Dept. of Process and Environmental Engineering

Master's Thesis

Assessing the potential for smart energy grids in the Northern Periphery

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UNIVERSITY OF OULU **Abstract of Thesis**
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Abstract

Global challenges of the 21st century marked a turning point in the energy markets. Global warming, energy delivery reliability, scarcity and competing use of resources became key factors in the development of energy networks. The hypothesis behind this work is that smart grids can be a tool to provide a solution to these challenges. The expression smart energy grid indicates an energy network that allows a two-ways communication between suppliers and consumers, while monitoring the network condition in *real time* (i.e. electricity production, consumption and distribution). This kind of energy system facilitates a more dynamic control of the electric network, making it possible to respond to the changes of the grid conditions more efficiently. It also enables end-users to make their own choices and be directly engaged with the energy markets.

Using real-time monitoring, together with smart control system capable of evaluating and improving its performance, the smart energy network can anticipate and mitigate power peaks or power quality problems. At the same time, it allows a more prominent market position for those renewable energy resources, which are characterized by discontinuous and irregular power generation.

In this thesis work, a hybrid micro-grid simulator was developed from the end-user's point of view. The simulator makes a (smart) use of available renewable energy sources (RES) based on a demand-response logic principle. The hybrid model includes a number of selectable elements: 3 bio-energy based CHP units, a small-scale wind turbine and a photovoltaic system. It also uses a plug-in hybrid electric vehicle (PHEV) as one of the storage elements. The main role of the simulator is to model the communication with the energy grid from the end-user's point of view, i.e. putting energy on the common network in case of excess production and taking energy from it in case the available renewable resources cannot respond to consumer needs.

The results indicate that there is a potential for smart energy grids in the North due to a number of favourable 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 system developed in this work is capable of answering to the power and thermal energy needs of the user. Furthermore, it allows 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 will, potentially, translate into reduced costs of the transmission and for distribution system operators.

This work was conducted within the Micro Waste to Energy Solutions (MicrE) project, funded by the EU's Northern Periphery Programme.

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Älykkäiden energiaverkkojen mahdollisuudet pohjoisen periferian alueella

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Tiivistelmä

Uuden vuosituhannen maailmanlaajuiset haasteet ovat muuttaneet energiamarkkinoita. Ilmaston lämpeneminen, energian toimitusvarmuus ja kilpailu vähäisistä resursseista ovat muodostuneet merkittäviksi energiaverkkojen kehitykseen vaikuttaviksi tekijöiksi. Eräs ratkaisu näihin uusiin haasteisiin on älykkään sähköverkon kehittäminen.

Älykäs energiaverkko -termi tarkoittaa energiaverkkoa, jossa tuottajat ja kuluttajat voivat seurata verkon tilaa (eli seurata sähkön tuottoa, kulutusta ja jakelua) reaaliajassa molempiin suuntiin. Tällainen energiajärjestelmä mahdollistaa energiaverkon dynaamisemman ohjauksen, jonka ansiosta verkossa tapahtuviin muutoksiin voidaan vastata tehokkaammin. Se myös antaa loppukäyttäjille mahdollisuuden valita ja vaikuttaa energiamarkkinoihin itse. Käyttämällä reaaliaikaista seurantaa, yhdessä älykkään ohjausjärjestelmän kanssa joka pystyy arvioimaan ja muuttamaan toimintaansa, voidaan ennakoida energiahuippuja tai tehoon liittyviä laatuongelmia. Älykäs energiaverkko mahdollistaa samalla myös aiempaa paremman markkina-aseman niille uusiutuville energialähteille, joille on ominaista katkonainen ja epätasainen sähköntuotanto.

Tässä opinnäytetyössä kehitettiin pienikokoinen verkkosimulaattori loppukäyttäjien tarpeista käsin. Simulaattori hyödyntää uusiutuvia energiavaroja kysyntä- ja tarjonta- logiikan periaatteen mukaisesti. Malli sisältää muun muassa kolme bioenergiaa tuottavaa CHP-yksikköä, pienen tuulivoimalan, aurinkokennojärjestelmän ja hybridi-sähköauton (PHEV) käytön varastoyksikkönä. Keskeisin simulaattorin toiminto on mallintaa energiaverkon kanssa tapahtuvaa kommunikaatiota loppukäyttäjän näkökulmasta. Kun energiaa tuotetaan yli oman tarpeen, energiaa siirretään verkkoon, kun uusiutuvat luonnonvarat eivät riitä oman kulutuksen kattamiseen, energiaa otetaan verkosta.

Saadut tulokset osoittavat, että älykkäillä energiaverkoilla on mahdollisuuksia pohjoisessa lukuisista eri syistä. Näitä ovat runsaat luonnonvarat, sosio-kulttuuriset taustatekijät sekä rahoitus-järjestelmät, jotka mahdollistavat Nord Pool Spotin -tapaisten edistyneiden energiamarkkinoiden kehittämisen. Työssä kehitetty malli pystyy vastaamaan käyttäjien lämpö- ja energiatarpeisiin. Tämän lisäksi eri tuotantoyksikköjen tuotoksia ja verkkoon tuotettua kokonaistuotosta voidaan seurata, mikä tasoittaa loppukäyttäjien energiankulutusta ja voi vastaavasti johtaa alempiin välitys- ja jakelukustannuksiin.

Tämä työ on toteutettu osana Micro Waste to Energy Solutions (MicrE) -hanketta, joka on rahoitettu Euroopan unionin ”Pohjoinen periferia” -ohjelmasta.

Säilytyspaikka

Oulun Yliopisto, Tiedekirjasto Tellus

Muita tietoja

Contents

List of Abbreviations

AD	Anaerobic Digestion
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DES	Distributed Energy Systems
DG	Distributed Generation
DRES	The distributed renewable energy sources
GHG	Green House Gases
MicrE	Micro Waste-to-Energy for Rural Enterprises
NP	Northern Periphery
NPS	Nord Pool Spot
PHEV	Plug-in Hybrid Electric Vehicle
PSS	Product-Service System
PV	Photovoltaic
RES	Renewable Energy Sources
SME	Small and Medium-size Enterprise
STC	Standard Testing Conditions
TSO	Transmission System Operator

Forewords

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Oulu, September 2011

Antonio Caló

Theoretical Part

1 Introduction

The global challenges, which rose at the turn of 21^{st} century, brought, among others, an unquestionable call for a new thinking of the energy distribution platform. Future trends for global energy consumption, increasing energy costs and environmental issues [International Energy Agency, 2009, U.S. Energy Information Administration, 2010] are pushing for an increasing use of renewable energy sources, smaller power plant and distributed generation (DG), improved efficiency and reduced environmental impact. In this framework, the future development of the European energy network, a major player in the green house gases (GHGs) emissions [International Energy Agency, 2009, U.S. Energy Information Administration, 2010], will have to be re-thought and re-shaped taking into account new needs and technological breakthroughs as well as the new economical environment. This leads toward numerous technical and non-technical challenges such as the assurance of reliable and cost-effective energy supply, and a more effective energy network management system that would facilitate an extensive and effective use of renewable energy sources (RES) and their integration in an envisioned energy network based on DG.

The smart energy grid is a solution that can provide a valuable answer to these needs, a solution where consumers are given the possibility to choose and be directly engaged. The expression smart energy grid indicates a power grid that allows suppliers and consumers to have a two ways communication monitoring in real time the grid condition (i.e. the electricity production, consumption and distribution). 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. The motivation behind studying the development of smart energy grids can be explained in terms of what a smart grids are expected to do. Using real time monitoring together with smart control system capable to evaluate and improve its performances, the envisioned smart grid based system can anticipate and mitigate power peaks and power quality problems. 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 power generation (i.e. wind power). The transition from a highly centralized energy network to a decentralized one is a transition that aims to re-think the energy industry business model: from growth through quantity to growth through quality.

A transition such as the one mentioned above implies a more interactive and participatory role of the consumer. Due to a real-time two ways communication, consumers are then able to effectively gain through a more efficient energy usage and the possibility to directly interact with the energy market. Furthermore, by enabling distributed power generation, it is possible to effectively initiate a process of democratization through participation of the energy market.

The work presented in this study was carried out under the Micro Waste-to-Energy for Rural Enterprises (MicrE) project [MicrE, 2008] financed by the European Union's Northern Periphery Programme [Andersson, 2004]. The project aims to develop and promote innovative renewable energy solutions for rural small and medium size enterprises (SME) in the Europe's Northern Periphery (Figure 1) with special emphasis on small scale energy solutions from by-products and waste. In this framework, this diploma work aims in particular to present the possibilities, the socio-economical 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 Northern Periphery (NP) area.

