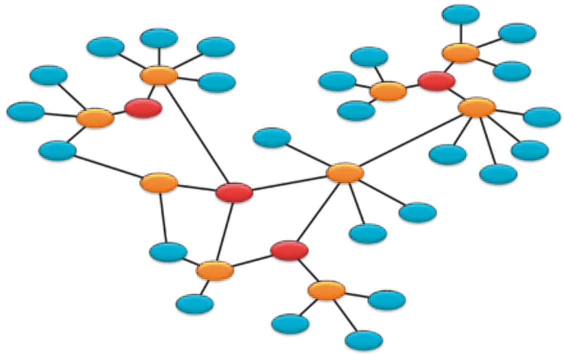
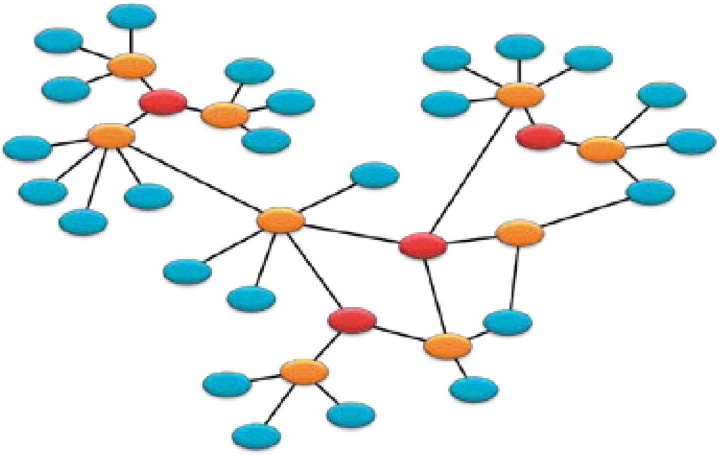
MicrE

Micro Energy
to Rural Enterprise



The Future of Energy Services

Potential of Smart Energy Networks
in the Northern Periphery



Report based on a diploma work conducted within
the Micro Energy to Rural Enterprise (MicrE) project

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Introduction and Background

Global challenges of the 21st century call for a new way of conceptualizing the energy distribution platform. Future trends for global energy consumption, increasing energy costs and environmental issues [1-2] are pushing for an increased use of renewable energy sources, smaller-sized power plants and distributed generation (DG), improved efficiency and reduced environmental impact. In this framework, the future development of the European energy network, a major contributor to global greenhouse gas (GHGs) emissions, will have to be re-thought. The re-shaping of the energy network will need to take into account growing demand, technological breakthroughs as well as the new economic environment. This leads to numerous technical and non-technical challenges such as reliability, cost-effectiveness, and a more ordered energy network management system that would facilitate an effective use of renewable energy sources (RES) and their DG. The smart energy network is a solution to these needs, through which consumers are given the possibility to be directly engaged.

This study was carried out under the Micro Energy to Rural Enterprises (MicrE) project. The project aims to develop and promote innovative renewable energy solutions for rural small and medium-sized enterprises in the Northern Periphery (NP) with special emphasis on small scale energy solutions from by-products and waste. In this framework, this work presents the possibilities, the socio-economic costs and benefits that a new way of thinking the energy production and distribution can offer, evaluating the scalability and adaptability of current technologies, and contributing to a sustainable energy development strategy in the NP area. Regions comprised in the NP area share important common features in terms of challenging climate, population density, and natural environment. Traditionally very resource intensive, these regions have been dependent of fossil energy mainly due to the challenging topography and harsh winters. These territories are also characterized by common strengths and challenges; a remarkable richness in natural resources accompanied by high quality education, high-tech and high standards of services.

What is a smart energy network?

The expression smart energy network indicates an energy production, transmission and distribution network that allows suppliers and consumers to have a two-ways communication monitoring in real time the network condition (i.e. the electricity production, consumption and distribution) [3]. This model of energy network allows for a more dynamic system control, making it possible to respond more efficiently to changes in the grid conditions. Using real time monitoring together with smart control system capable to evaluate and improve its performances, the envisioned smart network based system can anticipate and mitigate power peaks and power quality problems while, at the same time, it allows for a more prominent position on the market of those renewable energy resources characterized by a discontinuous and irregular generation (i.e. wind power).

The transition from a highly centralized energy network to a decentralized one implies a more interactive and participatory role of the consumer. Due to a real-time two-ways communication, consumers are empowered to gain through a more efficient energy usage and, by enabling distributed power generation, to directly interact with the energy market, initiating a participation in the energy market.

Smart energy network vs. Smart grids

The expression smart grid is usually considered to include only the electrical energy network (or power network). In our work we tried to differentiate ourselves from this more common understanding of the energy network for three reasons:

- from an economic point of view electricity represents only a fraction (15% to 20%) of the global energy consumption [4];
- from an environmental point of view, electricity is responsible only for a share of the GHGs emission [5];
- from a technical point of view, limiting the analysis to a single form of energy causes the misinterpretation and an underestimation of the potential of other energy vectors and their complex interplay.

Data courtesy Marc Imhoff of NASA GSFC and Christopher Elvidge of NOAA NGDC. Image by Craig Mayhew and Robert Simmon, NASA GSFC.

The development of energy systems

During the years the evolution of the energy network has been characterized by a number of transformations reflecting the social, economic, technological and political reality of the time. The future development and deployment of a smart energy network based system is also a result of this evolution, and understanding how we got where we are today can help us to understand the criteria behind the future choices. The modern power system is the result of a century long development based on an over a highly centralized model [6]. From the beginning, the structure of the power system has been built following a rather straightforward scheme (Figure 1): with a relatively small number of large production centers delivering power to consumers through the transmission and distribution networks.

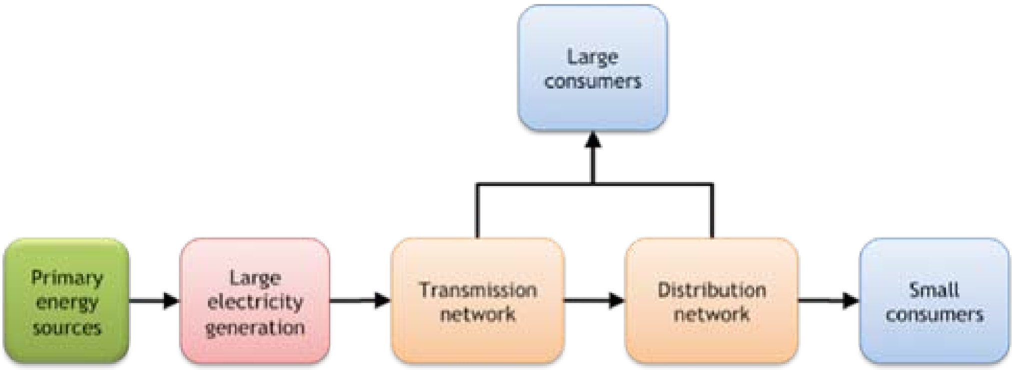


Figure 1. Schematic representation of the power supply system before liberalization. Figures based on [6].

