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Application of Optimization Procedure to the Management of Renewable Based Household Heating & Cooling Systems

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Abstract

Renewable heating and cooling systems are cited in the European policy as one of the major means for the decarbonisation of the energy sector. At the household level the main source of renewable energy is represented by solar energy. This energy can be collected and used in the electric or thermal form and more than often its efficient exploitation requires the use of storage facilities. Starting from the previous statements a household heating and cooling system can contain several components whose control and coordination is not easy to handle due to the load variations through the year and during the day, to the weather conditions etc. Simulation and optimization of the energy structure is very helpful in this task because it can provide a commitment of the power flows that ensures the minimal system operational cost together with the satisfaction of load requirements. An optimization procedure based on mixed integer linear programming has been developed and applied to evaluate several household configurations for a location in Northern Italy. Obtained results are compared and assessed in terms of economical saving in system running and of share of renewable energy.

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Keywords: Renewable heating/cooling; PhotoVoltaics; Heat Pumps; Optimization;

Nomenclature

BHS	Backup Heating System
COP	Coefficient Of Performance
DSO	Distribution System Operator
EES	Electric Energy Storage
FIT	Feed-In Tariff
LP	Linear Programming
MILP	Mixed Integer Linear Programming
PV	Photo Voltaic
PEV	Plug-in Electric Vehicle
PEN	Polygeneration Energy Node
REH	Resistive Electric Heater

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RES	Renewable Energy Source
RHP	Reversible Heat Pump
TC	Thermal Collector
TES	Thermal Energy Storage
TOU	Time Of Use
XEMS13	eXtended Energy Management System 2013

1. Introduction

European Policy strongly encourages the use of renewable energy for the heating and cooling in the residential sector [1]. The shift from a fossil fired heating to an electric based one, possibly supplied by a renewable source, can be one of the feasible ways to increase the share of renewable energy for the final users. For instance, when reversible heat pumps are used, the heating and cooling can be largely working on energy coming from a local PV plant.

Several advantages can be reached with this solution:

- increase of the renewable energy share for heating and cooling;
- increase of the energy independence of the house from centralized infrastructures;
- lower impact of the peak loads required by the house on the electrical infrastructure;
- more electric energy available to increase the supply of new renewable based loads like PEV etc.;
- energy supply available for new services to be offered to the electrical grid.

Most of the previous points require that the RES would be used together with an energy storage facility that allows the decoupling in time of primary source availability and of energy requirements [2].

Following the previous considerations an autonomous household system for heating and cooling modifies its structure. From a classical heating/cooling plant made up of one boiler and one air-conditioner component, generally controlled by simple temperature set-points, the system evolves toward PEN: a multi-component structure made of several components (PV, RHP, EES, TES, BHS etc.) whose coordination is not easy. The dispatching of different power sources is sometimes depending on energy prices (gas, network electricity) and some others on meteorological conditions, like the availability of power coming from PV or the thermal request of loads depending on the external temperature.

The use of simulation and optimization tools can help the operation of the household system coordinating the production scheduling in a short time range (one day, one week etc.) basing its strategy not on the application of predetermined rules but adapting the scheduling on the base of needs, available powers and time-varying energy costs. The primary target of the optimization can be the minimization of the operational costs while fulfilling all the house requirements, but also the maximization of energy independence of the house can be taken into account together with the minimization of the greenhouse gas emissions [3]. The optimization of the operational costs is based on an existing plant structure, but its results can be used as well to compare different plant layouts and thus it can be used in the planning phase of the system for the assessment of different options in terms of operational costs savings vs. investment cost.

In the following the main characteristics of the optimization tool will be outlined and then the results obtained in one test case made by a detached house located in Northern Italy are presented and discussed.

2. Optimization procedure XEMS13

The optimization procedure presented in this paper deals with a medium time scale time horizon, in the order of hours, and its main target is the definition of energy production share between the units in the PEN to optimize operational cost of the node, the main characteristics of this approach can be found in [4].