Regions comprised in the NP area share important common features in terms of

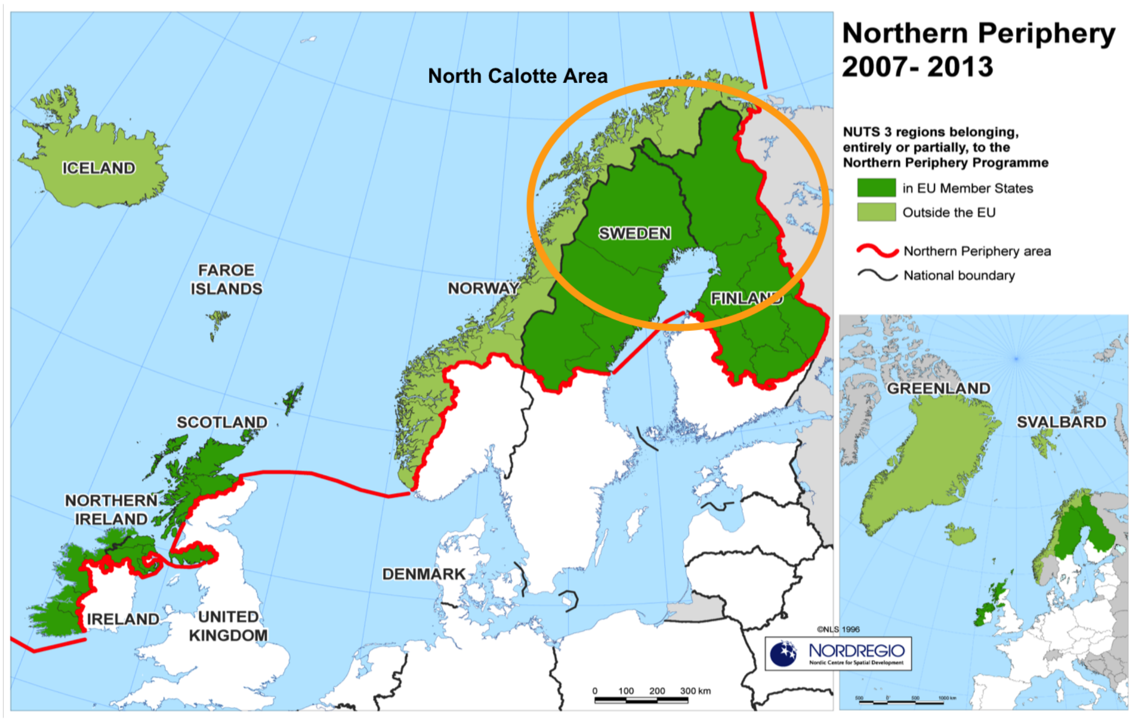


Figure 1: The Northern Periphery area, as defined from the Northern Periphery Programme, and the northern calotte, the main area of interest of the diploma thesis.

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. More in particular, the main area of interest of this work is approximately referable to the so called Northern Calotte area (Figure 1) which can be geopolitically described as the Finnish, Swedish and Norwegian territories comprised in the NP area.

These territories are characterized by common strengths and challenges. A remarkable richness in natural resources is accompanied by high quality education, high tech and high standards of services [U.S. Central Intelligence Agency, 2011]. The industrial strength of these territories relies on the so-called "heavy high-tech" industry: metallurgy, forestry, mining and chemical industry. On the other hand the very same richness in resources of high economic value gives ground to their exploitation raising the risk of the combined effect of climate change and increased human activity in a self reinforcing mechanism. This is a particularly important element to be taken into account considering that the northern nature is ecologically sensitive and it regenerates slowly. Another element to be taken into account and that explain the geographical area of interest of this work is related to the fact that the considered Countries are all members of the NordPool Spot Price market [Nord Pool Spot AS, 2011]. The first multinational market for electric power and the largest electricity market per traded volume (TWh), it operates in Finland, Sweden, Norway, Denmark and Estonia, covering more than 70% of the total electric energy consumption. An analysis concerning the future development of the region's energy grid and the employed resources need to take this aspect in consideration.

2 Sustainable Energy in the Northern Periphery

The territories in the NP area directly considered in this work spread across three Countries: Norway, Sweden and Finland. If the shared history and environmental conditions gave these Countries a similar social structure and cultural profile, they still retained a level of characteristic individuality. This dichotomy is reflected in the different Countries' energy profile: rich in different energy resources, each Country is developing a distinct future energy strategy while at the same time they are all part of the multinational common energy market mentioned earlier.

In this section, the current energy strategy of each Country is briefly summarized and concluded by a discussion of the elements that are more likely to affect the future development of a smart energy grid based system: nuclear power and the common electricity market.

2.1 Countries energy profile

2.1.1 Norway

Norway has a peculiar double role as strong advocate of climate change mitigation and as a major oil and gas producer [OECD/IEA, 2011b]. This double role allowed Norway to set for itself the challenge of major reduction of GHGs' emission (30% respect to 1990 levels by 2020 in order to become carbon neutral by 2050) with the financial support of its large petroleum revenue (Norway is the third world largest exporter of energy after Russia and Saudi Arabia,). At the same time Norway is in a favorable position for the further development of the already prominent role of the renewable energy sources (RES) in the Country, with a significant hydropower reservoir capacity that backed up with its variable wind power generation and an appropriate electricity network technology, could result in an important step forward in the Country's environmental performance.

2.1.2 Sweden

Sweden is today reporting one of the lowest levels of CO_2 emissions (either per GDP or per capita) and it is steadily moving toward a decarbonization of its economy [OECD/IEA, 2011c]. Despite its efficiency in energy use owing to solutions such as district heating, the electricity use per capita is one of the highest in the world. At the same time Sweden is one of the leading Countries for what concern the use of RES, especially biomass derived from its extensive forests as byproduct of wood-processing industries.

2.1.3 Finland

Despite the high energy consumption per capita, Finland represents a small electricity market by itself, making an intensive use of energy trading with its neighbors, including Russia and the Baltic states [OECD/IEA, 2011a]. The strong dependence on energy import is somehow balanced by a characteristic highly diversified domestic energy production. Still working to meet the Kyoto protocol targets, Finland's energy policies are generally advanced, two examples being energy efficiency, especially in the building sector, and R&D.

2.2 Nuclear Power in the NP

There are currently almost 450 nuclear reactors in operation in the world with 65 under construction [IAEA-PRIS, 2011]. They represent approximately 6% of the world energy supply corresponding to approximately 14% of the world electricity production [IEA, 2010]. Strictly speaking, there are no nuclear power stations in the interested area but Sweden and Finland are both generating a significant share of their electricity production using nuclear technology and this is an elements that needs to be taken into consideration in any discussion contemplating the future development of the energy network in these countries. In terms of primary source of energy, nuclear power represents approximately 18% [OECD/IEA, 2008a] and the 34% [OECD/IEA, 2008b] of the total energy supply of Finland and Sweden respectively. Even though Norway does not produce electricity using nuclear technology, being on a common electricity market is a factor likely to indirectly affect all stakeholders as almost 40% of the Swedish electricity production and almost 30% of the Finnish electricity production is generated by 14 nuclear reactors shared among 5 nuclear power stations in the two Countries [World Nuclear Association, 2011]. There are two main points to be taken in consideration concerning the near future development of nuclear power production in these Countries. From a strategic and logistic point of view, nuclear power production represents the nemesis of any smart energy grid based on distributed and renewable energy production: the highly centralized massive amount of power generated is likely to offset the short and medium term development of these technologies in a way that still remain to be understood. The second consideration concerns the socio-political aspect of the near future development of the nuclear technology that in a globalized market (nor Finland or Sweden have an independent nuclear industry) is likely to indirectly affect the near future economical aspiration of the NP territories.

2.3 The NordPool spot price energy market

Nord Pool Spot (NPS) electricity market [Nord Pool Spot AS, 2011] , whose ownership is shared among the national grid operators (Figure 2) operates in five countries (Figure 3). In 2010 the NPS market managed 74% of the total electricity market of the Countries for a turnover of 307 TWh.

The NPS operates in two markets, the Elspot and Elbas. The Elspot market is based on a day-ahead spot price concept, a system where the price of a commodity, in this case electrical energy, is quoted for immediate use. This differs from a more commonly perceived market system based on a so-called forward price concept, where the price is set immediately upon a delivery set to occur in a future date [OECD, 2001]. In the Elspot market the equilibrium between the supply and demand of the set for all hours of the following day. In order to avoid grid congestions, the market exchange area is geographically divided into bidding areas. In this system, grid congestion issues inside the bidding areas are handled by the transmission system operators (TSOs), using methods such as counter trading, while congestion issues across bidding areas is implicitly handled by the Elspot price calculation. A so-called system price for each hour is determined by the intersection of the aggregate supply and the demand curve for the entire Nordic region (Figure 4a). In case of congestion, area prices are then calculated by adding trading capacities (in a form of

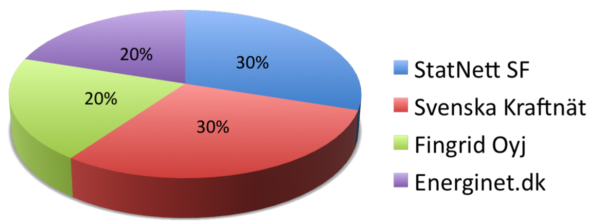


Figure 2: Ownership of Nord Pool Spot as shared among the Nordic transmission system operators.

