Energy Research & Social Science 15 (2016) 12–33

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Proposing an open-source model for unconventional participation to energy planning

Fabrizio Fattori*, Davide Albini, Norma Anglani

Dipartimento di Ingegneria Industriale e dell'informazione (DIII), University of Pavia, Via Ferrata 5, 27100 Pavia, Italy

ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form 12 February 2016
Accepted 17 February 2016

Keywords:
Energy policy
Energy system model
Lombardy
OSeMOSYS
Citizens participation
MELiSsa

ABSTRACT

In this paper we present MELiSsa, a local multi-regional energy system model of a specific area: the Lombardy region. MELiSsa, implemented through an open-code modeling framework (OSeMOSYS), is built upon transparent relations and open data. Building this model is a first step towards four main goals: (i) extending the energy planning process of the region to citizens and experts usually not involved; (ii) exploiting this uncommon participation for a crowd-source development; (iii) providing a simple tool for interested local citizens to get consciousness of the technological and behavioral limits of their energy system; (iv) providing a real-case-based platform for interdisciplinary research and academic purposes possibly beyond the region boundaries. The current structure and input data of MELiSsa are presented and discussed together with a demonstrative analysis. Preliminary results show that interdisciplinary participation is enabled as an opportunity and it is needed to properly model technological dynamics as well as non-technological issues that will be relevant within the path to reach environmental, economic and social targets.

1. Introduction

Energy planning is the process that helps to properly design the development of energy systems towards established targets (e.g. economical, environmental and social goals). Though the vision of targets may not be unique and unbiased, the research of the solutions that do meet the targets can and must be objective. Energy system models are instrumental tools, from this point of view, since they can describe with impartiality the systems and their dynamics throughout established mathematical relations and data. Many energy modeling frameworks and energy models have been built and used in the past decades, as proved by the number of reviews available in the literature (see for example [1–5]). Each model however is singular because it focuses on different case studies and different scales, pursues different purposes and uses different methods. With the model presented in this work we focus on a specific Italian subnational case study: the Lombardy Region and its administrative subregions. Few comprehensive energy system models have dealt with this area to this day: (i) the MarkAl-TIMES-based *MONET* [6] that modeled the Italian energy system detailing each administrative region (based on the national power system model *MATISSE* [7]), (ii) the MarkAl-TIMES-based model of [8] that exclusively focused on the Lombardy region as a whole single area and (iii) the *PPMM* MarkAl-based model of the Province of Pavia [9] that focused only on a particular portion of Lombardy. Programs and plans for the energy system of the region have come in succession as well since the beginning of the century: (i) the program *Programma Energetico Regionale* (PER) of 2003 operated through the plan *Piano d'Azione per l'Energia* (PAE) [10], (ii) the plan *Piano Strategico delle Tecnologie per la Sostenibilitá Energetica in Lombardia* [11], (iii) the plan *Piano per una Lombardia Sostenibile* [12] and (iv) the recent program *Nuovo Programma Energetico Ambientale Regionale* (PEAR) [13]. Though the development of models, programs and plans is generally open to public consultation and participation, it is not only our opinion (see Bazilian et al. [14]) that it can be improved by making this public sharing more effective through mass communication and information technologies.

1.1. Scope of the work and outline

MELiSsa (Modello Energetico della Lombardia per la Sostenibilità) has been built on the idea that the mass communication and information potential of today can be exploited (i) to create a free platform, based on transparent relations, open data and shared assumptions; and (ii) to reach citizens usually not directly involved within the decision making process. The scope of the project around

---

* Corresponding author.
E-mail addresses: fabrizio.fattori@unipv.it (F. Fattori), norma.anglani@unipv.it (N. Anglani).

http://dx.doi.org/10.1016/j.erss.2016.02.005

MELiSsa lies in two main fields: (i) improving the planning of energy systems and (ii) increasing the awareness of citizens. MELiSsa does not aim to reach them separately: by aiming at an open- and crowd-source tool it aims at two effects. The first is direct: citizens can (i) monitor the assumptions and evaluate the decisions of policy makers, (ii) actively contribute to the process by suggesting different ideas and assumptions, (iii) improve the reference database and (iv) offer manifold points of view. The second is indirect: by participating, citizens can get awareness of (i) their role in the energy systems (e.g. how much energy is consumed by households), (ii) the possibilities and limits of technologies (e.g. how much energy demand can be met by local renewable sources) and (iii) the possibilities and limits of human behaviors (e.g. to what extent car-pooling could reduce consumption and emissions related to transportation). Besides these main purposes, MELiSsa is addressed as well to the world of research and academy as they can both (i) positively affect the crowd-source development and (ii) benefit from this platform based on a real case study, for researches and teaching purposes, possibly beyond the boundaries of the region and the disciplinary sector. Aware that different important steps are needed to involve an unconventional participation in the energy planning process or debate, with this article we exclusively focus on kicking-off by building the model and by drawing attention to the necessity for participation.

The remainder of this paper is structured as follows: in Section 2 the structure and the data of the model are presented; in Section 3 the first demonstrative results are showed; in Section 4 the platform is discussed together with the analyses it can be used for and the existing experiences; finally, in Section 5 the conclusions are drawn.

2. MELiSsa model

In the present section the MELiSsa model is presented in detail. The section begins with a short description of the modeling framework that is used (Section 2.1) helping introducing and understanding the structure of the model (Section 2.2) and the code modifications (Section 2.3). The input data are then showed and the related assumptions explained (Section 2.4).

2.1. OSeMOSYS framework

OSeMOSYS (Open Source Energy Modeling System) is a long term energy system modeling framework that has been created and developed by an international team of institutes and research groups. It has been chosen for building up the MELiSsa model[1] given its simplicity and its open-source nature. A first presentation of OSeMOSYS and its mathematical formulation can be found in Howells et al. [15]. Updated features are described in Welsh et al. [16] and on the official website [17]. A brief description is given here to make the reader properly understand the structure of MELiSsa. OSeMOSYS is based on a linear optimization problem that aims to minimize the total discounted cost for satisfying the demand of energy services of a considered region, over a given period, under specific constraints. The solution of the problem is the optimal configuration of the energy system over that same period and can be constrained by the modeler to consider particular policy frameworks (e.g. upper limits on the emissions, minimum amount of renewable generation, etc.) and simulate the availability of technologies and resources. The basic logical structure, depicted in Fig. 1, is generically based on technologies that, in a given region, can use and produce energy carriers, satisfy energy services and generate emissions as byproduct. The installation of the technologies and their operation and maintenance imply a cost for the system as well as the penalties that can be related to emissions. Different inputs and outputs and different input/output ratios can be attributed to the same technology throughout different *modes of operations*. The framework includes a particular type of *technologies*, characterized by investment costs and efficiency, that can be installed and linked to the standard technologies to simulate a storage service. This basic logical structure based on technologies can be replicated as many times as needed by the modeler to virtually recreate all the different technologies and transformations of a real energy system, from a region to another, from the mining of primary resources to the generation of energy services.

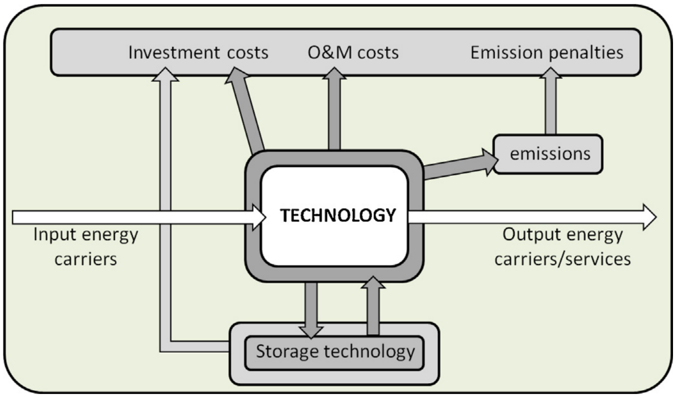

Fig. 1. Basic logical structure of the OSeMOSYS modeling framework. It can be used, throughout series and parallel combinations, to describe all the processes occurring within an energy system.

Throughout the OSeMOSYS bottom-up approach, the modeler is required to quantify the demand of energy services and descri be the technologies (in terms of efficiencies, capital and operating costs, emission factors, residual availability of technologies at the beginning of the analyzed time horizon, etc.). The optimal mix of technologies results as an output (in terms of installed capacity and use of each technology in a given period) as well as the costs, the consumptions and the emissions.

The time-horizon is made up of *time-slices* and the temporal resolution can therefore define the detail of the results but can have a strong influence on the computational burden and the resolution time. The subdivision of the time-horizon must hence be determined by the modeler according to the scope of the study.

2.2. Structure of MELiSsa

The MELiSsa model is based on the basic logical structure of OSeMOSYS depicted in Fig. 1. Throughout the use of seven different configurations of that structure, as summarized by Fig. 2, we replicated a virtual model of the processes that might occur within the next decades in the energy system of the Lombardy region.

Melissa is a multi-regional model made up of 11 areas corresponding to the administrative provinces.[2] As showed in Fig. 3, the overall time-horizon of the model spans over 45 years and is made up of 9 homogeneous five-year periods, from 2009–2013 to 2049–2053. Although OSeMOSYS is a yearly model, the code has not been modified to comply with the use of five-year periods. Input data for those parameters usually based on annual values refer, in MELiSsa, to five-year units (for instance, the CapacityToActivityUnit is multiplied by 5 whereas the OperationalLife is divided by 5).

---

[1] The considered version is *OSeMOSYS_2013_05_10_short*.

[2] The province of Monza and Brianza (only recently founded) is coupled with the province of Milan due to lack of data.

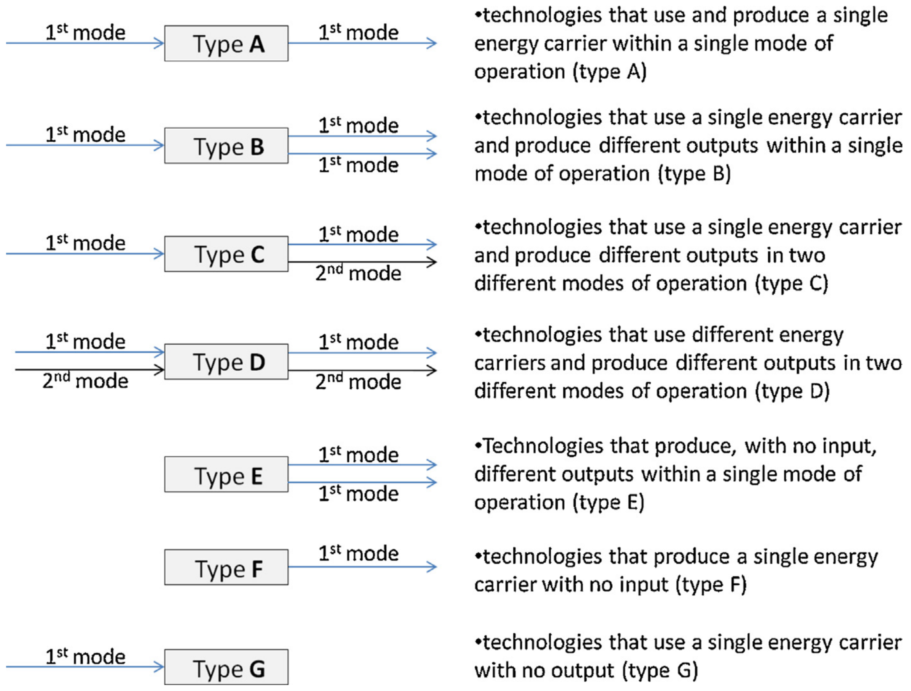

Fig. 2. The different configurations used to model the technologies in MELiSsa.

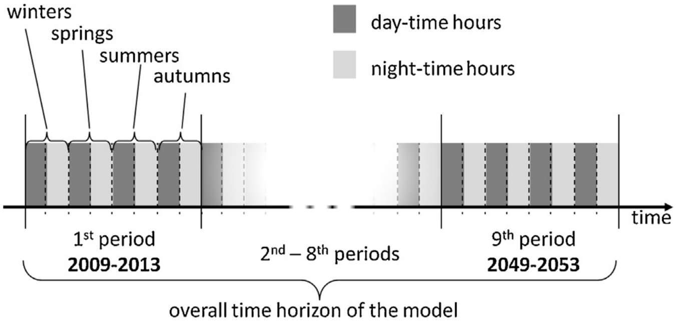

Fig. 3. Subdivision of the time-horizon in the MELiSsa model.

Each period is divided into four seasons and each season into days and nights.

On overall 173 *technologies* and 46 *fuels* are considered in the current version (MELiSsa.2015.06) to meet the demand of 21 different energy services, with a main focus on the residential segment. A complete image of the Reference Energy System (RES) of the model can be found online in the additional annexes and on the MELiSsa web page [18]. Its different parts are showed and analyzed individually in this paper for space reasons.

Each of the next paragraphs of Section 2.2 will focus on a specific part: (i) the thermal services, (ii) the services currently met only by electricity, (iii) the transportation, (iv) the conversion, generation, production and import of energy carriers, and (v) the exchanges, the transmission and the distribution of electricity. All the acronyms that define the name of technologies and fuels are listed in the tables from Tables 1–7 together with their description.

2.2.1. *Thermal services*

This section deals with the energy demand for thermal purposes, in the residential segment, in the tertiary sector and in the industries. Four energy uses are considered for the residential demand: (i) space heating, (ii) hot water production, (iii) air conditioning, and (iv) cooking. For the first three a distinction is made between the demands of detached households and apartment blocks. This is because these two types of dwellings can be served by different options. On the contrary, the tertiary sector and the industries are represented by few comprehensive demands and technologies. Given the big overall number of technologies, this part of the RES of MELiSsa is split into three figures: Figs. 4, 5 and 6.

