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# Environmental-constrained energy planning using energy-efficiency and distributed-generation facilities

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**Abstract**

In this paper linear programming optimisation procedure based on energy flow optimisation model (EFOM) is proposed for evaluating the contribution of distributed-generation (DG) production and energy-efficiency actions. The proposed methodology details exploitation of primary energy sources, power and heat generation, emissions and end-use sectors. The model framework has been enhanced to include a description of DG contributions and energy-efficiency improvements. In particular, a detailed description of the power grid has been made to take account of different voltage levels in electricity production and energy demand. The presence of mandatory energy-saving targets in the civil sector is considered under suitable constraints. By aiming to reduce environmental impact and operational costs, the following optimisation process provides feasible generation settlements between large-scale generation and DGs, and optimal diffusion of energy-efficiency technologies. The proposed methodology is applied to a realistic energy system.


*Keywords:* Energy planning; EFOM methodology; Renewable energy; Distributed generation; Energy-efficiency improvements; Energy saving

## 1. Introduction

Recently, energy systems have been undergoing a development trend characterised by three main areas [1,2]. Privatisation of the most important energy sectors (electricity and natural gas) has turned former monopolies into free-market competitors. This has been particularly the case with the unbundling of vertically integrated energy companies in the electricity sector where generation, transmission and distribution activities have been split. Community awareness of environmental impact caused by large conventional power plants is growing, together with a greater interest in distributed-generation (DG) technologies based upon renewable energy sources (RES) and cogeneration. The assignment of energy planning competence to regional, as opposed to national authorities, has definitely reduced the area of interest to smaller zones within national territories. This trend, which occurs in the majority of industrialised countries, has allowed energy-policy decision-makers to analyse in greater detail the development in the energy system, as well as for a deeper analysis of contributions from both conventional fossil fuel technologies and renewable source technologies.

Energy planning, which must take into account social and environmental factors, has to be carried out by studying all primary energy sources, from fossil fuels to RES, to determine optimal exploitation. It may seem that energy planning in the electricity sector has been superceded in a liberalised energy-production context where the electricity market is present. However, energy planning is a powerful tool for showing the consequences of certain energy policies, which helps decision-makers choose the most suitable strategies to promote the spread of cleaner DG-technologies that take into account environmental impact and costs to the community.

DGs include electrical generating units and co-generation units with nominal powers ranging from some kW to tens of MW, designed to deliver production to high voltage or medium voltage electricity networks or to cover, for a given amount, the load demand of single customers. For this reason DG facilities are often located close to load

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centres [3,4]. Energy sources employed in DG facilities can be divided into non-renewable fuels and RES. Non-renewable fuels are mainly used in co-generation appliances and micro-turbines systems, and include fossil fuels such as natural gas, diesel oil, process-by products (blast furnace gas, cokery gas, refinery gas). A distinction is made between non-combustible RES and renewable fuels. The former include wind energy, water flow energy, geothermal sources, solar energy, tide and wave energy. Solid biomass, biogas, liquid bio-fuels and refuse-derived fuels (RDF) fall into the category of renewable fuels.

In recent years, there has been a considerable expansion of DG technologies, thanks to progress in reliability, competitiveness and operation know-how and incentive policies adopted by many developed countries. The presence of DG facilities brings benefits both to the electric power system and the total energy system. With DGs energy can be generated directly where it is consumed. As a consequence, transmission and distribution networks are less charged; safety operation margins increase, and transmission costs and power losses are reduced. Since with most DG options renewable-based technologies are used, there is a lower environmental impact. At the very least, the spread of DG technologies enhances supply safety in the energy field by reducing dependence on fossil fuels.

The spread of DG facilities brings with it, however, technical and operational problems. In particular, medium voltage-distribution networks have always been conceived as a path to carry electric power from higher to lower voltage levels. The penetration of DGs in power systems, especially for installations that employ uncontrollable energy sources (e.g. photovoltaic panels and wind turbines), can influence the behaviour of protection devices and cause fluctuations in transmission-network power flows, which therefore require additional studies in network protection devices and flexible control [5].

A further aspect that has become apparent in recent years has been the issue of energy demand in end-use sectors. Demand side management aims to reduce energy consumption by means of energy conservation actions. With these a distinction is made between energy-saving actions and energy-efficiency improvement measures. On the one hand, energy-saving actions include a more responsible use of energy by customers, for instance paying more attention to stand-by losses in household appliances, or using energy only when it is needed (e.g. switching off lamps and using hot water on request). On the other hand, energy-efficiency improvement measures are actions that normally lead to a verifiable and measurable or estimable energy-efficiency improvement, which represents an increase in energy end-use efficiency as a result of technological and/or economic changes. Energy efficiency is concerned with the ratio between performance output, services, goods or energy and energy input [6]. Both end-user energy-efficiency enhancements and energy-saving actions produce primary energy savings that can help to reduce energy imports and cut down on greenhouse gas emissions.

DG penetration and the adoption of measures for energy-efficiency improvement have found advocacy in directives adopted by super-national organizations, such as the European Parliament and Council [7,8] which have subsequently been adopted by European member states.

The aim of this paper is to evaluate the contribution of DG and energy-efficiency actions when energy planning is carried out. To this purpose, the procedure proposed in [9] has been extended to take account of the presence of DG technologies and energy-efficiency actions. To provide a detailed description of DG production, a power grid scheme with various voltage levels and relevant power flows is considered. Planning procedure follows an optimisation process based on the energy flow optimisation model (EFOM) [10–12]. An objective function including industrial costs due to energy production is minimised in the presence of technical and energy-policy constraints. A multi-period linear approach is used, which is then applied to a regional energy system. In Section 2, a brief review of the spread of DG technologies and global initiatives for energy-efficiency improvements is reported. In Section 3, the formulation of the mathematical problem relating to the proposed optimisation procedure is illustrated. The test results of several scenarios applied to a realistic energy system are reported in Section 4.

## 2. DG and energy efficiency in the international context

Renewable energy technologies are emerging as potentially strong competitors for more widespread use. Despite the remarkable progress attained over the past decades, RES have not yet been fully integrated into the power sector. Some RES-technologies have already achieved a significant market share. The industry is now quite mature, although far from having developed its global potential. For example, small hydropower systems are well established, as are some sections of the biomass industry. Wind generators, which have been going through intense technology and market development, have achieved considerable market share in some countries, even though further technological improvements need to be made. Although the solar photovoltaics market is comparatively small, it has trebled volume in the last four years [13].

Data on the DG global contribution cannot be easily collected. In fact, studies of installed capacity and energy production from different primary energy sources are often carried out by using different classification criteria for power plants. Among these criteria there are various thresholds on installed power to distinguish between large-scale energy generation plants and DG facilities under different renewable source categories.

Classification of the global energy supply sector has been carried out by IEA [14] where data for renewables includes solid biomass, biogas, liquid bio-fuels, hydro, geothermal,

Table 1
World consumption of energy sources (2003)

| Zone | TPES (Mtoe) | Renewables | | Renewable energy sources | | |
|---|---|---|---|---|---|---|
| | | Mtoe | % | Hydro (%) | Geothermal, solar, wind, tide, wave (%) | Combustible renewables and waste (%) |
| Africa | 559 | 280 | 50.1 | 2.6 | 0.3 | 97.1 |
| Latin America | 464 | 135 | 29.2 | 35.9 | 1.4 | 62.6 |
| Asia | 1224 | 400 | 32.7 | 4.0 | 3.5 | 92.5 |
| China | 1426 | 243 | 17.1 | 10.0 | 0.0 | 90.0 |
| Non-OECD Europe | 103 | 10 | 9.4 | 40.8 | 0.7 | 58.5 |
| Former USSR | 962 | 27 | 2.9 | 69.7 | 1.1 | 29.2 |
| Middle East | 446 | 3 | 0.7 | 42.7 | 24.1 | 33.2 |
| OECD | 5395 | 305 | 5.6 | 35.1 | 11.7 | 53.3 |
| World | 10,579 | 1404 | 13.3 | 16.2 | 3.8 | 80.0 |

solar, wind, tide and wave energy and biodegradable municipal waste.

Total world consumption of energy sources at 2003 is illustrated in Table 1 by geographical area and including renewables.

Total primary energy supply (TPES) is 10,579 Mtoe, while RES account for 13.3% (1407 Mtoe). The rest is obtained from oil (34.4%), coal and non-biodegradable waste (24.4%), natural gas (21.2%) and nuclear (6.5%). Use of RES plays an important role in developing countries where combustible renewables are widely exploited. Among non-fuel RES, hydro-energy production is exploited where a remarkable amount of water is present, e.g. Latin America and the former USSR, whereas solar, wind, wave and geothermal sources are mainly used in OECD[1]countries.

An overview of electricity production in terms of primary energy sources at 2003 for the world and the 15 EU member states is reported in Table 2 [15]. It is worth pointing out that no distinction between biodegradable and non-biodegradable waste has been made. Both have been included in the RES definition, whereas in Table 1 only biodegradable waste has been accounted for.

Electricity production from renewables amounts to 18.2% of production. Among fossil fuels, 39.9% comes from coal, 19.3% from natural gas and 6.9% from oil, with 15.7% generated by nuclear plants. Furthermore, it can be seen that RES exploitation for electricity production in the 15 EU countries covers a remarkable percentage of world consumption, especially for new technologies such as wind, solar photovoltaic, wave and tide energy and for combustible renewable-based facilities.

Over the last few years, the problem of energy efficiency for end-users has spread in most of the developed countries. For instance, the Office of Energy Efficiency and Renewable Energy has been established by the US Department of Energy, with the aim of strengthening energy safety, environmental quality, and economic vitality in public–private partnerships that enhance energy efficiency and productivity and promote clean, reliable and affordable energy technologies.