The advantage of this model was in its simplicity: large power producing units could be made efficient and run by a relatively small amount of personnel, with transmission and distribution networks designed for a unidirectional flow and scaled to fit the consumers' loads.

With the liberalization of the energy market in Europe at the end of the 90's [7], the previously integrated service companies in charge of energy production, transmission and supply, were required to unbundle. This brought a significant change in the structure of the power supply system (Figure 2) with a separation between the management of the physical transmission and distribution networks from the corresponding supply markets (wholesale and retail respectively).

the ancillary service markets other power quality services were made available, such as reactive power, voltage control, etc.

In a liberalized market, the growing DG sector was prevalently playing a passive role: substantially an appendage of the distribution network without any real sizable interaction with the rest of the supply system. In more recent years, the combined effects of liberalization of the energy market on one side and the support for renewable energy solutions on the other produced new opportunities for participating in different markets.

What's next?

The market liberalization brought further modifications to the power supply system structure. Small scale distributed power gen-

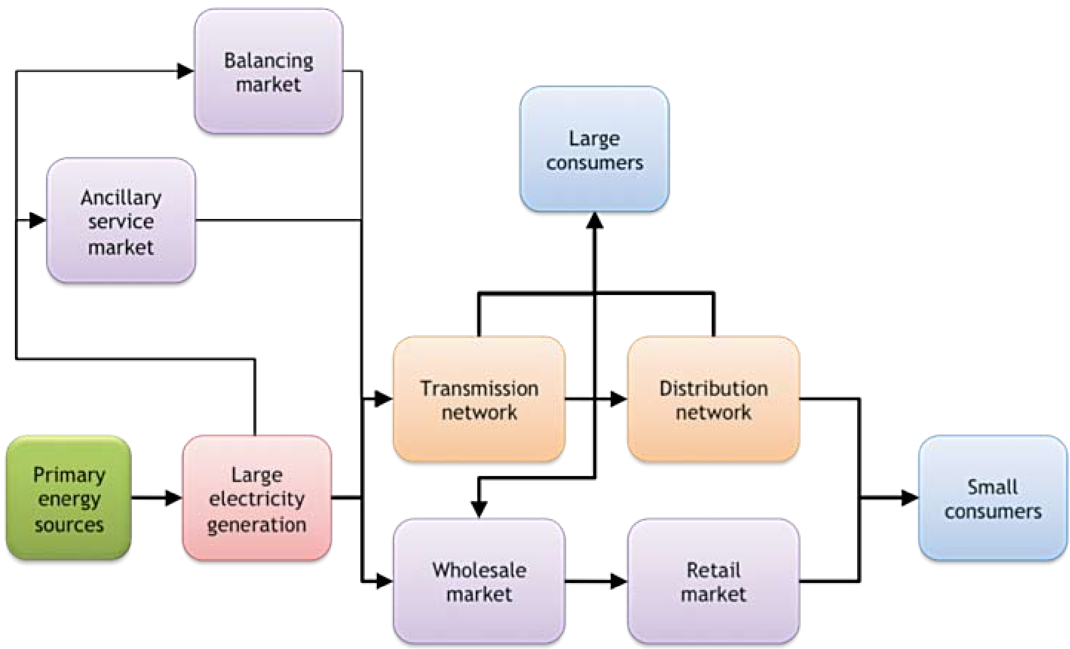


Figure 2. Schematic representation of the power supply system after liberalization. Scheme based on [6].

The new system opened the possibility for the development of two more markets: the balancing and the ancillary services markets. In a now more complex system with a growing number of interacting players, it became increasingly important for transmission system operators (TSOs) to be able to purchase surplus power in order to maintain a balanced network, now more exposed than before to unbalances between supply and demand. On

erators, by tapping into previously unused RES, are now able to directly deliver power to consumers or to operate via electricity markets (Figure 3).

The implications on the required system development at the infrastructural level are of primary importance. A network designed for a radial structured unidirectional power flow has to be converted in a networked bi-direc-

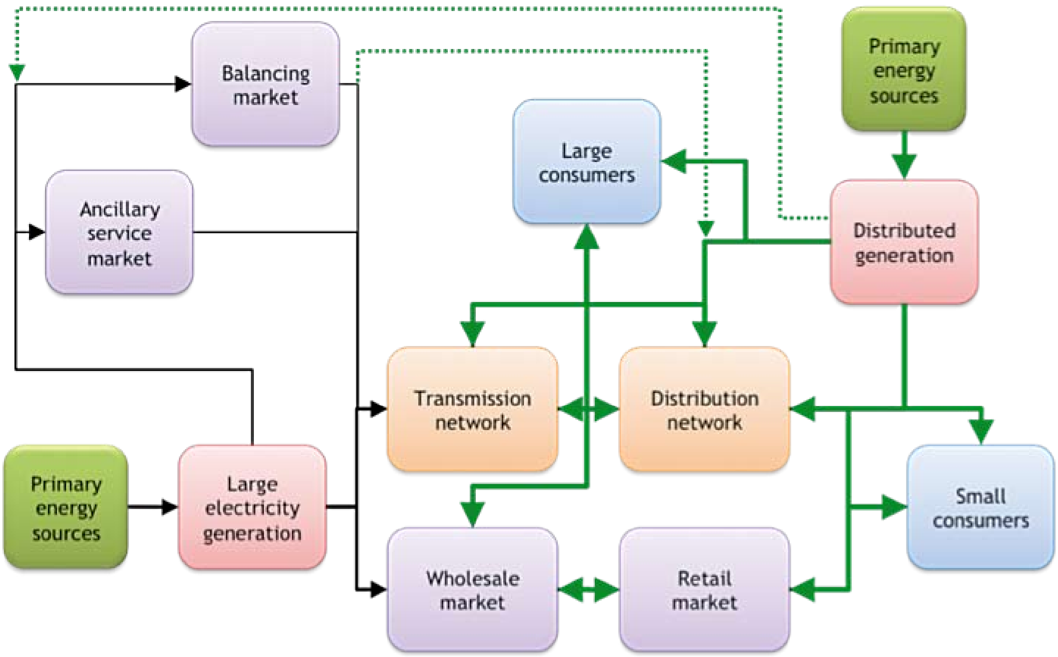


Figure 3. Schematic representation of the power supply system in a liberalized market with the integration of DG based on RES. Scheme based on [6].

tional flow structure. The very role of the network and, consequently, of all the players operating in it, is expected to change. The network will not only distribute power, but will also need to provide access among the connected parties. As the role of DG is expected to grow and develop, so it is reasonable to expect from its role on the markets, including eventually the balancing and the ancillary service markets. This last stage of the evolution of the power grid has not reached maturity yet. It is within the framework of this last evolutionary step of the power grid that the smart energy grid based system envisioned in this work is to be developed.

Evaluation of the potential of smart energy networks in the Northern Periphery

In our analysis, we have been addressing the potential and the adaptability of a smart grid system within the Northern Periphery area. A hybrid micro-grid simulator was developed (Figure 4), which makes a smart use of the available renewable energy resources based on a demand-response logic principle. The hybrid system includes a number of selectable energy production units: 3 bioenergy-based CHP units, a wind turbine and a PV system. It also uses a plug-in hybrid electric vehicle (PHEV) as one of the storage elements. Weather records of Northern Finland are used to determine the contribution of renewable power sources (i.e. wind turbine), as well as the energy demand (i.e. built environment heating system). Pre-modeled power and thermal energy needs are monitored by the system and matched using the available selectable resources. Power storages are programmed to compensate for energy surpluses or deficits and, in the case of the PHEV, to meet the users' requests concerning the use of the vehicle.