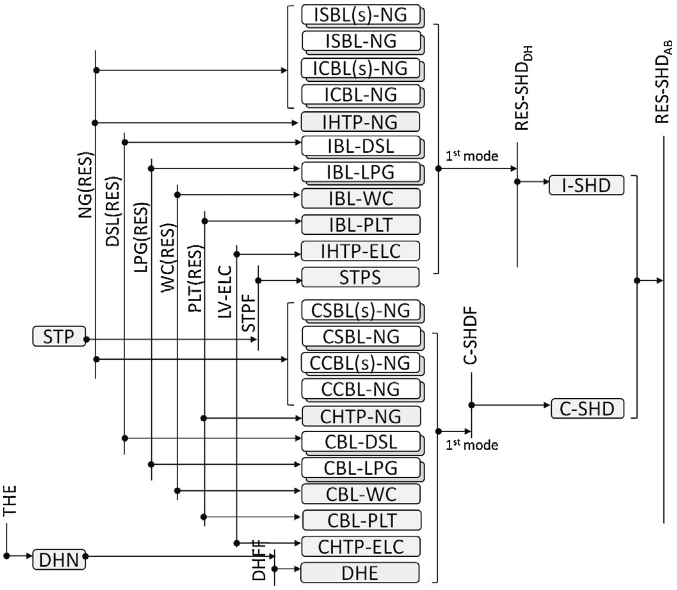

Fig. 4. Reference Energy System of MELiSsa: focus on the residential demand for space heating in detached households and apartment blocks. The dark boxes behind technologies mean that, for those technologies, both the current version and a new more efficient version are available. White boxes mean that the technologies are installed but new investments are not possible. Please, refer to Table 1 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

Fig. 4 focuses on the residential space heating. The model includes: (i) boilers for both shared and independent applications (fed by either natural gas, diesel, liquefied petroleum gas, wood chips or pellet), (ii) heat pumps for both shared and independent applications (fed by either electricity or natural gas), (iii) district

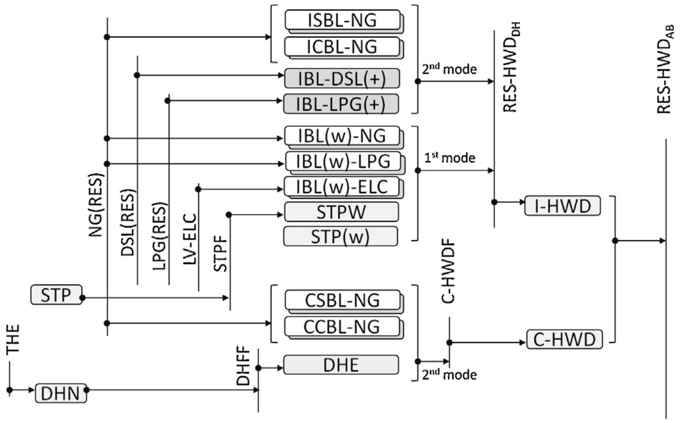

Fig. 5. Reference Energy System of MELiSsa: focus on the demand for residential hot water. Dark boxes (also behind some technologies) indicate new and more efficient versions. White boxes mean that the technologies are installed but new investments are not possible. Please, refer to Table 1 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

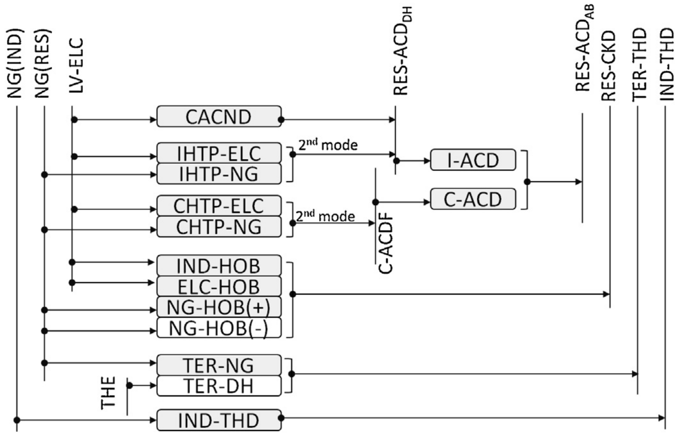

Fig. 6. (Reference Energy System of MELiSsa: focus on the (i) residential demand for cooking and (ii) space conditioning and on the (iii) demand for thermal services of the tertiary sector and industries. White boxes mean that the technologies are installed but new investments are not possible. Please, refer to Table 1 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

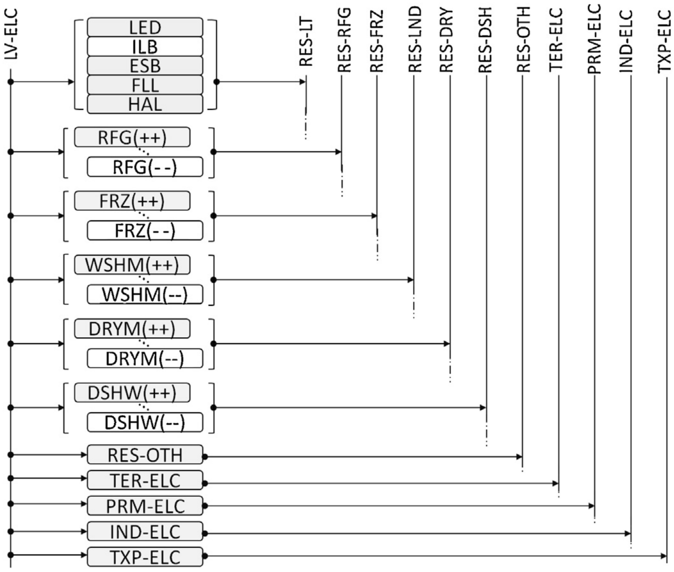

Fig. 7. Reference Energy System of MELiSsa: focus on the demand of services currently met only by electricity. The symbols (++) and (−−) identify respectively the best and the worst technologies (in terms of efficiencies) among the five that meet each relative demand. The three intermediate technologies (in terms of efficiencies) are represented by the three dots for space reasons. White boxes mean that the technologies are installed but new investments are not possible. Please, refer to Table 2 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

heating facilities (from the pipes of the district heating network to the household exchangers), and (iv) distributed thermal solar panels.

Fig. 5 focuses on the residential demand for hot water. The hot water can be provided by most of the space heating systems and by dedicated technologies: smaller boilers (fed by natural gas, liquefied petroleum gas or electricity) and thermal solar panels. No electric showers (or similar instantaneous heaters) have been considered because, for different reasons, the contractual power limit for almost all the Italian households is 3 kW.

Fig. 6 focuses on the residential air conditioning and cooking demands, the tertiary sector and the industries. The air conditioning can be provided by conventional air-conditioners and by the heat pumps used in the conditioning mode of operation. The cooking demand (excluding the use of ovens, implicitly considered within the services met only by electricity – Section 2.2.2) can be satisfied through induction hobs, conventional electric hobs and natural gas hobs. The thermal needs of the industry and the tertiary sector are met by fictitious technologies that comprehensively take into account different technical options. In particular, the industrial demand is met by one single technology that uses natural gas; the demand of the tertiary sector is met by a technology that uses natural gas and a technology that uses the thermal energy coming from centralized plants that produce heat and power or simply heat.

A more in depth description is needed for some particular technologies and for their configuration in the RES. They are fictitious technologies that we called *partitioners*. It is the case of (i) I-SHD, C-SHD, I-HWD, C-HWD, I-ACD and C-ACD, and the case of (ii) STPS and STPW. In the first case these fictitious technologies are needed to properly consider the practicability of centralized solutions for apartment blocks and independent solutions for both apartment blocks and detached households. Those technologies marked by the letter *I* can convert the output of independent solutions into a *fuel* that enables them to satisfy also the demand of apartment blocks. They represent those dwellings that, despite being part of apartment blocks, use independent solutions. Those technologies marked by the letter *C* can convert the output of collective solutions into a *fuel* that can satisfy only the demand of apartment blocks. By properly limiting the installed capacity of these six technologies, the modeler can define to which extent this possibility is practicable. In the second case, the two fictitious technologies are used to split the output of solar thermal panels into the hot water and heating services.

2.2.2. *Services currently met only by electricity*

The part of the RES of MELiSsa that focuses on the services currently met only by electricity is showed in Fig. 7. The MELiSsa model includes all those main residential services that are met only by electric appliances: lighting, refrigeration and freezing, laundry, dish washing and drying. Each of these demands can be met by five solutions. In the case of lighting, the five options represent different types of technologies (LED lamps, incandescent light bulbs, energy saving bulbs, fluorescent lamps, halogen lamps). In all the other cases, the five options represent different efficiency classes for a same type of technology. In the current version a lower detail is considered for all the other household electricity uses and for the electricity demands related to the primary, secondary and tertiary sectors and to the electric public transportation (trains, tram,

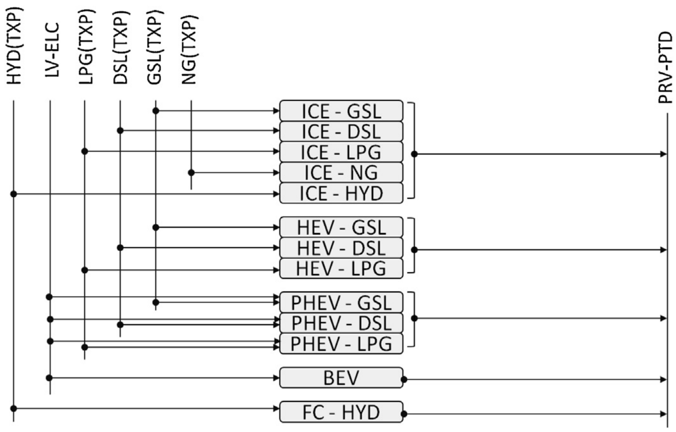

Fig. 8. Reference Energy System of MELiSsa: focus on the demand of private passengers transportation. Please, refer to Table 2 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

trolleybus, etc.). These are considered throughout a comprehensive demands of electricity met by single comprehensive technologies.

2.2.3. *Transportation*

Besides the electric public transportation, MELiSsa currently considers the transportation demand of private cars. This sector of the RES, showed in Fig. 8, includes different types of drivetrains and fuels: (i) simple internal combustion engines fed by gasoline, diesel, liquefied petroleum gas, natural gas and hydrogen, (ii) hybrid electric vehicles that cannot be charged directly through plugs, fed by gasoline, diesel and liquefied petroleum gas, (iii) plug-in hybrid electric vehicles that can be charged through a connection with the power grid, fed by gasoline, diesel and liquefied petroleum gas, (iv) pure-battery electric vehicles that are charged through a connection with the power grid, (v) fuel cell vehicles fed by hydrogen. The storage of electricity within the electric vehicles is not endogenously modeled. The electricity demanded by the electric vehicles has been set to simulate a given charging profile. Intelligent control strategies related to electric vehicles, like smart charging and vehicle-to-grid, are not yet modeled in this version. These simplifications are mainly due to the need to keep the size of the optimization problem circumscribed: (i) at this stage, the use of the so called *storage technologies* would sensibly increase the time and the memory required by the solver; (ii) the low temporal resolution (required to limit the domain of the problem) would not detect important short-term dynamics.

2.2.4. *Conversion, generation, production and import*

In this section we describe all the technologies that represent the processes that make the energy carriers available to be used by the demand technologies. This part of the RES, showed in Fig. 9, is made up of several technologies:

- Three types of centralized power plants that inject electricity upstream of the transmission grid: two fed by natural gas (an old and a new version) and one fed by fuel oil.
- Four types of combined heat and power (CHP) plants that inject (i) electricity downstream of the transmission grid and (ii) thermal energy into the district heating systems. They respectively represent: conventional gas turbines, combined cycle gas turbines, steam turbines and reciprocating gas engines.
- three types of hydro-power plants: impoundments, diversions and pumped storage plants. The storage service that the latter can provide is exogenously considered and cannot be decided endogenously. This is due to the same reasons that have been mentioned for the storage within electric vehicles (Section 2.2.3).
- Two groups of five technologies that represent respectively (i) the production of electricity and (ii) the combined production of heat and power, by using biomass and wastes. In each group, each technology refers to a different input: waste, biogas from wastewater treatments and landfills, other biogas, lignocellulosic

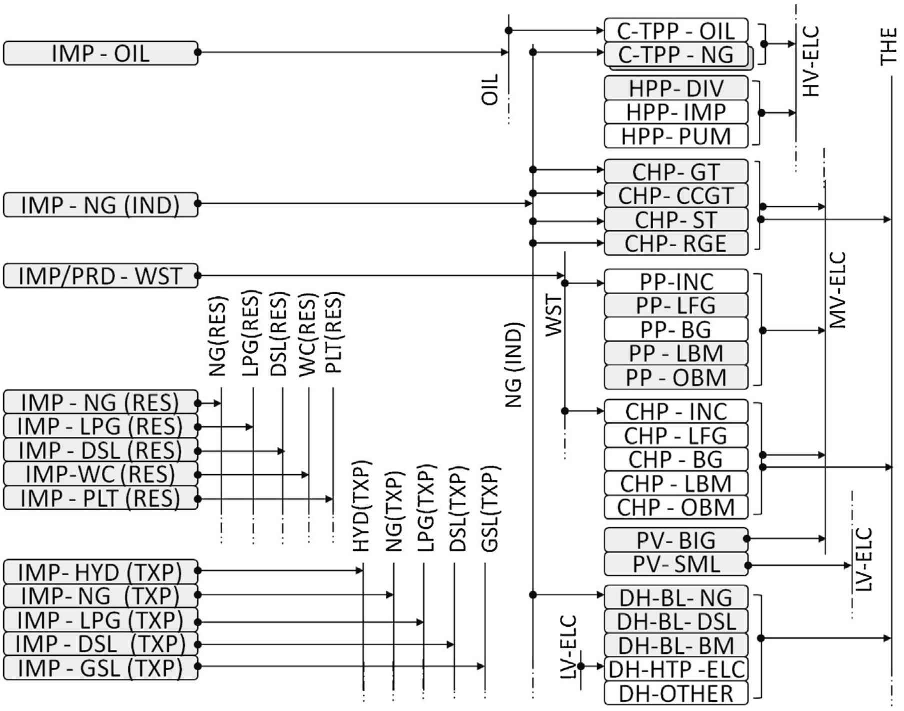

Fig. 9. Reference Energy System of MELiSsa: focus on the conversion, generation, production and import (excluding the import of electricity). The dark box behind the C-TTP-NG technology means that, for that technology, both the current version and a new more efficient version are available. White boxes mean that the technologies are installed but new investments are not possible. Please, refer to Table 3 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

biomass and other biomass types. In the second group, a copy of each technology of the first group is implemented with an additional output (heat). Whereas the consumption of wastes of the incinerator is modeled, the other technologies are meant to comprehensively represent the entire process from the production of biomass/biogas to their combustion and conversion. Although these eight technologies have no input fuel, the fuel cost is taken into account within their variable cost.

- two technologies that represent photovoltaic power plants: one for big centralized plants and one for small distributed systems.
- Five further technologies that generate only heat for the district heating systems: centralized boilers fed by natural gas, diesel and biomass, heat pumps and other systems (the latter is represented through a comprehensive technology).
- thirteen technologies that represent the introduction of the energy carriers into the system (excluding electricity, discussed in the next section). Different technologies are considered for same energy carriers depending on their final use so that a differentiation can be made on the base of their different prices (e.g. the natural gas has different costs for households, vehicles refueling stations or industries).

2.2.5. Exchanges, transmission and distribution of electricity

This part of the RES is showed in Fig. 10. For each province:

- Two technologies are used to model the import of electricity from outside the Lombardy region (thus excluding the electricity coming from other provinces), respectively for the day-time and for the night-time import. These two technologies, in a second mode of operation, can virtually convert the electricity into a fictitious form that can be exported.
- A further technology is used to represent the export of electricity over the borders of the Lombardy Region. This technology can use the fictitious form of electricity discussed in the previous point and a negative cost can be attributed to its activity.
- The flows of electricity within the Lombardy Region are implemented throughout: (i) one technology that represents the distribution grid, (ii) one technology that represents the part of the transmission grid delivering electricity within the province and (iii) a variable number of technologies that are used to model the part of the transmission grid that links other provinces (in each province the number depends on the number of links with the other provinces).

2.3. Code changes

Some changes and additions to the OSeMOSYS code were necessary in order to adapt its structure to the case study of the Lombardy Region. These changes are listed and described in the following paragraphs together with their mathematical formulation. The indexes and the full-length names of variables and parameters are consistent with the original description of OSeMOSYS by [15] and with later versions available on the website [17]. In the equations we use however acronyms for compactness.

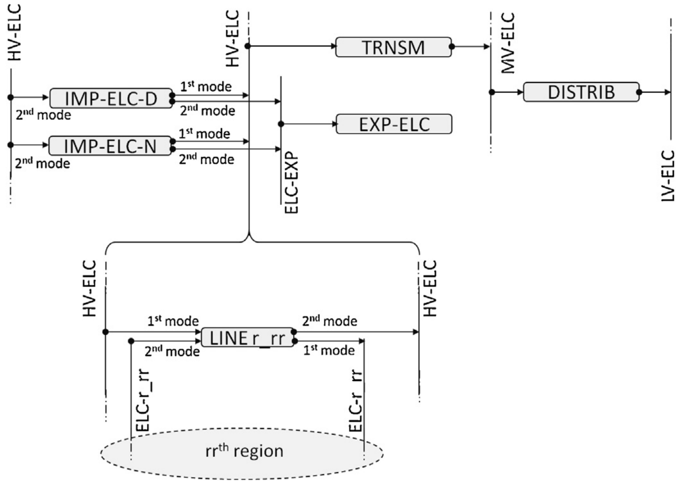

Fig. 10. Reference Energy System of MELiSsa: focus on the exchanges and the transmission and distribution of electricity. Please, refer to Table 4 for the nomenclature of technologies and refer to Tables 5–7 for the nomenclature of fuels.