Significant initiatives concerning energy efficiency have been developed in the European Union, such as the directive adopted by the European Council [16] in September 1993 to limit carbon dioxide emissions. Energy efficiency has been improved through the implementation of programmes in energy certification of buildings, third-party financing for energy-efficiency investments in the public sector, thermal insulation of new buildings, inspection of boilers, energy audits of activities with high energy consumption. These programmes have also included laws, regulations, economic and administrative instruments, information, education and voluntary agreements.

Against this background, the "Energy Efficiency Commitment" (EEC) was issued by the UK in 2000. All electricity and gas suppliers with more than 15,000 customers were required to save a total of 62 TW h of fuel-standardised energy from 2002 and by 2005. While this efficiency drive only covered energy supply for civil/residential users [17,18], the EEC 2002–2005 (EEC 1) is now complete, and the total energy saving achieved over the three year period is 86.8 TW h. A saving target under EEC 1 was set for twelve supplier groups, ten of which hit their targets. According to the Ofgem[2] report [19], the main measure offered by suppliers is insulation, which constitutes 56% of total savings. The distribution of energy-efficient light bulbs amounts to 24% of the total saving. Household appliances cover 11% of the total saving and heating measures 9%. With the EEC 2005–2008 (EEC 2) which began on 1 April 2005 a new target for suppliers was set to save energy for residential consumers. The energy-saving target for EEC 2 is 130 TW h, more than double that set by EEC 1. Six suppliers have chosen to carry over the

[1]OECD includes EU-15, Poland, Czech Republic, Slovak Republic, Hungary, Norway, Iceland, Switzerland, Turkey, USA, Canada, Mexico, Australia, New Zealand, Japan and Korea.

[2]Office for Gas and Electricity Market.

Table 2
Energy sources consumption for electricity production (2003)

| Production energy sources | | World | | EU-15 | | RES in EU-15 |
|---|---|---|---|---|---|---|
| | | GW h | % | GW h | % | (% of total) |
| Fossil fuels | Coal | 6,681,339 | 39.908 | 767,037 | 27.75 | – |
| | Oil | 1,151,729 | 6.879 | 150,496 | 5.44 | – |
| | Gas | 3,224,699 | 19.261 | 526,296 | 19.04 | – |
| Nuclear | Nuclear | 2,635,349 | 15.741 | 898,234 | 32.49 | – |
| RES | Solid biomass | 120,057 | 0.717 | 27,059 | 0.98 | 22.5 |
| | Biogas | 18,150 | 0.108 | 9872 | 0.36 | 54.4 |
| | Waste | 62,493 | 0.373 | 24,976 | 0.90 | 40.0 |
| | Hydro | 2,725,824 | 16.281 | 308,812 | 11.17 | 11.3 |
| | Geothermal | 53,735 | 0.321 | 5434 | 0.20 | 10.1 |
| | Solar photovoltaic | 555 | 0.003 | 456 | 0.02 | 82.2 |
| | Solar thermal electricity | 548 | 0.003 | 0 | 0.00 | 0.0 |
| | Wind | 63,001 | 0.376 | 44,085 | 1.59 | 70.0 |
| | Tide, wave, ocean | 572 | 0.003 | 539 | 0.02 | 94.2 |
| Other | Other sources | 3833 | 0.023 | 1158 | 0.04 | – |
| Total electricity production | | 16,741,884 | 100.000 | 2,764,454 | 100.00 | – |
| Total RES electricity production | | 3,044,935 | 18.188 | 421,233 | 15.24 | 13.8 |

energy saving exceeding their EEC 1 targets, so that roughly 25% of the EEC 2 target has already been met.

Following an increasing saving trend, targets for reducing electricity consumption by 1.6 Mtoe and gas consumption by 1.3 Mtoe against a business-as-usual scenario from 2005 to 2009 were set by two ministerial decrees in Italy (July, 2004) [20]. The national target has been set for electricity and gas suppliers with more than 100,000 customers according to their individual market shares. The decrees also provide for energy savings from other sources such as diesel oil. The saving-recognition mechanism is ruled by the AEEG[3], which has also drawn up a list of eligible energy-efficiency improvement measures, mainly in civil and industrial sectors. A trading mechanism based on bilateral exchanges of energy savings and a White Certificate market, initiated in March 2006, are managed by the GME[4] [21].

Recently, both the European Parliament and Council have adopted a new directive on end-use efficiency [6]. Following this directive, which repeals [16], the aim is to enhance the cost-effective improvement of energy end-use efficiency in member states by providing indicative targets, incentives and institutional mechanisms, and creating the conditions for the development of a market for the delivery of energy-efficiency improvement measures to end-users. European member states must achieve a national energy-saving target of 9% through energy services and other energy-efficiency improvement measures by the year 2015. Member States must promote practicable and reasonable measures for reaching this target, and must ensure that the public sector sets the example by focusing on cost-effective measures that generate the largest energy savings in the shortest time. A list of energy-efficiency improvement measures in civil, industry and transport sectors has also been indicated.

The so-called "bottom-up" and "top-down" methods have been proposed to measure and verify energy savings. With the "bottom-up" method, energy savings obtained through the implementation of an energy-efficiency improvement action is measured in energy units (kW h, J, toe) and added to energy savings resulting from other measures. In the "top-down" method, energy savings are calculated using national aggregate sector levels of energy savings to give a fair indication of total energy-efficiency improvements. The bottom-up method has been adopted for energy-efficiency programmes in the UK and Italy.

## 3. Model formulation

In this section, the general features of the optimisation procedure are illustrated taking into account the presence of DG technologies and energy-efficiency measures.

### 3.1. Energy system model

Following the modular structure of EFOM [12], the energy system is represented as a network of energy chains, starting from the primary energy supply and ending with end-use sectors as shown in Fig. 1.

The model is driven by an exogenous energy demand. Following the energy chain network, the model is built into sub-systems according to specific availabilities and requirements. The model consists of a *primary source* sector, a *power and heat generation* sector and *end-use* sectors.

The primary source sector includes fossil fuels (coal, oil, natural gas, etc.), industrial by-products (blast furnace gas, cokery gas, refinery gas) and local renewables (biomass,

[3]Italian Authority for Electricity and Gas.
[4]Italian Market Operator.

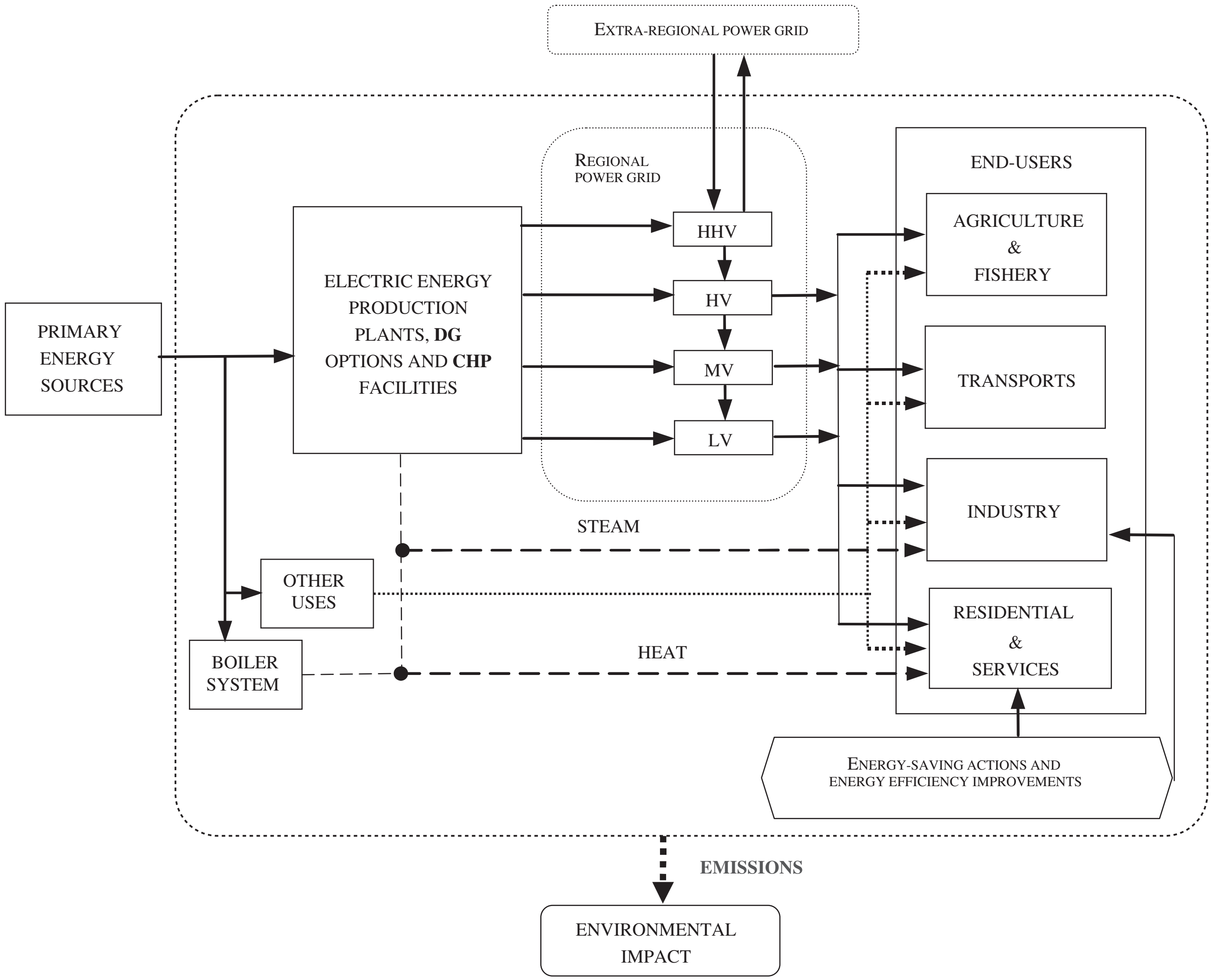


Fig. 1. Modular structure of energy system.

solid waste and natural resources). This sector provides for electricity and heat derived from large-scale as well as small-scale technologies and for other needs directly in end-use sectors.