The main point of the simulator is to model the communication with the energy network from the end-user's point of view, serving as a blueprint for the modeling of a smart energy network. At this first stage of the development, communication with the power grid has been monitored, however, the modular structure of the simulator makes it easy to add further components.

System Architecture

The micro-grid simulator has been developed using as a reference a small- or medium-size enterprise (SME) located in a semi-urban environment in Northern Finland. This allowed the possibility to consider electrical and district heating network connections. Figure 4 presents a schematic representation of the system components and their interconnections.

The main components of the system architecture are:

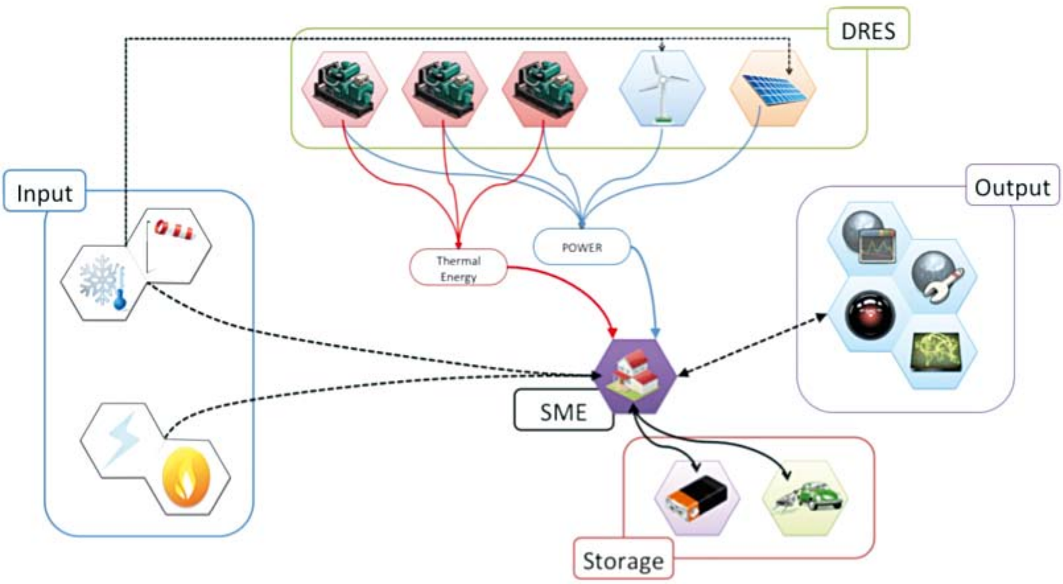


Figure 4. The elements of the modeled micro-grid and their interconnections. The built environment is monitored ( ) by the smart system which is able to answer to the energy needs ( ) on a demand-response energy principle, and regulate the communication with the grid. Our target is to further develop the system ability to adapt to changes in the grid conditions ( ) and to monitor the behavior of a large scale model ( ).

- The SME block, containing the description of the built environment with the corresponding need of electric and thermal energy

- The Input block, providing the necessary environmental and system information.

- The distributed renewable energy sources (DRES) block with the description of a number of selectable energy production systems, some of which related to the environmental data.

- The Storage block describing the electric energy storage device, and a sub-block considering the possibility to of a plug in hybrid electric vehicle.

- The Output block where all the necessary data are collected and monitored.

All the considered scenarios were based on predetermined common power and thermal energy requirements. All the reported data covered a period of one year, from the zero hour of the 1st of January to the midnight of the 31st of December 2010.

System and Environmental inputs block

The input block contains the system and environmental information required for a proper functioning of the simulator and it includes:

- Selectable indoors temperatures and power consumption profiles. The electrical energy consumption was modeled following a $\cos^2$ trend in order to mimic the seasonal variation of power consumption (Figure 5). The thermal energy requirements were determined by the outdoor temperature, which on the basis of the modeled built environment, could be assumed to be directly proportional to the total thermal energy needs; simulation results verified the validity of this assumption (Figure 6).

- The actual indoor temperature and the need of thermal energy were determined by the heat losses of the previous hour, in turn directly proportional to the indoor/outdoor temperature gradient. Consequently, the outdoor temperature could function as a reliable indicator of the thermal energy needs.

- Environmental and weather information such as outdoor temperature, wind, cloud cover and PV system performance. Changing the geographical location of the considered case study affects the overall performance of the system as the outdoor temperature and the environmental condition have strong influence on the requirements of the heating system and on the performance of RESs, in particular wind and solar power generation.

- Electricity prices for the corresponding time and location were included. Prices indicated the electricity cost at retailer and at the (nationally averaged) consumer level, providing a basic comparative evaluation on the economic performance of the system.

- Input related to the use of the plug-in hybrid electric vehicle (PHEV). Data include car and battery usage, the battery consumption and recharging time. Most of this input data were randomly produced following a predetermined statistical distribution.

It has to be underlined that the system has been designed to model the role of a micro-grid within a larger smart-energy network. As such a system is expected to guarantee the possibility for end-user (now small distributed producers) to share surplus of energy, the economical performance of different scenario includes the calculation of output of energy. Considering that the first step toward a smart-energy network is likely to be a smart energy consumption coupled with small scale distributed generation using locally available resources, our study was limited to the role of a smart-microgrid within a unidirectional energy network.

The built environment

The SME block contains all the necessary information for a basic modeling of the built environment: in the considered scenario a medium size building for commercial use. While architectural sophistications have not been included, structural energy losses have been

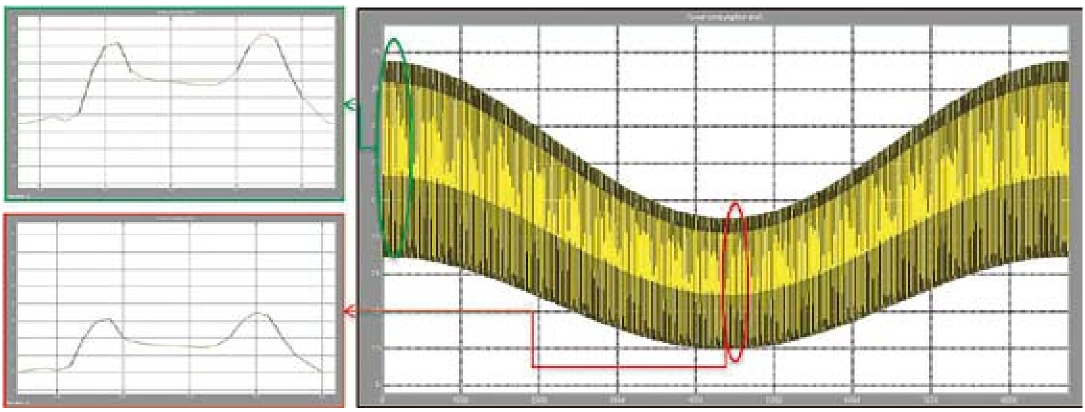


Figure 5. Predetermined power consumption profile used in the simulated scenarios. The winter (upper left) and summer (lower left) consumption follow a similar profile differing for a 2/3 scale factor.