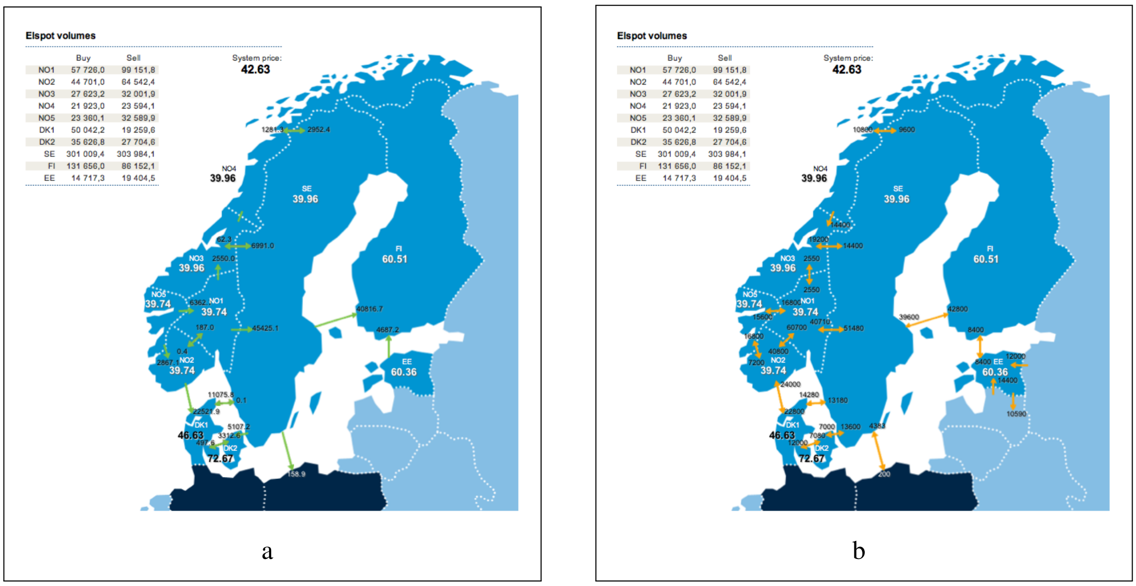


Figure 3: Maps showing the of the Nord Pool Spot market operating areas. On the web site it is possible to have real time visualization of the regional energy prices, including (a) power flows and (b) production capacities.

independent purchase or sale in the surplus or deficit areas respectively) shifting the equilibrium point in a grid acceptable range (Figures 4b and 4c). The operations for the area prices are performed in an iterative manner so that to maximize the potential between different areas.

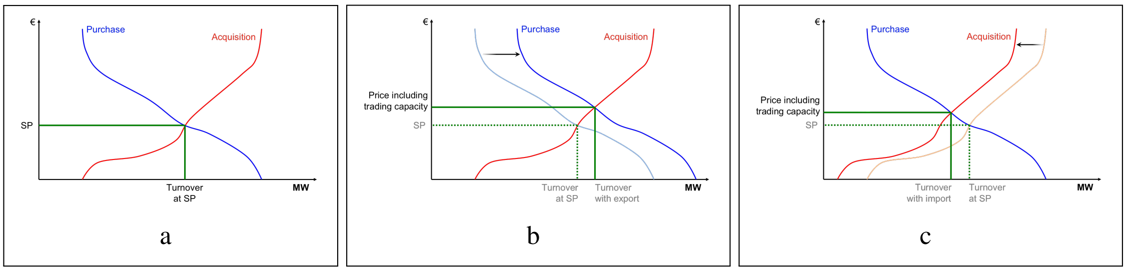


Figure 4: The definition of the system price is based on the equilibrium between the aggregated surplus and demand disregarding transmission limitations (a). Trading capacities are then matched increasing the prices in deficit areas (b) or by lowering them in the surplus areas (c), redefining in this way the corresponding energy turnovers.

The Elbas is an intraday market where electricity can be traded up to one hour before the due delivery time. Its purpose, beside allowing intraday bilateral agreement within the bidding areas, it is to allow the market players to exchange as required in order to guarantee the balance of the system up to the delivering time [IPA Energy + Water Consulting, COWI A/S and SGA Energy, 2008].

3 The Development of the Energy System

This chapter is dedicated to the description of the current energy system and the possibilities offered by the application of economic models. Starting from a fast overview of the economic concept of service, the chapter describes the evolution of the energy system and its possible development in the near future.

3.1 What is ”service”?

In economics, there are different definitions of service which, for the purpose of this work, can be described as follow:

> *A service can be described as any commercial activity where the predominant characteristic is not the production of an artifact.* [Graedel and Allenby, 2003].

An application of this concept can be seen for example in the leasing process where at the centre of the transaction is the use of a certain asset (a car, an electrical appliance, etc.) and not its ownership.

In the service economic sector, the leading fields are generally knowledge and information related services, a consequence of the tremendous scientific and technological advances of the second half of the 20^{th} century.

In most of the developed world economies the service sector is the main form of economic activity [Soubbotina, 2004]. A result this which all the growing economies are likely to encounter as the final stage of a three stages development scheme. Initially agriculture is a community's primary sector. Subsequently, as the population income increases, and demands are met, communities' needs shift toward industrial goods giving rise to an industrialization process. As the population income continues to rise, another shift in the communities' needs occurs demanding more immaterial goods. This give rise to a post-industrialization process and the development of service based economies.

The post-industrialization era brings with it the possibility to replace consumption with services, a process often referred to as dematerialization, with potentially important effect on the environmental performance of some economic sectors. It has been furthermore argued that replacing material consumption through services is a design challenge more than a technological one [Lifset, 2000]. The word design here is to be understood not to be limited to technological or logistical aspect of the production but to be applied to the all system where a product is consumed [Ryan, 2000]. A shift toward a so-called product-service system (PSS), if not pursued in its entire complexity, is likely to bring only partial improvement if any. A classical example in this sense is the rebound effect, where the overall response to new technology tends to offset the intended beneficial effect.

3.2 History of energy systems

The modern power system has been developed over the last 50 years following a highly centralized model [M. Donkelaar, 2004]. The structure of the power system was rather straightforward (Figure 5), with a relatively small number of large production centers delivering power to consumers through the transmission and distribution networks. 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

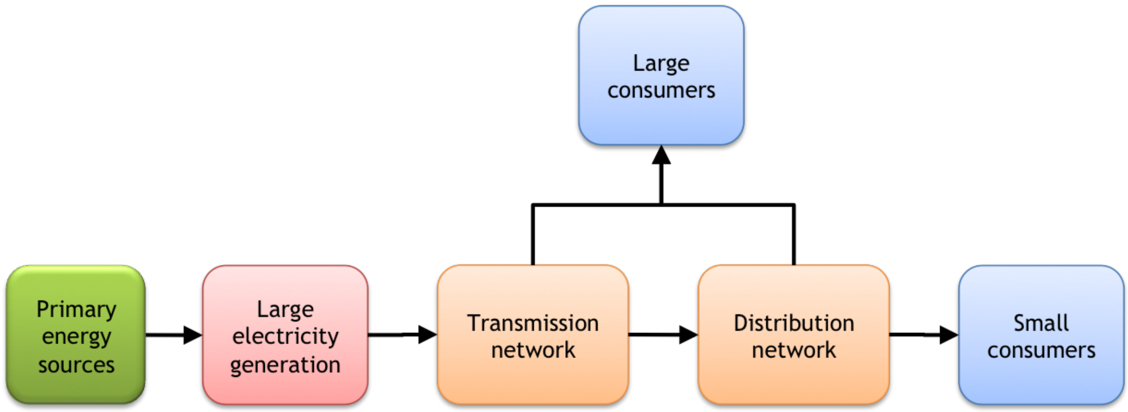


Figure 5: Schematic representation of the power supply system before liberalization. Figures based on [M. Donkelaar, 2004].

personnel, with transmission and distribution network 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 [Union, 2003], the previously integrated services 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 6) with a separation between the management of the physical transmission and distribution networks from the corresponding supply markets (wholesale and retail respectively). Furthermore, the new system left space for the development of two more markets: the balancing and the ancillary services markets. In a now more complex system that sees 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 open than before to unbalances between supply and demand. On the ancillary service markets other power quality services were made available, such as reactive power, voltage control, etc. In this framework, the growing DG sector was prevalently playing a passive role: substantially an appendage of the distribution network, it did not have any real sizable interaction with the rest of the supply system. In more recent years, environmental policies revitalized the already growing general interest in this sector. The combined effects of liberalization of the energy market on one side and