Energy conversion given by several generation options comprises: large-scale power plants (conventional steam and gas turbines, combined cycles, hydroelectric plants), small- and medium-scale power plants dealing exclusively with electricity generation (mini-hydro, on-shore and off-shore wind farms, mini-wind turbines, biomass-to-energy and waste-to-energy plants), industrial combined heat and power (CHP) plants and civil production facilities (photo-voltaic systems, solar thermal panels, micro-turbines). End-use sectors include the residential sectors and services, industry, transport, agriculture and fisheries. In the first two sectors, energy-saving actions and energy-efficiency improvements are applied in the first. Examples of energy-efficiency improvement actions in the civil sector are heat pumps, new efficient boilers, wall cavity and roof insulation, double glazing of windows, new efficient household appliances and light-bulbs, co-generation appliances, solar thermal applications and solar photovoltaic systems. Energy-efficiency improvements in the industrial sector can be achieved by means of electronically controlled motors, high-efficiency motors, variable-speed drives, co-generation appliances, installation of capacitors to reduce reactive power and low-losses transformers [6].

The regional power grid is modelled by considering four different voltage levels: very high voltage (HHV), high voltage (HV), medium voltage (MV), and low voltage (LV). Generation options are divided into four groups with respect to the voltage of the grid where generated electric energy is delivered. Electric energy at HV, MV and LV levels is withdrawn by end-users.

### 3.2. Energy planning optimisation procedure

The energy planning optimisation procedure adopted here can be represented by the following expression:

$$\begin{cases} \min \mathbf{f}' \cdot \mathbf{x} \\ \mathbf{A_{eq}} \cdot \mathbf{x} = \mathbf{b_{eq}} \\ \mathbf{A_{ineq}} \cdot \mathbf{x} \leqslant \mathbf{b_{ineq}} \end{cases} \quad (1)$$

where $\mathbf{x}$ is the state variable vector, $\mathbf{f}' \cdot \mathbf{x}$ is the objective function, $\mathbf{A_{eq}} \cdot \mathbf{x} = \mathbf{b_{eq}}$ includes the set of equality constraints and $\mathbf{A_{ineq}} \cdot \mathbf{x} \leqslant \mathbf{b_{ineq}}$ contains the inequality constraints.

The optimisation procedure developed in [9] is improved by involving the contribution of DG technologies and energy-efficiency actions.

While large-scale electricity production plants and industrial CHP facilities have been the main focus in [9], a more detailed set of DG technologies is considered in this paper, as reported in Table 3. According to the size of hydroelectric and wind power plants, power is injected at different voltage levels in the power grid.

In [9], the energy demand was assumed as an exogenous variable, whereas in this formulation it experiences a reduction due to energy-efficiency actions in the civil sector. The energy-efficiency improvement measures considered in the procedure are taken from the Italian standard [22], as shown in Table 4.

Solar thermal collectors and photovoltaic roofs are involved in the energy-saving outline, since they are able to generate energy savings by substituting other energy sources (fuels for heating or electricity from the grid).

State variables, such as power flows between different voltage levels in the power grid scheme and energy-efficiency measures, are added to new power installations, generated electrical and thermal power, and steam flows in industrial CHP systems.

### 3.3. Objective function

Total actualised cost of primary energy conversion over selected time horizon is minimised. In particular, the sum of total actualised investment cost of selected technologies $C_I$, total fixed cost $C_F$, variable costs $C_V$ and external costs $C_E$ are considered:

$$\mathbf{f}' \cdot \mathbf{x} = C_I + C_F + C_V + C_E. \quad (2)$$

The investment cost $C_I$ consists of two terms

$$C_I = C_A + C_S \quad (3)$$

with $C_A$ capital investment cost and $C_S$ stripping cost. Capital cost is further divided into two terms. The first includes the sum of annuities over power plant lifetime, evaluated as in [9], whereas the second takes into account investment cost of energy-efficiency improvement

Table 4
Energy-efficiency improvement measures

| No. | Measure | Reference unit |
|---|---|---|
| 1 | High-efficiency natural gas water heater instead of electric water heater (EB → GB) | 1 boiler |
| 2 | High-efficiency natural gas water heater in the place of older natural gas boiler (HEGB) | 1 boiler |
| 3 | Very high-efficiency gas boiler instead of high-efficiency natural gas boiler (HHEGB) | 1 boiler |
| 4 | Use of compact fluorescent lamp in the place of incandescent lamp (FLUO) | 1 lamp |
| 5 | Dual pane window installation in the place of single pane window (DPW) | 1 $m^2$ |
| 6 | Improvement of heat insulation of external walls and ceilings (HI) | 1 $m^2$ |
| 7 | Substitution of an high-efficiency electric household appliance for an older one (HHA) | 1 appliance |
| 8 | Installation of low-flux showerhead in the place of an older one (LFS) | 1 showerhead |
| 9 | Aerated jet breaker for water taps instead of an older one (AJB) | 1 jet breaker |
| 10 | Installation of a heat pump rather than natural gas water heater (HP) | 1 heat pump |
| 11 | Installation of solar thermal collectors (Sol.th) | 1 $m^2$ |
| 12 | Installation of photovoltaic plants, with less than 20 kW installed capacity (PV) | 1 kW |

Table 3
Energy production options in the conversion sector

| Large-scale electric energy production plants | DG production plants | Civil thermal/electric energy production facilities | Industrial CHP facilities |
|---|---|---|---|
| (1) Coal-fuelled thermoelectric plants | (5) Wind turbines (HV) | (12) Solar thermal collectors (Sol.th) | (15) Gas turbines (GT) |
| (2) Oil-fuelled thermoelectric plants | (6) Hydroelectric (HV) | (13) Photovoltaic roofs (PV) | (16) Steam turbines (ST) |
| (3) Gas-fuelled thermoelectric plants | (7) Solid waste-to-energy | (14) Micro-turbines (μT) | |
| (4) Combined cycles (CC) | (8) Biomass-to-energy | | |
| | (9) Mini-hydroelectric (MV) | | |
| | (10) Mini-wind turbines (MV) | | |
| | (11) Off-shore wind turbines | | |

measures, as in the following expression:

$$C_A = \sum_{t=1}^{N_t} \frac{1}{(1+\mathrm{DR})^t} \left[ \left( \sum_{j=1}^{N_j} \frac{1}{\mathrm{AF}_j} \sum_{\tau \in \Omega_{\mathrm{AM}_{j,t}}} KI_{j,\tau} I_{j,\tau} \right) + \left( \sum_{b=1}^{N_b} KI_{b,t} u_{b,t} \right) \right], \tag{4}$$

where $KI_{j,\tau}$ is unit capital cost (€/MW) of $j$th installation type at $\tau$th year, $\Omega_{AM_{j,t}} = \{\max(1, t - A_j + 1), \ldots, t\}$ is amortization period of $j$th technology, $\mathrm{AF}_j$ is amortization factor of $j$th investment type and $KI_{b,t}$ is unit capital cost (€/unit) due to application of $b$th energy-saving measure at $t$th year, assuming that no amortization period is required for installation. For $\mathrm{AF}_j$ the following expression is assumed:

$$\mathrm{AF}_j = \sum_{\tau=1}^{A_j} 1 \Big/ \left( 1 + \frac{\rho - \varphi}{1 + \varphi} \right)^{\tau} \tag{5}$$

with $\rho$ as interest rate of capital and $\varphi$ as inflaction rate.

Stripping cost consists of two terms. The first relates to stripping cost of power plants [9], the second to stripping cost connected to energy-saving actions, which can be expressed as follows:

$$C_S = \left( \sum_{j \in \Omega_{ST}} \sum_{t=1}^{N_t - D_j} \frac{KS_{j,t+D_j} I_{j,t}}{(1+\mathrm{DR})^{t+D_j}} \right) + \left( \sum_{t=1}^{N_t} \frac{KS_{b,t} u_{b,t}}{(1+\mathrm{DR})^t} \right), \tag{6}$$

where $KS_{j,t+D_j}$ is the unit stripping cost (€/MW) of $j$th generation option installed at $t$th year, $\Omega_{\mathrm{ST}}$ is the set of all $j \in \{1, \ldots, N_j\} \ni' N_t - D_j > 0$ representing power plants being stripped over time horizon, and $KS_{b,t}$ is unit stripping cost (€/unit) due to application of $b$th energy-efficiency improvement measure at $t$th year.

Total actualised fixed cost $C_F$ represents operation and maintenance cost of electricity generation options [9].