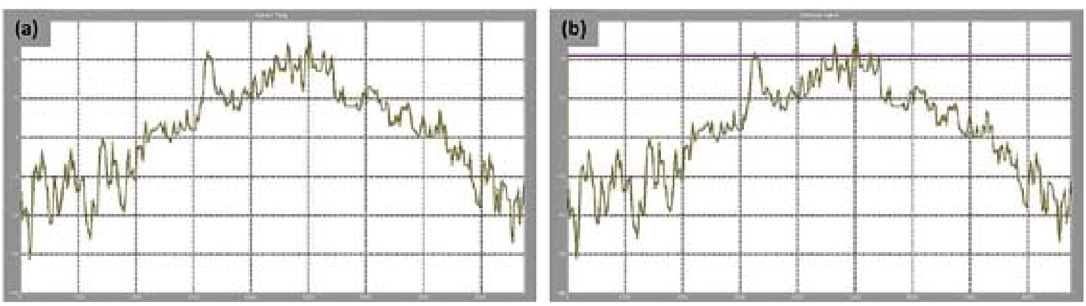


Figure 6. Comparison between the hourly variation of (a) the Oulu 2010 year temperature and (b) the corresponding simulated indoor temperature for the considered built environment if no thermal power is considered. The Purple line in the second graph indicates the (user) selected indoor temperature.

accurately considered including U-Values from the European Insulation Manufacturer Association for sustainable buildings [8].

The thermal and electrical energy requirements of the structure (Figure 7) were considered to be independent, with the building including an underfloor water heating system. The electricity needs were arbitrarily premodeled and no electric heating or thermal effects due to the illumination or the electrical appliances were included.

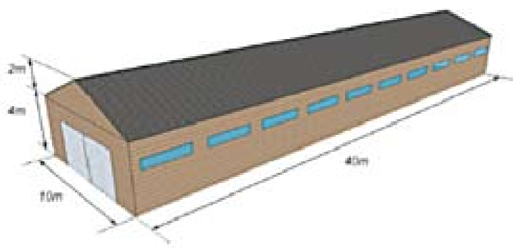


Figure 7. The building structure considered in the presented case study.

The system compares the set indoor temperature with the actual indoor temperature at one hour interval. A relay then switches on/off the system once the predetermined lower/upper temperatures limits (respectively) have been reached. The imported heat (either produced or imported) is then transformed in heat transfer and, once heat losses have been considered, the new temperature is calculated.

Energy sources

The energy source block contains five selectable elements reproducing the energy contribution of technologies:

3 CHP units: a small-scale combustion system (using pellets as fuel), a gasification unit and an anaerobic digestion unit. The energy outputs have been arbitrarily chosen to be 10 kW (power + thermal) based on the information from [9] and [10].

A 10 kW wind turbine, a 3 blades model operating in wind condition below 25 m/s whose output is described by the power curve shown in figure and is determined considering the weather records.

A 10 kW PV system whose performance is calculated taking in consideration the monthly average sun radiation values and the hourly cloud cover data.

All the technical characteristics of each element (i.e. thermal and/or power input, efficiency, etc.) can be easily modified.

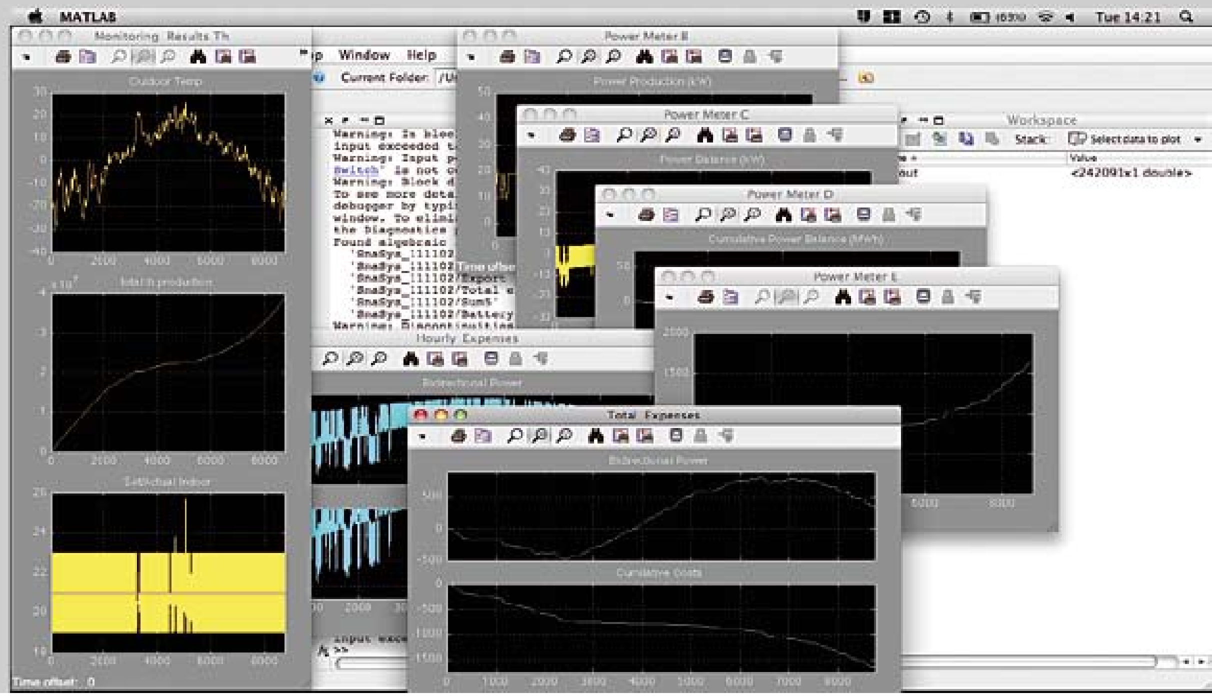
Energy storage

The energy storage system is further divided in two components: a fixed electric energy storage and the electric energy storage of a plug-in hybrid electric vehicle (PHEV). As in the previous cases, also these elements are built following a modular structure, in order to make them easily selectable or modifiable.

On an hourly base, the system power balance is monitored and if the produced power exceeds the system needs, the battery is loaded. In case of power need, energy is drawn from the battery. The size of the battery, in our case 600 kWh, is likely to affect the number of battery cycles, partial load and battery life and, therefore, the economic performance of the system.

The algorithm regulating the behavior of the battery for the PHEV (in our case set for 50 kWh) was the same as the one for the fixed battery. Additional elements take in consideration when the car is needed, if the car is plugged and the recharging time.

The battery of the PHEV is considered to be always plugged if the vehicle is not used. Energy is always drawn from the battery unless the vehicle is needed, in which case at time *t – recharging time* the battery begins to recharge and it is delivered at 100% of its capacity at the due time. The choice of modeling a PHEV and not an electric vehicle allows more freedom from the car usage point of view: the negative values in the car battery levels indicate that the car would have compensate for the lack of battery load using conventional fuel.