The PEN can gain many opportunities by a strict coordination of the power production units, for instance by controlling profiles of power got from external network shaving peaks and/or by shifting loads maximum exploitation of primary energy sources (both conventional and renewable) by-passing possible infrastructural limits.

The system under analysis is defined by an input file and is made of three power networks: electrical, heating and cooling. These networks are subject to power balance equations and interact with electrical and natural gas infrastructures.

Loads are applied to each of the network as time profile of electric loads, heating and cooling loads. These loads are considered to be known or are based on some forecasting. Environmental impact of the system can be computed as emissions by the fuel burning components; emissions can be of two kinds: the amount of the greenhouse gases, which impacts on the global environment, or the exhausts of the fuel burning like nitrogen oxides, carbon monoxide, which impact on the local environment. Environment interacts with the system also at the level of temperature, which modifies the technical characteristics of some components, or changes the heating/cooling load. Another environmental datum is the solar irradiation that supplies possible PV or TC present in the structure.

The simulation/optimization of the system is carried out on a finite time horizon. To this aim, a scheduling time period is defined, as one day or one week, and a number of intervals of equal length (one hour, ¼ hour, etc.) is considered. In each of the time intervals both the control variables, as the power provided by the grid or by the storage, and the imposed ones, like the power produced by the PV plant, the power consumption of the user etc., are considered as constant.

Each of the source components of the PEN is characterized by a constitutive equation which is deemed to be linear or linearized by means of piecewise linear interpolation. Technical constraints can be set on each component by means of limits on the variables, for instance minimum and maximum values for generated power, minimum turn-on or shutdown time, self-discharge of the storage system etc. A complete list of the constraints that can be handled in the procedure can be found in [3]. Production cost of the energy is different for each component and is based on a marginal cost approach with fixed on cost and linear term. Storage of energy is considered both as EES and TES (hot and cold). The presence of storage unit makes the problem dynamical, that is each time interval is coupled to the others and no single instant optimization can be adopted. Each storage unit is characterized by its technical constraints and efficiency values. Aging effects on EES can be also considered as in [5].

A library of commercially available components (combined heat-power, heat pumps, boilers etc.) has been created to facilitate the input of the system. Environmental data, like temperature and solar irradiation, are considered as time profiles given in input to the system and can be provided by weather forecast data. Load data are provided as time profile as well as energy prices. Electricity prices are considered both for the electrical power purchased from and for the power sold to the grid. Prices vary throughout the scheduling period for instance as time-of use bands or on hourly basis as in the market situation. Economic incentives for the energy sold to the network can be considered as well.

The optimization problem can be formulated in terms of the minimization of the management cost of the PEN, which can be expressed as the sum on all intervals of the cost for the production of energy minus the earnings obtained by the selling of the energy to the grid. Maintenance and wearing out costs related to some components can be considered in the management cost. Constraints are set on power balances and technical quantities.

The particular structure of the objective functions and of balance constraints would allow one to use LP optimization procedures. Unfortunately, several technical constraints, like the on/off status of some component, require the use of integer values and thus a MILP formulation is used.

3. Technical layout of the household heating and cooling system

In order to highlight the advantages of the use of a renewable based heating and cooling, a household system with conventional structure is defined; all the results obtained by the optimizer will be then compared with this baseline case. The schematic layout of the conventional test case is shown in fig. 1. The system is made by three loads: electric heating and cooling load profiles. These profiles are obtained by the following assumptions:

- detached house situated in Northern Italy (climatic zone, as defined by Italian regulation "E" [6]) with an overall surface of 200 m^2;
- house energy class "D" [6], corresponding to a specific thermal requirement for the heating season of 98.1 $kWh/m^2/year$;
- house electric load profile obtained, on the basis of an average 3.6 number of occupants, from the source [7];

In the baseline case electric and thermal loads are satisfied by the electric and gas infrastructures. The electric grid is characterized by a TOU scheme for energy purchased with a peak price ranging from 8 am to 7 pm during weekdays, as defined by the Italian Electric Authority. Overall electric energy price [8], including taxes, applied to residential costumers from the most diffused Italian DSO is 23.26 c€/kWh in peak TOU, while off-peak price is 22.56 c€/kWh. Natural gas price [9], including taxes and fixed costs, applied to residential costumers is flat and equal to 0.96 €/sm^3, as used by boiler in the conventional configuration, which is considered to have a constant efficiency of 90% [10].