Variable cost represents the cost of procurement for all fuels necessary for electrical generation, process-steam production and civil-heat production over the planning horizon. It has the following expression:

$$C_V = \sum_{t=1}^{N_t} \frac{1}{(1+\mathrm{DR})^t} \left[ C_{V,t}^{P} + C_{V,t}^{S} + C_{V,t}^{H} \right], \tag{7}$$

where $C_{V,t}^{P}$ represents fuel costs for electric power plants, $C_{V,t}^{S}$ includes fuel costs for industrial steam production and $C_{V,t}^{H}$ stands for procurement cost of fuels for civil heat consumption, all evaluated at $t$th year. These terms have the following expressions:

$$C_{V,t}^{P} = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} KF_{i,t} c_{i,j} \sum_{p=1}^{N_p} P_{j,t,p} T_p, \tag{8a}$$

$$C_{V,t}^{S} = \sum_{i \in \Omega_{\mathrm{HP}}} KF_{i,t} h_i \sum_{p=1}^{N_p} H_{i,t,p} T_p + \sum_{i \in \Omega_{\mathrm{MP}}} KF_{i,t} m_i \sum_{p=1}^{N_p} M_{i,t,p} T_p, \tag{8b}$$

$$C_{V,t}^{H} = KF_{3,t} \left[ \left( Nb_{3,t} - \sum_{\tau=1}^{t} u_{2,\tau} \right) \mathrm{Eb}_{3,1} + \mathrm{Eb}_{3,2} \times \sum_{\tau=1}^{t} (u_{1,\tau} + u_{2,\tau}) + \mathrm{Eb}_{3,3} \sum_{\tau=1}^{t} \sum_{z=1}^{N_z} u_{3,z,\tau} \right] + \sum_{\substack{i=1 \\ i \neq 3}}^{N_i} KF_{i,t} \mathrm{Nb}_{i,t} \mathrm{Eb}_i, \tag{8c}$$

where $KF_{i,t}$ is unit price (€/toe) of $i$th fuel in $t$th year and $\Omega_{\mathrm{HP}} = \Omega_{\mathrm{MP}} = \{1, 9, 10, 11\}$ represent the set of fuels exploited by High Pressure and Medium Pressure boilers respectively.

External costs consist in the economic burden of energy chains on population and environment. These costs, which relate to fuel consumption, are analogous to variable costs:

$$C_E = \sum_{t=1}^{N_t} \frac{1}{(1+\mathrm{DR})^t} \left[ C_{E,t}^{P} + C_{E,t}^{S} + C_{E,t}^{H} \right], \tag{9}$$

where $C_{E,t}^{P}$ represents external costs for electric power plants, $C_{E,t}^{S}$ includes external costs for industrial steam production and $C_{E,t}^{H}$ stands for external costs for civil heat consumption. The expression of these terms is obtained in the same way as the corresponding terms for variable costs, by substituting $KF_{i,t}$ with $KE_{i,t}$, which is the external unit cost (€/toe) for assessing impact due to use of $i$th fuel in $t$th year.

It can be noted that objective function (2) encompasses additional terms representing investment costs relating to new generation technologies. Investment costs referring to unit installation of energy-efficiency improvement measures are reported in Eq. (4), together with stripping costs of substituted technologies in Eq. (5). The expression for variable costs also takes into account the distinction between civil boiler technologies (7) and evaluation of external costs relating to fuel consumption (9).

### 3.4. Constraints

Together with the constraints in [9], modified to take into account DG technologies, other constraints included are on renewable energy potential necessary for all non-fuel RES technologies. The related constraint can be written as follows:

$$\frac{1}{4.86} \sum_{p=1}^{N_p} P_{j,t,p} T_p \leqslant RP_{j,t}, \quad j = 5, 6, 9 \div 13. \tag{10}$$

where 4.86 is the gross MW h-to-toe ratio.

Operation limits have to be considered in terms of maximum energy production. Furthermore, a minimum availability factor is defined to force the correspondent technology to work for a minimum period per year. The following inequality constraint can be added to the previous constraint:

$$\sum_{p=1}^{N_p} P_{j,t,p} T_p \geqslant \mathrm{av}_j \left( B_{j,t} + \sum_{\tau \in \Omega_{\mathrm{DUR}_{j,t}}} I_{j,t} \right). \quad (11)$$

In Fig. 2 illustrating details of the electric grid model it can be seen that large-scale generation plants (see Table 3) deliver at HHV levels, whereas industrial CHP facilities and mid-scale DG technologies such as on-shore and off-shore wind farms and hydroelectric plants deliver their production at HV level. Small-scale DG technologies, including waste-to-energy and biomass-to-energy plants, mini-hydroelectric and mini-wind turbines, deliver at MV levels, and civil electric production facilities deliver at LV levels. Electricity demand in the end-use sector is divided into three terms $Q1_{t,p}$, $Q2_{t,p}$, $Q3_{t,p}$, according to voltage levels at which they are withdrawn, HV, MV and LV, respectively. Only the LV-electric demand $Q3_{t,p}$ is influenced by the presence of energy-efficiency improvements.

The presence of grid losses is taken into account by means of suitable loss factors on power flows, and analogous factors are used for modelling demand from auxiliary generation services in each generation option.

Energy generation and consumption balance is formulated following the proposed grid model, which includes electric power export, grid energy losses, auxiliary generation services and electric energy saving due to civil energy-efficiency improvement measures. Relating equality constraints have the following expressions:

$$\alpha_1 \left( \sum_{j=1}^{4} (\mathrm{auxil}_j P_{j,t,p}) - \frac{1}{\alpha_{01}} \mathrm{Exp}_{t,p} \right) + \sum_{j \in \Omega_{HV}} (\mathrm{auxil}_j P_{j,t,p}) = Q1_{t,p} + PT12_{t,p}, \quad (12)$$

$$\sum_{j=7}^{10} (\mathrm{auxil}_j P_{j,t,p}) + \alpha_{12} PT12_{t,p} = Q2_{t,p} + PT23_{t,p}, \quad (13)$$

$$\sum_{j=13,14} (\mathrm{auxil}_j \cdot P_{j,t,p}) + \alpha_{23} PT23_{t,p} = Q3_{t,p} - 4.86 \cdot \mathrm{ES}_{t,p}, \quad (14)$$

where $\Omega_{HV} = \{5, 6, 11, 15, 16\}$ is the set of technologies injecting power production at the HV level. In Eq. (14), $\mathrm{ES}_{t,p}$ represents electricity savings achieved in $p$th step of $t$th year, obtained by fitting global electricity savings in a step-wise curve:

$$\sum_{z=1}^{N_z} \sum_{b=1}^{11} (\psi_{el,b,z} \mathrm{GUS}_{b,z} u_{b,z,t}) = \sum_{p=1}^{N_p} \mathrm{ES}_{t,p} T_p. \quad (15)$$

It is worth pointing out that in Eq. (15) electricity savings do not contain the contribution of photovoltaic plants ($b = 12$), since these facilities are numbered among supply technologies ($j = 13$) in Eq. (14).

In Eqs. (12)–(14), end-use sector withdrawal is subdivided among different voltage levels through suitable

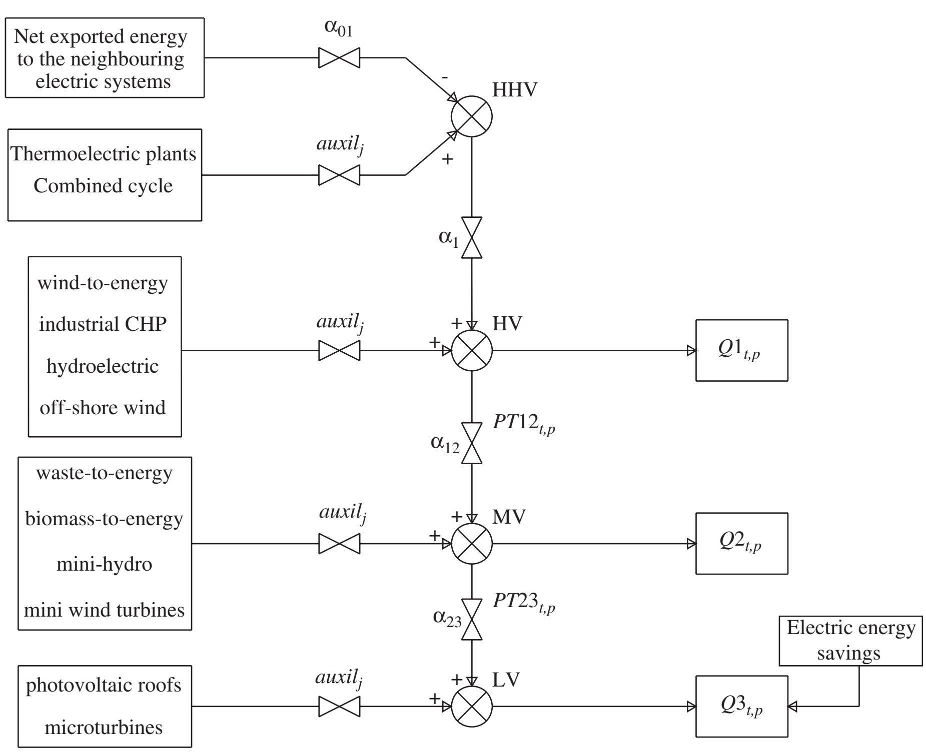


Fig. 2. Electric power grid scheme.