Results

Figure 8 and 9 show an excerpt of the simulation results with data for the electrical and thermal energy displayed on the left and right respectively. First, in Scenario 1, all the energy producing elements are excluded. This allow for the monitoring of the energy requirements of the simulated system. In Scenario 2, includes all the elements: 3 CHP units, wind turbine, PV system and 2 electricity storage units (one of which is the PHEV battery) allowing a motoring of the overall energy performance.

Calculations are based on the cumulative power balance results and the power price for the corresponding period in the considered region [11]. From the result showed in Figure 8, we can have an approximate idea of the scale of the system, with the power budget, in the absence of a local power production, being a mirror image of the power consumption of Figure 5. This corresponds to a yearly consumption of approximately 140 MWh, equivalent to yearly expenses of almost 15000€. Figure 9a shows an irregular local power production throughout all the year, resulting in a almost constantly positive power balance Figure 9b. This is also verified by the cumulative power balance of Figure 9c, which shows a growing trend.

In Figure 9a the power production graph shows a rather irregular shape with two easily recognizable characteristics. The first one is the pseudorandom variation of the energy production due to constantly changing wind energy production and in the power storing capabilities (primarily due to the usage of the PHEV); the second characteristic is the average increase of power production in the first half of the year and a decrease in the second half, with a significant variation between mid April and mid September (2500-6200 hours), reflecting the strong variations of the PV power production. The resulting power balance graph, with the selected size of the power production units, shows a clear surplus of energy, with deficits due mainly to low production from wind and solar and with negative power balances only in the colder periods (till mid-April and from the beginning of September). As a consequence, the corresponding yearly costs in this case are merely a fraction of those obtained in the previous case. Even though the nature of our work did not allow us to provide a precise quantitative

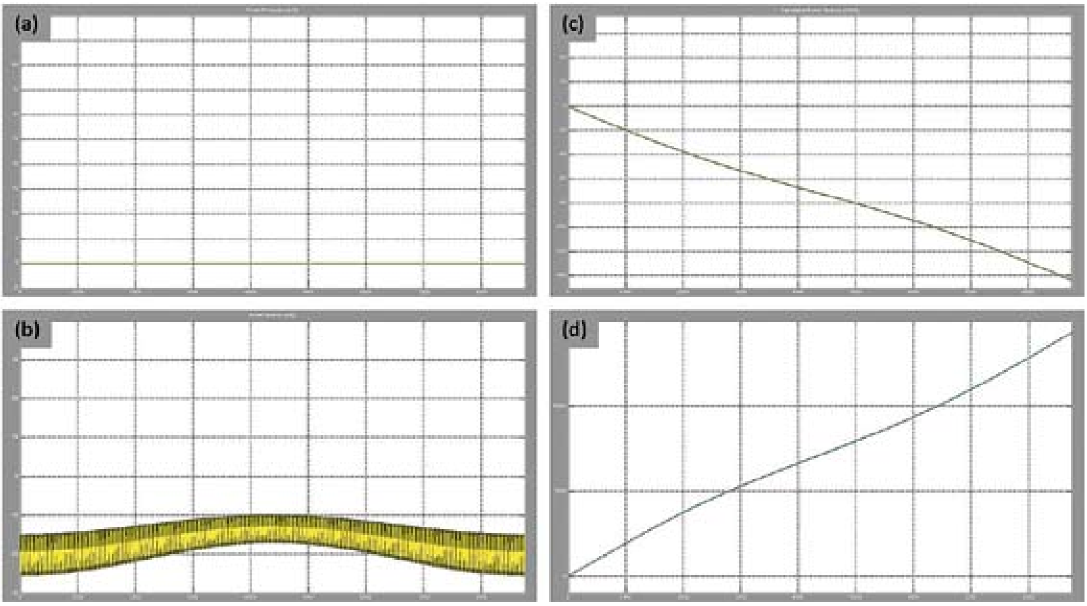


Figure 8. Scenario 1: Simulation results for all energy producing elements deactivated.

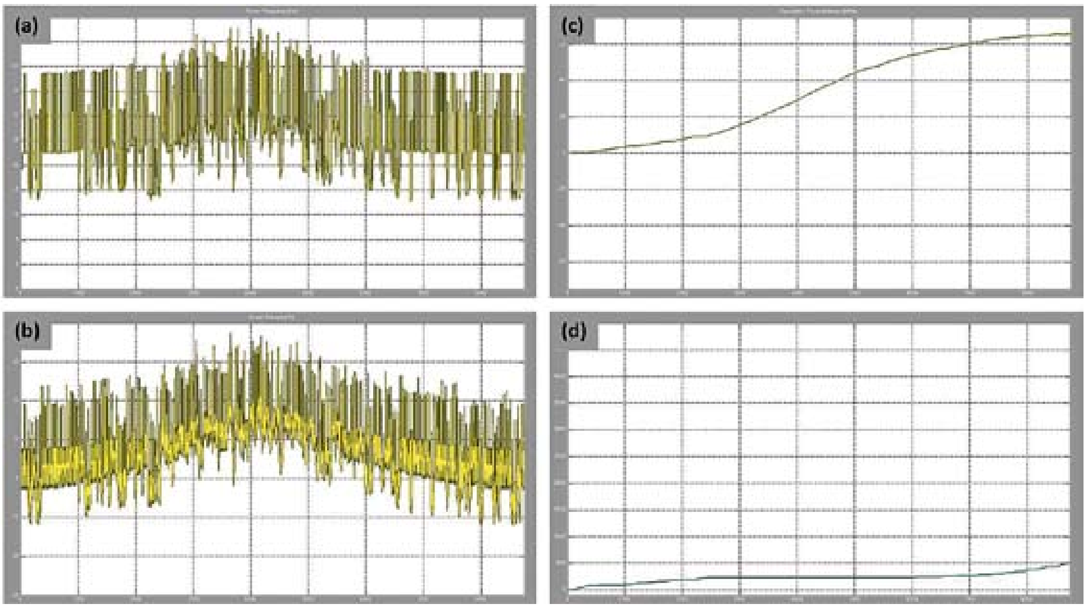


Figure 9. Scenario 2: Simulation results for all the energy producing elements activated.

Legend:

(a) Local power production - includes the sum of all the electrical energy produced by the 5 units of the DRES block plus the power released by the storage units.

(b) Power balance calculated as the difference between the local power production and consumption

– Positive values indicating a surplus of energy production

– Negative values indicate a deficit of energy

(c) Cumulative power balance, i.e. the difference between the energy produced and the energy imported from the grid, monitoring the overall energy budget over one year period

– Growing trend indicates a surplus of energy

– Decreasing trend indicates a deficit of energy

(d) Power budget in terms of financial costs.

analysis of the economical performance of the system, the discrepancy between these cases remains remarkable.

For what concern the thermal energy production, if in the first case the system was completely dependent on external inputs, now the system is fully capable to autonomously maintain the indoor temperature near the selected value. The system has been tested for a number of selected constant indoor temperatures and for a number of indoor temperature profiles reflecting for example difference between the desired temperatures of weekends, holidays and working days (Figure 10).

tion maintaining the pseudorandom variation due to the wind turbine contribution. The effects on the power balance and the cumulative power balance, over one year period, are similar to the previously described case with an overall lower production.