2.3.1. Different operating profiles for different modes of operation

The *CapacityFactor* parameter (that indicates the fraction of the rated capacity of a technology that is available in each time-slice) was modified to depend also on the *mode of operation* of some technologies. This was needed to model the production of different fuels by means of a same technology with different utilization profiles (e.g. boilers that produce both hot water and space heating). The change required two equations of the core code of OSeMOSYS to be modified (in particular the *CAa4_Constraint Capacity* and *CAb1_Planned Maintenance* as defined in [15]) as follows:

$$\sum_{m} ROA_{r,l,t,m,y} \le \begin{cases} TAC_{r,t,y} \cdot CF_{r,t,l,y} \cdot CTAU_{r,t} & \forall t: CFtag_t = 0 \\ \sum_{m} TAC_{r,t,y} \cdot MDCF_{r,t,m,l,y} \cdot CTAU_{r,t} & \forall t: CFtag_t = 1 \end{cases} \tag{1}$$

$$\sum_{m}\sum_{l} ROA_{r,l,t,m,y} \cdot YS_{l,y} \le \begin{cases} \sum_{l} TAC_{r,t,y} \cdot CF_{r,t,l,y} \cdot YS_{l,y} \cdot AF_{r,t,y} \cdot CTAU_{r,t} & \forall t: CFtag_t = 0 \\ \sum_{m}\sum_{l} TAC_{r,t,y} \cdot MDCF_{r,t,m,l,y} \cdot YS_{l,y} \cdot AF_{r,t,y} \cdot CTAU_{r,t} & \forall t: CFtag_t = 1 \end{cases} \tag{2}$$

where $CFtag_t$ is a newly introduced parameter that the modeler uses to tag ($CFtag_t = 1$) the technologies characterized by a different capacity factor for each mode of operation; $ROA_{r,l,t,m,y}$ (*RateOfActivity*) indicates the use of each technology, in each region, time-slice, mode of operation and year; $TAC_{r,t,y}$ (*TotalAnnualCapacity*) is the annual installed capacity of the *t*th technology in the *r*th region and *y*th year; $CF_{r,t,l,y}$ (*CapacityFactor*) is the capacity factor of those technologies characterized by a unique capacity factor for all their modes of operation; $MDCF_{r,t,m,l,y}$ (*ModeDependentCapacityFactor*) is the newly introduced capacity factor that refers to the *m*th mode of operation of those technologies characterized by different capacity factors; $CTAU_{r,t}$ (*CapacityToActivityUnit*) relates the units of capacity to the units of activity; $YS_{l,y}$ (*YearSplit*) is the fraction of the *y*th year covered by the *l*th time-slice; and $AF_{r,t,y}$ (*AvailabilityFactor*) is the fraction of the *y*th year in which the *t*th technology is available in the *r*th region.

2.3.2. Capacity limits on group of technologies

Another addition was implemented to consider limits on the installed capacity of group of technologies. The option of limiting the installed capacity of single technologies – by default included in the original version of OSeMOSYS – is still available and instrumental for MELiSsa. This addition is useful for representing dynamics that apply to cluster of technologies rather than specific technologies (e.g. the analyst may want to focus generally on *boilers*, instead of a specific type of boilers) The different clusters and the different technologies belonging to each cluster are set through the $CT_{c,t}$ (ClusterTag) newly introduced parameter (it can be either 1 if the tth technology is included in the cth cluster or 0 otherwise). The total installed capacity, in each region and year, is then calculated through the newly introduced added variable $TCC_{r,c,y}$ (*TotalClusterCapacity*), as:

$$TCC_{r,c,y} = \sum_{t} TAC_{r,t,y} \cdot CT_{c,t} \tag{3}$$

Finally, the variation of the installed capacity from one year to another is bound in:

$$TAmCC_{r,c} \leq (TCC_{r,c,y} - TCC_{r,c,y-1}) \leq_t TAMCC_{r,c} \tag{4}$$

where $TAmCC_{r,c}$ (*TotalAnnualMinClusterCapacity*) and $TAMCC_{r,c}$ (*TotalAnnualMaxClusterCapacity*), both newly added, are respectively the lower and upper limits, fixed by the modeler, on the cluster capacity variation from one year to another.

2.3.3. Capacity limits for multiple technologies that represent a same single item

In MELiSsa some items and processes are split on multiple technologies for different reasons. It is the case of: (i) that part of the transmission grid that allows the import of electricity from outside the Lombardy boundaries and (ii) that part of the transmission grid that allows the electricity flowing from a province to another within the region boundaries. In the first case two different costs for day and night are associated to two different technologies for each transmission line. In the second case two different technologies are installed for each transmission line on two different provinces. For these cases, for each represented item or process, it was necessary to make the capacities of the different technologies equal each other. This was done throughout the following specific equations:

$$NC_{r,t=\text{“IMPELC\_D”},y} = NC_{r,t=\text{“IMPELC\_N”},y} \tag{5}$$

and

$$NC_{r,t=\text{“Line\_r\_rr”},y} = NC_{rr,t=\text{“Line\_r\_rr”},y} \tag{6}$$

where $NC_{r,t,y}$ (*New Capacity*) is the capacity of the tth technology newly installed in the rth region in the yth year; *IMPELC-D* is the technology that represents the transmission line when it imports electricity in day-time hours, *IMPELC-N* is the technology that represents the transmission line when it imports electricity in night-time hours, and *Line_r_rr* is the technology that represents the line linking the rth region to the rrth region.

2.3.4. Aggregated emission limits

A final addition was required to consider an aggregated emission limit for the whole Lombardy region. The possibility of setting different limits for each province – as in the original version of OSeMOSYS – is still available and can be used in MELiSsa. The addition is summarized by the following equation:

$$\sum_{r} AE_{r,e,y} \leq MAEL_{e,y} \tag{7}$$

where $AE_{r,e,y}$ (*AnnualEmissions*) is the calculated overall production of the eth emission within the rth region in the yth year; and $MAEL_{e,y}$ (*ModelAnnualEmissionLimit*) is the newly added parameter that can be used to set a collective limit on the eth emissions in the yth year.

2.4. Input data

In this section the main input data of the current version of the model are presented together with the assumptions and the sources. Sections 2.4.1–2.4.4 focus on the data that define the demands of energy services while Sections 2.4.5 and 2.4.6 present and provide the data that describe the technologies.

2.4.1. Residential space heating demand

Two procedures were used for the estimation of the residential space heating service, respectively considering (i) the energy performance certificate and (ii) the year of construction of the buildings. For each province, the final value was chosen within the range resulting from the two procedures, in order to reach the best match with the historical data of consumption for space heating. The energy performance certificate procedure is based on the certificates of those buildings that have been already classified and included in the official register [19]. With this procedure, the overall residential space heating demand $RES\text{-}SHD_{t,p}$ [GWh] is calculated for each tth type of dwelling (detached household or apartment in building block), in each pth province, according to the following equation:

$$RES\text{-}SHD_{t,p} = \sum_{i} \left(\sum_{j} (ETH_{i,j,p} \cdot F_{i,j,p}) \cdot \lambda_{i,p} \right) \cdot \frac{n_{t,p}}{\sum_{t} n_{t,p}} \tag{8}$$

where $ETH_{i,j,p}$[3] (elaborated starting from [19]) is the specific net final energy demand for heating the jth household, rated to the ith class, in the pth province $[GWh/(m^2 \cdot y)]$; $F_{i,j,p}$ (from [19]) is the floor area of the jth household, rated to the ith class, in the pth province $[m^2]$; $n_{t,p}$ is the number of households in the pth province (based on the census data of 2001 [20]); and $\lambda_{i,p}$ is a coefficient that is used to take into account that not all the houses of the region have been evaluated and included in the register. It is assumed that all the houses whose consumption is in the range of high classes (from A^+ to D) are newly built or renovated and thus have been all surveyed, as defined by the local law. For these classes the coefficient $\lambda_{i,p}$ is equal to 1. For all the other classes, the share of rated households is projected to the rest of the houses in the provinces, and thus $\lambda_{i,p}$ is defined as:

$$\lambda_{i,p} = \frac{\sum_{t} n_{t,p} \cdot AF_p - \sum_{i_{(+)},j} F_{i_{(+)},j,p}}{\sum_{i,j} F_{i,j,p}} \tag{9}$$

where AF_p is the average floor area of the households in the pth province [m^2] (based on the census data of 2011 [21]) and the index i_+ is meant to indicate the high performance classes (from A^+ to D).

The second procedure lies on the hypothesis that buildings of the same age are likely built with similar technologies and materials and thus have similar performances. This procedure however does not take into account modernizations and renovations that can improve the performances of the buildings. The overall residential heating demand of each province in this second case comes from the combination of the number of buildings built in a given period with the average performances of those households, within the register, that refer to the same period, according to:

$$RES\text{-}SHD_{t,p} = \sum_{y} \left(\left(\frac{\sum_{j} \left(ETH_{y,j,p} \cdot F_{y,j,p} \right)}{\sum_{j} F_{y,j,p}} \right) \cdot n_{y,p} \cdot AF_p \right) \cdot \frac{n_{t,p}}{\sum_{t} n_{t,p}} \tag{10}$$

---

[3] ETH here refers to the energy that is needed to keep adequate comfort conditions in the heated environment, despite the variation of the outdoor air temperature. It does not take into account the type of heating system, the efficiencies of generation, accumulation and distribution.

where $ETH_{y,j,p}$ is the specific net thermal energy demand for heating the jth household built in the yth range of years in the pth province [GWh/(m^2 y)]; $F_{y,j,p}$ is the floor area of the jth household built in the yth range of years in the pth province [m^2] (coming from [20]) and $n_{y,p}$ is the number of households built in the yth range of years in the pth province (elaboration on data coming from [20,21]).

2.4.2. Demand of other thermal services

Residential hot water demand. The estimation of the energy demand for hot water production, $RES\text{-}HWD_{t,p}$ [GWh], is obtained by assuming (i) a daily per capita consumption of 60 liters and (ii) an average temperature difference of 25 °C to cover (from 15 °C to 40 °C). These assumptions are combined, for each province and for both types of dwellings, as in:

$$RES\text{-}HWD_{t,p} = q \cdot i_p \cdot H \cdot \Delta T \cdot \frac{n_{t,p}}{\sum_t n_{t,p}} \tag{11}$$

where q is the average per capita annual consumption of hot water [kg]; i_p is the number of inhabitants in the pth province; H is the specific heat capacity of the water and ΔT is the temperature difference.

Residential conditioning service. The evaluation of the air conditioning demand $RES\text{-}ACD_{t,p}$ is based on the method used by Lanati et al. [7] for the MATISSE model, represented by the following equation:

$$RES\text{-}ACD_{t,p} = nc_p \cdot SD \cdot \frac{1}{2} AF_p \cdot \frac{n_{t,p}}{\sum_t n_{t,p}} \tag{12}$$

where nc_p is the number of households in the pth province with an air conditioner (coming from [21]); SD is the specific conditioning demand of a household, set by [21] as 25 Wh$_{ref}$ m^{-2} year^{-1} and AF_p is the average floor area of the households that demand this service (it is assumed that a lower temperature is required only for half of the floor area of the households).

Residential cooking demand. The thermal energy demand for cooking of each pth province, $RES\text{-}CKD_p$, is estimated by assuming that the annual consumption of a kitchen fueled by natural gas, NGC, is 140 Sm^3/year and that the average efficiency of currently installed gas cookers, η_c, is 45%:

$$RES\text{-}CKD_p = NGC \cdot LHV \cdot n_p \cdot \eta_c^{-1}\ [\text{GWh}] \tag{13}$$

where LHV is the lower heating value of the natural gas; n_p is the number of households in the pth province.

Thermal needs of the other sectors. The thermal needs of the tertiary sector are estimated by considering the two contributes that currently satisfy the demand: (i) the direct use of natural gas and (ii) the use of district heating systems. The heating demand of the tertiary sector of the pth province, $TER\text{-}THD_p$ is thus calculated as:

$$TER\text{-}THD_p = (CNG_p \cdot TNG_p/\eta_{tt}) + TDH_p \tag{14}$$

where CNG_p is the average civil consumption of natural gas for the years 2010–2012 [22] in the pth province; TNG_p is the share of natural gas consumption for the tertiary sector, based on [23]; η_{tt} is the average efficiency of the technologies that use natural gas to satisfy the tertiary heating demand, assumed to be 76%; and TDH_p is the net thermal energy currently provided by existing district heating systems, elaboration based on estimations of the Italian association promoting the diffusion of district heating facilities [24].

The thermal needs of the industry are simply estimated as the average industry consumption of natural gas for the years 2010–2012 [22].

2.4.3. Demand of services currently met only by electricity

The evaluation of the residential demand of services met only by electricity is based on the method used by Lanati et al. [7] for the MATISSE model. To estimate the lighting demand, in terms of luminous flux needed in each pth province throughout the year, the households are supposed to be divided, on average, into six different rooms characterized by specific illuminance requirements. Finally, the average floor area of each room is considered and the contributions of all the rooms are summed up and multiplied by the number of household of each single province. The refrigeration and freezing demands refer to the volume of refrigerators and freezers that need to be powered throughout the year. For the starting five-year period they are calculated as a specific volume per appliance multiplied by the number of household where these appliances are installed (assumed to be 97% and 32.5% of the households in each province, respectively). The needs related to washing machines, dryers and dishwashers are estimated by assuming an average annual use per appliance (cycles per year) and a specific distribution in each province (assumed to be 97.5%, 7% and 42.5% of the households in each province, for washing machines, dryers and dishwashers, respectively). The *RES-OTH* demand refers to the overall electricity demand due to (i) entertainment appliances (TV, computers, etc.), (ii) other small devices (e.g. hair dryers, vacuum cleaners, etc.) and (iii) general services for the building (e.g. water pumping). The first two come from the combination of the number of cycles and their diffusion. The third component comes from elaboration of the data provided by the Italian Transmission System Operator [25].

The Italian Transmission System Operator [25] provides as well the annual demand of electricity related to the tertiary and secondary sector and the demand of electricity for powering electric public transportation.

2.4.4. Private passenger transportation demand

The demand of private passengers transportation in each province, $PRV\text{-}PTD_p$, is obtained in terms of passenger-km from the equation:

$$PRV\text{-}PTD_p = PRV\text{-}PTD_{Italy} \cdot \frac{P_p}{P_{Italy}} \tag{15}$$

where $PRV\text{-}PTD_{Italy}$ is the annual demand of private passengers transportation in Italy, averaged on the period 2011–2013 [26]; P_{Italy} is the Italian population [27] in the same period; and P_p is the population of each province [27] in the same period.