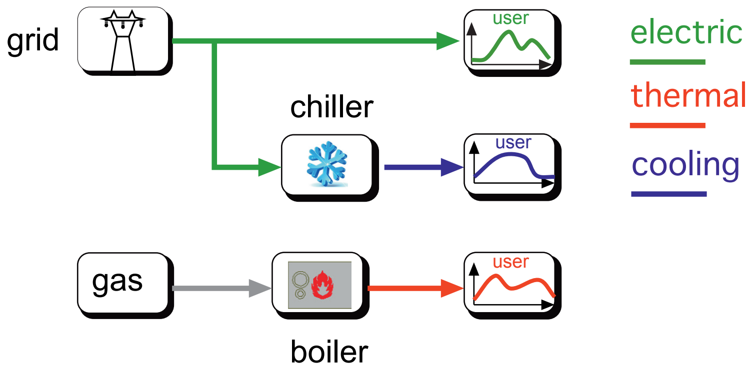


Fig. 1. Conventional heating and cooling system for the test case, referred as Case 0.

An upgraded configuration of the baseline case is obtained by the integration of the renewable house technical plant that contains two sources: a PV plant and a solar thermal collector. The PV plant is devoted to supply the house electrical loads and to provide power to the thermal heating and cooling generator that is a reversible heat pump. It is assumed that no FITs for PV systems are available to sell electrical energy to the grid. Under this assumption, the price of the electricity sold is derived from [11]. Selling of electrical power to the grid is possible but is economically not convenient since the selling price is 40% lower than the purchasing one, thus the most convenient use of the PV power is self-consumption. To increase the exploitation of energy self-consumption, two energy storage components are inserted: one EES and one TES, as reported in fig. 2. The first one is mainly used to store the excess energy produced by the PV plant during summer for supplying evening and morning loads. The second one is used mainly during winter to accumulate heat produced by the heat pump in the middle of the day when PV power is available, for later use during the evening peak thermal load. The thermal solar collector is mainly used to meet domestic hot water demand. A backup heating system, based on REH, is inserted to integrate the production of RHP in case of peak winter thermal loads due to low external temperature values. The efficiency of this system is obviously smaller than that of the RHP by the COP factor.

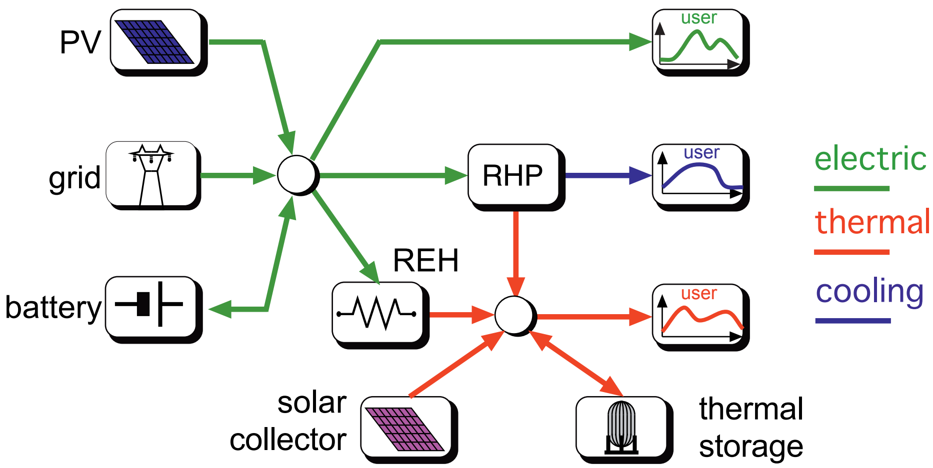


Fig. 2. Proposed technical layout of the new household system, referred in text as Case 2.