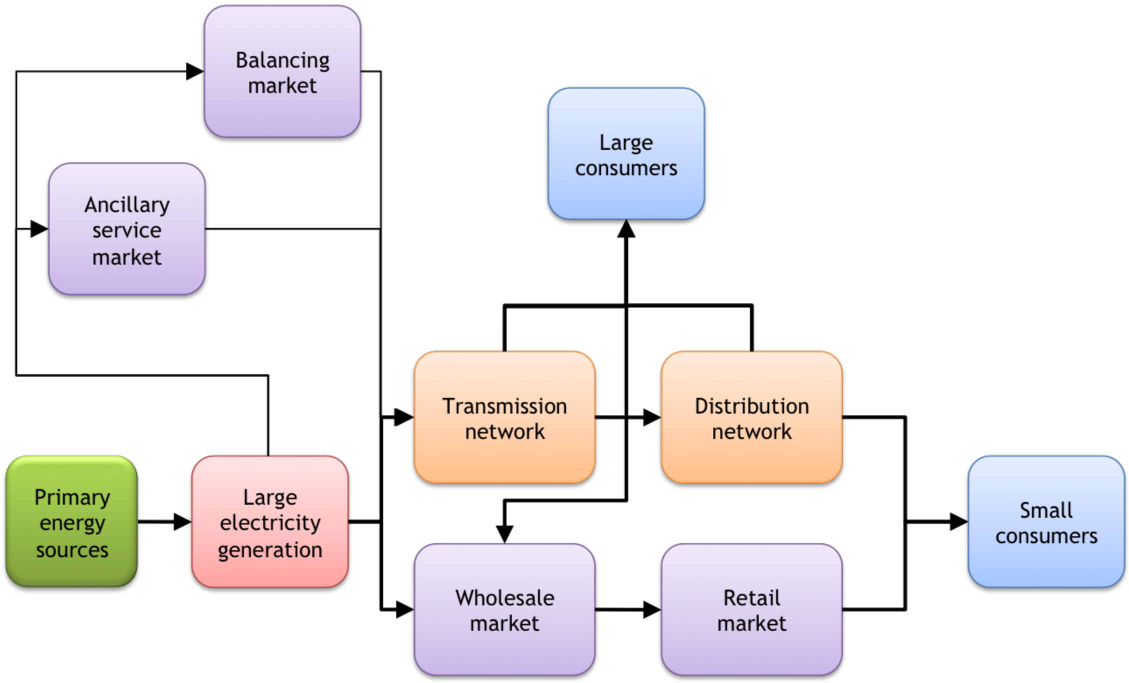


Figure 6: Schematic representation of the power supply system after liberalization. Scheme based on [M. Donkelaar, 2004].

the support for – prevalently small-scale – renewable energy solutions on the other produced new opportunities for participating in different markets. This brought a further modification of the power supply system structure (Figure 7). Small scale distributed power generators, by tapping into previously unused RES, are able to directly deliver power to consumers or to operate via electricity markets. The implications on the required system development at the infrastructural level are, in this case, of primary importance. A network designed for a radial structured unidirectional power flow (Figure 8a) has to be converted in a networked bidirectional flow structure (Figure 8b).

The very role of the network and, consequently, of all the players operating on it is expected to change: not only it will distribute power but it will need to provide access among the connected parties. As the role of the 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.

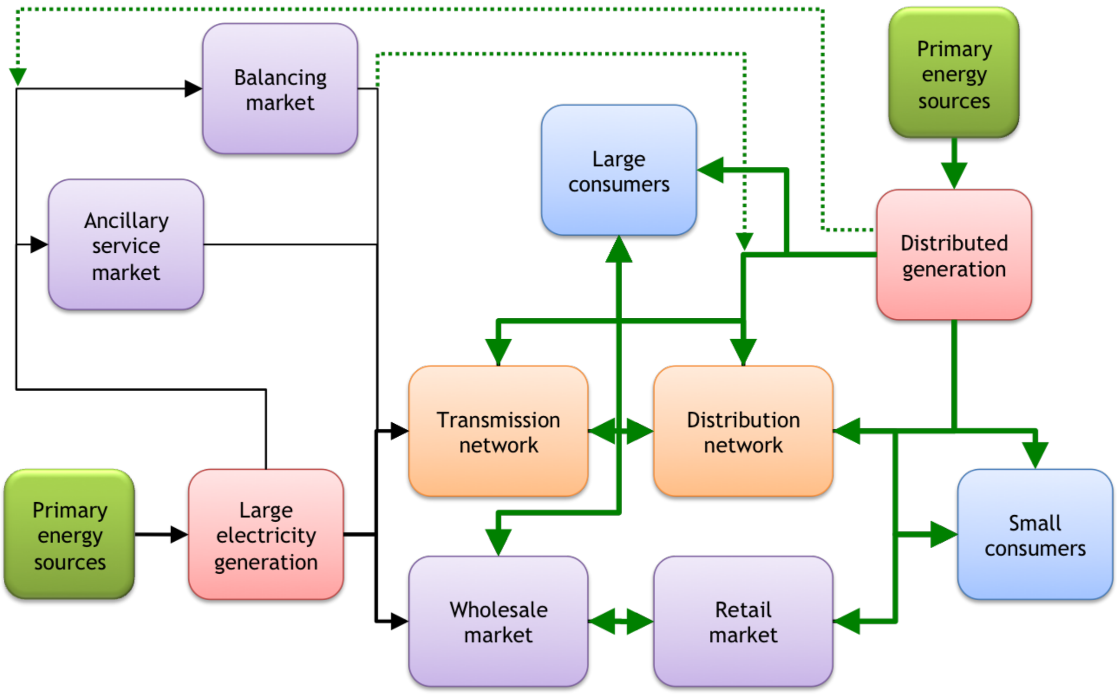


Figure 7: Schematic representation of the power supply system in a liberalized market with the integration of DG based on RES. Scheme based on [M. Donkelaar, 2004].

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.

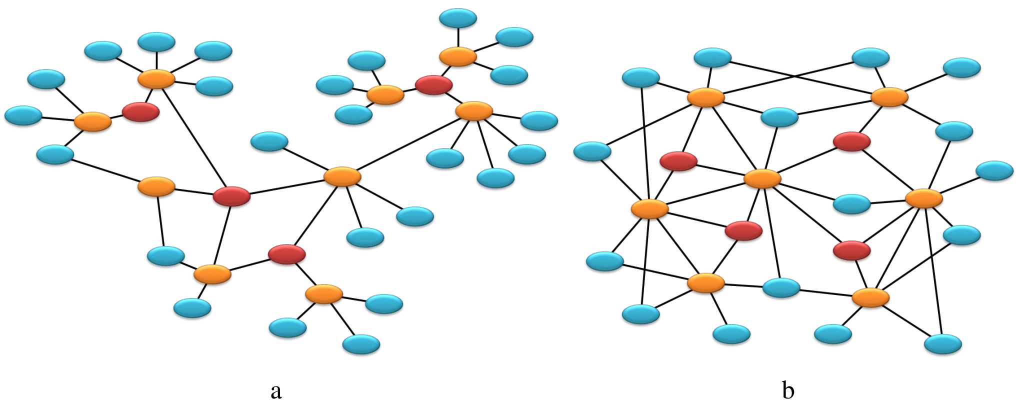


Figure 8: Schematic representation of (a) radial structured and (b) meshed networks.

3.3 Smart Grid and energy services

The development of a smart energy grid based system allows the application of concepts borrowed from the service economy to the energy market. Following the path described in the previous section, different players on the energy market are expected to invest on the renovation of the existing infrastructure. One of the key elements of this renovation will have to be energy efficiency, an aspect likely not to fit the current economic model based on the increasing sales. The adoption of an energy service model would decouple the pursued economic growth from the actual sales of energy. This alternative model, in contrast to the one centered on the selling of energy as a commodity, aims to provide energy services such as hour of illumination and heat, running of appliances to satisfy the every ay needs and the provision of all the necessary technical and logistical conditions to sustain these services in time (i.e. the stability of the power grid).

4 Distributed energy systems

The description of distributed energy systems (DES) includes the discussion of distributed energy generation, often referred to in terms of distributed energy resources (DER) and the corresponding energy management, i.e. the set of operations required to guarantee the effective functioning of the system.

Envisioning the development of a distributed energy system based on sustainable use of local renewable resources, in this section a set of available technologies and the potential of DER in the NP are introduced. The first part is devoted to energy generation, the second part is dedicated to two other important and interconnected aspects: energy storage and system predictability and controllability.

4.1 *Classical* Renewable Resources

The most important renewable resources (in terms of presence on the energy market) are hydropower, bio-energy, wind energy and solar energy. While the use of hydropower has been present for some decades in all the countries, bio-energy – as bio-fuels and including peat – are more used in Finland and Sweden. Concerning wind power, large potential has been recently identified in these areas (Figure 9) but the plans that thereby followed focused mainly on the development of large wind farms.