2.4.5. Technologies

Tables 8–13, in the annexes, provide a practical overview of the most important information on the input data describing the technologies, sector by sector. The complete database (including data sources) can be found online in the additional annexes and on the web page of MELiSsa [18]. In this section we discuss some details for those technologies that require an in-depth description and some observations:

- The annual generation of electricity by means of photovoltaic plants is differentiated among the provinces within the region because of the different climatic conditions and latitudes. This differentiation is done based on the results provided by the PVGIS tool [28].
- The investment cost for the district heating network, in terms of specific cost per unit of energy provided in one year, is calculated by multiplying the assumed specific cost of 500 €/m by the extension of existing infrastructures [24] and dividing the resulting value by their annual thermal energy production in 2012 [24].
- The cost of building new transmission lines or enhancing existing ones, in terms of cost per transit capacity, is:

$$C_l = \frac{CmD_l}{Pm} \tag{16}$$

where C_l is the cost of the lth line; Cm is the average specific cost per distance unit, assumed to be 500 k€/km; D_l is the average distance between the administrative centers of the provinces connected by the lth line; and Pm is the average transit capacity considered. The resulting cost is then equally distributed over the two technologies representing the lines (see Section 2.2.5). For transmission lines going outside the region boundaries, the cost is an average of the costs calculated above.

2.4.6. Limits on the penetration and operation of technologies

The limits on the penetration and operation of the technologies, and their evolution within the time horizon, are used by the modeler to represent dynamics that are not implicitly modeled. The assumptions that lead to quantify these limits introduce uncertainties in the results and we thus present here the most important ones:

- The investment on the cogeneration technologies, except for the reciprocating engines, is inhibited. This assumption is necessary to take into account some short-term dynamics that make the different technologies actually unsuitable for certain purposes (for instance, the reciprocating engines can be start-up or shut-down to follow the heat demand profile without relevant extra-costs, whereas it is not feasible for the others). The need for this *manual* correction could be eliminated in future developments by detailing these dynamics.
- The capacity of small and large photovoltaic plants is limited both in terms of maximum annual investments and maximum exploitation of the surfaces (the latter is applied only to small (roof-top) plants). The maximum annual investment is assumed to equal the largest historical investment in a year in the provinces (registered in 2011 [29] in presence of high national subsidies). The available roof-top surfaces (RS_p) are calculated by multiplying the estimations of the photovoltaic potential of Southern Europe, given by [30] in terms of average surface per person (ASP_{SE}), by the population of the Lombardy region and then distributing the resulting value on the provinces. The distribution is weighted to the number of buildings in each province (nb_p) compared to the number of buildings in the region ($nb_{Lombardy}$), both provided by [21].

$$RS_p = ASP_{SE} \cdot P_{Lombardy} \cdot \frac{nb_p}{nb_{Lombardy}} \tag{17}$$

- The investment on hydro-power plants is allowed only for the small run-of-the-river types. This assumption is based on the hypothesis that the potential for impoundments and pumped storage types is completely exploited. The small potential of the run-of-the-river types in the region (about 15 MW) results from [31] and is distributed on each single province based on a thematic map provided in the same document.

3. Results

Combining the data presented in Section 2.4 into the structure described in Section 2.2 results in a platform that enables monitoring the optimal evolution of the Lombardy energy system under different scenarios. The main purpose of this article is presenting the MELiSsa model as a reference for future applications by stressing the focus on newly added parameters and equations and by presenting how the model has been conceived along with the sources. Nevertheless, in order to show its potential, in this section we give an overview on the results it can provide through a simple trend-line scenario. The scenario is based on the following drivers: (i) all the demands in the provinces are set to increase with the same rate of increase of the relative populations as forecasted by [32]; (ii) the penetration of new technologies is limited according to the assumptions described in Section 2.4; (iii) no limits are set on the emissions; (iv) all the costs are kept constant throughout the time horizon. It is assumed that power quality problems driven by photovoltaic penetration are overcome in the future through short-term storage systems coupled with plants. A null discount rate has been chosen for this first application – meaning that the same importance is attributed to costs and to benefits throughout the modeled time-horizon. Different discount rates will likely affect the optimal mix of technologies (the higher the rate, the higher the importance of upfront costs versus operating costs). The most appropriate values must be chosen in accordance with a good knowledge of the economic profile of the area, with the considered time horizon and with the purposes. In [33] a clear discussion on discount rates in energy system analysis is presented and some criteria for a thoughtful choice explained.

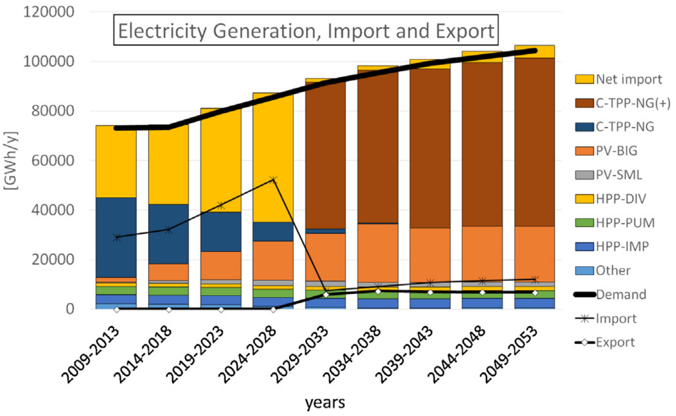

Fig. 11. Import and generation of power [GWh/y] throughout the analyzed period in a trend-line scenario: share per type of technologies.

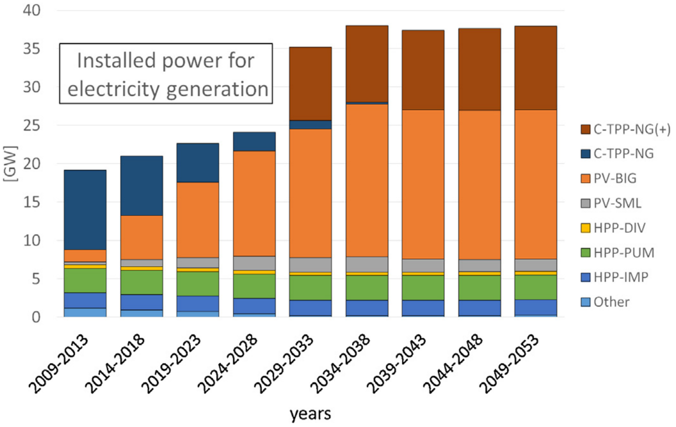

Fig. 12. Average installed generation capacity in each five-year period, throughout the analyzed period in a trend-line scenario.

The following sections focus on the most interesting results of some selected sectors and technologies. In particular, Section 3.1 deals with the generation, uses and exchanges of electricity; Section 3.2 with the space heating demand and with the uses of natural gas; and Section 3.3 with the emissions of CO_2.

3.1. Generation, use and exchanges of electricity

Fig. 11 shows how the electricity is generated throughout the analyzed period and how much of that electricity is imported or exported over the boundaries of the region. The contribution of existing conventional plants visibly decreases while approaching

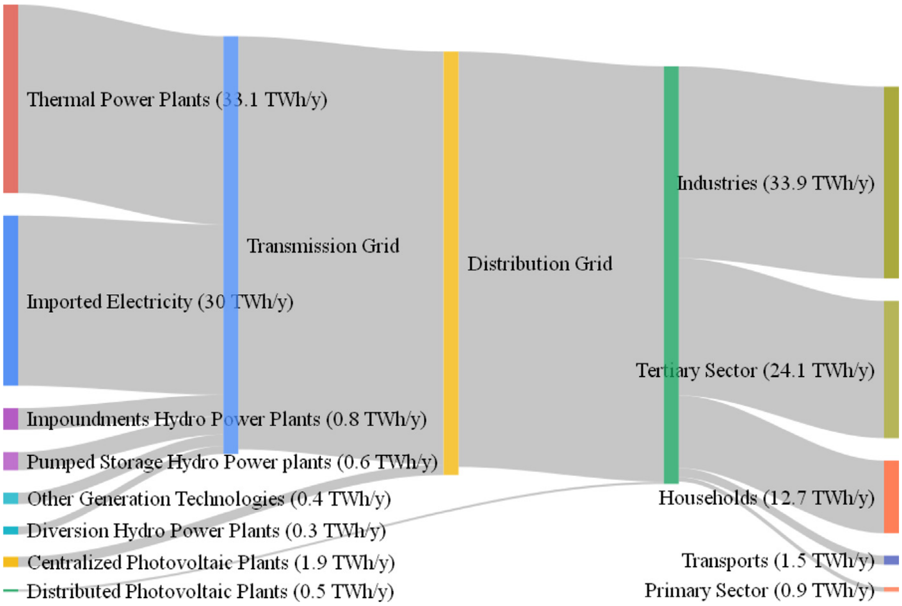

Fig. 13. Average annual flow of the electricity [TWh/y], from the generation and import, throughout the transmission and distribution grids, to the final uses and export in the first five-year period (2009–2013).

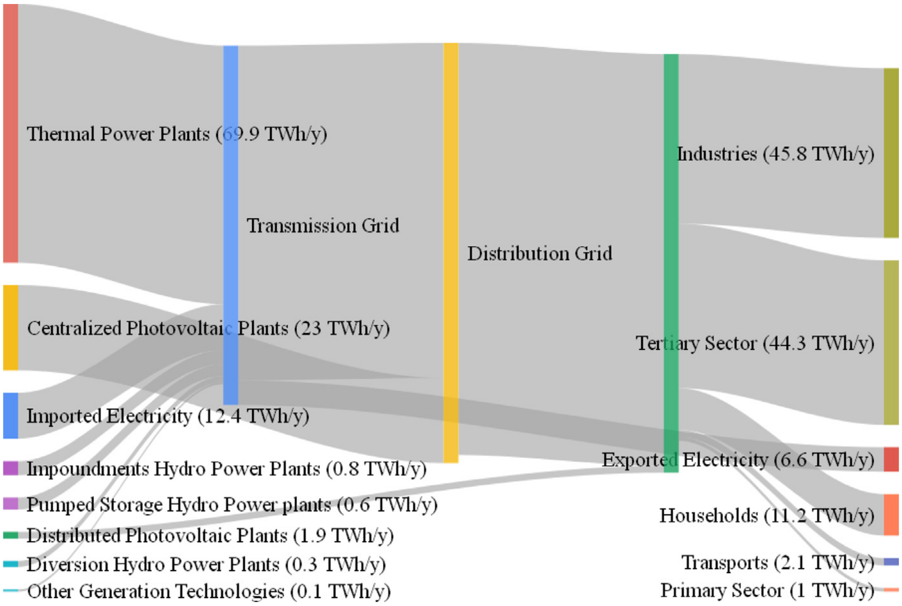

Fig. 14. Average annual flow of the electricity [TWh/y], from the generation and import, throughout the transmission and distribution grids, to the final uses and export in the last five-year period (2049–2053).

the end of their operational life and the region imports more electricity to compensate it. In 2028–2033 a more efficient centralized generation technology come into operation, despite the high investment cost, and the region starts exporting electricity (though, on overall, it is still an importer). The production by means of big photovoltaic power plants reach the maximum allowed level. Hydro power plants cover a not-negligible portion of the demand and their contribution is basically constant throughout the horizon. The demand (black solid line) results slightly lower than the sum of generation and net import because it does not take into account grid losses. Fig. 12, that shows the average installed generation capacity in each of the five-year period, leads to the same conclusions but allows an interesting comparison with Fig. 11. The technologies assume different shares in the two graphs, due to the different capacity factors (especially between photovoltaic and thermal plants).

The Sankey diagrams of Figs. 13 and 14 show the flows of the electricity, from the generation and import, throughout the transmission and distribution grids, to the final uses and export. The two figures refer respectively to the first five-year period (2009–2013) and to the last one (2049–2053). By analyzing them, we can detect the same trends of Figs. 12 and 11 (for example, the import of electricity decreases while the export and the photovoltaic generation increase). Furthermore, these two diagrams provide a different point of view on the contribution and responsibility of the different sectors and technologies in the energy system. For example, in quantitative terms, from Fig. 13 we can say that the big generation share of thermal power plants is barely enough to power just the

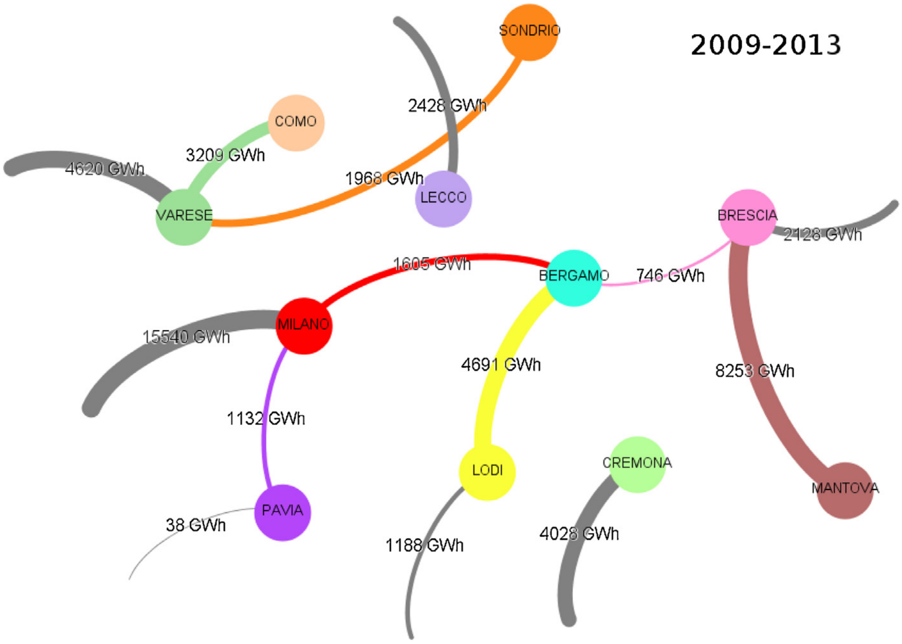

Fig. 15. Annual average energy flows [GWh/y] among provinces in the initial period (2009–2013). Direction of flows is clockwise.

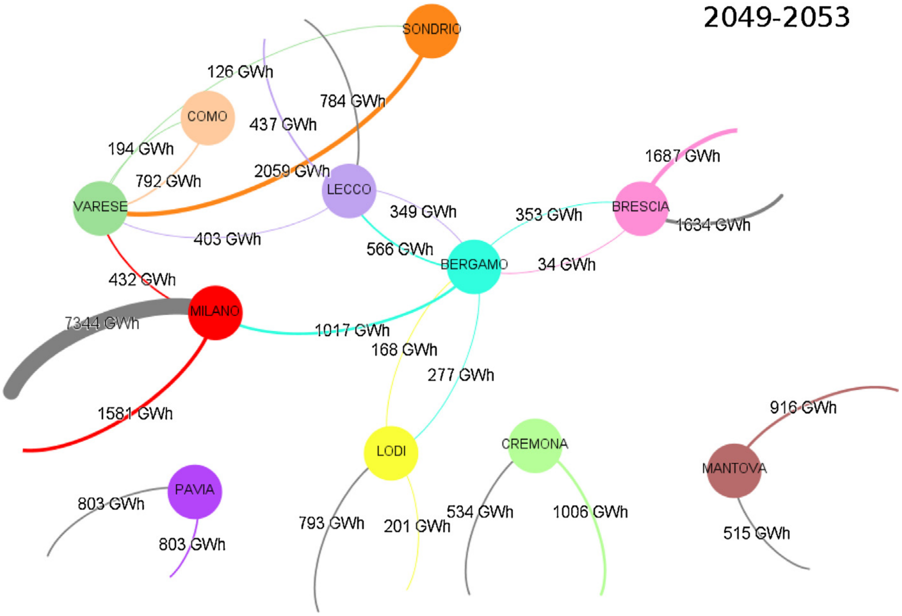

Fig. 16. Annual average energy flows [GWh/y] among provinces in the final period (2049–2053). Direction of flows is clockwise.

industries; and from Fig. 14 we can say that the very high penetration of photovoltaic, together with the other renewable generation technologies, is not enough to cover just the demand of the tertiary sector. Finally, the two diagrams show that the electricity consumed by the households decreases. This is due to the introduction of more efficient technologies, despite the number of dwellings is supposed to increase.