Assessing the performance of a system without the small wind turbine system in Scenario 4 (Figure 12), it is easy to notice how the overall power production still maintains the two characteristics mentioned before, with the difference that, as expected, the pseudorandom variations are somewhat attenuated and, consequently, the average power output present a proportionally larger variation

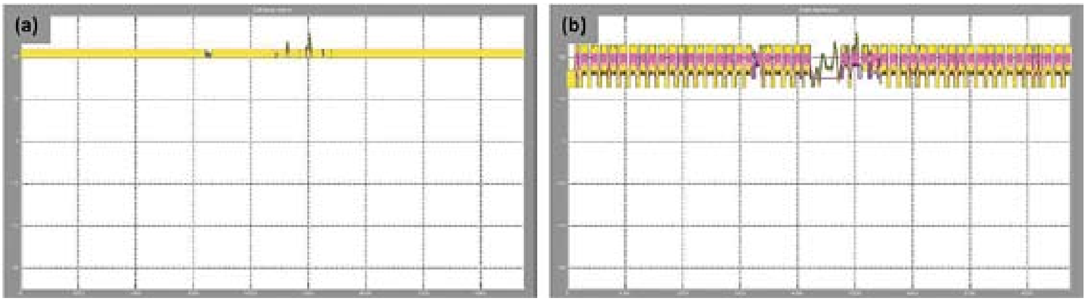


Figure 10. Comparison between the simulated indoor temperature for the considered built environment for (a) a constant temperature (b) a time dependent temperature. In both cases the purple line indicates the (user) chosen indoor temperature and the yellow line the actual indoor temperature sustained from the system.

In the second stage of our analysis, we considered different system configuration in order to single out, the contribution of each element as follows:

- Scenario 3 (Figure 11): The PV unit is excluded
- Scenario 4 (Figure 12): The wind turbine is excluded
- Scenario 5 (Figure 13): Excluding both the PV and wind turbine units
- Scenario 6 (Figure 14): Excluding the PV, the wind turbine and the storage units
- Scenario 7 (Figure 15): One of the CHP units is excluded

In Scenario 3, the exclusion of the photovoltaic system (Figure 11), eliminates the strong seasonal variation of energy produc-

due to the, now more important, solar power production. For the power balance it is possible to notice how the colder months have a clear negative contribution with cumulative power production graph showing a clear negative power budget in the first half of the year and a net positive one in the second part of the year, with an overall slightly negative end result (power needs to be acquired from the common grid). Analogously to the previous case, no effects are to be noticed on the thermal energy aspects of the system.

The exclusion of the wind and solar power production system in Scenario 5 (Figure 13) shows a power production whose variations are exclusively due to the contribution of the battery units, which are set to be the first choice of power supply in case of needs. For the fixed battery, variations are the exclusive consequence of the difference between system power demand and supply (varying consistently over

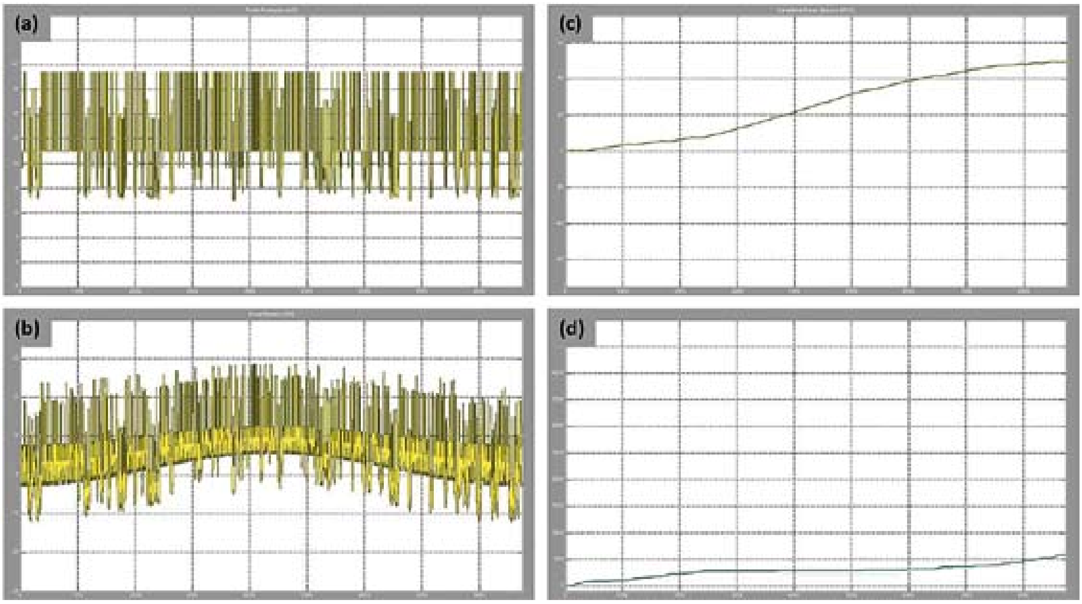


Figure 11. Scenario 3: Simulation results for the system excluding the photovoltaic system.

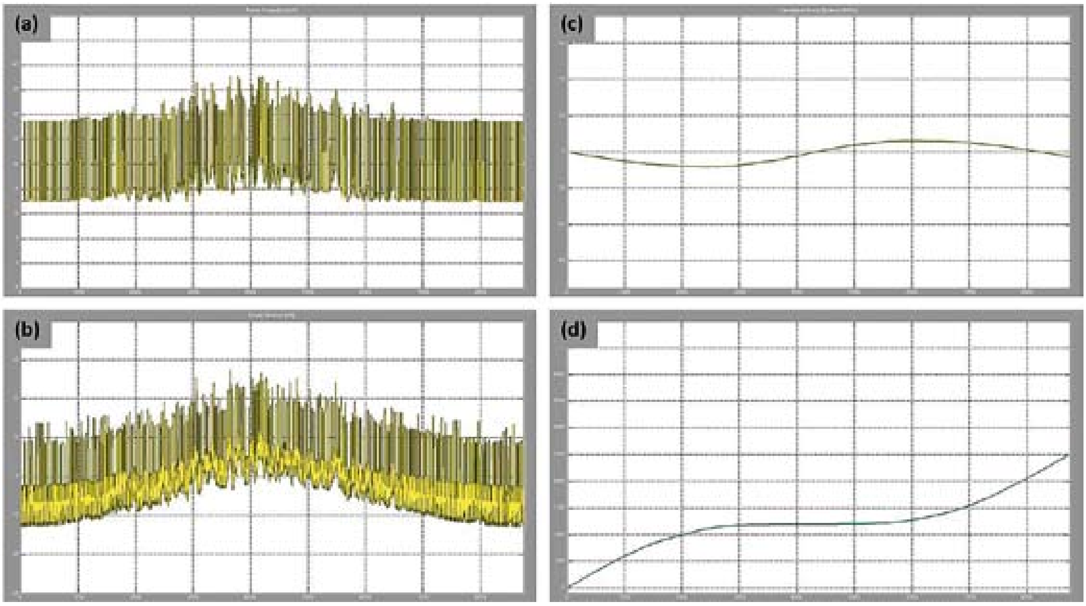


Figure 12. Scenario 4: Simulation results for the system excluding the wind turbine system.

the year), with the battery limits: the battery storing capacity and the discharge limit (which does not allow release of power for battery levels below 10 kWh). For the PHEV the variations are related to the usage of the vehicle.