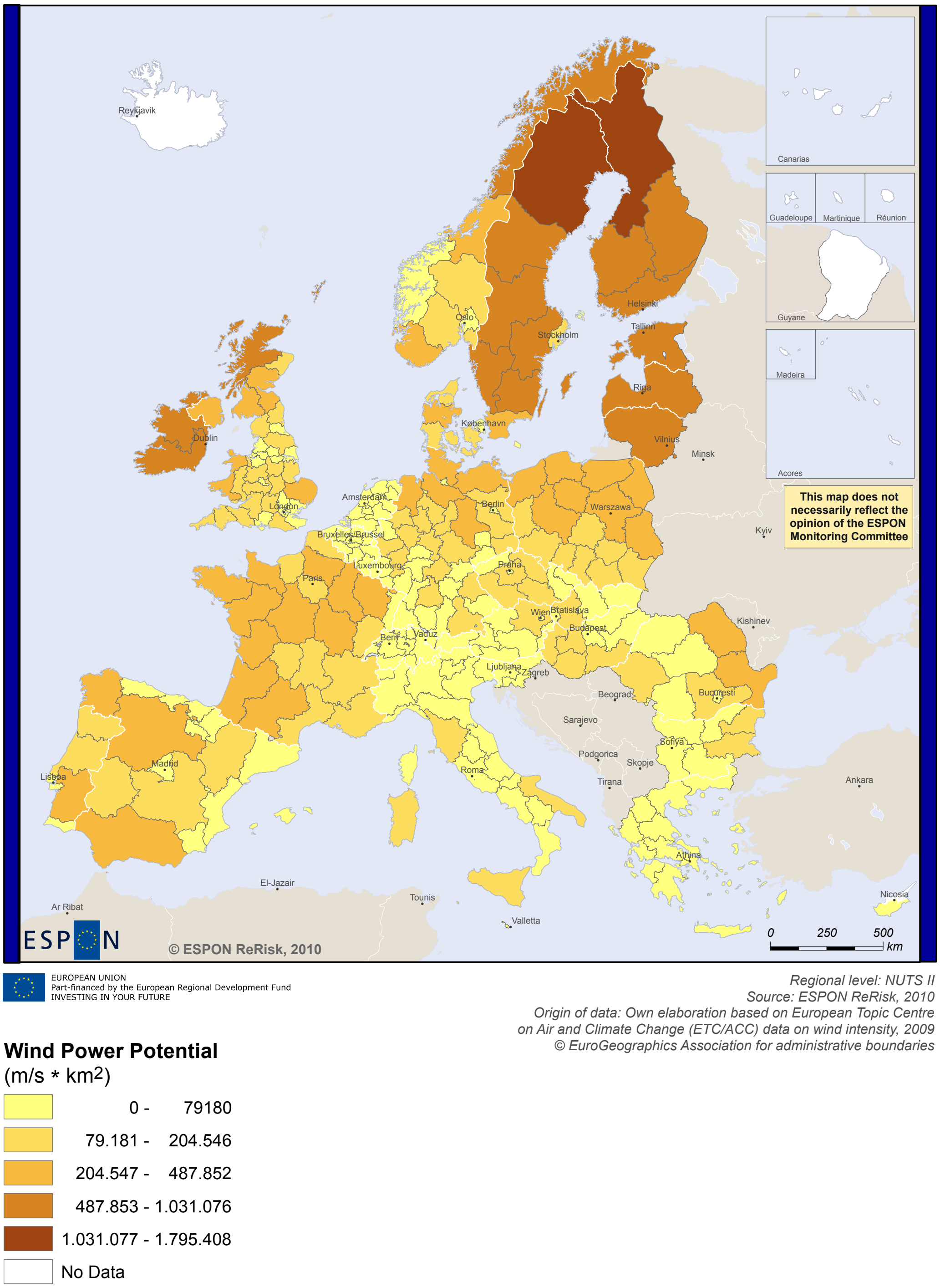


Figure 9: Map Showing the potential for wind picture production in different regions of Europe. Wind potential is calculated considering wind speed (m s^{-1}) data and the size of the available area (Km^2). Values reported on the map, although completed considering primarily wind speed data, are also taking into account a number of restraint of socio-economical, environmental and practical nature that are likely to affect the feasibility of on-shore win power generation projects. Map reproduced from [ESPON, 2011]. Data and further information available on [ESPON and Innobasque, 2010].

4.1.1 Wind power

Beside the large scale wind power systems, the number of applications for medium- and small-scale wind turbines is steadily growing [American Wind Energy Association, 2010]. Traditionally, more competitive in remote sites for battery recharging and water pumping, small scale wind power generators find today new applications in isolated and remote areas providing a portion of the electricity requirement in (envisioned) hybrid power systems.

Small-scale wind power generation refers to systems with rated capacity under 100 kW [American Wind Energy Association, 2011]. According to Global Data [GlobalData, 2011], the leading market for small wind turbine is US, with UK and Canada representing the largest potential markets [REM, 2011]. In Europe, attention has been mainly dedicated to large-scale, multi-megawatt wind farm installations, but the market for the small-scale wind generation, still in its infancy, is gaining pace. Its role in rural and remote areas, where electrification is limited and power production traditionally relies on fossil fuel based generators, has been recently officially recognized.

Wind power technology improved dramatically in the last 20 years, with modern systems operating automatically and autonomously. The typical components for a modern turbine are (Figure 10):

- A rotor, nowadays typically with 3 blades, which converts the wind kinetic energy into mechanical energy.
- A nacelle, where the gearbox and the generator are located and where the mechanical energy of the rotor is converted into electrical energy.
- A tall tower and solid foundations which allow to capture the high wind speeds even in harsh climatic conditions and carry the electrical connections.

- A control system that de/activates the wind turbine and monitors the machine operations.

Small-scale wind energy production can be used for off- or on-grid applications. Off-grid applications usually represent a competitive possibility in remote areas, where connection to the main grid or transportation of fuels is, if possible, too expensive. On-grid applications include the production of at least a portion of the required power, integrating an existing system which is either connected to the grid or, for hybrid systems, relies on an independent generator running on fuel.

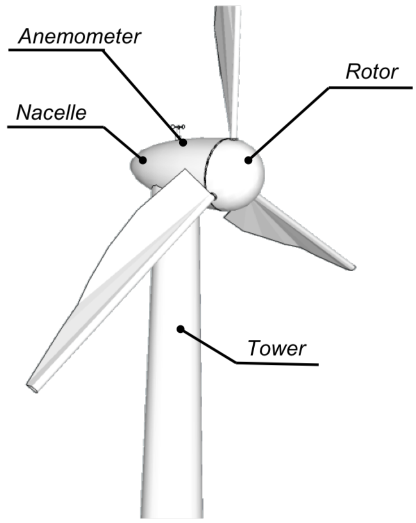


Figure 10: Schematic representation of a wind turbine and its main components. The indicated anemometer is connected with the control system usually placed inside the nacelle (see text for further details).

Wind energy systems are expected to be more financially viable in "windy" areas as the wind kinetic energy is proportional to the cube of the wind speed. However, it has to be kept in mind that the actual performance of a wind turbine, i.e. the produced power, is usually proportional to the square of the average of the wind speed. This can be explained taking in consideration aerodynamic, mechanical and electrical conversion factors [Energy Technology Centre CANMET, 2004].

There are usually two aspects that need to be considered for the installation of a small scale wind power generator. The first one is the wind probability density in the chosen site and the second is the wind power plant itself, i.e. its size and type.

For large scale projects such as large wind farms, wind resource assessment can take years and at least a full year of measurement is usually recommended. For small scale projects such as those mentioned before this is often not a viable option as the wind monitoring costs are, in this case, likely to be higher than the acquisition and installation costs [Energy Technology Centre CANMET, 2004].

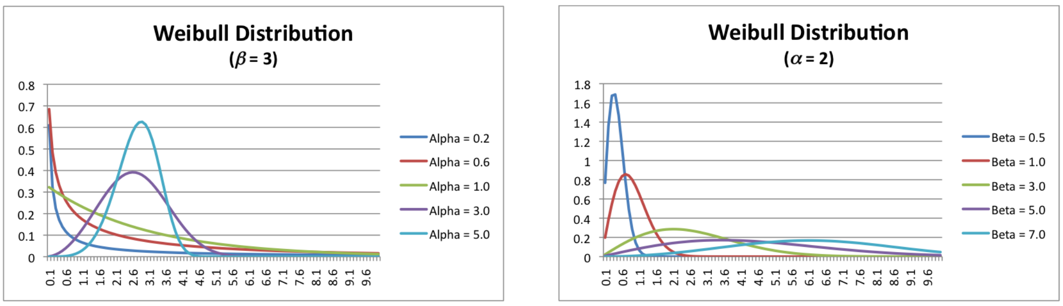
The wind probability density profile $p(x)$ can in many cases be approximated by the Weibull probability function [Weibull, 1952] which can be defined as follow:

$$p(x) = \begin{cases} \left(\frac{\alpha}{\beta}\right)\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left[\left(-\frac{x}{\beta}\right)\right] & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases} \tag{4.1}$$

where $\alpha > 1$ – for wind probability profiles – and $\beta > 0$. k is the shape parameter; typically $1 < \alpha < 3$ where a smaller value indicates a more spread distribution of the wind speeds around the average (Figure 11a), usually translating in a higher energy production for a given average wind speed. β is the scale factor (Figure 11b) and it is calculated as follow:

$$\beta = \frac{\bar{x}}{\Gamma\left(1 + \frac{1}{\alpha}\right)} \tag{4.2}$$

where $\bar{x}$ is the average wind speed and Γ is the gamma function.



a b

Figure 11: Effects of the shape parameter (a) and the scale parameter (b) on the Weibull probability distribution.

The power generated is calculated as follow:

$$P = \frac{1}{2}\rho A v^3 \tag{4.3}$$

where P is the power (W) generated by an air mass of density ρ (kg m^{-3}) flowing at speed v (m s^{-1}) through an area A (m^2). The power described in the formula is the total energy per unit of time that can be extracted as mechanical energy from the turbine rotors by reducing the speed of the air mass. As the air mass cannot be completely stopped, the power described in the formula cannot be completely extracted. In 1926 Betz calculated that the theoretical maximum that could be extracted was 59% of the total wind power [Ackermann, 2005].