The spatial detail (the subdivision of the energy system in different areas) allows the analysis of the exchanges of electricity among the provinces. These flows can be seen in Figs. 15 and 16 respectively for the first five-year period (2009–2013) and for the last one (2049–2053). This kind of graph (generated with the open and free *Gephi* software) allows a direct overview on the links between provinces. A first interesting result is that the number of interconnections is generally more in the last period and that provinces become generally more independent. These two features could be interpreted as an increased resilience of the energy system. Through the comparison, it is worth noting that Bergamo and Lecco, from electricity importers, become electricity exporters and, on overall, the region starts exporting electricity (as already said about the previous figures). We point out that although the energy exchanges through a single line are lower in the last period, this does not necessarily mean that congestion of lines is lower (because the figure – and neither the temporal detail of this kind of model – specify when these flows occur). Moreover we make it clear that these flows (like the import-export flows of previous figures) do not consider current actual flows and transit throughout the region due to lack of information. This lack is one main evidence of the need for

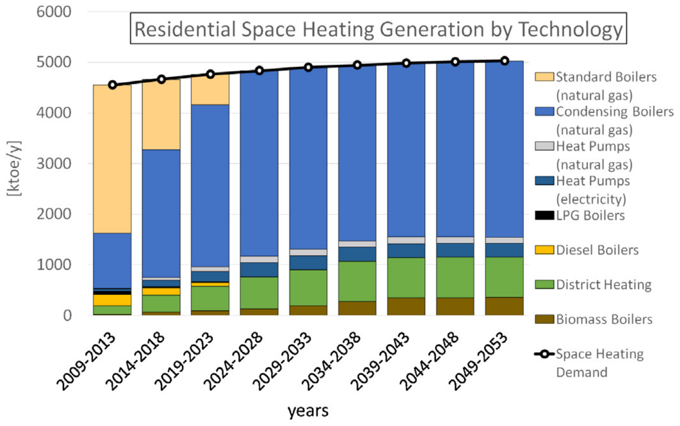

Fig. 17. Annual average generation of thermal energy for residential space heating [ktoe/y] throughout the analyzed periods: share by technology.

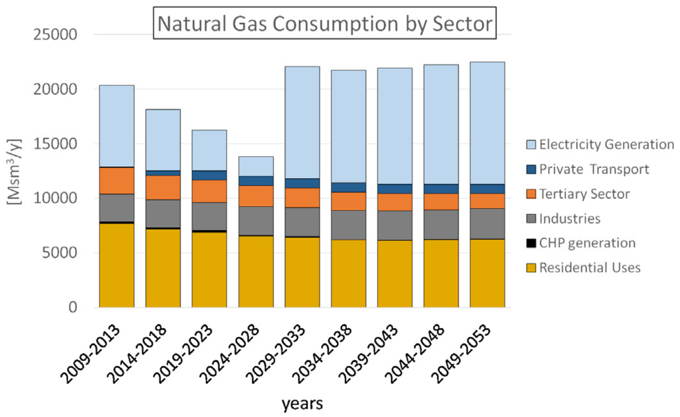

Fig. 18. Annual average consumption of natural gas [MSm^3/y] throughout the analyzed period in a trend-line scenario: share per sector.

an open participation in the development of the model (we discuss this point in Section 4.2).

3.2. Space heating and natural gas uses

Fig. 17 shows how the thermal energy for space heating is generated throughout the analyzed period. The biggest contribution to meet the demand throughout the entire period clearly comes from the natural gas. Technologies that use natural gas change: from the standard boilers used in the first fifteen years, to the condensing boilers and to the heat pumps. On overall, the contribution of natural gas-fed technologies slightly decreases and let the district heating solutions penetrate the energy system up to cover an important portion of the demand (about 16% in the last period). Moreover, the energy system experiences an important penetration of biomass boilers and heat pumps fed by electricity (both types of heat pumps reach the maximum allowed penetration level).

Fig. 18 shows the use of natural gas by sector. The most evident variation throughout the years is due to the electricity generation sector. The particular trend depicted is directly related to the fact that the installed capacity of thermal power plants decreases for the first twenty years and then new thermal plants are operative (as previously showed in Fig. 12). A second interesting result is that a relative big consumption of natural gas is due to the private cars fed by this fuel. Natural gas-fed vehicles penetrate the overall car fleet yet in the second and third five-year-period and then their share is constant. A decreasing trend can be seen with respect to the other sectors, except for industries.

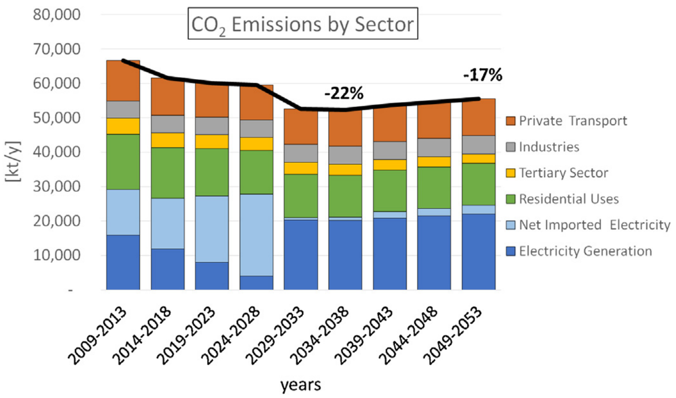

Fig. 19. Average annual CO$_2$ emissions throughout the analyzed period [kt/y]: share per sector. The trend decreases down to −22% in the first half of the period and slightly increases in the second half leading to a final overall value of −17%.

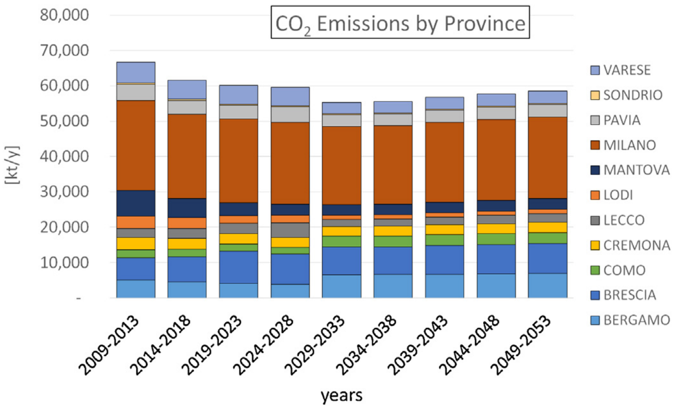

Fig. 20. Average annual CO$_2$ emissions throughout the analyzed period [kt/y]: share per province.

3.3. Emissions

Figs. 19 and 20 show the overall emissions of the region throughout the modeled time horizon, respectively by sectors and by provinces. The first important result we can see in Fig. 19 is that, despite the increase in the demands, the emissions of CO$_2$ decrease down to −22% in the first half of the period and slightly increase in the second half leading to a final overall value of −17%. This decrease, either in the medium or in the long term, is surprisingly driven simply by the economic convenience of some technical solutions (no emission caps are set as scenario drivers). The biggest variations among the sectors are related to the generation of electricity inside and outside the region although the sum of the two contributions is more or less stable. The emissions related to the electricity exported outside the region are subtracted from the emissions related to the imported electricity. In our opinion, this procedure enable the best representation of the responsibility of the Lombardy region in the emission assessment. We point out however that we chose this procedure only for the electricity although, for congruence, this should be done for all the commodities exchanged by the region (e.g. food produced by the primary sector, goods produced by the industries, etc.). We discuss this point in Section 4.2.

Finally, the contribution of each province is assessed in Fig. 20. No big variations are depicted in the graph; little changes occur for (i) Mantova, Varese and Lodi, that experience a decrease in the emissions, and for (ii) Bergamo and Como, whose emissions slightly increase. Milan keeps being the most important contributer, being responsible of about 40% of the emissions in the region. These considerations however should take into account that in Fig. 20 the emissions include the ones related to the exported electricity.

In general we must point out, for both the figures, that some sectors are not modeled yet in MELiSsa (e.g. the public transports) and thus these values do not comprehensively represent the emissions of the region (but only what is actually included in the model).

4. Discussion on the resulting tool

In this section we briefly discuss the strengths (Section 4.1) and the limits (Section 4.2) of MELiSsa at this earlier stage. The discussion, based also on the first results, aims to provide the basis for future applications and developments.

4.1. Strengths

MELiSsa is characterized by two main interesting features: it is open-source and enables a crowd-source development. Though it is specifically focused on the Lombardy region, these peculiarities enable MELiSsa being interesting also outside the region boundaries. The next sections deal with the positive interests respectively within and outside the region

4.1.1. Interests specific for the region

MELiSsa is addressed (i) to the region policy makers (like it has conventionally and historically been for this kind of models) that can plan the building of infrastructures, make agreements, set taxes and subsidies to drive the system toward chosen directions and (ii) especially to the citizens in the region that can get conscious about the energy system they are part of and that can take part to the system evolution by monitoring the decisions of policy makers and hopefully by changing their own behaviors. Several parts of the reference energy system are well detailed due to a relative high number of technologies and services. Although this high number of technologies -and thus data- may appear non-user-friendly, this feature is relatively negligible once the structure is defined and most of the data is known. The relatively small area under focus (about 24 000 km^2) and the spatial detail (the subdivision in 11 areas) allow exploiting the knowledge of the territory considering the real limits and possibilities of the case study. A crowd-source possibility could thus further improve the model with a focus on the specificity of the territory (e.g. the demand, the behavior of people, the availability of resources, etc.) MELiSsa, already at this earlier stage, can give an overview on the resources the region is based on, the energy flows among provinces, the dependence on external sources and the resilience of the system in terms of internal resources capacity, the role in the emissions of green-house gases and so on.

4.1.2. Interests not limited to the region

From a more general point of view, MELiSsa (i) is addressed also to the research community, that can profit of this real-case-based platform for research and teaching purposes and (ii) can be an interesting precedent for energy planners and policy makers outside the region. The different data and the assumptions are transparently made available and both can be a general reference for other similar models. A crowd-source development could deal also with those features that are independent from the specific case study (the efficiency of technologies, the cost of some technologies, some technical dynamics, etc.). MELiSsa enables interdisciplinary researches that can look, for example, more specifically at the environment (by considering further emission types, other forms of impact, local environmental limits, etc.) or can be addressed to assess the role of people behavior (by quantifying the cost and the limits due to the inertia of people in the transition process, etc.). Besides being an opportunity, interdisciplinary participation is a necessity, in an epistemological framework. Energy systems are driven by dynamics and solutions that involve different fields of knowledge and are not simply technical. Politics, economy, environment and socio-psychological issues are some of the most important examples. Developing MELiSsa requires different competences throughout these fields (e.g. knowing the effect of range anxiety on drivers could help setting the maximum penetration of electric vehicles).

MELiSsa has been already instrumental for teaching purposes and for interesting analyses on the code of OSeMOSYS (e.g. on the equations that model the storage, the photovoltaic production and the trade of electricity among subregions, not yet introduced in this version). A first example of crowd-source development has been already experienced, through the expansion of the structure due to the work of students of energy engineering.

4.2. Limits

MELiSsa is still limited in several parts due to its recent creation. This mainly refers to three points: the usability, the structure, and the data.

4.2.1. Usability

Although all the necessary softwares and files are open and made available free of charge, the model usability is compromised by the fact that no interface is available yet. A user-friendly interface (created specifically for MELiSsa or generally for the OSeMOSYS framework) would potentially increase the number of users. A second limitation on the usability is related to the running of the model. Due to the interlinks between provinces, the memory required to solve the optimization problem (on which MELiSsa is based) is close to the capacity of conventional personal computer and the runs are time-requiring (in the order of hours). Two solutions (both under study) can overcome this problem: (i) working on a more concise method for considering the exchanges of electricity and (ii) providing a parallel version of the model considering the Lombardy region as a whole (drastically reducing the time needed, on the one hand, while loosing spatial detail on the other hand).

4.2.2. Structure

Several dynamics, technologies, process and options, of current and future energy systems, are not detailed or not considered yet in MELiSsa. In general, this is due to (i) the limited geographical area, (ii) the linearization of non-linear relations (e.g. the dependence of the efficiency of a technology on the actual load), (iii) the lack of data (see the considerations in Section 4.2.3), and (iv) its earlier development stage. Improvements of the structure are discussed in the following paragraphs: (i) *Parts to be detailed*, (ii) *Parts to be included* and (iii) *Differences among actors*.

Parts to be detailed. The inability of photovoltaic to be dispatched and the different reserve provision capacities of other generating plants are considered throughout black-box limits on the penetration of technologies whereas a better approach could detail the dynamics that lead to the need for ancillary services and could model their market value. Similarly, the effect on the electricity demand profile due to the potential electrification of transportation is considered throughout an upper limit on the penetration of electric vehicles whereas this type of implications could be modeled in a more detailed approach. The demand and its satisfaction, in the industry, the agriculture and the tertiary sector are modeled as simple representative and comprehensive items. The storage service provided in the future by the existing technologies is determined a priori and other installable storage systems are not considered. The biomasses production and the technologies that uses biomasses are not detailed.

Parts to be included. Some technologies, process and options are not yet considered at all. It is the case of intelligent charging of vehicles and vehicle-to-grid strategies, demand-side-management systems, the internal production of hydrogen, the use of biofuels for transportation, the emission of pollutants other than CO_2, the concentrated solar power plants, the carbon capture and storage and the insulation of buildings. Besides the technologies, also entire sectors of the energy demand are not considered in this earlier version, i.e. the freight transportation and the public passenger transportation.

Differences among actors. A latter consideration is related to the mathematical structure of OSeMOSYS that makes no difference among the different actors in the systems (since the latter is seen as a whole) implying that the optimal solution for the system might not be optimal or feasible for some of the actors. For example, turning off a dispatchable power plant when photovoltaic generation is available might minimize the cost of the whole system but might not be the optimal solution for the owner of the power plant.

4.2.3. Data

The lack of data mainly affects the description of the availability of some resources (e.g. biomass), the installed capacity of some existing technologies (e.g. the machines operating in the industries), the natural penetration limit of some technologies (e.g. the extent of parking lots for photovoltaic applications), the penetration rates of some technologies (e.g. electric vehicles), usage and demand profiles (e.g. heating systems), existing dynamics within the region (e.g. the current electricity transits between provinces and throughout the Lombardy) and over its boundaries (e.g. the current use of pumped storage hydro-power plants for a storage service that might be demanded also outside the region). The availability of data can strongly influence the gap between the real and the modeled energy system. This is nevertheless one of the issues that could be more easily overcome throughout a crowd-source and interdisciplinary development.

5. Conclusion

The energy system model presented in this paper is one of the first comprehensive application of the OSeMOSYS modeling framework and, as far as the authors concern, differently from other models for energy system analysis and planning (but coherently with the ethics of OSeMOSYS), it is characterized by an open-source nature and aims for a crowd-source development. The interesting potential of MELiSsa is based on these two features. With this paper we show that MELiSsa is able to conventionally provide insights for policy makers and we make it a reference application available to the academy and research. MELiSsa is a first step towards enabling the citizens of the Lombardy Region to actively participate to the evolution of their local energy systems, by using it, by suggesting ideas and analyses, by improving it with additional data and tools. Though it is made up of many technologies, it is relatively simple to understand. Although about 24 man-months of work were required to build the current version, MELiSsa is still at its earlier stage and shows several limits that mainly refer to the usability, the structure and the data. However, these issues could be overcome, especially throughout interdisciplinary collaborations and an open participation to its development. Further steps are certainly required to involve unconventional participants in the development of the model and in the planning process. This should be the focus of larger initiatives in the future. The demonstrative analysis has showed that the optimal economic solution, based on the implemented technologies, slightly reduces the greenhouse-gas emissions while satisfying the demand of services. This reduction however would not stop the concentration of CO_2 in the atmosphere to increase and is anyway far from the targets set by the European Union and the national government. Besides the need of including all the technologies not yet implemented, this suggests that also non-technological options should be considered in the optimization problem. This could refer for example to tele-commuting and car-pooling solutions, to the transferability from private transportation to public means, to other changes in the user's behavior (like the rational use of some appliances and so on).