sharing coefficients $\beta_{s,\mathrm{HV}}$, $\beta_{s,\mathrm{MV}}$ , $\beta_{s,\mathrm{LV}}$:

$$Q1_{t,p} = \sum_{s=1}^{N_s} (QP_{s,t,p}\beta_{s,HV}), \tag{16a}$$

$$Q2_{t,p} = \sum_{s=1}^{N_s} (QP_{s,t,p}\beta_{s,MV}), \tag{16b}$$

$$Q3_{t,p} = \sum_{s=1}^{N_s} (QP_{s,t,p}\beta_{s,LV}). \tag{16c}$$

A correspondence between installed capacity and energy-saving measures regarding solar technologies is imposed. As $I_{j,t}$ is measured in MW with a reference unit of $1\,\mathrm{m}^2$ for solar thermal panels and 1 kW for photovoltaic plants, and supposing that 1 kW of solar thermal panels is equivalent to $2.5\,\mathrm{m}^2$ of panels, the following expressions can be written:

$$1000 I_{12,t} = 2.5 \sum_{z=1}^{N_z} u_{11,z,t}, \tag{17}$$

$$1000 I_{13,t} = \sum_{z=1}^{N_z} u_{12,z,t}. \tag{18}$$

DG technologies are often required to cover a given minimum amount of the whole electricity demand, so that the following constraint can be stated:

$$\sum_{j=5}^{14} \sum_{p=1}^{N_p} P_{j,t,p} T_p \geqslant \mathrm{DG}p_t \sum_{s=1}^{N_s} \sum_{p=1}^{N_p} QP_{s,t,p}. \tag{19}$$

Energy savings achieved by means of all energy-efficiency improvement measures have to reach the global energy-saving target, that is the sum of the two targets set for electricity ($\mathrm{OBJEL}_t$) and gas ($\mathrm{OBJH}_t$) distributors:

$$\sum_{\tau=1}^{t} \left[ \sum_{b=1}^{12} \left( \sum_{z=1}^{N_z} u_{b,z,\tau} \mathrm{GUS}_{b,z} \right) \right] \geqslant \mathrm{OBJEL}_t + \mathrm{OBJH}_t. \tag{20}$$

It can be observed that all energy-efficiency actions implemented in the years preceding $t$th year help to attain the energy-saving target set for $t$th year. Here it is assumed that the lifetime of energy-efficiency improvement measures is longer than the planning horizon. Moreover, specific targets for electric energy savings and natural gas savings have to be satisfied. These targets are evaluated at 50% of the global target imposed on electricity and gas distributors, respectively, which leaves the remaining quota to be covered by other savings:

$$\sum_{\tau=1}^{t} \left[ \sum_{b=1}^{12} \left( \psi_{\mathrm{el},b,z} \sum_{z=1}^{N_z} u_{b,z,\tau} \mathrm{GUS}_{b,z} \right) \right] \geqslant 0.5 \cdot \mathrm{OBJEL}_t, \tag{21}$$

$$\sum_{\tau=1}^{t} \left[ \sum_{b=1}^{12} \left( \psi_{3,b,z} \sum_{z=1}^{N_z} u_{b,z,\tau} \mathrm{GUS}_{b,z} \right) \right] \geqslant 0.5 \cdot \mathrm{OBJH}_t. \tag{22}$$

Depending on the features of civil end-users, such as number of flats per building, number of floors per building, number of rooms per flat, unitary flat superficies and unitary flat wall extension, the maximum number of each energy-efficiency improvement measure is imposed so that the following constraint can be written:

$$\sum_{t=1}^{N_t} u_{b,z,t} \leqslant \mathrm{ESP}_{b,z}. \tag{23}$$

Energy saving is related to climatic zones with the number of energy-efficiency improvement measures divided among zones directly proportional to zone population. For instance, supposing the existence of three climatic zones, the following equality constraints are stated:

$$\frac{u_{b,1,t}}{\mathrm{Pop}_{1,t}} = \frac{u_{b,2,t}}{\mathrm{Pop}_{2,t}} = \frac{u_{b,3,t}}{\mathrm{Pop}_{3,t}} \tag{24}$$

Since further heating facilities in the civil sector are taken into account, together with energy-efficiency improvement measures, thermal power balance can be modified as follows:

$$\begin{aligned} &\sum_{p=1}^{N_p} QT_{t,p} - 12.44 \sum_{z=1}^{N_z} \sum_{b=3}^{10} \left( \sum_{i=1}^{N_i} \psi_{i,b,z} \right) \mathrm{GUS}_{b,z} u_{b,z,t} \\ &\quad = \sum_{j=12,14} \sum_{p=1}^{N_p} R_{j,t,p} T_p + 12.44 \left[ \sum_{\substack{i=1 \\ i \neq 3}}^{N_i} \frac{\mathrm{Nb}_{i,t} \mathrm{Eb}_i}{\eta_i} \right. \\ &\qquad + \frac{(\mathrm{Nb}_{\mathrm{el},t} - \sum_{\tau=1}^{t} u_{1,\tau}) \mathrm{Eb}_{\mathrm{el}}}{\eta_{\mathrm{el}}} + \frac{(\mathrm{Nb}_{3,t} - \sum_{\tau=1}^{t} u_{2,\tau}) \mathrm{Eb}_{3,1}}{\eta_{3,1}} \\ &\qquad \left. + \frac{\mathrm{Eb}_{3,2} \sum_{\tau=1}^{t} (u_{1,\tau} + u_{2,\tau})}{\eta_{3,2}} + \frac{\mathrm{Eb}_{3,3} \sum_{\tau=1}^{t} \sum_{z=1}^{N_z} u_{3,z,\tau}}{\eta_{3,3}} \right]. \end{aligned} \tag{25}$$

where 12.44 is the net MW h-to-toe ratio.

In the civil sector energy outline reported in Fig. 3, civil LV electricity demand $Q3_{1,t,p}$ is satisfied by a certain amount of power from MV grid $PT23_{t,p}$, and by DG civil options, photovoltaic and micro-turbines burning natural gas (NG), as mathematically described by Eq. (14). Heat power demand in the civil sector $QT_{t,p}$ is covered, as can be seen in Eq. (25), by recovered thermal power obtained from micro-turbines and solar thermal panels and by the civil boiler system exploiting fuel oil (OIL), coal (CO), NG, diesel (DI), liquid propane gas (LPG) and biomass (BIO). The contribution of passive energy-efficiency improvement measures targeted at reducing both electricity and heat demand is evaluated by means of the coefficients $\psi_{\mathrm{el},b,z}$ and $\psi_{i,b,z}$, respectively. As previously mentioned, power generation options involved in the energy-saving outline (photovoltaic plants, solar thermal panels, household gas boilers) do not affect the evaluation of energy demand reduction. In fact, in the outline reported in Fig. 3, they appear on the generation facility side.

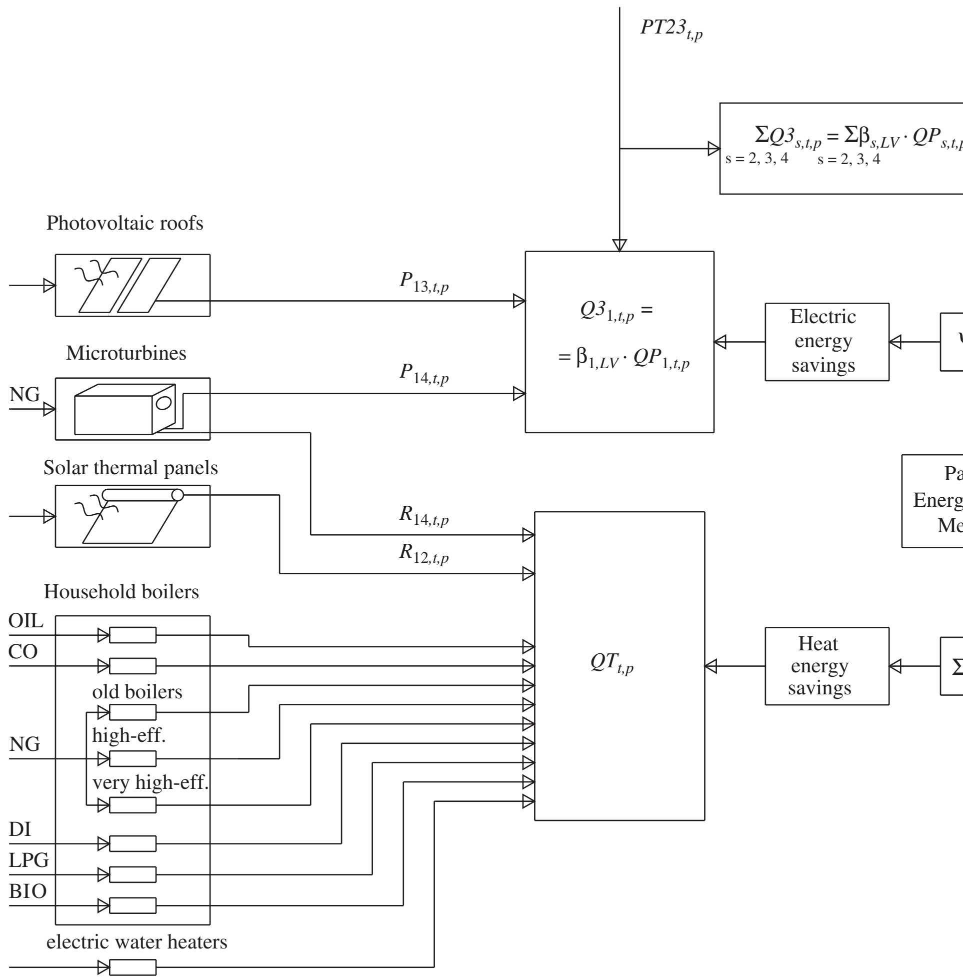


Fig. 3. Civil low-voltage electric system and heating facilities outline.

## 4. Test results

In order to show the effectiveness of the proposed procedure several scenarios have been analysed for a test energy system over a time horizon of 10 years (see Tables 5–9).

The balance of primary energy sources is reported in Table 5. Primary energy sources are classified as solid fuels (coal, blast furnace gas and cokery gas); oil products (fuel oil, diesel oil, petrol, LPG and refinery gas); gas fuels (natural gas); renewable fuels (RDF, biomass) and renewable non-fuels (hydro, wind, photovoltaic). Electric energy is estimated at 2200 kcal/kW h for primary uses and at 860 kcal/kW h for end-use consumption.

