,803.0	7,715.0	10,778.0	7,215.0
HV	CHP – gas turb.	637.0	0.0	0.0	0.0	0.0	0.0	4,095.0	4,459.0	4,459.0	4,459.0	4,459.0	4,459.0
	CHP – steam turb.	480.0	0.0	0.0	0.0	0.0	0.0	3,088.0	3,360.0	3,360.0	3,360.0	3,360.0	3,360.0
	Hydro	0.8	0.4	0.4	0.4	0.4	0.4	1.8	2.5	0.9	2.5	2.5	2.5
	On-shore Wind	363.0	0.0	837.8	837.8	0.0	837.8	545.5	825.3	2,733.8	2,733.8	825.3	2,733.8
	Off-shore Wind	0.0	0.0	0.0	299.7	0.0	299.7	0.0	0.0	0.0	794.1	0.0	794.1
MV	Waste-to-energy	15.0	0.0	0.0	110.0	0.0	110.0	58.0	113.2	113.2	931.7	113.2	931.7
	Biomass-to-energy	48.0	0.0	0.0	121.0	0.0	120.0	200.0	209.9	209.9	740.4	209.9	736.3
	Mini-hydro	0.0	0.5	0.5	0.5	0.5	0.5	0.0	2.4	2.4	2.4	2.4	2.4
	Mini-wind	0.0	0.0	0.0	22.1	0.0	22.1	0.0	0.0	0.0	48.6	0.0	48.6
LV	Micro-turbines	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Photovoltaic panels	24.0	0.0	0.0	44.0	13.0	46.9	40.6	40.6	40.6	116.2	62.6	120.3
	Total DG		0.9	838.9	1,435.5	13.9	1,437.4	8,028.9	9,012.9	10,919.8	13,188.7	9,034.9	13,188.7

The system is modeled as a network of energy flows, starting from primary energy sources and ending in end-use sectors. The conversion of primary energy sources into useful energy forms is carried out by means of several generation technologies. The end-use sectors considered in the procedure are: industrial, transport, agriculture and fishery, residential and commercial. The model is driven by a set of exogenous energy demands: electricity demand of each end-use sector, civil heat demand and process steam demand.

The aim of the procedure is to obtain the evolutionary trends of state variables over the planning horizon.

TEST RESULTS

A realistic energy system is employed to show the effectiveness of the proposed approach.

At the reference year, the total installed generation capacity amounts to 4,980 MW. The main part of the installed plants, 4,530 MW, burns fossil fuels (coal, oil and gas), 63 MW are biomass- and waste-to-energy power plants, 24 MW consist of photovoltaic for civil uses and wind farm installations for 363 MW are present. With an internal electricity demand of 17,055 GWh, the system under study exports 10,500 GWh towards the neighboring systems. The energy planning study is carried out on a time horizon of 10 years.

In Scenario 1, no minimum level of expansion is imposed on DG and EE technologies, neither any form of incentive is considered. In Scenario 2, investment subsidies on DG are supposed to be present in the procedure, by lowering the capital cost of RES-based technologies and of civil production technologies by the 40%. In Scenario 3, a RPS is employed by fixing a percentage of the internal demand to be covered by DG plants, reaching 27% after 10 years, together with the presence of a TREC system. The TREC price is assumed to be 100 €/MWh and yearly increases by the 2%. In Scenario 4 an obligation system on energy efficiency is considered, aiming to save at least 270 GWh compared to the business-as-usual demand, together with investment incentives covering 60% of the initial cost. Finally, in Scenario 5 the assumptions of Scenarios 3 and 4 are contemporaneously present.

The influence of incentive systems on DG spreading is shown in Table 1. The investment subsidies on DG (Scenario 2) have little effects on the global installations, whereas the RPS policy backed by TRECs imposed in Scenario 3 encourages further DG installations. Most significant variations are observed in the energy production. In fact, DG technologies are more and more called to cover the energy demand, with a minor exploitation of already existing conventional technologies.

Table 2 reports the amount of EE measures installed in Scenarios 1, 3, 4. As no incentive is applied on EE actions, in Scenario 1 only the cheapest technologies are installed, whereas the RPS in Scenario 3 causes a deeper exploitation of photovoltaic panels. In Scenario 4, the electric saving obligation produces a sensible growth of EE installations. The same contribution is observed in Scenario 5. The energy saving levels achieved by means of the application of those measures are reported in the last row of Table 2.