In Scenario 6, the results (Figure 14) proved to be consistent with the scenarios obtained if also all the storing devices are excluded from the system. Beside the more obvious and direct effects on the energy balance, the variations due directly to the environmental factors (wind and solar radiation) are more evident, together with the features described in the other previous cases.

Excluding one of the CHP units (Figure 14) is also considered in Scenario 7. It is easy to see how the overall result in these cases is the reduction of the power production of a

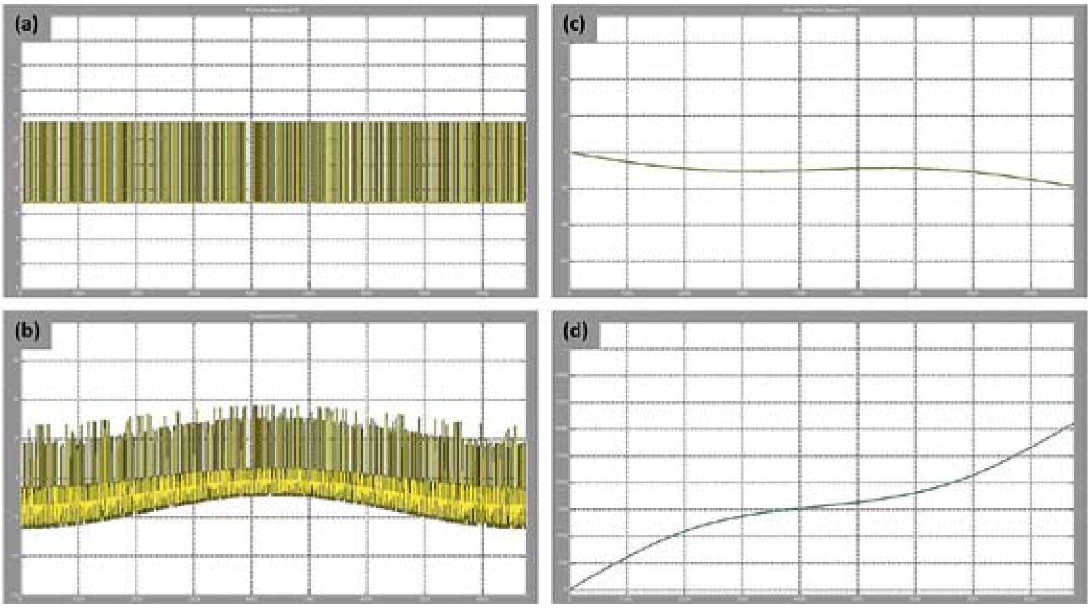


Figure 13. Scenario 5: Simulation results for the system excluding the photovoltaic and the wind turbine system.

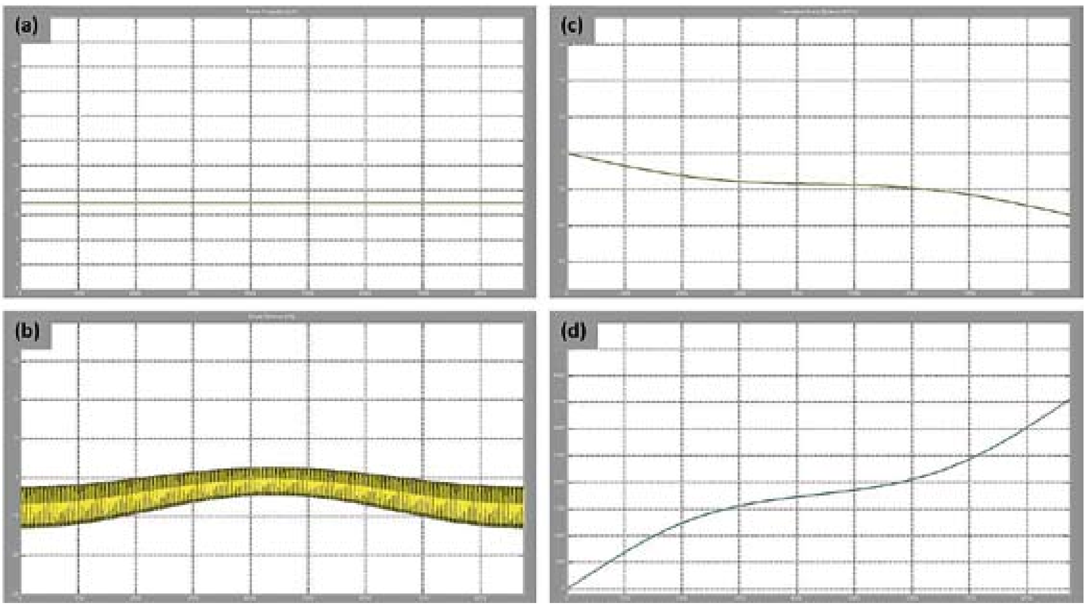


Figure 14. Scenario 6: Simulation results for the system excluding the photovoltaic and wind turbine systems, and the power storage units.

constant factor, with no sizable consequence on the qualitative aspect on the production. Similar consequences can be notices also on the thermal energy production and on the cumulative thermal energy production graphs, where, as the outdoor temperature signal remained unchanged, the outcome is a scale but similar result as on the previous cases.

One element that can be noticed when comparing all the scenarios, is the overall variation of power demand. If entirely depended on the external network, it is varying quite significantly between winter and summer seasons (Figure 5 and Figure 8b), oscillating between 15 kW and 25 kW in the colder months and between 19 kW and 17 kW in the

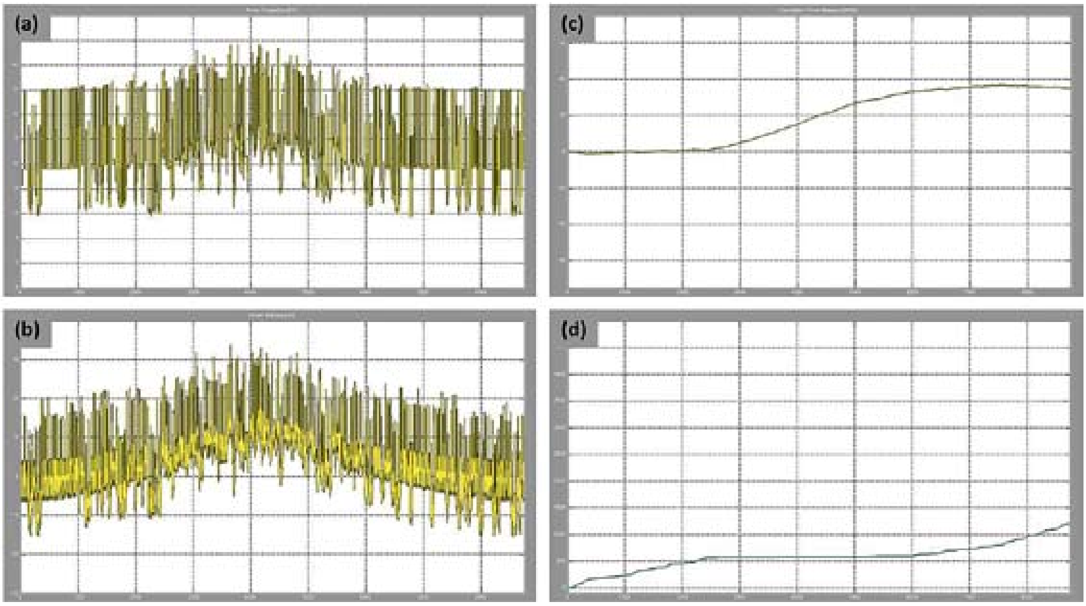


Figure 15. Scenario 7: Simulation results for the system excluding of one of the CHP units.