In Table 6, installed electric generation capacity is reported for each existing generation option. The installed plants mainly burn coal together with smaller contributions from oil and natural gas, and process by-products in industrial CHP facilities.

In Table 7, grid energy losses, power exchanges with the neighbouring systems and generation auxiliary services have been taken into account.

End-use consumption for each end-use sector is illustrated in Table 8 where it can be seen that the widespread gas network allows for full exploitation of natural gas by both civil and industrial sectors, whereas oil products are essentially used for transportation.

Total emission of $CO_2$, $NO_x$, $SO_x$ and particulates due to end-use consumption of fuels and electricity production are reported in Table 9.

Given the fact that the internal production capacity of the system under study is not well-dimensioned for internal demand, electricity has to be imported from neighbouring systems. Electricity production relies exclusively on fossil fuels, since RES are not employed at all. Plants deliver energy at HHV and HV levels, far from load centres, which causes high grid losses relating to transmission, transformation and distribution of energy.

Annual growth rates of electricity demand are set at 1.1% in Residential and Service sectors, 1.93% in the Industry sector, 1.95% in Agriculture and Fisheries and 0.3% in the Transport sector. The annual growth rate of civil heat/heating demand is 1.75% and the growth rate of steam process demand is 1.0%.

Table 5
Primary energy source balance at the reference year

| | Solid fuels (ktoe) | Oil products (ktoe) | Gas fuels (ktoe) | Renewables | | Electric energy (ktoe) | TOTAL (ktoe) |
|---|---|---|---|---|---|---|---|
| | | | | Fuels (ktoe) | Non-fuels (ktoe) | | |
| Gross consumption | 2669 | 4536 | 1898 | 0 | 0 | 202 | 9305 |
| Electric energy production | −2072 | −651 | −662 | 0 | 0 | 3385 | 0 |
| Consumption/losses energy sector | −180 | −227 | −13 | 0 | 0 | −2143 | −2563 |
| Other uses | 135 | 361 | 0 | 0 | 0 | 0 | 496 |
| End-use consumption | 282 | 3297 | 1223 | 0 | 0 | 1444 | 6246 |

Table 6
Installed electric generation capacities at the reference year

| Generation options | Installed capacity (MW) |
|---|---|
| Coal-fuelled thermal power plant | 1400 |
| Oil-fuelled thermal power plant | 400 |
| Gas-fuelled thermal power plant | 150 |
| Combined-cycle power plant | 400 |
| Industrial co-generation steam turbines | 200 |
| Total generation capacity | 2550 |

Table 7
Electric energy grid balance at the reference year

| | Electric energy (GW h) |
|---|---|
| Gross production | 16,655 |
| Generation auxiliary services | −1145 |
| Net electric energy import | 2347 |
| Network losses | −1060 |
| End-use consumption | 16,797 |

Table 8
End-use consumption at the reference year

| | Solid fuels (ktoe) | Oil products (ktoe) | Gas fuels (ktoe) | Electric energy (ktoe) | Total per sector (ktoe) |
|---|---|---|---|---|---|
| Residential and services | 33.0 | 181.3 | 802.7 | 636.4 | 1653.4 |
| Industry | 248.5 | 334.0 | 382.0 | 743.5 | 1708.0 |
| Agriculture and fishery | 0.0 | 448.0 | 5.0 | 40.6 | 493.6 |
| Transport | 0.0 | 2,334.0 | 33.0 | 24.0 | 2391.0 |
| Total energy sources | 281.5 | 3297.3 | 1222.7 | 1444.5 | 6246.0 |

In *Base Scenario*, no minimum level of expansion is imposed on DG technologies. Constraint (18) is ignored, and no energy-efficiency measures are considered, i.e. constraints (19)–(23) are not taken into account.

Table 9
Emissions to air energy source at the reference year

| | $CO_2$ (ton) | $NO_x$ (ton) | $SO_x$ (ton) | Particulates (ton) |
|---|---|---|---|---|
| Solid fuels | 10,049,200 | 35,140 | 51,763 | 4763 |
| Oil products | 12,043,661 | 99,106 | 44,583 | 9134 |
| Gas fuels | 4,316,061 | 7727 | 0 | 377 |
| Renewable fuels | 0 | 0 | 0 | 0 |
| Total | 26,408,922 | 141,973 | 96,346 | 14,268 |

In *DG30 Scenario*, the percentage of electricity production relating to DG technologies must reach 30% of total production by end of planning horizon ($\mathrm{DG}p_{10} = 0.29$).

In *EE Scenario*, DG installations are not considered, whereas increasing energy-saving targets are imposed. Energy savings from electricity and gas distributors are required to reach the OBJEL target of 39 ktoe and the OBJH target of 29.6 ktoe, respectively[5] by the fifth year. From the fifth year energy-saving values are assumed to be constant.

In *DG30 + EE Scenario*, all the constraints and the assumptions of the previous two scenarios are considered to be contemporaneously present.

In *DGMAX + EE Scenario*, maximum DG penetration, on the other hand, is evaluated according to maximum RES exploitation and to minimum yearly availability of fossil fuelled-power plants.

An analogous investigation is carried out in *DG30 + EEMAX Scenario* to determine, according to the previously mentioned constraints, maximum employment of energy-efficiency actions. In this case, energy-saving targets have the same trend described in the *EE Scenario* for the first five years, and go on increasing until the last year, when the OBJEL target is of 88.8 ktoe and the OBJH target is of 71.6 ktoe.

Maximum DG penetration and highest reachable energy-saving targets are also investigated in the *DGMAX+ EEMAX Scenario*.

[5]These values are obtained from Italian Decrees [20] where energy-saving targets must be met within five years.

Table 10
Cost outline

| Scenario | Total real cost (M€) | Rise rate to base scenario (%) | EE cost | |
|---|---|---|---|---|
| | | | M€ | (% of the total cost) |
| *Base* | 10,998.2 | – | – | – |
| *DG30* | 11,252.5 | 2.3 | – | – |
| *EE* | 11,228.0 | 2.1 | 129.8 | 1.16 |
| *DG30 + EE* | 11,498.7 | 4.6 | 130.8 | 1.14 |
| *DGMAX + EE* | 12,039.8 | 9.5 | 218.4 | 1.81 |
| *DG30 + EEMAX* | 12,999.6 | 18.2 | 1745.7 | 13.43 |
| *DGMAX + EEMAX* | 13,363.4 | 21.5 | 1685.8 | 12.62 |

Table 14
Achieved energy saving (ktoe)

| Scenario | Electricity saving | Gas saving | Total saving |
|---|---|---|---|
| *Base* | – | – | – |
| *DG*30 | – | – | – |
| *EE* | 82.1 | 195.9 | 484.2 |
| *DG*30 + *EE* | 80.8 | 195.8 | 484.2 |
| *DGMAX + EE* | 62.6 | 159.3 | 484.2 |
| *DG*30 + *EEMAX* | 84.9 | 358.1 | 700.3 |
| *DGMAX + EEMAX* | 69.0 | 334.2 | 691.2 |

Table 11
Energy production plant installations (MW)

| Scenario | Thermoelectric | | | CC | CHP | | Distributed generation | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coal | Oil | Gas | | ST | GT | Hydro | Wind | Offshore | Waste | Biom. | Minihydro | Miniwind | μT | PV | Sol.th |
| *Base* | 0 | 0 | 0 | 574 | 0 | 0 | 145 | 1100 | 45 | 0 | 0 | 3 | 22.1 | 156 | 0.0 | 0.0 |
| *DG*30 | 0 | 0 | 0 | 491 | 0 | 0 | 145 | 1200 | 300 | 61 | 93 | 3 | 22.1 | 156 | 0.0 | 0.0 |
| *EE* | 0 | 0 | 0 | 546 | 0 | 0 | 145 | 1200 | 92 | 0 | 0 | 3 | 0.0 | 208 | 8.3 | 71.1 |
| *DG*30 + *EE* | 0 | 0 | 0 | 458 | 0 | 0 | 145 | 1200 | 300 | 0 | 147 | 3 | 22.1 | 249 | 8.3 | 71.3 |
| *DGMAX + EE* | 0 | 0 | 0 | 44 | 0 | 0 | 145 | 1200 | 300 | 83 | 195 | 3 | 22.1 | 450 | 43.9 | 22.2 |
| *DG*30 + *EEMAX* | 0 | 0 | 0 | 443 | 0 | 0 | 145 | 1200 | 300 | 0 | 49 | 3 | 22.1 | 266 | 57.4 | 78.4 |
| *DGMAX + EEMAX* | 0 | 0 | 0 | 30 | 0 | 0 | 145 | 1200 | 300 | 83 | 155 | 3 | 22.1 | 474 | 57.4 | 78.4 |

Table 12
Primary source consumption for electricity production (ktoe)

| Scenario | Gas fuels | | RES | |
|---|---|---|---|---|
| | Initial | Final | Initial | Final |
| *Base* | 662 | 1460.6 | 0 | 612.0 |
| *DG*30 | | 1155.8 | | 1083.6 |
| *EE* | | 1457.2 | | 708.5 |
| *DG*30 + *EE* | | 1236.7 | | 1052.6 |
| *DGMAX + EE* | | 1298.0 | | 1320.2 |
| *DG*30 + *EEMAX* | | 1281.3 | | 917.7 |
| *DGMAX + EEMAX* | | 1335.6 | | 1373.1 |