The main data regarding the test case are reported in Table 1. No particular architectural constraints are considered for the renewable sources so that their layout is considered, in the present case, corresponding to the most favorable conditions (orientation azimuth at South and tilt angle optimal for energy production). Solar irradiation profile is obtained by the PVGIS database [12].

The user loads are set on the basis of database defining the requirements in terms of the different energy forms present in the household environment: heating, electric and cooling. The main literature sources for the present case have been: [7] for the thermal load, [13] for the electric one and [14] for the cooling requirement.

Three cases are considered:

1. conventional case (Case 0);
2. renewable based system without thermal and electric storage (Case 1);
3. renewable based system with thermal and electric storage (Case 2).

In the upgraded configuration, the air to water RHP is assumed to have an average COP of 4.7 and 3.1 for heating and cooling application, respectively. Instead, the REH is assumed to have an average efficiency equal to 95%, while the efficiencies of the PV plant and the solar collector are 15% and 50%, respectively.

Table 1. Main data of components present in the case study.

Component	Quantity	Unit	Value	Case 1	Case 2
RHP	Power	kW	6.5	Yes	Yes
PV plant	Power	kW	6	Yes	Yes
Thermal solar collector	Surface	m^2	4	Yes	Yes
REH	Power	kW	6	Yes	Yes
EES	Energy	kWh	10	No	Yes
TES	Energy	kWh	20	No	Yes

4. Results and discussion

The optimization procedure XEMS13 has been applied to the three configurations of the test case as presented in the previous section.

The thermal load profile, as defined for the case of an average winter day in Northern Italy, is larger than the thermal power provided by the RHP, so the use of TES is crucial to satisfy heating requirements without resorting to the backup electric heater whose specific cost is higher.

In case 1 it is necessary to employ the REH, thus the economic cost is higher, in case 2 the use of storage avoids the action of the REH.

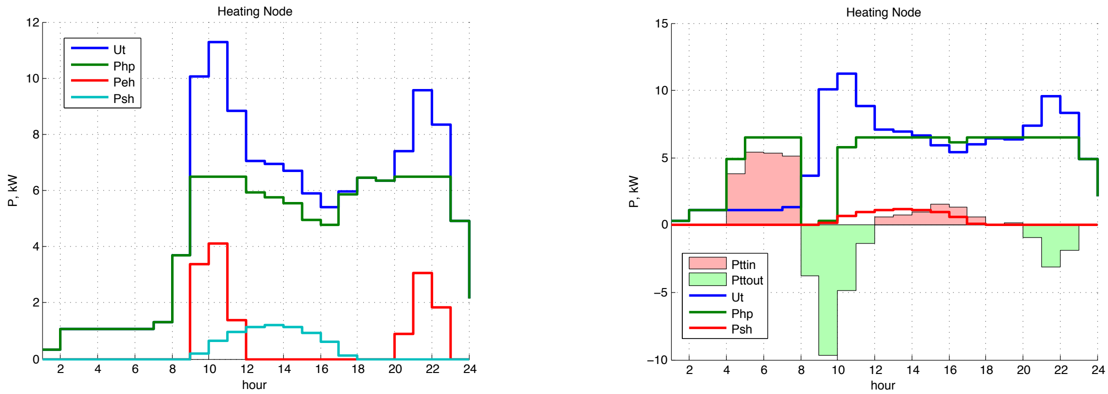
The hourly profile of the commitment of the various units in terms of thermal quantities is shown in fig. 4 for case 1 and 2. As it can be seen, the house thermal requirement is satisfied completely by the RHP and peak thermal loads are covered by TES in case 2 while the activation of REH is needed in case 1 to meet the house heating demand. In case 2, the storage of energy is made in two phases: during the night when grid electricity price is in the off-peak band and during the day exploiting the electrical energy coming from the PV plant. This behavior can be seen in fig. 6 where the behavior of the energy stored in TES is shown.

