Toward Sustainable Energy Communities

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Abstract: Currently energy resources are adapted to user requests. In the perspective of an increasingly sustainable use of energy, it will be more and more useful to aggregate the consumption of groups of buildings of various types (for example for residential, office, commercial and industrial use), forming the so-called "Energy Communities". In that way the overall requests for energy can be easily adapted to the available energy resources, in terms of both overall consumption and hourly distribution. The AUTENS (Sustainable Energy Autarchy) project aims to identify possible solutions for the complete energy self-sufficiency of "Energy Communities" through innovative methods optimizing the integration of electrical and thermal systems (generators and storages), supplied only by renewable sources produced locally. This will be targeted by means of suitable integration of ICT technologies, artificial intelligence and social sciences. We intend to examine situations in which it is not possible, or sustainable, to use the primary power and gas grid, and therefore the use of energy from an "Energy Community" must be made with only renewable sources to be produced locally through solar and wind energy, geothermal and biomass. The project also proposes the construction of some demonstrators.

1 INTRODUCTION

One of the most important challenges that awaits humanity is to prepare society for the goal of a decarbonized society at 2050, as clearly states also by the European Commission President Ursula von der Leyen "We are doing everything in our power to keep the promise that we made to Europeans: make Europe the first climate neutral continent in the world, by 2050".

The initiatives promoted by Greta Thumberg have brought climate changes to the attention of civil society and governments. Controversial discussions also of a scientific kind was born facing from one side "negationism" issues based on the observation that climate changes has been many times experienced in the past and from the other side remarks that in our age there is a very high speed of climate changes with respect to the past.

However there is an aspect that cannot be neglected, namely that the anthropization of the planet is truly an absolute novelty compared to past eras and this entails consequences that will most likely strongly conflict with the habitability on the planet and the quality of life of the human race in the near future even in the medium term.

If it is true that a great improvement of the "average" quality of life of many populations in the last century is due to the use of energy and the availability of raw materials, and that the availability of both on the planet is limited, then it is clear that the models of current economic development are inadequate to reconcile an always increasing economic development with the resources available on the planet. The risk is that the lack of resources makes it impossible at some point to maintain the "wealth" achieved, prefiguring very worrying scenarios of socio-political instability and conflict.

It is therefore necessary not only to move towards production systems based on circular economy but in particular to be ready to transform the present social behaviors.

One possible way is to aggregate individual consumption (both of individual citizens and industries) in groups called energy communities, where on a medium / small scale they go to reconcile and even negotiate individual needs to ensure the

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needs of everyone on average. We could thus move to a vision (whose realization today is facilitated by the digital revolution) in which the sustenance of the communities was provided by the resources that one was able to self-produce. In particular, in the case of communities of users that are close even geographically, the self-produced energy may also depend on the agro-energy resources available locally, thus also preserving biodiversity.

2 BACKGROUND

The starting point of the project is a software developed in the framework of a previous project able to carry out an optimal evaluatation of Hybrid Renewable Energy System (HRES) investments (Noh et al., 2016). The software is based on a simulation approach that consider all the involved subsystems (photovoltaics, small wind turbines, solar thermal, heat pump, electric and thermal storages, heating and cooling emitters, building envelope, traditional back-up systems) and their mutual interactions. A multi-objective optimization finds the Pareto frontier that maximizes Net Present Value (NPV) and minimizes CO_2 emissions in three relevant scenarios, taking into account the high sensitivity to the conventional fuel cost variation.

The output of the methodology may steer the decision maker to a more in-depth analysis and characterization of the critical variables and possibly towards a more robust design choice. and people behaviours with regards to energy use. Furthermore, it can improve academic teaching programmes, steering them towards a global vision.

2.1 Software Application Example

The medium-long term planning of the construction of an integrated thermal and electrical energy production system fed by renewable sources – also known as Hybrid Renewable Energy Systems (HRES) – is an interesting, albeit tricky, investment decision, which occurs under heterogeneous uncertainty. In fact, in recent years, the deregulation of the electrical energy sector and the growing attention towards environmental concerns have significantly stimulated the energy production market and, consequently, have both raised the attention of investors and added new variables and constraints that further complicate such investment decisions (McGovern and Hicks, 2004). For example, see the call for reduction of greenhouse gas emissions, the new targets for penetration of Renewable Energy Sources (RES) in the electricity generating mix, and the Energy Performance of Buildings Directive (European Parliament and Council, 2012), which requires new buildings to be nearly zero-energy by the end of 2020.