Acknowledgments

We would like to acknowledge: the participants to the *MELiSsaDay* event and, in particular, G. Pireddu, D. Grosso and F. Lanati for the precious insights; F. Legnazzi for the contribution on the residential electric appliances; the AIRU associations for providing the data in the format we required; the developers of the open and free softwares we used (OSeMOSYS, Gephi, GLPK, GUSEK).

Annexes

Table 1
List of the acronyms that define the technologies – relative descriptions and types (as defined in Fig. 2) – part 1.

Name	Description	Type	Fig.
CBL-DSL	Collective Diesel Boilers	A	Fig. 4
CBL-DSL(+)	Collective Diesel Boilers (new version)	A	Fig. 4
CBL-LPG	Collective LPG[b] Boilers	A	Fig. 4
CBL-LPG(+)	Collective LPG[b] Boilers (new version)	A	Fig. 4
CBL-PLT	Collective Pellet Boilers	A	Fig. 4
CBL-WC	Collective woodchips Boilers	A	Fig. 4
CCBL(s)-NG	Collective Condensing Boilers (space heating only)[a]	A	Fig. 4
CCBL(s)-NG(+)	Collective Condensing Boilers (space heating only) (new version)[a]	A	Fig. 4
CSBL(s)-NG	Collective Standard Boilers (space heating only)[a]	A	Fig. 4
CSBL(s)-NG(+)	Collective Standard Boilers (space heating only) (new version)	A	Fig. 4
C-SHD	Partitioner for collective space heating demand	A	Fig. 4
IBL-DSL	Individual Diesel Boilers	A	Fig. 4
IBL-LPG	Individual LPG[b] Boilers	A	Fig. 4
IBL-PLT	Individual Pellet Boilers	A	Fig. 4
IBL-WC	Individual wood chips boilers	A	Fig. 4
ICBL(s)-NG	Individual Condensing Boilers (space heating only)[a]	A	Fig. 4
ISBL(s)-NG	Individual Standard Boilers (space heating only)[a]	A	Fig. 4
ISBL(s)-NG(+)	Individual Standard Boilers (space heating only) (new version)[a]	A	Fig. 4
I-SHD	Partitioner for individual space heating demand	A	Fig. 4
STPS	Partitioner for STP in space heating production use	A	Fig. 4

Table 1 (*Continued*)

Name	Description	Type	Fig.
CCBL-NG	Collective Condensing Boilers	C	Figs. 4 and 5
CCBL-NG(+)	Collective Condensing Boilers (new version)	C	Figs. 4 and 5
CSBL-NG	Collective Standard Boilers	C	Figs. 4 and 5
CSBL-NG(+)	Collective Standard Boilers (new version)	C	Figs. 4 and 5
DHE	District Heating Exchangers	C	Figs. 4 and 5
DHN	District Heating Network	A	Figs. 4 and 5
IBL-DSL(+)	Individual Diesel Boilers (new version)	C	Figs. 4 and 5
IBL-LPG(+)	Individual LPG[b] Boilers (new version)	C	Figs. 4 and 5
ICBL-NG	Individual Condensing Boilers	C	Figs. 4 and 5
ICBL-NG(+)	Individual Condensing Boilers (new version)	C	Figs. 4 and 5
ISBL-NG	Individual Standard Boilers	C	Figs. 4 and 5
ISBL-NG(+)	Individual Standard Boilers (new version)	C	Figs. 4 and 5
STP	Solar Thermal Panels for space heating and hot water	F	Figs. 4 and 5
CHTP-ELC	Collective Geothermal Heat Pumps	C	Figs. 4 and 6
CHTP-NG	Collective Natural Gas Heat Pumps	C	Figs. 4 and 6
IHTP-ELC	Individual Geothermal Heat Pumps	C	Figs. 4 and 6
IHTP-NG	Individual Natural Gas Heat Pumps	C	Figs. 4 and 6
C-HWD	Partitioner for collective hot water demand	A	Fig. 5
IBL(w)-ELC	Individual Electric Boilers (how water only)	A	Fig. 5
IBL(w)-ELC(+)	Individual Electric Boilers (how water only) (new version)	A	Fig. 5
IBL(w)-LPG	Individual LPG[b] Boilers (how water only)	A	Fig. 5
IBL(w)-LPG(+)	Individual LPG[b] Boilers (how water only) (new version)	A	Fig. 5
IBL(w)-NG	Individual Natural Gas Boilers (how water only)	A	Fig. 5
IBL(w)-NG(+)	Individual Natural Gas Boilers (how water only) (new version)	A	Fig. 5
I-HWD	Partitioner for individual hot water demand	A	Fig. 5
STP(w)	Solar Thermal Panels (hot water only)	F	Fig. 5
STPW	Partitioner for STP in hot water production use	A	Fig. 5
C-ACD	Partitioner for collective air conditioning demand	A	Fig. 6
CACND	Conventional Air Conditioners	A	Fig. 6
ELC-HOB	Electric hobs	A	Fig. 6
I-ACD	Partitioner for individual air conditioning demand	A	Fig. 6
IND-HOB	Induction hobs	A	Fig. 6
IND-THD	Facilities for industrial thermal services	A	Fig. 6
NG-HOB(−)	Natural Gas hobs	A	Fig. 6
NG-HOB(+)	Natural Gas hobs (more efficient version)	A	Fig. 6
TER-DH	District heating facilities of the tertiary sector	A	Fig. 6
TER-NG	Technologies using natural gas in the Tertiary sector	A	Fig. 6

[a] Natural gas-fed technologies.
[b] Liquefied petroleum gas.

Table 2
List of the acronyms that define the technologies – relative descriptions and types (as defined in Fig. 2) – part 2.

Name	Description	Type	Fig.
DRYM	High Performance Dryers	A	Fig. 7
DRYM(−)	Medium Performance Dryers	A	Fig. 7
DRYM(−−)	Low Performance Dryers	A	Fig. 7
DRYM(+)	Very High Performance Dryers	A	Fig. 7
DRYM(++)	New generation of Dryers	A	Fig. 7
DSHW	High Performance Dishwashers	A	Fig. 7
DSHW(−)	Medium Performance Dishwashers	A	Fig. 7
DSHW(−−)	Low Performance Dishwashers	A	Fig. 7
DSHW(+)	Very High Performance Dishwashers	A	Fig. 7
DSHW(++)	New generation of Dishwashers	A	Fig. 7
ESB	Energy Saving Bulbs	A	Fig. 7
FLL	Fluorescent lamps	A	Fig. 7
FRZ(−)	Medium Performance Freezers	A	Fig. 7
FRZ(−−)	Low Performance Freezers	A	Fig. 7
FRZ(+)	Very High Performance Freezers	A	Fig. 7
FRZ(+)	High Performance Freezers	A	Fig. 7
FRZ(++)	New generation of Freezers	A	Fig. 7
HAL	Halogen lamps	A	Fig. 7
ILB	Incandescent light bulbs	A	Fig. 7
IND-ELC	Technologies using electricity in the industries	A	Fig. 7
LED	LED Bulbs	A	Fig. 7
PRM-ELC	Technologies using electricity in the primary sector	A	Fig. 7
RES-OTH	Other technologies using electricity for residential purposes	A	Fig. 7
RFG	High Performance Refrigerators	A	Fig. 7
RFG(−)	Medium Performance Refrigerators	A	Fig. 7
RFG(−−)	Low Performance Refrigerators	A	Fig. 7
RFG(+)	Very High Performance Refrigerators	A	Fig. 7
RFG(++)	New generation of Refrigerators	A	Fig. 7

Table 2 (*Continued*)

Name	Description	Type	Fig.
TER-ELC	Technologies using electricity in the tertiary sector	A	Fig. 7
TXP-ELC	Public transportation technologies fed by electricity	A	Fig. 7
WSHM	High Performance Washing Machines	A	Fig. 7
WSHM(−)	Medium Performance Washing Machines	A	Fig. 7
WSHM(−−)	Low Performance Washing Machines	A	Fig. 7
WSHM(+)	Very High Performance Washing Machines	A	Fig. 7
WSHM(++)	New generation of Washing Machines	A	Fig. 7
BEV	Pure Battery electric vehicles	A	Fig. 8
FC-HYD	Fuel cell vehicles fed by hydrogen	A	Fig. 8
HEV-DSL	Hybrid electric vehicles fed by diesel that cannot be charged through plugs	A	Fig. 8
HEV-GSL	Hybrid electric vehicles fed by gasoline that cannot be charged through plugs	A	Fig. 8
HEV-LPG	Hybrid electric vehicles fed by liquefied petroleum gas that cannot be charged through plugs	A	Fig. 8
ICE-DSL	Internal combustion engine vehicles fed by diesel	A	Fig. 8
ICE-GSL	Internal combustion engine vehicles fed by gasoline	A	Fig. 8
ICE-HYD	Internal combustion engine vehicles fed by hydrogen	A	Fig. 8
ICE-LPG	Internal combustion engine vehicles fed by liquefied petroleum gas	A	Fig. 8
ICE-NG	Internal combustion engine vehicles fed by natural gas	A	Fig. 8
PHEV-DSL	Plug-in hybrid electric vehicles fed by diesel	A	Fig. 8
PHEV-GSL	Plug-in hybrid electric vehicles fed by gasoline	A	Fig. 8
PHEV-LPG	Plug-in hybrid electric vehicles fed by liquefied petroleum gas	A	Fig. 8

Table 3
List of the acronyms that define the technologies – relative descriptions and types (as defined in Fig. 2) – part 3.

Name	Description	Type	Fig.
CHP-BG	Combined heat and power production from biogas	E	Fig. 9
CHP-CCGT	Combined cycle gas turbines for combine heat and power production	B	Fig. 9
CHP-GT	Turbogas plants for combine heat and power production	B	Fig. 9
CHP-INC	Incinerators for combine heat and power production	B	Fig. 9
CHP-LBM	Combined heat and power production from lignocellulosic biomass	E	Fig. 9
CHP-LFG	Combined heat and power production from biogas of wastewater treatments and landfills	E	Fig. 9
CHP-OBM	Combined heat and power production from other biomass types	E	Fig. 9
CHP-RGE	Reciprocating gas engines for combine heat and power production	B	Fig. 9
CHP-ST	Steam Turbines for combine heat and power production	B	Fig. 9
C-TPP-NG	Centralized Thermal Power Plants fed by natural gas	A	Fig. 9
C-TPP-NG(+)	Centralized Thermal Power Plants fed by natural gas (next generation)	A	Fig. 9
C-TTP-OIL	Centralized Thermal Power Plants fed by fuel oil	A	Fig. 9
DH-BL-BM	Centralized boilers fed by biomass for district heating	F	Fig. 9
DH-BL-DSL	Centralized boilers fed by diesel for district heating	F	Fig. 9
DH-BL-NG	Centralized boilers fed by natural gas for district heating	A	Fig. 9
DH-HTP-ELC	Heat pumps for district heating fed by electricity	A	Fig. 9
DH-OTHER	Other systems for district heating	F	Fig. 9
HPP-DIV	Diversion Hydro Power Plants	F	Fig. 9
HPP-IMP	Impoundment Hydro Power Plants	F	Fig. 9
HPP-PUM	Pumped Storage Hydro Power plants	F	Fig. 9
IMP/PRD-WST	Import/production of wastes	F	Fig. 9
IMP-DSL(RES)	Import of diesel for residential uses	F	Fig. 9
IMP-DSL(TXP)	Import of diesel for transportation	F	Fig. 9
IMP-GSL(TXP)	Import of gasoline for transportation	F	Fig. 9
IMP-HYD(TXP)	Import of hydrogen for transportation	F	Fig. 9
IMP-LPG(RES)	Import of liquefied petroleum gas for residential uses	F	Fig. 9
IMP-LPG(TXP)	Import of liquefied petroleum gas for transportation	F	Fig. 9
IMP-NG(IND)	Import of Natural Gas for industrial uses	F	Fig. 9
IMP-NG(RES)	Import of Natural Gas for residential and commercial uses	F	Fig. 9
IMP-NG(TXP)	Import of natural gas for transportation	F	Fig. 9
IMP-OIL	Import of fuel oil	F	Fig. 9
IMP-PLT	Import/production of pellet for residential uses	F	Fig. 9
IMP-WC	Import/production of wood chips for residential uses	F	Fig. 9
PP-BG	Power production from biogas	F	Fig. 9
PP-INC	Incinerators for power production only	A	Fig. 9
PP-LBM	Power production from lignocellulosic biomass	F	Fig. 9
PP-LFG	Power production from biogas of wastewater treatments and landfills	F	Fig. 9
PP-OBM	Power production from other biomass types	F	Fig. 9
PV-BIG	Big centralized Photovoltaic plants	F	Fig. 9
PV-SML	Small distributed Photovoltaic plants	F	Fig. 9

Table 4
List of the acronyms that define the technologies – relative descriptions and types (as defined in Fig. 2) – part 4.

Name	Description	Type	Fig.
DISTRIB	Distribution of electricity	A	Fig. 10
EXP-ELC	Export of electricity (downstream the IMP-ELC technologies used in mode 2)	G	Fig. 10
IMP-ELC-D	Import (mode 1) and export (mode 2) of electricity during day-time hours	F	Fig. 10
IMP-ELC-N	Import (mode 1) and export (mode 2) of electricity during night-time hours	F	Fig. 10
LINE-BG-LC	Transmission lines between Bergamo and Lecco	D	Fig. 10
LINE-BG-LO	Transmission lines between Bergamo and Lecco	D	Fig. 10
LINE-BG-SO	Transmission lines between Bergamo and Sondrio	D	Fig. 10
LINE-BS-BG	Transmission lines between Brescia and Bergamo	D	Fig. 10
LINE-BS-CR	Transmission lines between Brescia and Cremona	D	Fig. 10
LINE-BS-MN	Transmission lines between Brescia and Mantova	D	Fig. 10
LINE-BS-SO	Transmission lines between Brescia and Sondrio	D	Fig. 10
LINE-CO-LC	Transmission lines between Como and Lecco	D	Fig. 10
LINE-CO-SO	Transmission lines between Como and Sondrio	D	Fig. 10
LINE-CO-VA	Transmission lines between Como and Varese	D	Fig. 10
LINE-CR-BG	Transmission lines between Cremona and Bergamo	D	Fig. 10
LINE-LO-CR	Transmission lines between Lodi and Cremona	D	Fig. 10
LINE-MI-BG	Transmission lines between Milan and Bergamo	D	Fig. 10
LINE-MI-CO	Transmission lines between Milan and Como	D	Fig. 10
LINE-MI-CR	Transmission lines between Milan and Cremona	D	Fig. 10
LINE-MI-LC	Transmission lines between Milan and Lecco	D	Fig. 10
LINE-MI-LO	Transmission lines between Milan and Lodi	D	Fig. 10
LINE-MI-VA	Transmission lines between Milan and Varese	D	Fig. 10
LINE-MN-CR	Transmission lines between Mantova and Cremona	D	Fig. 10
LINE-PV-LO	Transmission lines between Pavia and Lodi	D	Fig. 10
LINE-PV-MI	Transmission lines between Pavia and Milan	D	Fig. 10
LINE-SO-LC	Transmission lines between Sondrio and Lecco	D	Fig. 10
LINE-VA-LC	Transmission lines between Varese and Lecco	D	Fig. 10
LINE-VA-SO	Transmission lines between Varese and Sondrio	D	Fig. 10
TRANSM	Transmission of electricity	A	Fig. 10

Table 5
List of the acronyms that define the fuels – relative descriptions and types – part 1.