Concerning the wind turbine size and model it is to be considered that the relationship between the wind speed and the height above ground follows a power law profile [E.W. Peterson, 1978]:

$$v = v_r \left(\frac{z}{z_r}\right)^{\alpha} \tag{4.4}$$

where v is the wind speed (m s^{-1}) at the height z (m) and v_r is a known reference wind speed at the height z_r. The exponent α is an empirically derived constant related to the atmospheric turbulence. Its commonly assumed value, 0.143, for relatively small height level differences ($\Delta z < 50$ m) normally introduce no sizable errors. For small-scale plant it is instead important to take into consideration the roughness of the terrain and the consequent effects on the wind due to the presence of obstacles at ground level. In this case the mentioned value of the constant α may result not sufficiently accurate and a logarithmic profile is preferred:

$$v = v_r \ln\left(\frac{z - z_r}{z_0}\right) \tag{4.5}$$

where z_0 is a known reference wind speed at the reference height of and is the surface roughness expressed in meters. A short list of terrain classification in terms of surface roughness length values is reported in the Table 1.

Table 1: Roughness values and classifications. Table reproduced from [Khalfallah, 2007]

z_0	Terrain	Class
1.00	City	3
	Frost	
0.50	Suburbs	
0.30	Shelter Belts	
0.20	Many trees or bushes	2
0.10	Farmland with closed appearance	
0.05	Farmland with open appearance	
	Farmland with very few buildings, trees, etc.	
0.03	Airport areas with buildings and trees	
0.01	Airport runway areas	1
	Mown grass	
0.005	Bare soil (smooth)	
0.001	Snow surface (smooth)	
0.0001	Sand surface (smooth)	0
	Water areas (lakes, fjords, open sea)	

The Table below indicates the average wind speed in a number of locations across the considered area. Values are reported in m s^{-1} and indicate the average wind speed measured in the corresponding month at 50m above ground level. Each monthly average is calculated as the numerical average of 3-hourly values for the given month.

Table 2: Average monthly wind speed (m s^{-1}) in few locations across the considered area for the year 2010. Data from [Weather Underground Inc., 2011]

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oulu	3	3	3	3	3	4	3	3	3	4	3	3
Luleå	3	2	3	3	3	4	4	3	3	4	3	3
Tromsø	6	4	4	4	4	4	4	3	3	4	4	5
Rovaniemi	3	3	3	3	3	4	4	4	3	5	4	4
Umeå	3	3	3	3	3	3	3	3	2	4	3	3

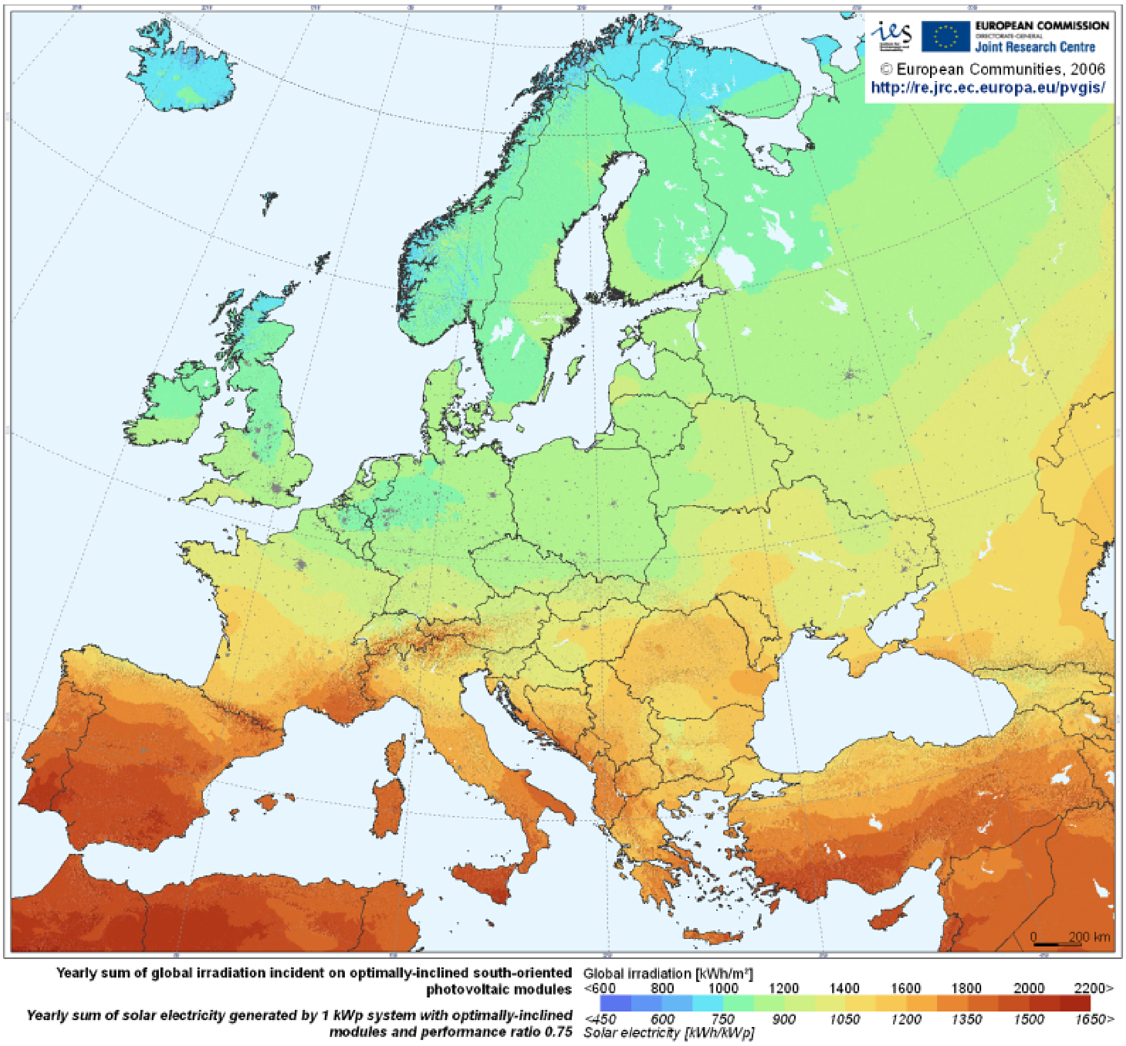


Figure 12: PV potential in Europe. Both the yearly sum of global radiation and the corresponding electricity generated (kW_h/kW_p) are indicated. Values are calculated over a 10-years average period (1981-1990). For comparison it is to be underlined that the color code is the same as for Figures 15.

4.1.2 Solar power

Up till now, in the regions considered in this work, solar energy has not been used for power generation to any sizable extent even though there is a potential for solar energy. The map in Figure 12 shows that for optimally-inclined south-oriented photovoltaic (PV) modules, the potential for solar power production calculated over one year period is comparable to central Europe.

PV application can be grouped as for off- or on-grid applications and they are rated according to the standard testing conditions (STC): 1 kW/m^2 of sunlight with PV modules at 25°C temperature. The corresponding output is expressed in peak-Watt or nominal capacity (W$_p$). On-grid applications consist of small and medium scale systems ranging from 2 to 4 kW$_p$ for single residence uses to 100 kW$_p$ for commercial buildings.

The advantages of an on-grid application translates in reduced costs and environmental benefits as the generators are generally located close to the load, reducing energy and capacity losses. In off-grid applications the PV generators usually consist of small systems, typically less than 10 kW$_p$, with batteries. Owing to the growing worldwide demand over the last 20 years, in remote areas PV technology is rapidly becoming a valuable low-cost option, with the higher competitiveness of PV systems for off-grid applications represented by the generally high costs for grid extensions.

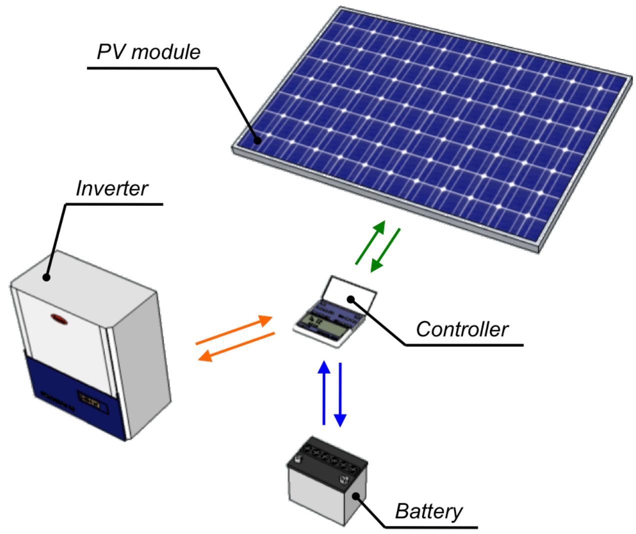


Figure 13: Schematic representation of a PV system and its main components (see text for further details).

A PV system can be made of a number of components, depending on the designed application. The typical components are (Figure 13):

- The PV module, that this is the primary element of the system.
- A battery whose role is to allow energy on demand. Its role can be replaced by the network in on-grid applications, while it plays a key role in off-grid

applications. Moreover battery technology represent an important part of smart energy grids development as a whole, and it will be more accurately discussed in the section 4.3.

- Inverters that transform the direct current in alternate current.
- Controllers that manage the energy fluxes between storage and load.
- Structure where the PV modules are physically installed.