Such trends call for a robust and integrated investment evaluation approach to deal with the increasing complexity of the decision context, to reliably model the dynamics of the subsystems involved in an HRES (Electrical, Thermal components and Buildings), and to control their deep interconnections.

The software presents an integrated, multi-objective, four-stage methodology to evaluate long-term HRES investments by comparing different system configurations, coping with the above-mentioned issues. The methodology includes a simulation-based optimization procedure that integrates the electrical generation, the thermal systems, and the building of the investigated HRES, and provides useful information concerning the investment choice and the analysis of the output reliability. Furthermore, it considers the minimization of the equivalent CO_2 emissions corresponding to the possible HRES configurations.

Simulation-based procedures are among the most adopted approach for investigating electric production of HRES (Bernal-Agustín and DufoLópez, 2009a; Zhou et al. 2010) and very effective and favorable for building-energy systems (Hamdy et al., 2013; Kapsalaki et al., 2012) and in building energetic studies (ASHRAE, 2009; Nguyen et al., 2014).

The analyzed case study is a small-size building powered by a HRES – specifically, an offgrid thermo-electric system). These systems usually have strict budget limitations, which force designers to find the optimal sizing of technologies in terms of cost-benefits. In smallscale systems, accurate input data are generally available and manageable, allowing the simulation models to deepen the analysis of the energy system. A peculiar case of such systems is an autonomous system, *i.e.* an off-grid system, serving both electric and thermal demand, which is typical of rural areas, mountains, and small islands and quite common far from the urban environment and socially important for certain communities. An autonomous system is an example of nearly Zero-Energy Buildings (nZEBs), as sought by international energy directives and initiatives.

Specifically, to apply and test the proposed methodology, we chose a stand-alone farm hostel located in Enna, in the south of Italy, at 931 m above sea level. The climate is cold in winter (Heating

Degree Days: 2248) and hot in summer and the building requires energy for space heating and cooling, ventilation, domestic hot water (DHW) production, induction cooking, lighting, and other electric uses, *e.g.* household appliances, refrigerators, dehumidifiers, and electronic devices. Besides, renewable energy sources, such as sun, wind, and biomass, are locally available.

In this site, an integrated microgeneration system with small wind turbines, photovoltaics, and solar thermal technologies has to be optimally designed. Proper thermal and electric energy storages are employed and an electrically-driven heat pump provides the net thermal energy demand. As mentioned, the building is off-grid, relying on renewable energy sources, which should be optimally exploited and managed. An electrical energy generator (a diesel engine) is the only back-up, needed to cope with the residual energy requirements. The integration among energy sources and the overall must be effectively tackled to avoid unnecessary oversizing and inefficiencies of the installed technologies.

For each component, the most reliable and commercially available technology was selected. The rationale behind this choice is due to the small scale of the system and the investment context. Yet, whether necessary, the methodology may be easily extended to evaluate different available technologies for each energy system (*e.g.*, different PV cells or wind turbines, etc.).

Further details on the typical hourly and seasonal users' presence and behavior and on the characteristics of the building and systems for this specific case study are given in Testi et al., (2016a).

2.1.1 The Simulation Model

The HRES design strongly depends on the dynamic performance of its individual components, on the available RES, and on the end uses. Figure 1 illustrates a schematic of the integrated system, including the electric and thermal energy fluxes

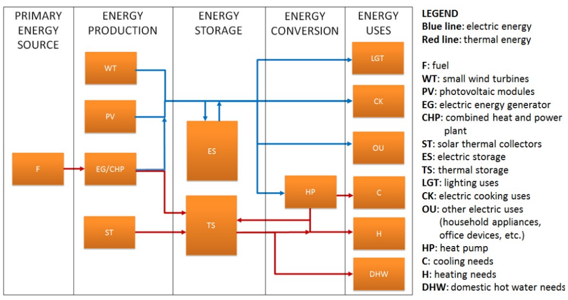

Figure 1: Simulated sub-systems and interconnections.

The input variables of the simulation model and their bounds, which define the search space, will be shown in Table 1 for the sake of brevity.

Table 1: Design variables and bounds.