Name	Description	Type
IND-ELC	Electricity demand of the industries	Demand
IND-THD	Thermal demand of the industries	Demand
PRV-PTD	Private passenger transportation demand	Demand
PRM-ELC	Electricity demand of the primary sector	Demand
RES-ACD$_{AB}$	Residential demand for air conditioning in apartment blocks	Demand
RES-HWD$_{AB}$	Residential demand of hot water in apartment blocks	Demand
RES-SHD$_{AB}$	Residential demand for space heating in apartment blocks	Demand
RES-ACD$_{DH}$	Residential demand for air conditioning in detached households	Demand
RES-HWD$_{DH}$	Residential demand of hot water in detached households	Demand
RES-SHD$_{DH}$	Residential demand for space heating in detached households	Demand
RES-CKD	Residential demand for cooking services	Demand
RES-DRY	Residential demand of drying clothes	Demand
RES-DSH	Residential demand of dish washing	Demand
RES-FRZ	Residential demand of freezing	Demand
RES-LND	Residential demand of laundry	Demand
RES-LT	Residential demand of lighting	Demand
RES-OTH	Residential demand of other services	Demand
RES-RFG	Residential demand of refrigeration	Demand
TER-ELC	Electricity demand of the tertiary sector	Demand
TER-THD	Thermal demand of the tertiary sector	Demand
TXP-ELC	Electricity demand of the public transportation (train, trolleybus, etc.)	Demand

Table 6
List of the acronyms that define the fuels – relative descriptions and types – part 2.

Name	Description	Type
DSL(RES)	Diesel for residential uses	Energy carrier
DSL(TXP)	Diesel for transportation	Energy carrier
ELC-EXP	Electricity that is exported	Energy carrier
GSL(TXP)	Gasoline for transportation	Energy carrier
HV-ELC	High-voltage electricity	Energy carrier
HYD(TXP)	Hydrogen for transportation	Energy carrier
LPG(RES)	Liquefied petroleum gas for residential uses	Energy carrier
LPG(TXP)	Liquefied Petroleum Gas for transportation	Energy carrier
LV-ELC	Low-voltage electricity	Energy carrier
MV-ELC	Medium-voltage electricity	Energy carrier
NG(IND)	Natural gas for industrial uses	energy carrier
NG(RES)	Natural gas for civil uses	Energy carrier
NG(TXP)	Natural gas for transportation	Energy carrier
OIL	Fuel oil	Energy carrier

Table 6 (*Continued*)

Name	Description	Type
PLT(RES)	Diesel for residential uses	Energy carrier
THE	Thermal energy coming from centralized heat (or heat and power) production plants	Energy carrier
WC(RES)	Wood chips for residential uses	Energy carrier
WST	Wastes	Energy carrier

Table 7
List of the acronyms that define the fuels – relative descriptions and types – part 3.

Name	Description	Type
C-ACDF	Thermal energy addressed to air conditioning. Name used upstream the C-ACDF dummy technology	Energy carrier tagged for a particular context or purpose
C-HWDF	Thermal energy addressed to the hot water demand. Name used upstream the C-HWDF dummy technology	Energy carrier tagged for a particular context or purpose
C-SHDF	Thermal energy addressed to space heating. Name used upstream the C-SHDF dummy technology	Energy carrier tagged for a particular context or purpose
DHFF	Thermal energy from the district heating network. Name used upstream the DHFF dummy technology	Energy carrier tagged for a particular context or purpose
ELC-BG-LC	Electricity that transit through the transmission lines between Bergamo and Lecco	Energy carrier tagged for a particular context or purpose
ELC-BG-LO	Electricity that transit through the transmission lines between Bergamo and Lodi	Energy carrier tagged for a particular context or purpose
ELC-BG-SO	Electricity that transit through the transmission lines between Bergamo and Sondrio	Energy carrier tagged for a particular context or purpose
ELC-BS-BG	Electricity that transit through the transmission lines between Brescia and Bergamo	Energy carrier tagged for a particular context or purpose
ELC-BS-CR	Electricity that transit through the transmission lines between Brescia and Cremona	Energy carrier tagged for a particular context or purpose
ELC-BS-MN	Electricity that transit through the transmission lines between Brescia and Mantova	Energy carrier tagged for a particular context or purpose
ELC-BS-SO	Electricity that transit through the transmission lines between Brescia and Sondrio	Energy carrier tagged for a particular context or purpose
ELC-CO-LC	Electricity that transit through the transmission lines between Como and Lecco	Energy carrier tagged for a particular context or purpose
ELC-CO-SO	Electricity that transit through the transmission lines between Como and Sondrio	Energy carrier tagged for a particular context or purpose
ELC-CO-VA	Electricity that transit through the transmission lines between Como and Varese	Energy carrier tagged for a particular context or purpose
ELC-CR-BG	Electricity that transit through the transmission lines between Cremona and Bergamo	Energy carrier tagged for a particular context or purpose
ELC-LO-CR	Electricity that transit through the transmission lines between Lodi and Cremona	Energy carrier tagged for a particular context or purpose
ELC-MI-BG	Electricity that transit through the transmission lines between Milan and Bergamo	Energy carrier tagged for a particular context or purpose
ELC-MI-CO	Electricity that transit through the transmission lines between Milan and Como	Energy carrier tagged for a particular context or purpose
ELC-MI-CR	Electricity that transit through the transmission lines between Milan and Cremona	Energy carrier tagged for a particular context or purpose
ELC-MI-LC	Electricity that transit through the transmission lines between Milan and Lecco	Energy carrier tagged for a particular context or purpose
ELC-MI-LO	Electricity that transit through the transmission lines between Milan and Lodi	Energy carrier tagged for a particular context or purpose
ELC-MI-VA	Electricity that transit through the transmission lines between Milan and Varese	Energy carrier tagged for a particular context or purpose
ELC-MN-CR	Electricity that transit through the transmission lines between Mantova and Cremona	Energy carrier tagged for a particular context or purpose
ELC-PV-LO	Electricity that transit through the transmission lines between Pavia and Lodi	Energy carrier tagged for a particular context or purpose
ELC-PV-MI	Electricity that transit through the transmission lines between Pavia and Milan	Energy carrier tagged for a particular context or purpose
ELC-SO-LC	Electricity that transit through the transmission lines between Sondrio and Lecco	Energy carrier tagged for a particular context or purpose
ELC-VA-LC	Electricity that transit through the transmission lines between Varese and Lecco	Energy carrier tagged for a particular context or purpose
ELC-VA-SO	Electricity that transit through the transmission lines between Varese and Sondrio	Energy carrier tagged for a particular context or purpose
STPF	Thermal energy produced by the thermal solar panel upstream the STPS and STPW dummy technologies	Energy carrier tagged for a particular context or purpose

Table 8
Data related to the distributed technologies that can meet the demand of thermal services. Please, refer to Table 1 for the nomenclature.

Technology	Capital cost [€/power unit][a]	Fixed cost	Mode	Efficiency	Output
ICBL-NG		50	1	78.9%	Space Heating
			2	88.4%	Hot Water
ICBL(s)-NG		50	1	78.9%	Space Heating
ISBL-NG		50	1	75.0%	Space Heating
			2	84.1%	Hot Water
ISBL(s)-NG		50	1	75.0%	Space Heating
IHTP-NG	10,000		1	119.9%	Space Heating
			2	57.4%	Cooling Energy
IHTP-ELC	17,000		1	299.8%	Space Heating
			2	342.7%	Cooling Energy
IBL-LPG		50	1	75.0%	Space Heating
IBL-DSL		50	1	75.0%	Space Heating
IBL-PLT	4000	50	1	77.1%	Space Heating
CCBL-NG		75	1	79.7%	Space Heating
			2	89.3%	Hot Water
CCBL(s)-NG		75	1	79.7%	Space Heating
CSBL-NG		75	1	76.1%	Space Heating
			2	85.2%	Hot Water
CSBL(s)-NG		75	1	76.1%	Space Heating
CHTP-NG	8500		1	119.9%	Space Heating
			2	51.4%	Cooling Energy
CHTP-ELC	13,600		1	299.8%	Space Heating
			2	342.7%	Cooling Energy
CBL-LPG		75	1	76.1%	Space Heating
CBL-DSL		75	1	76.1%	Space Heating
CBL-PLT	3400	75	1	76.2%	Space Heating
CACND	1200		1	241.0%	Cooling Energy
IBL(w)-NG			1	81.6%	Hot Water
IBL(w)-LPG			1	81.6%	Hot Water
IBL(w)-ELC			1	81.6%	Hot Water
ICBL-NG(+)	2000	50	1	84.0%	Space Heating
			2	94.1%	Hot Water
ISBL-NG(+)	1350	50	1	78.8%	Space Heating
			2	88.3%	Hot Water
ISBL(s)-NG(+)	1350	50	1	78.8%	Space Heating
IBL-LPG(+)	2000	50	1	82.2%	Space Heating
			2	84.8%	Hot Water
IBL-DSL(+)	2000	50	1	83.1%	Space Heating
			2	84.8%	Hot Water
CCBL-NG(+)	1700	75	1	89.1%	Space Heating
			2	99.8%	Hot Water
CCBL(s)-NG(+)	1700	75	1	89.1%	Space Heating
CSBL-NG(+)	1147.5	75	1	80.5%	Space Heating
			2	90.2%	Hot Water
CSBL(s)-NG(+)	1147.5	75	1	80.5%	Space Heating
CBL-LPG(+)	1700	75	1	84.0%	Space Heating
CBL-DSL(+)	1700	75	1	84.0%	Space Heating
IBL(w)-NG(+)	900		1	86.4%	Hot Water
IBL(w)-LPG(+)	900		1	86.4%	Hot Water
IBL(w)-ELC(+)	400		1	86.4%	Hot Water

[a] The power unit is the power capacity that can provide the space heating service for an average household.

Table 9
Data related to all the end-user technologies, not listed in Table 8, that can meet the demand for thermal services. Please, refer to Table 1 for the nomenclature.

Technology	Capital cost	Fixed cost	Mode	Efficiency	Output
NG-HOB(+)	500 €/household		1	55.0%	Cooking
IND-HOB	980 €/household		1	92.0%	Cooking
NG-HOB(−)			1	45.0%	Cooking
ELC-HOB	700 €/household		1	50.0%	Cooking
STP(w)	1300 €/m^2		1	100% (fictitious)	Hot Water
STP	1500 €/m^2	50 €/year	1	100% (fictitious)	STPF
STPS			1	85.7%	Space Heating
STPW			1	96.0%	Hot Water
DHE	1200 €/unit [a]		1	90.0%	Space Heating
			2	90.0%	Hot Water
DHN	500 k€/km	25 €/(km year)	1	88.0%	Thermal Energy
TER-NG			1	76.2%	
TER-DH			1	80.0%	

[a] The power unit is the power capacity that can provide the space heating service for an average household.

Table 10
Data related to the technologies that can meet the demands currently met only by electricity. Please, refer to Table 2 for the nomenclature.

Technology	Capital cost	Specific consumption	Output
RFG(+)	900 €/unit	180.0 kWh/(unit year)	Refrigeration
RFG	550 €/unit	280.0 kWh/(unit year)	Refrigeration
RFG(−)		400.0 kWh/(unit year)	Refrigeration
RFG(−−)		550.0 kWh/(unit year)	Refrigeration
RFG(++)	1170 €/unit	162.0 kWh/(unit year)	Refrigeration
FRZ(+)	900 €/unit	250.0 kWh/(unit year)	Freezing service
FRZ(+)	550 €/unit	300.0 kWh/(unit year)	Freezing service
FRZ(−)		350.0 kWh/(unit year)	Freezing service
FRZ(−−)		400.0 kWh/(unit year)	Freezing service
FRZ(++)	1170 €/unit	225.0 kWh/(unit year)	Freezing service
WSHM(+)	800 €/unit	180.0 kWh/(unit year)	Washing Cycles
WSHM	400 €/unit	250.0 kWh/(unit year)	Washing Cycles
WSHM(−)		300.0 kWh/(unit year)	Washing Cycles
WSHM(−−)		380.0 kWh/(unit year)	Washing Cycles
WSHM(++)	1040 €/unit	157.5 kWh/(unit year)	Washing Cycles
DRYM(+)	1100 €/unit	240.0 kWh/(unit year)	Drying Cycles
DRYM	1000 €/unit	350.0 kWh/(unit year)	Drying Cycles
DRYM(−)	800 €/unit	400.0 kWh/(unit year)	Drying Cycles
DRYM(−−)		500.0 kWh/(unit year)	Drying Cycles
DRYM(++)	1430 €/unit	216.0 kWh/(unit year)	Drying Cycles
DSHW(+)	800 €/unit	200.0 kWh/(unit year)	Washing Cycles
DSHW	400 €/unit	250.0 kWh/(unit year)	Washing Cycles
DSHW(−)		350.0 kWh/(unit year)	Washing Cycles
DSHW(−−)		430.0 kWh/(unit year)	Washing Cycles
DSHW(++)	1040 €/unit	234.0 kWh/(unit year)	Washing Cycles
LED	10 €/bulb	0.011 W/lumen	Luminous Flux
ILB		0.087 W/lumen	Luminous Flux
ESB	15 €/bulb	0.007 W/lumen	Luminous Flux
FLL	7 €/bulb	0.013 W/lumen	Luminous Flux
HAL	2 €/bulb	0.050 W/lumen	Luminous Flux
RES-OTH		100% efficiency (fictitious technology)	RES-OTH
TER-ELC		100% efficiency (fictitious technology)	TER-ELC
PRM-ELC		100% efficiency (fictitious technology)	PRM-ELC
IND-ELC		100% efficiency (fictitious technology)	IND-ELC
TXP-ELC		100% efficiency (fictitious technology)	TXP-ELC

Table 11
Data related to the centralized conversion technologies that can produce electricity and or thermal energy. Please, refer to Table 3 for the nomenclature.