Table 2. Energy-efficiency outline at the end of the planning horizon.

	unit	Scen. 1	Scen. 3	Scen. 4
Gas boiler in place of electric	n.	0	0	15,152
Fluorescent lamps	n.	105,613	0	654,545
Efficient household appliances	n.	0	0	1,048,290
Low Flux Showerheads	n.	247,606	148,563	245,455
Aerated Jet Breakers	n.	0	0	392,727
Photovoltaic panels	kW	0	44,036	12,930
Solar thermal panels	m^2	111,961	111,961	111,961
Efficient electric motors	kW	90,909	27,273	68,308
Inverter in pumping systems	n.	0	0	2,727
Energy savings achieved	GWh	150	160	270

The energy savings achieved in Scenarios 4 and 5 do not produce notable variations in the needed installations of power plants rather than in energy production (see Table 1). The evolutionary trends of CO_2 emissions are illustrated in Fig. 2. For purpose of clarity, Scenarios 1, 2 and 3 are reported, since Scenarios 4 and 5 yield the same final values of Scenarios 1 and 3 respectively. The initial value is 47.85 Mt, and the emission constraint reaches 41 Mt at the fifth year. The spreading of DG in Scenario 2 due to investment subsidies causes a reduction of emissions in the first years, whereas the presence of the RPS policy in Scenario 3 causes a further reduction of emissions in the last years, reaching 39.4 Mt at the end of the time horizon.

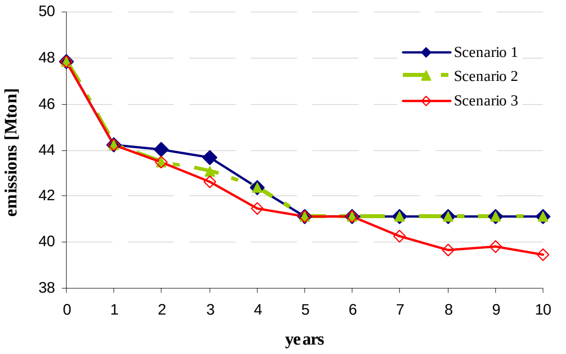

Fig. 2. CO_2 emissions.

Grid losses are reported in Fig. 3. The diffusion of DG technologies makes grid losses decrease, as a lower amount of electric energy has to flow through different voltage levels to reach load centres. Electric savings have a minor contribution in losses reduction, as can be seen by comparing Scenarios 3 and 5.

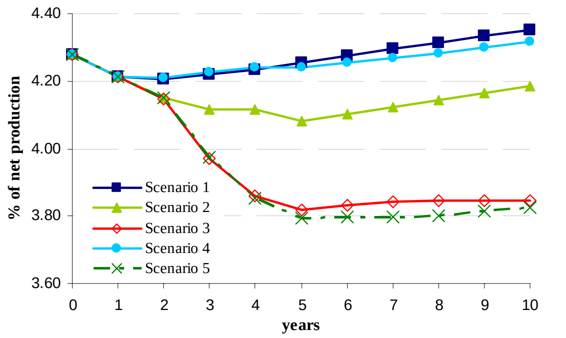

Fig. 3. Electric grid losses.

Finally, in Table 3 an economic overview of the energy planning is carried out. As little differences are present between Scenarios 1 and 2, their economic indexes are also comparable. The RPS policy considered in Scenario 3 causes a remarkable reduction of suppliers' costs due to the variable cost subsidies.

Table 3. Cost outline [G€].

		Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5
Suppliers	Revenue	18.815	18.804	18.730	18.802	18.720
	Cost	14.964	14.688	12.898	15.007	13.141
	SP	3.851	4.116	5.832	3.795	5.579
End-users	Benefit	0.034	0.022	0.030	0.047	0.046
	Cost	0.026	0.024	0.019	0.163	0.054
	CEV	0.008	0.018	0.019	–0.116	–0.008
SB		3.859	4.134	5.851	3.679	5.771
SB w/o subsidies		--	3.722	3.075	3.365	2.387
Subsidies		--	0.412	2.776	0.314	3.384

The presence of obligation on electric savings causes higher investments for end-users, even not covered by benefits (Scenarios 4-5). This is reasonable since the aim of the procedure is the maximisation of the social benefit (SB). Table 3 also illustrates the amount of the SB in absence of subsidies. The maximum diffusion of DG (Scenario 3), without incentives, would half the global SB, whereas the use of EE measures (Scenarios 4-5) has a lower impact on the global SB.

CONCLUSIONS

The paper aims to evaluate the contribution of DG technologies and EE actions in an energy planning study. An optimisation procedure able to reduce environmental impact and economic efforts has been employed. The analysis of various scenarios has shown that, for attaining the procedure goals, a policy based on obligations and incentives is needed. In particular, maximum benefits and lowest emissions are achieved with highest incentives on DG variable cost. Subsidies on EE actions yield slight variations on social benefit and CO_2 emissions. As a result, it can be observed that incentive policy applied to EE actions is not enough to ensure an economic benefit for end-users. On the other hand, the combination of subsidies on DG and EE allows to achieve acceptable economic benefits and environmental impacts.

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