The commitment of the electric power flow is shown in fig. 5, again for Case 1 and 2. The hourly values of the different electric productions/consumptions are shown. As it can be seen, in case 2 the combined use of TES and EES allows the complete self-consumption of the energy produced by the PV plant which can be used directly in the mid day hours by the RHP. The excess production is stored, mainly in the EES for later use in the evening, but also in the TES when the house thermal load is lower than the RHP rated power. On the contrary, in Case 1 the excess of PV production is sold to the network during the central hours of the day which leads to a lower economic income due to the low price for selling.

For what concerns the operating costs, the house thermal requirement is satisfied with a cost that is 26 % of that of the Case 0 in Case 2, while Case 1 reduce the cost to the 47 % of case 0. In analogous way, the CO_2 emissions in Case 2 are 24 % of those of Case 0 considering an emission factor of 0.459 CO2 kg/kWh of the average electrical energy power stations in Italy [15]. In case 1 the reduction is of 45 %. In the considered case, during the winter day the average share of RES heating is of about 67 % for Case 2 while is 55 % in Case 1.

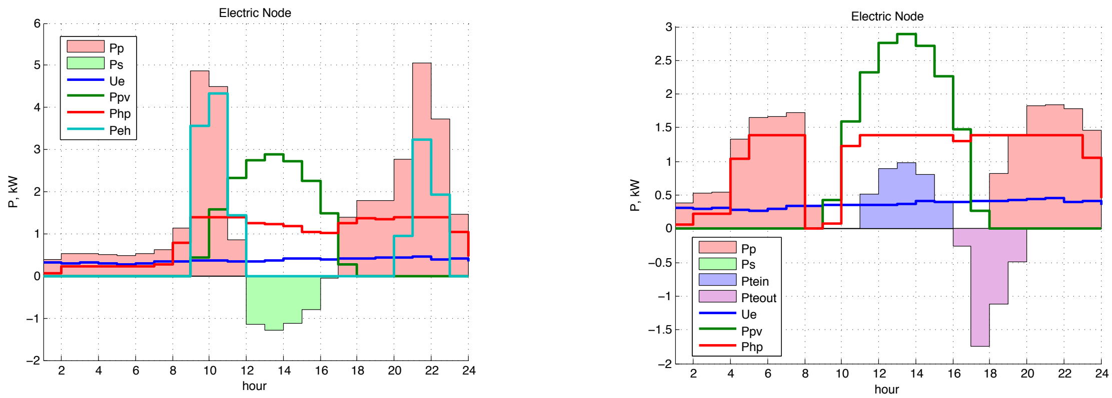
Table 2. Main results obtained in test cases.
Results are shown in percentage of the conventional configuration (Case 0).

	Economic cost	CO_2 emissions	RES heating share
Case 0	100	100	0
Case 1	47	45	55
Case 2	26	24	67



(a) (b)

Fig. 4. Profile of heating power as provided by the optimizer: (a) Case 1, (b) Case 2. Ut thermal user requirement, Php power provided by RHP, Peh power from electric heater, Psh power from solar thermal collector. Painted areas refer to the power exchanged by the TES.



(a) (b)

Fig. 5. Profile of electric power as provided by the optimizer: (a) Case 1, (b) Case 2. Ue electric user requirement, Ppv power provided by PV, Php power consumption of RHP. Painted areas refer to power exchanged with the grid (Pp purchased and Ps sold) and exchanged with EES.