Table 13
Installed energy-efficiency measures

| Scenario | FLUO (n.) | EB → GB (n.) | HHEGB (n.) | HEGB (n.) | DPW ($m^2$) | HI ($m^2$) | PV (kW) | Sol.th ($m^2$) | HHA (n.) | LFS (n.) | AJB (n.) | HP (n.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Base* | – | – | – | – | – | – | – | – | – | – | – | – |
| *DG*30 | – | – | – | – | – | – | – | – | – | – | – | – |
| *EE* | 1,000,000 | 15,152 | 0 | 0 | 1,758,267 | 0 | 8,350 | 177,975 | 0 | 300,000 | 600,000 | 0 |
| *DG*30 + *EE* | 1,000,000 | 15,152 | 0 | 0 | 1,748,194 | 0 | 8,348 | 178,195 | 0 | 300,000 | 600,000 | 0 |
| *DGMAX + EE* | 1,000,000 | 0 | 0 | 37,637 | 2,426,437 | 0 | 43,906 | 55,586 | 0 | 300,000 | 600,000 | 0 |
| *DG*30 + *EEMAX* | 1,000,000 | 15,152 | 0 | 637,884 | 2,425,937 | 14,777,242 | 57,445 | 195,931 | 455,527 | 300,000 | 600,000 | 0 |
| *DGMAX + EEMAX* | 1,000,000 | 15,152 | 0 | 637,884 | 2,426,700 | 14,799,120 | 57,445 | 195,931 | 455,528 | 300,000 | 600,000 | 0 |

In Table 10, total real cost (see Eq. (2)), of energy planning for the considered scenarios is reported. The increasing rate of total costs for each scenario in relation to *Base Scenario* is also illustrated together with costs due to energy-efficiency measures. It can be noted that total costs increase by imposing more severe constraints on DG exploitation and energy-saving targets. The contribution to total cost of energy-efficiency actions, which include photovoltaic plants and solar thermal panels, increases as energy-saving targets increase. Total cost in the *DGMAX + EEMAX Scenario* is 21.5% higher than the *Base Scenario* cost.

In Table 11, total new installations of power plants are reported. The presence of constraint on DG technologies to cover 30 % of electricity production makes the combined-cycle installations decrease by roughly 80 MW, whereas application of energy-efficiency actions in the *EE Scenario* causes a reduction of 30 MW. Maximum diffusion of DG technologies and energy-efficiency measures allows for a reduction of 540 MW in combined-cycle installations. It is worth remarking that PV plants and solar thermal panels are more common in the latter two scenarios, since they are linked to the energy-saving framework.

Primary energy consumption relating to electricity production in Table 12 focuses on gas and RES exploitation at beginning and end of the time horizon. The presence of a proper emission constraint and of external costs in the objective function pushes the system to employ greater amounts of natural gas (where consumption rises to 120%) and RES to reach maximum local potential with a significant reduction in solid fuels (44%) and oil product exploitation (31%). These results bring a reduction in $CO_2$ emissions ranging between 2.5 Mton (−9.4%) and 3 Mton (−11.3%).

In Fig. 4, which shows DG contributions to electricity production, it can be observed that in *Base*, *DG30 + EE* and *DGMAX + EE Scenarios* electricity production covered by DG technologies reaches 20%, 30% and 47%, respectively, by final year of planning horizon.

In Fig. 5, the grid loss trends for the same scenarios analysed in Fig. 4 are reported. Comparing the two figures, it can be seen that the higher the DG penetration, the lower grid loss percentage, since power flows through different voltage levels in the electric grid decrease. Grid energy losses, which are 6.8% of total electricity production in the first year, decrease at different rates in each scenario and reach 4.25% where DG is fully exploited. If energy-saving targets are increased, no significant change in losses is observed, since global savings are a very small percentage of global electricity demand.

Details of energy-efficiency measures selected in each scenario are described in Table 13. In *EE Scenario*,

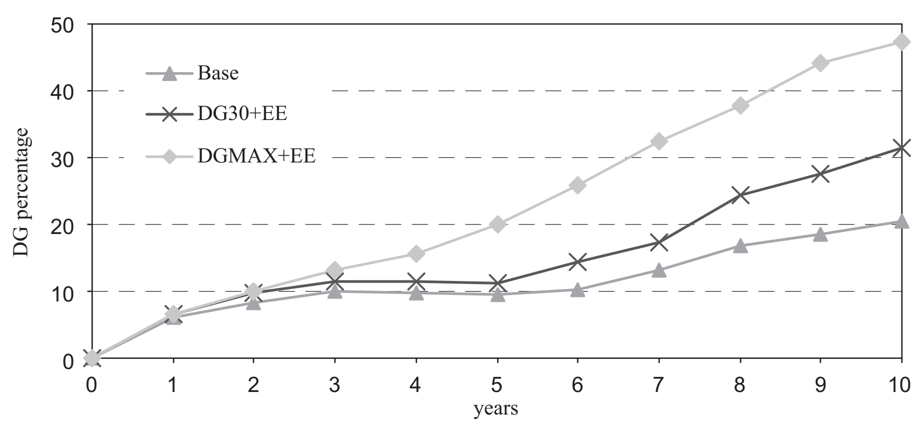


Fig. 4. DG contribution to total electricity production.

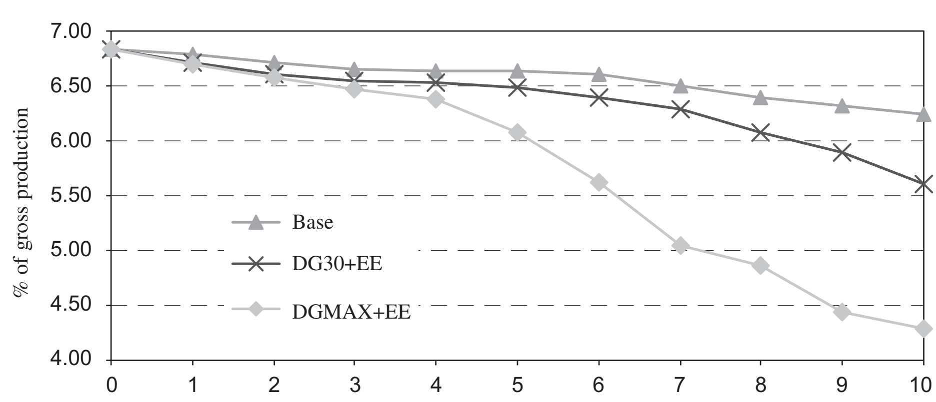


Fig. 5. Grid losses percentage.

energy-efficiency measures are chosen according to cost per energy saved. Fluorescent lamps (FLUO), low-flux showerheads (LFS) and aerated jet breakers (AJB) are exploited at maximum potential, together with the substitution of electric boilers with gas boilers (EB $\rightarrow$ GB). Minor contributions come from double pane windows (DPW), PV plants and solar thermal panels. Outputs are approximately the same in $DG30 + EE$ and $DGMAX + EE$ *Scenarios* where PV plants are used. With these scenarios energy-saving targets are more drastic, so that less cost-efficient measures are used as well, such as installation of more efficient gas boilers (HEGB), new household appliances (HHA) and improvements in wall and roof heating insulation (HI). As already noted in Table 12, PV plants and solar thermal panels are exploited at maximum potential.

Total savings achieved over the whole time horizon are reported in Table 14. Total savings are higher in $DG30 + EE$ and $DGMAX + EE$ *Scenarios*, which is also the case for gas savings. Although PV plants are numbered among energy-efficiency measures, contributions to the system are considered in terms of energy production rather than energy demand reduction. PV plant installations nevertheless affect global electricity savings by lowering percentages if they are installed early in the planning horizon. In the $DGMAX + EEMAX$ *Scenario*, smaller electricity saving are observed than in the $DG30 + EEMAX$ *Scenario*, even if global PV installations are the same.

In Fig. 6, electricity saving trends are reported as a percentage of demand for electricity in the civil sector. The $DGMAX + EE$ *Scenario* curve shows that energy saving targets are reached by choosing PV plants, even if $EEMAX$ *Scenario* percentages do not double percentages reached in *EE Scenario*, as might be expected, because of strong PV contribution.

Total saving percentages decrease in *EE Scenarios*, since savings remain constant while energy demand increases. Total electricity savings reach 2% per year of the civil sector demand. Total savings are less than 1% of total demand for electricity, since civil sector demand accounts for 44% of total demand.

## 5. Conclusions

An optimisation model has been adopted to investigate DG diffusion and energy-efficiency actions in energy planning studies. The proposed approach is based on EFOM modular structure that details the exploitation of primary energy sources, power and heat generation, emissions and end-use sectors. Particular care has been given to the description of DG technologies and their energy injections in the electric grid. To this purpose, a representation of the electric grid with various voltage levels has been considered. Energy-efficiency measures have also been applied to the civil sector. The effectiveness of the proposed methodology has been shown by carrying out simulations on a realistic energy system. Test results have proved that energy policies aimed at reducing environmental impact of electricity production can be supported by combined cycle power plants and DG technologies (mainly hydroelectric and wind power). By promoting exploitation of DG technologies, reduction in CC production has occurred with a consequent decrease in transmission losses. Targets on energy efficiency have been met by implementing less expensive technologies, though these seem to have a minimal influence on energy demand reduction. The adoption of DG technologies and energy-efficiency actions in energy planning has involved higher energy system costs.