Design parameter	Bounds	
	Min	Max
Number of small wind turbines: nWT	0	4
Number of photovoltaic modules: n_{PV}	0	60
Number of solar thermal collectors: n_{ST}	0	6
Volume of the thermal storage [L]: V_{TS}	500	5000
Capacity of the electric energy storage [kWh]: C_{ES}	1	100
Electric power of the storage converter [kW]: P_{ES}	6	10
Electric energy generator with/without recovery	0	1
Installation of a biomass boiler: Yes (1) or No (0)	0	1
Thermal storage temperature for switching off the heat pump [°C]: T_{TS_HPoff}	46	56

2.1.2 Results and Discussion

Figure 2 shows the Pareto front determined by the NSGA-II algorithm on the simulation data, representing 70 points that are equally optimal for the three selected scenarios (scenarios A, B, and C, where diesel fuel cost is estimated to be, respectively, 1.2, 1.6, and 2.0 €/L).

When CO_2eq emissions are considered, all the presented solutions outperform the Option Zero (No-RES configuration), which fulfils the energy demand exclusively by means of the electric generator. Option Zero has high CO_2eq emissions (18 tons per year) and NPV is conventionally equal to 0.

Nevertheless, some optimal designs found on the Pareto set show a negative NPV, in particular those belonging to scenario A and/or that minimize the CO_2eq emissions, because they require to maximize the adoption of energy-efficient production and conversion technologies and energy storages.

The scenario analysis highlights that NPV is very sensitive to the cost of fuel. This confirms the relevance of a careful and accurate forecast of the underlying value, such as the fuel price, or of the electricity price in the cases of on-grid plants.

As expected, the Pareto front shows a similar shape in all the three scenarios, while they are shifted with respect to the NPV value. For the sake of clarity and brevity, we discuss three relevant optimal candidates from the nominal scenario B (B1, B2, and B3 in Figure 2) and, in the section 5.2, only one candidate from scenarios A and C (A1 and C2 in Figure 2).

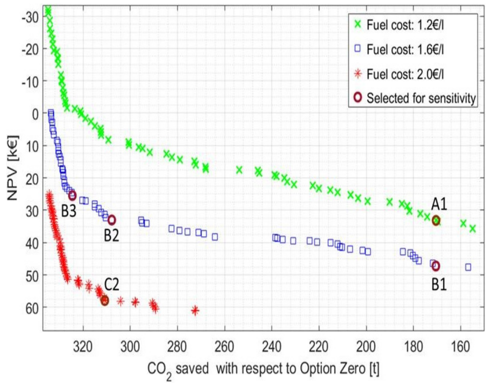

Figure 2: Pareto optimal front in the three scenarios; solutions of the Pareto optimal set, shown in a circle, are identified to compare the sensitivity of design configurations.

Looking at the Pareto front by an economic perspective, the best solutions identified by NSGA-II, which present the maximum NPV and also the highest PI, suggest minimizing the use of wind turbines and solar thermal collectors and not to adopt heat recovery for the electric energy generator. The optimal design, differently from the other solutions, also limits the installation of electrical batteries. The final estimate for NPV is 47.2 k€, while CO_2eq saving amount is about 170 t, which is around 50% of the maximum CO_2eq savings provided by the most sustainability-oriented configurations.

This evidence, which remains confirmed for all the investigated scenarios, is due to the high impact of wind turbines and electrical battery initial capital costs and also of battery replacement costs on the NPV evaluation. The use of these technologies is not justified, especially when the fuel cost is low, since we always perform a comparison with the highlyconsuming Zero Option. Nonetheless, in scenario C, we can observe that the configurations of optimal NPV have lower greenhouse emissions, since an additional investment on renewable technologies is economically justified by the high fuel cost.

On the opposite border of the frontier, the optimal solution that seems to better perform in minimizing CO_2eq emissions. Besides, the design candidate suggests investing into heat recovery: a combined heat and power (CHP) unit is adopted. Under these conditions, initial installation and replacement costs rise up. Yet, lifetime costs are still lower than the Zero Option.

Other optimal candidates are obviously available. The decision maker can use the Pareto front to choose the most adequate design configuration according to her/his own needs, balancing the economic-financial perspective with the system sustainability.

3 AUTENS PROJECT

The AUTENS (Sustainable Energy Autarchy) project of the University of Pisa aims to implement research activities to the creation of new strategic ideas for sustainable development, by studying new paradigma for energy production from renewables and people behaviours with regards to energy use. Furthermore, it can improve academic teaching programmes, steering them towards a global vision.