Not all the systems require the mentioned components while in some cases other devices are to be included. Especially for off-grid applications, for example, conventional fuel based generation can be integrated in a hybrid system requiring rectifiers to convert AC in DC and additional battery charge controllers.

The values reported in Figure 12 are determined taking into consideration a number of key factors such as (Figure 14) latitude, declination (δ), slope (β), surface azimuth angle (γ), angle of incidence (θ), solar (ω) and sunset (β_s) hour angles, extraterrestrial radiation (H_0) and the clearness index (K_p).

Declination is calculated as the angular position of the sun at (solar) noon with respect to the plane of the equator (Figure 14). It is calculated using the Cooper's equation [Cooper, 1969]:

$$\delta = 23.45\left(2\pi\frac{284+n}{365}\right) \tag{4.6}$$

where δ is the declination in degree and n is the number of the day (i.e. 1.1 $n = 1$, 1.2 $n = 32$, 25.12 $n = 359$, etc.).

The slope β is the angle between the considered surface and the horizontal plane. $0° \leq \beta \leq 180°$ with $\beta \geq 180°$ indicating a surface facing downward.

The surface azimuth angle γ is the projection on the horizontal plane of the angle between the normal to a vertical surface and the local meridian. $-180° \leq \gamma \leq 180°$

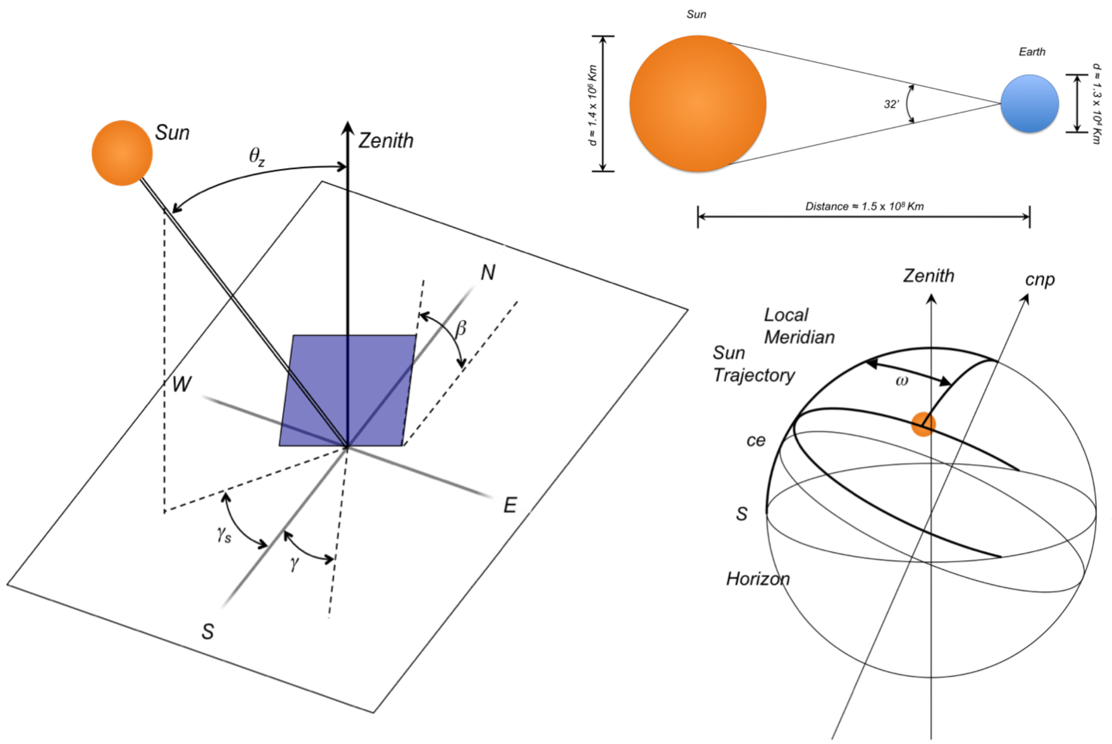


Figure 14: Graphic representation of the main factors considered for the determination of the yearly sum of global irradiation (see text for further details).

with 0° indicating south, east positive and west negative. Accordingly, the solar azimuth angle γ_s is the projection of the angle between the solar beam and the local meridian.

The solar hour angle ω is the angular displacement of the sun respect to the local meridian. Its values, negative in the morning, at (solar) noon and positive in the afternoon, is calculated as 15 degrees per hour from solar noon

$$\omega(9\ \text{a.m.}) = 15 \cdot (-3) = -45°. \tag{4.7}$$

The sunset hour angle ω_s is the hour angle at the sunset time and it is calculated as follow:

$$\cos \omega_s = \tan \phi \cdot \tan \delta \tag{4.8}$$

where ω_s is the sunset hour angle in degrees, ϕ is the latitude of the considered location and δ is the declination as defined in Eq. 4.6.

The angle of incidence θ indicates the angle between the solar radiation and the zenith. By knowing latitude, declination and slope, the angle of incidence can be calculated as

$$\begin{aligned}\cos\theta &= \sin\delta\cdot\sin\phi\cdot\cos\beta - \sin\delta\cdot\cos\phi\cdot\sin\beta\cdot\cos\gamma \\ &\quad + \cos\delta\cdot(\cos\phi\cdot\cos\beta\cdot\cos\omega + \sin\phi\cdot\sin\beta\cdot\cos\gamma\cdot\cos\omega + \sin\beta\cdot\sin\gamma\cdot\sin\omega)\end{aligned} \tag{4.9}$$

Despite the apparent complexity of its nature, in many practical cases equation 4.9 assume much simpler forms. For example for fixed surfaces sloped toward south (i.e. $\gamma = 0$) obtaining

$$\begin{aligned}\cos\theta &= \sin\delta\cdot\sin\phi\cdot\cos\beta - \sin\delta\cdot\cos\phi\cdot\sin\beta \\ &\quad + \cos\delta\cdot(\cos\phi\cdot\cos\beta\cdot\cos\omega + \sin\phi\cdot\sin\beta\cdot\cos\omega)\end{aligned} \tag{4.10}$$

while for horizontal ($\beta = 0°$) and vertical ($\beta = 90°$) Eq. 4.9 becomes:

$$\beta = 0° \quad \Rightarrow \cos\theta = \sin\delta\cdot\sin\phi + \cos\delta\cdot\cos\phi\cdot\cos\omega \tag{4.11}$$

$$\beta = 90° \quad \Rightarrow \cos\theta = -\sin\delta\cdot\cos\phi\cdot\cos\gamma + \cos\delta\cdot(\sin\phi\cdot\cos\gamma\cdot\cos\omega + \sin\gamma\cdot\sin\omega) \tag{4.12}$$

The optimal inclination can play a crucial role in the economically feasibility of photovoltaic electricity potential, especially at large latitudes. An example of the relevance of this element is showed in Figures 15 (It is to be underlined that Figure 12 and Figures 15 have the same color legend). Although significantly smaller when compared with the southern European Countries, there is a potential that until now have been untapped mainly due to high costs.

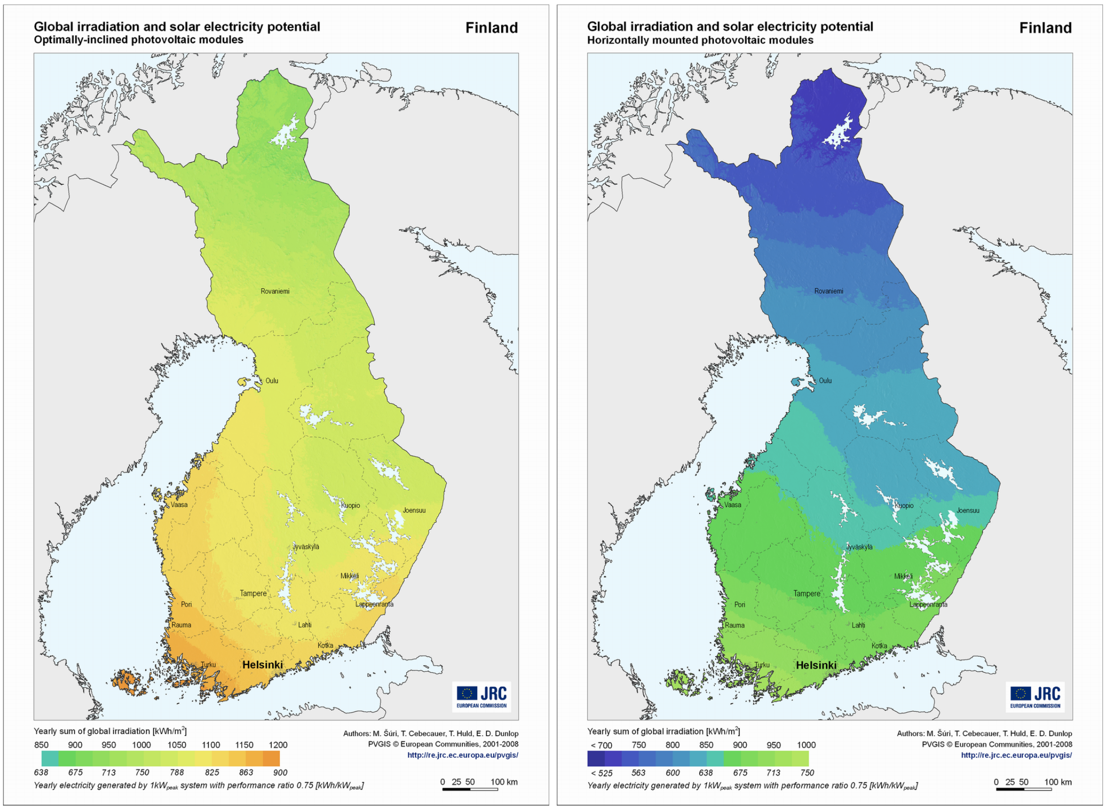


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Figure 15: PV potential in Finland. Both the yearly sum of global radiation and the corresponding electricity generated (kW$_h$/kW$_p$) are indicated. The comparison between the two maps allows a better understanding of the improvement in energy generation that the (a) optimal orientation ($\gamma = 0°$ and $40° < \beta < 46°$, see text for further details) of the PV module provides when compared with the production generated by (b) horizontally mounted PV modules. The color code, for both maps, is the same as for Figure 12.