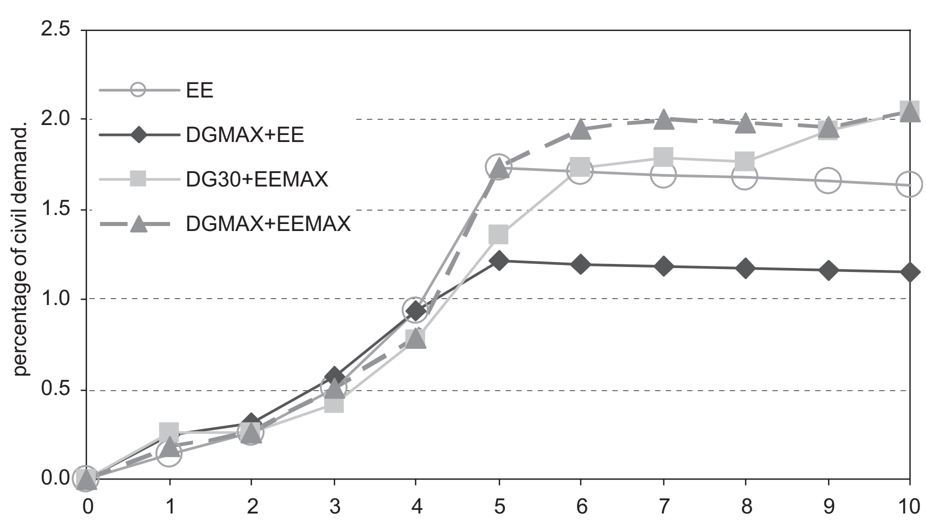


Fig. 6. Electricity savings excluding PV contribution.

## Appendix A. List of symbols

### A.1. Indices

$t$ represents mid-time periods (year): $t = 1, \ldots, N_t$;
$p$ represents the time intervals of load duration curve: $p = 1, \ldots, N_p$;
$i$ stands for primary energy sources:

| | |
|---|---|
| $i = 1$ | fuel oil |
| $i = 2$ | coal |
| $i = 3$ | natural gas |
| $i = 4$ | diesel oil |
| $i = 5$ | petrol |
| $i = 6$ | liquid propane gas |
| $i = 7$ | municipal waste |
| $i = 8$ | biomass |
| $i = 9$ | blast furnace gas |
| $i = 10$ | cokery gas |
| $i = 11 = N_i$ | refinery gas |

$j$ represents the primary energy conversion options:
*Centralized electric energy production plants*

| | |
|---|---|
| $j = 1$ | coal-fuelled thermoelectric |
| $j = 2$ | oil-fuelled thermoelectric |
| $j = 3$ | gas-fuelled thermoelectric |
| $j = 4$ | combined cycle |

*Distributed electric energy production plants*

| | |
|---|---|
| $j = 5$ | wind |
| $j = 6$ | hydroelectric |
| $j = 7$ | solid waste-to-energy |
| $j = 8$ | biomass-to-energy |
| $j = 9$ | mini-hydroelectric |
| $j = 10$ | mini-wind turbines |
| $j = 11$ | off-shore wind |

*Civil thermal/electric energy production facilities*

| | |
|---|---|
| $j = 12$ | solar thermal collectors |
| $j = 13$ | photovoltaic roofs |
| $j = 14$ | micro-turbines |

*Industrial CHP facilities*

| | |
|---|---|
| $j = 15$ | gas turbines |
| $j = 16 = N_j$ | steam turbines |

$s$ stands for end-use sectors:

| | |
|---|---|
| $s = 1$ | residential and services |
| $s = 2$ | industry |
| $s = 3$ | agriculture and fishery |
| $s = 4 = N_s$ | transports |

$b$ represents the energy-saving measures:

| | |
|---|---|
| $b = 1$ | high-efficiency natural gas water heater instead of electric water heater |
| $b = 2$ | high-efficiency natural gas water heater in place of older natural gas water heater |
| $b = 3$ | very high-efficiency natural gas boiler instead of high-efficiency natural gas water heater |
| $b = 4$ | use of compact fluorescent lamp in place of incandescent lamp |
| $b = 5$ | dual pane window installation in place of single pane window |
| $b = 6$ | improvement of heat insulation of walls and ceilings |
| $b = 7$ | substitution of high-efficiency electric household appliance for older one |
| $b = 8$ | installation of low-flux showerhead in the place of older one |
| $b = 9$ | aerated jet breaker for water taps instead of older one |
| $b = 10$ | installation of heat pump rather than natural gas water heater |
| $b = 11$ | installation solar thermal collectors |
| $b = 12 = N_b$ | installation of photovoltaic plants, with less than 20 kW installed capacity |

$z$ represents the climatic zones: $z = 1, \ldots, N_z$ ($N_z = 1-6$)

*Parameters*

| | |
|---|---|
| $T_p$ | operation time fraction of the LDC $p$th interval (h) |
| $\alpha_{01}$ | loss factor for energy transmission grid connecting to neighbouring electrical systems |
| $\alpha_1, \alpha_{12}, \alpha_{23}$ | power-loss factor from HHV to HV grids, from HV to MV grids, from MV to LV grids, respectively |
| $\mathrm{auxil}_j$ | percentage of gross electric power consumed in auxiliary generating services by the $j$th installation type |
| $\beta_{s,\mathrm{HV}}, \beta_{s,\mathrm{MV}}, \beta_{s,\mathrm{LV}}$ | electric energy demand sharing coefficient, for HV-, MV- and LV-users, respectively, of the $s$th end-use sector |
| $\mathrm{A}_j$ | amortisation period of investment in $j$th installation type (y) |
| $D_j$ | life period of$j$th installation type (y) |
| DR | discount rate |

*Energy conversion system*

| | |
|---|---|
| $\mathrm{AV}_j$ | availability factor of $j$th installation type (h/y) |
| $\mathrm{av}_j$ | minimum availability factor of $j$th installation type (h/y) |
| $c_{i,j}$ | unit consumption of $i$th fuel by $j$th conversion option (toe/MW h) |

*Industrial sub-system*

| | |
|---|---|
| $h_i$ | unit consumption of $i$th fuel by HP steam boilers (toe/ton) |
| $m_i$ | unit consumption of $i$th fuel by MP steam boilers (toe/ton) |

*Civil sub-system*

| | |
|---|---|
| $\eta_i$ | $i$th energy conversion efficiency of boiler systems ($i \neq 3$) |
| $\eta_{\mathrm{el}}$ | conversion efficiency of electric boiler systems |

$\eta_{3,1}, \eta_{3,2}, \eta_{3,3}$ energy conversion efficiency of older natural gas boilers, high-efficiency natural gas boilers, and very high-efficiency natural gas boilers, respectively

$Eb_i$ unit consumption of $i$th fuel ($i \neq 3$) by boilers for civil heat demand (toe/unit/yr)

$Eb_{el}$ electric civil boilers unit electric energy consumption (toe/unit/yr)

$Eb_{3,1}, Eb_{3,2}, Eb_{3,3}$ unit natural gas consumption by older natural gas boilers, high-efficiency natural gas boilers, very high-efficiency natural gas boilers, respectively (toe/unit/yr)

*Energy saving*

$GUS_{b,z}$ gross unitary energy saving of $b$th energy-efficiency improvement measure in $z$th climatic zone (toe/unit/yr)

$\psi_{el,b,z}$ percentage of electric energy saving of $b$th energy-saving measure for $z$th climatic zone

$\psi_{i,b,z}$ percentage of energy saving of $b$th energy-saving measure related to $i$th fuel ($i = 3, 4$) for $z$th climatic zone

*Variables*

*Explanatory variables*

'Explanatory' variables generally define evolutionary scenarios in system.

$RP_{j,t}$ available energy potential for renewable-based generation option ($j = 5-13$) at the $t$th year (toe)

$B_{j,t}$ total capacity of $j$th generation option already existing at beginning of planning horizon and still in operation at $t$th year (MW)

$Exp_{t,p}$ net electric power exported during the $p$th interval of the $t$th year (MW)

$QP_{s,t,p}$ electric power demand of $s$th end-user during $p$th interval of $t$th year (MW)

$Q1_{t,p}$, $Q2_{t,p}$, $Q3_{t,p}$ electric power demand, by HV-, MV- and LV-users, respectively, at $p$th interval of $t$th year (MW)

$QT_{t,p}$ civil thermal power demand at $p$th interval of $t$th year (MW)

$Nb_{i,t}$ number of civil boilers using $i$th energy form in action in $t$th year (unit)

$Nb_{el,t}$ number of civil electric boilers in $t$th year (unit)

$OBJEL_t, OBJH_t$ total saving target of electricity and heat energy, respectively, in $t$th year (toe)

$Pop_{z,t}$ percentage of population of $z$th climatic zone in $t$th year with respect to whole region population

$ESP_{b,z}$ maximum amount of $b$th energy-efficiency improvement measure in $z$th climatic zone over whole planning horizon

$DGp_t$ percentage of global electric demand to be covered by means of Distributed Generation technologies in $t$th year

*State variables*

$I_{j,t}$ additional capacity of $j$th installation type at $t$th year (MW)

$R_{j,t,p}$ recovered thermal power from $j$th generation option during $p$th interval of $t$th year (MW)

$P_{j,t,p}$ power output of $j$th generation option during $p$th interval of $t$th year (MW)

$PT12_{t,p}$ power flow from HV grid to MV grid during $p$th interval of $t$th year (MW)

$PT23_{t,p}$ power flow from MV grid to LV grid during $p$th interval of $t$th year (MW)

$H_{i,t,p}$ industrial HP steam boilers outlet from $i$th fuel during $p$th interval of $t$th year (ton/h)

$M_{i,t,p}$ industrial MP steam boilers outlet from $i$th fuel during $p$th interval of $t$th year (ton/h)

$u_{b,z,t}$ units of $b$th energy-efficiency improvement measure installed in $z$th climatic zone during $t$th year.

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