warmer months. If the actual values of the electricity demand depend on the arbitrary choices of the modeled simulator, the represented trends reflect a realistic situation. This translates in capital costs for energy providers and high GHGs emissions usually due to the necessity to cover energy demands in the peak hours. A comparison with all the other cases showed that the stress on the energy network is, if not eliminated, at least reduced as one common effect recorded in all the considered scenarios is the partial stabilization of the energy dependence on the common grid.

The simulations also illustrate the potential of interplay among different energy vectors. An example of these aspects surfaced in our analyses when, for example, we included the use of a plug-in hybrid electric vehicle (PHEV) as a possible household energy storage. From the power consumption point of view, it appeared as if the use of a PHEV brought no benefit to household energy budget. A closer look, on the other hand, revealed a substantial reduction in fuel consumption, providing an environmental and an economic benefit otherwise undetectable analyzing merely the overall power consumption.

Results obtained in this work revealed the potential for smart energy grids in the Northern Periphery. This is related to a number of favorable characteristics: richness of natural resources, socio-cultural background and financial instruments for the development of an advanced energy market such as the Nord Pool Spot run power market. The developed micro-grid system has been proven capable of answering to the power and thermal energy needs of the user in Nordic environmental conditions. Furthermore, it allowed monitoring the contribution of the included elements and their combined effect on the common networks, stabilizing the energy consumption profile of the end user. This, potentially, translating into reduced costs of the transmission and distribution system operators.

The future of the energy market and energy services

In this work, different aspects that contribute to define the potential for the development of smart energy grids in the NP territories have been discussed. It was seen how these territories present significant possibilities due to a number of important characteristics: natural resources, socio-cultural background and financial instruments for the development of an advanced form of energy market. The analysis conducted in this study was intended to provide a realistic example of the possibilities of using a number of already developed technologies in a smart and interconnected way. Firstly, it was possible to underline how the potential of these applications could be evaluated in terms of efficiency and, on the medium term, in economic benefits. Moreover, it illustrated a profound transformation in the way the energy market is to be conceived; a complex interplay between production, transmission, distribution and consumption of energy as illustrated in Figure 16. This transition to a smart energy system implies a new way to understand the energy market.

The technological means for the development of an energy network, based primarily on distributed energy production, are technologically mature, in both what we can call the classical RES and waste-to-energy RES. These technologies can be combined to serve the needs of the end-users which, in turn, come to assume the role of small (distributed) producers playing a primary role in the energy production (Figure 3). The new liberalized and decentralized energy market would include a number of new elements (i.e. PHEV) and a new way to assess the energy needs basically based on an on-demand local energy production scheme. In addition, it stresses the needs for the energy providers to redefine their role in the energy market.

In order to sustain a radical transformation of the future energy network, such as the one illustrated in Figure 16, it is required that an important share of the future energy business is to move from the production and commercialization of energy to the offering of comprehensive energy services.

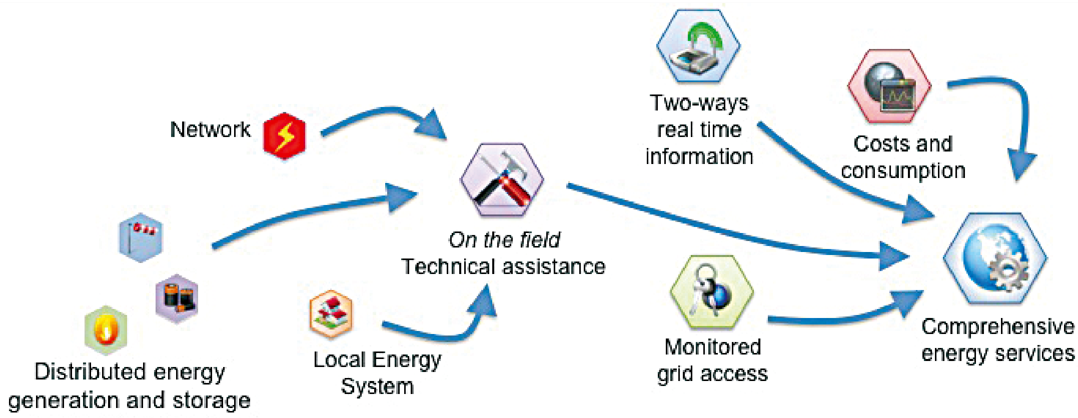


Figure 16. Indicative representation of the different elements required for an effective and comprehensive energy service to play a role in a smart grid based energy system.

Customers' services would include, among others, monitored grid access, real-time information on costs and consumption, possibility to customize the service's profile and the possibility to sell small renewable energy production in an open, transparent and easily accessible manner and technical assistance.

These energy services are currently not available or shared among a number of market players in a non-user-friendly way, especially in regions characterized by sparsely populated areas and harsh climate where the delivery of these services also entails a number of logistical problems. Furthermore, each element of the network needs monitoring and assistance, they need to be combined at the local level and they need to be properly included in the common grids where their activity can be properly monitored in order to maintain the efficiency and the stability of the common networks. All these elements, even if, in most of the cases, are technically available, are not provided in a coordinated and viable fashion to the end-users. Other elements, especially for what concern the inclusion of the models considered in this work in the common grids, are currently not available. Apart from a number of administrative and political aspects, there are a number of technical obstacles that need to be overcome. A first step in this direction would be the direct communications of the energy prices to the end-user. In a system as the one described in this work, it could be used to redistribute the electrical energy consumption during the day. At the same time the system itself would be given the possibility to add an extra element for the decision making process. The local energy management system would match the energy needs and minimize the energy expenses deciding by, for example, rethinking the usage of the stored energy. This has two important consequences: on the environmental side it contributes to the reduction of GHGs emission while on the other side it provides economic benefits for the market which translate in reduced expenses in energy distribution and transmission. This would create the economic mean for further investments in the development of a smart energy network. At the same time, the energy consumption would rationalize on a number of levels, e.g. the end user would probably not reduce the overall energy consumption but would redistribute it over time.

Ultimately, this will require a transition of the energy industry business model, and a need to evolve from the paradigm of growth through quantity to growth through quality.

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