The Project focused also on the relationship with local institutions in order to achieve a wider vision, to provide new and useful tools, through responsible cooperation, for a rapidly changing world.

Furthermore education and dissemination instruments will be defined to inform students and citizens on the clean and affordable energy goals as clearly stated in the SDG 7 to strenghten the principles of Sustainable Development and Agenda 2030 goals.

Presently the current approach for the energy providers can be described as follows. On the basis of an energy need (e.g. hourly production of hot water at a certain temperature), an energy system is designed to fulfill the request, while trying to maximize energy, exergetic, economic and environmental performance (the so-called 4E). Therefore the energy requirement constitutes a constraint for the supplier who uses the existing solutions to satisfy it.

In the perspective of an energy autonomy of users, it is instead necessary to prefigure a completely innovative case study, overturning the current paradigm and providing a scenario in which it will be necessary to adapt the energy demands of users (also by negotiating consumption for civil and industrial uses) with the energy resources available, in terms of both overall consumption and hourly distribution.

4 PROGRAMMED ACTIVITIES

The AUTENS project goals are to identify possible solutions for the complete energy self-sufficiency of communities through innovative methods for the integration of electrical and thermal systems (generators and storages), feeded only by renewable sources produced locally, through the integration of ICT technologies, artificial intelligence and social sciences. In particular, we intend to examine situations in which it is not possible, or sustainable, to use the power and gas grid, and therefore the energy supply of civil or industrial buildings must be made only with renewable sources to be produced locally through solar, wind, geothermal and biomass energy.

This pespective push towards a strong change of current social habits and lifestyles, both in terms of citizens' consumption and productive activities. It is therefore important an innovative combined scientific-technological, social and regulatory study that foreshadows possible solutions to be ready to face these scenarios. Furthermore it becomes strategic and necessary to integrate research groups that tackle the problems by simultaneously considering the social and technological aspects.

For this reason, the project integrates different types of expertise with a highly interdisciplinary approach necessary to systemically address issues related to energy and its close connections with economic, social and political sustainability. In particular, the project combines the electrical, electronic, thermal, chemical aspects related to energy production with data analysis and artificial intelligence techniques, as well as economic and market ones. Furthermore, it also includes the necessary social and legal-regulatory aspects.

To develop system corresponding to the AUTENS scenario, it is necessary to study the ways in which users, both in single and aggregate form, can become completely autonomous in energy supply. For this purpose, the project includes the following activities.

- Socio-economic survey to (i) obtain profiles of electrical and thermal energy needs in the current context and (ii) understand the social acceptability of the predicted energy self-sufficiency scenarios, including the availability to changes in energy consumption styles due to a limited energy availability and negotiation with consumption for production activities.
- Solutions for the integration of storage systems, and renewable sources, with ICT technologies and electronic platforms that maximize flexibility and energy efficiency, minimizing the impact on people's wellbeing and industry activities.
- Combination of quantities of energy production from biomass to be grown locally according to the climatic characteristics of the specific place.
- Development of intelligent techniques based on the monitoring of energy consumption and climatic conditions of buildings and industry plants to provide users with an expert system to support decisions. An interdisciplinary study will be carried out to define appropriate models for the collection, use and circulation of data, also considering privacy aspects
- Study of regulatory norms for the self-production of energy (Renewable Energy Community) in the national and European legal framework, to verify their ability to represent a real incentive for AUTENS systems

Finally, the project will use an existing "hardware in the loop" laboratory facility for emulation of the systems under study. This allow to measure the performance of hybrid thermal / photovoltaic (PV / T) solar panels, geothermal heat pump systems (GSHP) , the phase change accumulations (PCM). Finally, it will be possible to implement a monitoring and control system with machine learning algorithms.

5 CONCLUSIONS

The AUTENS project will consider innovative methods for the integration of electrical and thermal systems (generators and storages), supplied only by renewable sources produced locally. Situations in which it is not possible, or sustainable, to use the primary power and gas grid, will be studied. Distinctive features of the project will be suitable integration of ICT technologies, artificial intelligence and social sciences. Furthermore, the use of energy from an "Energy Community" will be considered be made of only renewable sources to be produced locally through solar and wind energy, geothermal and biomass. The project also proposes the construction of some demonstrators.

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