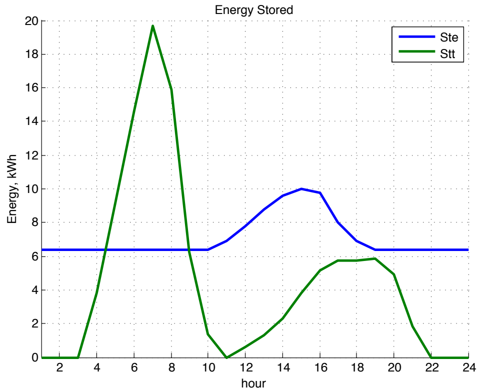
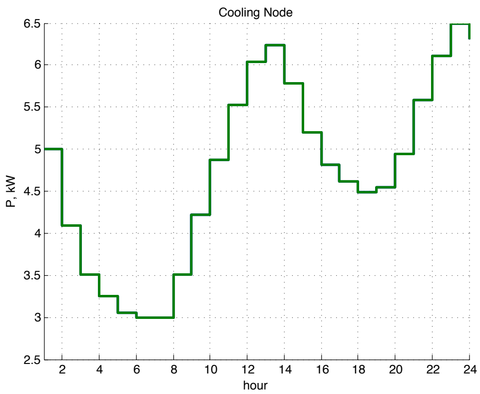
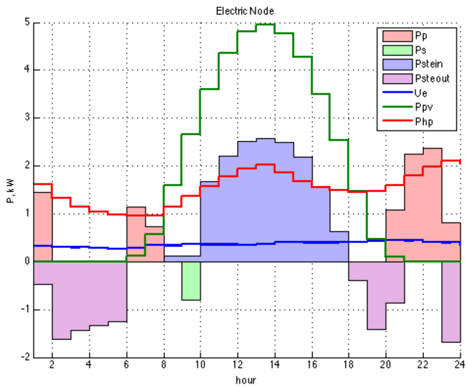


Fig. 6. Profile of energy stored in TES (Stt green line) and EES (Ste blue line) as provided by the optimizer.

The same structure is simulated during a summer day. In this case the thermal load is given only by sanitary hot water demand, while a cooling requirement is present. The variation of the cooling load during the day is shown in fig. 7, together with the electric power production. As it can be seen, the use of an electric storage is crucial to keep a high level of self-consumption which, in the present case, reaches the value of 98 % of the PV production. During the summer season, the cost reduction of the renewable based case is lower with respect to the winter case. The management cost of the renewable case in summer is 79 % of the conventional one, while CO_2 emissions are reduced at the 80 %.



(a)



(b)

Fig. 7. Summer day: (a) profile of the cooling load, (b) electric power as provided by the optimizer.

5. Conclusions and Perspectives

One energy management procedure has been developed for the management of poly-generation nodes where more than one power supply is present and where different energy requirements (heating, electric and cooling) are interconnected by means of components like the heat pump. The procedure has been applied to a household test case located in Northern Italy and energy requirements have been simulated in terms of the energy class of the house and on the basis of load databases.

The procedure has shown that, with an optimal management of renewable energy production and of energy storage, it is possible to cut the running costs of one house of more than 70% in the winter season. Similar encouraging results have been obtained also in the summer season with a high level of PV production self-consumption but with lower impact on the running costs. The simulation of two cases: one without and one with energy storage has highlighted how the use of storage is crucial to increase the economic convenience and the share of renewable energy consumed inside the house.

The production profiles, provided by the optimization procedure, are based on the minimization of the operational costs. This control strategy is not currently present in the control systems, mainly devoted to the implementation of rigid control loops based on temperature set-points, an that, as a consequence, cannot exploit the use of storage at its best. The implementation of the proposed approach inside the run-time control of the system requires the forecast of the renewable productions and of the consumptions. Weather forecasts can be used for this purpose at two levels: one in the forecasting of the energy produced by PV and solar thermal collector and one in the prevision of the loads.

The obtained results can be used to quantify the advantage the possible saving in the operating costs and thus can be the cash flow input for an economical evaluation of the costs/benefits coming from a major overhauling of the household technical plant.

The use of renewable energy sources gives a more than significant contribution to the reduction of the greenhouse emissions by the residential sector, one of the major contributors to the carbon dioxide pollution.

The work will go on in defining the requirements for a real-time optimization environment, which can implement the energy management procedure in a “smart” controller able to cope with weather and load forecasts and with different environmental and technical dynamical requirements.

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