Technology	Capital cost	Fixed cost	Variable cost	Efficiency (output)
CHP-RGE	2000 €/kW	20.0 €/(kW year)	0.015 €/kWh	35.0% (Electric Energy) 40.0% (Thermal Energy)
CHP-GT	2000 €/kW	20.0 €/(kW year)	0.010 €/kWh	30.0% (Electric Energy) 50.0% (Thermal Energy)
CHP-ST	1000 €/kW	10.0 €/(kW year)	0.005 €/kWh	20.0% (Electric Energy) 60.0% (Thermal Energy)
CHP-CCGT	2500 €/kW	25.0 €/(kW year)	0.010 €/kWh	40.0% (Electric Energy) 40.0% (Thermal Energy)
PP-INC	4279 €/kW	252.8 €/(kW year)	0.129 €/kWh	26.0% (Electric Energy)
CHP-INC	5135 €/kW	252.8 €/(kW year)	0.129 €/kWh	26.0% (Electric Energy) 58.0% (Thermal Energy)
C-TPP-NG	1600 €/kW	16.0 €/(kW year)	0.010 €/kWh	46.0% (Electric Energy)
C-TPP-NG(+)	6000 €/kW	60.0 €/(kW year)	0.010 €/kWh	65.0% (Electric Energy)
C-TTP-OIL	€/kW	24.0 €/(kW year)	0.030 €/kWh	25.0% (Electric Energy)
PP-BG	2136 €/kW	236.8 €/(kW year)	€/kWh	30.0% (Electric Energy)
CHP-BG	2563 €/kW	236.8 €/(kW year)	€/kWh	30.0% (Electric Energy) 35.0% (Thermal Energy)
PP-LBM	4282 €/kW	286.3 €/(kW year)	0.080 €/kWh	24.0% (Electric Energy)
CHP-LBM	5138 €/kW	286.3 €/(kW year)	0.080 €/kWh	24.0% (Electric Energy) 50.0% (Thermal Energy)
PP-LFG	9040 €/kW	345.8 €/(kW year)	0.050 €/kWh	35.0% (Electric Energy)
CHP-LFG	10,848 €/kW	345.8 €/(kW year)	0.050 €/kWh	35.0% (Electric Energy) 40.0% (Thermal Energy)
PP-OBM	3179 €/kW	182.7 €/(kW year)	0.134 €/kWh	35.0% (Electric Energy)
CHP-OBM	3815 €/kW	182.7 €/(kW year)	0.134 €/kWh	35.0% (Electric Energy) 45.0% (Thermal Energy)
HPP-DIV	4500 €/kW	135.0 €/(kW year)		No input is modeled
HPP-IMP	3803 €/kW	114.1 €/(kW year)		No input is modeled
HPP-PUM	3802 €/kW	114.0 €/(kW year)		No input is modeled
PV-SML	2500 €/kW	68.3 €/(kW year)		No input is modeled
PV-BIG	1500 €/kW	45.0 €/(kW year)		No input is modeled
DH-BL-NG	1420 €/kW			91.2%

Table 11 (*Continued*)

Technology	Capital cost	Fixed cost	Variable cost	Efficiency (output)
DH-BL-DSL	1420 €/kW		0.157 €/kWh	91.8%
DH-BL-BM	1420 €/kW		0.025 €/kWh	87.2%
DH-HTP-ELC	5000 €/kW			3.0
DH-OTHER				100% efficiency (fictitious technology)

Table 12
Data related to the technologies representing the vehicles that can meet the private passenger transportation demand. Please, refer to Table 2 for the nomenclature.

Technology	Capital cost	Fixed cost		Specific consumption	Specific CO_2 eq. emissions
ICE-GSL	17.5 k€/vehicle	1045 €/(vehicle year)		0.052 l/km	120.0 g/km
ICE-DSL	18.4 k€/vehicle	1045 €/(vehicle year)		0.039 l/km	104.0 g/km
ICE-LPG	19.5 k€/vehicle	1045 €/(vehicle year)		0.066 l/km	107.0 g/km
ICE-NG	19.9 k€/vehicle	1045 €/(vehicle year)		0.040 Sm^3/km	86.0 g/km
ICE-HYD	25.3 k€/vehicle	1045 €/(vehicle year)		1.564 MJ/km	0.0 g/km
HEV-GSL	19.4 k€/vehicle	1045 €/(vehicle year)		0.035 l/km	80.8 g/km
HEV-DSL	20.3 k€/vehicle	1045 €/(vehicle year)		0.038 l/km	101.3 g/km
HEV-LPG	22.4 k€/vehicle	1045 €/(vehicle year)		0.042 l/km	68.0 g/km
PHEV-GSL	24.5 k€/vehicle	1045 €/(vehicle year)	Gasoline mode	0.052 l/km	60.0 g/km
			Electricity mode	0.140 kWh/km	0.0 g/km
PHEV-DSL	25.4 k€/vehicle	1045 €/(vehicle year)	Diesel mode	0.039 l/km	52.0 g/km
			Electricity mode	0.140 kWh/km	0.0 g/km
PHEV-LPG	26.5 k€/vehicle	1045 €/(vehicle year)	LPG mode	0.066 l/km	53.5 g/km
			Electricity mode	0.140 kWh/km	0.0 g/km
BEV	32.0 k€/vehicle	1045 €/(vehicle year)		0.140 kWh/km	0.0 g/km
FC-HYD	66.0 k€/vehicle	1045 €/(vehicle year)		0.878 MJ/km	0.0 g/km

Table 13
Data related to the technologies that (i) introduce or produce the energy carriers in the energy system (please, refer to Table 3 for the nomenclature) and (ii) exchange electricity throughout the region (please, refer to Table 4 for the nomenclature).

Technology	Capital cost	Mode	Variable cost	Efficiency	Specific CO_2 eq. emissions[a]
IMP-NG(RES)	–	1	1.000 €/Sm^3	–	1.957 kg/Sm^3
IMP-NG(IND)	–	1	0.600 €/Sm^3	–	1.957 kg/Sm^3
IMP-LPG(RES)	–	1	3.500 €/Sm^3	–	6.558 kg/Sm^3
IMP-DSL(RES)	–	1	1.714 €/kg	–	3.173 kg/kg
IMP-PLT	–	1	0.230 €/kg	–	–
IMP-WC	–	1	0.038 €/kg	–	–
IMP/PRD-WST	–	1	0.080 €/kg	–	0.733 kg/kg
IMP-OIL	–	1	1.153 €/kg	–	3.160 kg/kg
IMP-LPG(TXP)	–	1	0.699 €/l	–	
IMP-DSL(TXP)	–	1	1.494 €/l	–	
IMP-NG(TXP)	–	1	0.983 €/kg	–	
IMP-HYD(TXP)	–	1	3.000 €/MJ	–	
IMP-GSL(TXP)	–	1	1.634 €/l	–	
IMP-ELC-D	8.5 €/kW	1	0.150 €/kWh	–	0.443 kg/kWh
		–	–	99.6%	–
IMP-ELC-N	8.5 €/kW	1	0.150 €/kWh	-	0.443 kg/kWh
		–	–	99.6%	–
EXP-ELC	–	1	−0.140 €/kWh	–	–
TRANSM	–	1		99.1%	–
DISTRIB	–	1		96.5%	–
LINE-PV-MI	10.8 €/kW	1,2		99.6%	–
LINE-PV-LO	10.8 €/kW	1,2		99.6%	–
LINE-MI-LC	19.5 €/kW	1,2		99.6%	–
LINE-MI-VA	17.9 €/kW	1,2		99.6%	–
LINE-MI-LO	10.2 €/kW	1,2		99.6%	–
LINE-LO-CR	15.1 €/kW	1,2		99.6%	–
LINE-MI-BG	16.7 €/kW	1,2		99.6%	–
LINE-CO-VA	9.3 €/kW	1,2		99.6%	–
LINE-BS-BG	16.4 €/kW	1,2		99.6%	–
LINE-BG-LC	10.8 €/kW	1,2		99.6%	–
LINE-BS-CR	17.3 €/kW	1,2		99.6%	–
LINE-BS-MN	22.2 €/kW	1,2		99.6%	–
LINE-BG-LO	18.8 €/kW	1,2		99.6%	–
LINE-VA-SO	39.8 €/kW	1,2		99.6%	–
LINE-VA-LC	17.0 €/kW	1,2		99.6%	–
LINE-MN-CR	20.4 €/kW	1,2		99.6%	–
LINE-CR-BG	24.7 €/kW	1,2		99.6%	–
LINE-BS-SO	43.2 €/kW	1,2		99.6%	–
LINE-MI-CO	15.4 €/kW	1,2		99.6%	–
LINE-CO-LC	9.6 €/kW	1,2		99.6%	–

Table 13 (*Continued*)

Technology	Capital cost	Mode	Variable cost	Efficiency	Specific CO_2 eq. emissions[a]
LINE-CO-SO	33.0 €/kW	1,2		99.6%	–
LINE-BG-SO	34.3 €/kW	1,2		99.6%	–
LINE-SO-LC	25.0 €/kW	1,2		99.6%	–
LINE-MI-CR	26.4 €/kW	1,2		99.6%	–

[a] In the model, emissions are attributed to the demand technologies (not to the import). Nevertheless, since the emissions attributed to the demand technologies are directly related to their fuel use and we chose to show this value here. Emissions related to transportation technologies however are treated differently since in our model they are not exclusively related to the fuel use.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.erss.2016.02.005.

References

[1] S. Rath-Nagel, A. Voss, Energy models for planning and policy assessment, Eur. J. Oper. Res. 8 (2) (1981) 99–114, http://dx.doi.org/10.1016/0377-2217(81)90249-6.
[2] D. Connolly, H. Lund, B. Mathiesen, M. Leahy, A review of computer tools for analysing the integration of renewable energy into various energy systems, Appl. Energy 87 (4) (2010) 1059–1082, http://dx.doi.org/10.1016/j.apenergy.2009.09.026.
[3] M. Manfren, P. Caputo, G. Costa, Paradigm shift in urban energy systems through distributed generation: methods and models, Appl. Energy 88 (4) (2011) 1032–1048, http://dx.doi.org/10.1016/j.apenergy.2010.10.018.
[4] G. Mendes, C. Ioakimidis, P. Ferrão, On the planning and analysis of Integrated Community Energy Systems: a review and survey of available tools, Renew. Sustain. Energy Rev. 15 (9) (2011) 4836–4854, http://dx.doi.org/10.1016/j.rser.2011.07.067.
[5] J. Timmerman, Techno-economic energy models for low carbon business parks, Chem. Eng. Trans. 2 (2013) 571–576, http://dx.doi.org/10.3303/CET1335095 http://www.ace-low-carbon-economy.eu/files/Publicaties/Techno-EconomicEnergyModelsforLowCarbonBusinessParks_CET.pdf.
[6] R. De Miglio, M. Gargiulo, A. Gelmini, F. Lanati, The multiregional energy system model: MONET—a comprehensive tool for energy-environmental analysis at both regional and national level in Italy, in: 12th IAEE European Energy Conference, Venice, Italy, 2012.
[7] F. Lanati, A. Gelmini, M. Borgarello, A scenario analysis for a challenging energy policy in Italy, in: 2010 7th International Conference on the European Energy Market, IEEE, 2010, pp. 1–6, http://dx.doi.org/10.1109/EEM.2010.5558677.
[8] M. Galeotti, A. Bigano, A. Goria, L. Marazzi, F. Sferra, D. Zanoni, R. De Miglio, M. Gargiulo, E. Lavagno, Progetto Kyoto Lombardia – Adozione e applicazione di MARKAL-TIMES per la costruzione di un piano di mitigazione per la regione, Tech. rep., Fondazione Eni Enrico Mattei (FEEM), 2008 http://kyotolombardia.it/materiale-scientifico/terza-annualita/LineaScenariePoliticheSP1Relazionefinale.pdf (Italian).
[9] N. Anglani, G. Muliere, Answering the question of local biomass deployment: the use of energy modelling with case study for non industrial customers, Chem. Eng. Trans. 18 (2009) 659–664, http://dx.doi.org/10.3303/CET0918107 http://www.aidic.it/cet/09/18/107.pdf (cited 21.05.15).
[10] Piano d'Azione per l'Energia, 2007 http://sirena.finlombarda.it/sirena/download/PAE_Documento_di_Piano.pdf (cited 25.05.15).
[11] Piano Strategico delle Tecnologie per la Sostenibilità Energetica in Lombardia.pdf. http://sirena.finlombarda.it/sirena/download/Piano_Strategico_Tecnologie.pdf (cited 25.05.15).
[12] Piano per Una Lombardia Sostenibile. http://sirena.finlombarda.it/sirena/download/PLS.pdf (cited 25.05.15).
[13] Programma Energetico Ambientale Regionale. http://www.reti.regione.lombardia.it/shared/ccurl/1007/354/ProgrammaEnergeticoAmbientaleRegionale.pdf (cited 25.05.15).
[14] M. Bazilian, A. Rice, J. Rotich, M. Howells, J. DeCarolis, S. Macmillan, C. Brooks, F. Bauer, M. Liebreich, Open source software and crowdsourcing for energy analysis, Energy Policy 49 (2012) 149–153, http://dx.doi.org/10.1016/j.enpol.2012.06.032.
[15] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian, A. Roehrl, OSeMOSYS: The Open Source Energy Modeling System, Energy Policy 39 (10) (2011) 5850–5870, http://dx.doi.org/10.1016/j.enpol.2011.06.033.
[16] M. Welsch, M. Howells, M. Bazilian, J. DeCarolis, S. Hermann, H. Rogner, Modelling elements of smart grids – enhancing the OSeMOSYS (Open Source Energy Modelling System) code, Energy 46 (1) (2012) 337–350, http://dx.doi.org/10.1016/j.energy.2012.08.017.
[17] OSeMOSYS Official Website. http://www.osemosys.org/ (cited 10.09.15).
[18] MELiSsa Official Webpage. https://melissaunipv.wordpress.com/homepage/ (cited 10.09.15).
[19] Catasto Energetico CEER – Dati CENED – OpenData, Infrastrutture Lombarde S.p.A. http://www.cened.it/opendata (cited 15.12.13).
[20] 14 censimento generale della popolazione e delle abitazioni 2001, Tech. rep., Istat – Istituto nazionale di statistica, 2003 http://dawinci.istat.it/MD/ (cited 09.07.15).
[21] 15 censimento generale della popolazione e delle abitazioni 2011, Tech. rep., Istat – Istituto nazionale di statistica, 2013 http://www.istat.it/it/censimento-popolazione/censimento-popolazione-2011 (cited 10.09.15).
[22] Statistiche dell'Energia – Consumi di Gas Naturale Provinciali, Ministero dello Sviluppo Economico. http://dgerm.sviluppoeconomico.gov.it/dgerm/consumigasprovinciali.asp (cited 13.07.15).
[23] Final Energy Consumption by Sector, SiReNa – Sistema Informativo Regionale ENergia Ambiente (Informative System for Environment and Energy). http://sirena.finlombarda.it/sirena/private/region/enask/index.jsp (cited 13.07.15).
[24] Riscaldamento Urbano – Annuario Dicembre 2013, Tech. rep., AIRU – Teleriscaldamento, 2013 http://www.airu.it/riscaldamento-urbano-annuario-dicembre-2013/.
[25] Consumi Energia Elettrica per Settore Merceologico – Province, Terna. http://www.terna.it/default/Home/SISTEMA_ELETTRICO/statistiche/consumi_settore_merceologico/consumi_settore_merceologico_provincie.aspx (cited 13.07.15).
[26] Conto nazionale delle infrastrutture e dei trasporti – anni 2012–2013, Tech. rep., Ufficio di statistica del Ministero delle Infrastrutture e dei Trasporti, 2014.
[27] Popolazione residente – bilancio, Istat – Istituto nazionale di statistica. http://dati.istat.it/Index.aspx?DataSetCode=DCIS_POPORESBIL1&Lang= (cited 13.07.15).
[28] Photovoltaic Geographical Information System – Interactive Maps – PV Potential Estimation Utility. http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=europe (cited 14.07.15).
[29] Atlasole – atlante degli impianti fotovoltaici. http://atlasole.gse.it/atlasole/ (cited 28.02.15).
[30] Potential for Building Integrated Photovoltaic, Tech. rep., International Energy Agency – Photovoltaic Power Systems Programme, 2002 www.iea-pvps.org/index.php?id=9&eID=dam_frontend_push&docID=394 (cited 10.09.15).
[31] J.A. Alterach, M.A. Peviani, L. Gilli, G. Quaglia, Valutazione della disponibilità idrica e del potenziale di producibilità idroelettrica a scala nazionale e di bacino, Tech. rep., CESI Ricerca, 2006 (Italian).
[32] Il Futuro Demografico del Paese – Previsioni regionali della popolazione residente al 2065, Tech. rep., Istat – Istituto nazionale di statistica, 2011 https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnxwcm9nZXR0b2d1bGxpdmVyMnxneDo3YmJlZDNjYzY3NzJhNmZj.
[33] J. Steinbach, D. Staniaszek, Discount Rates in Energy System Analysis – Discussion Paper, 2015, May.