The extraterrestrial radiation is the solar radiation calculated without considering the atmospheric effects. The daily extraterrestrial radiation on a horizontal surface can be calculated as:

$$H_0 = \frac{86400 \cdot G_{sc}}{\pi} \left[1 + 0.033 \cdot \left(\frac{2\pi \cdot n}{365} \right) \right] \cdot (\cos\phi \cdot \cos\delta \cdot \cos\omega_s + \omega_s \cdot \sin\phi \cdot \sin\delta) \quad (4.13)$$

where n, ϕ, δ, ϕ, ω_s are the day of the year, latitude, declination and sunset hour angle as previously defined and G$_{sc}$ is the solar constant:

$$G_{sc} = 1353\ \mathrm{W/m^2}. \quad (4.14)$$

The solar constant is the energy generated from the sun and striking Earth calculated per unit of area on a surface perpendicular to the direction of the radiation at the Earth mean distance from the sun (G_{sc} = 1353 W/m^2) without atmospheric interference. The clearness index represents the atmospheric attenuation of the extraterrestrial solar radiation and it is calculated as follow:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \tag{4.15}$$

where $\bar{H}$ is the monthly average daily solar radiation, $\bar{H}_0$ is the monthly average extraterrestrial radiation on an horizontal surface, and $\bar{K}_T$ is the clearness index whose value usually range from 0.3 (overcast location) to 0.8 (sunny location).

In many practical cases, the solar radiation is to be calculated on a tilted surface. This is usually calculated on data for solar irradiation on the horizontal surface, as these are usually the most commonly available data. The ratio between the beam radiation on a tilted surface to that on horizontal surface is calculated as:

$$R = \frac{\cos\theta}{\cos\theta_z} \tag{4.16}$$

where $\cos\theta$ and $\cos\theta_z$ are from equations (4.9) and (4.12).

4.2 Bio-energy Technologies

This work is a follow-up to previous studies under MicrE and, in its selection of bio-energy technologies, considers those suitable for use in the Northern Periphery mapped earlier [Kauriinoja, 2010, MicrE, 2010]. The following sections contains a brief description of the selected bio-energy technologies.

4.2.1 Biomass

In the context of renewable energies, biomass indicates material derived from living, or recently living organisms. Often used to indicate plant based material, biomass can equally indicate animal based material as well. [Biomass Energy Centre, 2011]. There are different types of biomasses, the value of which depends primarily in their chemical and physical properties. Classified according to their origin or their physical characteristics [Khan et al., 2009], the type of biomass define the more appropriate energy conversion processes which can provide energy (as electricity and heat), transport fuels (biogas) and chemical feedstock.

The production of biomass (and consequently its potential for energy production) in the NP areas is subject to very particular conditions likely to strongly influence its environmental as well as its socio-economical performance. Long and dark winters severely limits the production of vegetable based biomass, while long and warmer summer days considerably increase the amount of available biomass. Furthermore the sparsely inhabited regions, especially in the rural areas, offer a great potential for biomass based energy production. On the other hand the potential impact of an intensive use of the available biomass can have severe consequences in terms of environmental impact and competing use of the available resources.

4.2.2 Pelletization

Pelletization is a process in which biomass is dried and compressed under high pressure into cylindrical shaped pieces as shown in Figure 16. The most common material for pelletization is wood, typically wastes and residuals of wood industries, but herbaceous crops and grasses can also be used. A comprehensive description of the process and the different suitable solution for pellet production is available on

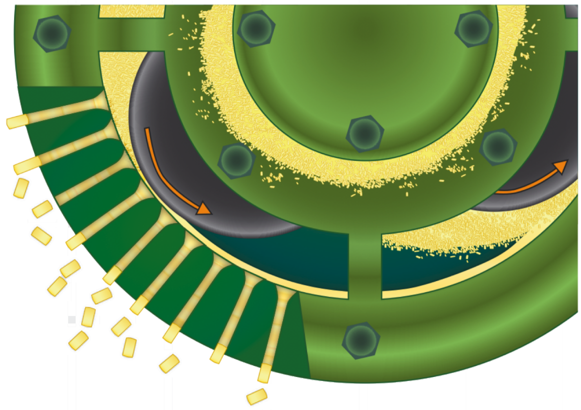


Figure 16: In the pellet press raw material is compressed by rolling wheels compress through the press channel (picture from [MicrE, 2010]).

[North Karelia University of Applied Sciences, 2010].

A pelletization units includes a number of processes (Figure 17): the used biomass is dried and its moisture content is reduced to 10-15%; the dried biomass is then grinded into fine fractions before being sent to the pelletizer where the actual pellets are made; finally pellets are cooled for stabilization and hardening before being stored. ([Uslu, 2005] p. 45).

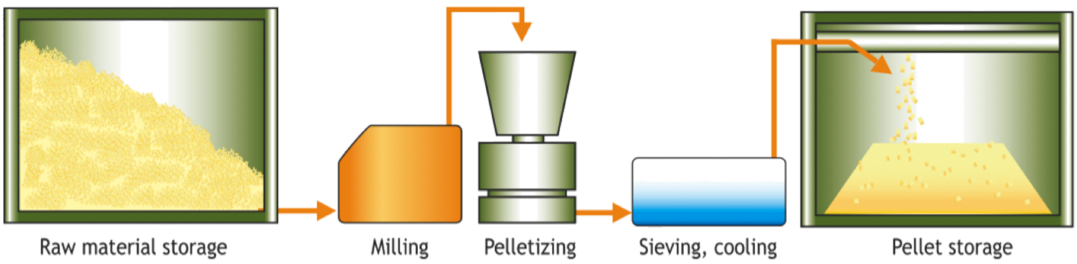


Figure 17: Schematic representation of the pelletization process and the functioning of the different components of a pelletization unit.

The advantages of pellets utilization compared to raw biomass is the higher energy content per unit of volume, the reduce amount of dust and the uniformity of the fuel (add references also for control and prediction). Useful applications include small scale combustion, CHP or gasification.

The pellet market development in the study areas is quite heterogeneous ([J.-N. Louis and E. Pongrácz, 2011] and references therein): Sweden represents one of the largest market in the world (in relation to its inhabitants) while in Norway the pellet market is of minor importance; in Finland the pellet market has not a prominent role but it is rapidly growing. Pelletizing technology investment costs can vary quite significantly with the size of the production. More informations can be found in [North Karelia University of Applied Sciences, 2010, MicrE, 2010] and references therein.

4.2.3 Combustion

The oldest and still the most common way to convert biomass into energy, it is based on the direct oxidation of the elements of the organic materials. Covering a wide range of energy production application, from small to large scale, it is nevertheless a rather inefficient process, especially when compared with other technologies such as gasification. Combustion systems require inputs with limited amount of moisture (<50%), preferred fuel being pellets, biomass and wood based waste. Useful applications concern primarily the production of heat.

4.2.4 Gasification

In the gasification process, the carbon in the biomass is converted into a gas mixture called synthetic gas (or syngas) by partial oxidation at high temperature; the produced syngas is composed primarily of CO and hydrogen following simple reaction paths. The advantage of gasification is that using the syngas is potentially more efficient than direct combustion of the original fuel because it can be combusted at higher temperature.

The size of a gasification plant cover a broad range, depending on the deployed technology and the intended use. The preferable inputs include forest products, biowaste and organic material with moisture content below 45%. Scandinavian countries are leader in implementation of biogas gasification systems. More informations can be found in [Kauriinoja, 2010] and references therein.

4.2.5 Anaerobic Digestion

In Anaerobic Digestion (AD), organic matter is decomposed and stabilized in an oxygen free environment producing methane rich biogas and digestate. The latter, a mixture of water and nutrients from the utilized organic material, can be treated and used as fertilizer. The produced biogas can be utilized in a number of applications: i.e. it can be used as fuel for an in situ CHP unit or upgraded as vehicle fuel (methane). The AD process can be more specifically described as follows:

$$OrganicMatter + H_2O = CH_4 + CO_2 + biomass + NH_3 + H_2S + heat \qquad (4.17)$$

Suitable feedstocks are agricultural, industrial and domestic organic wastes and byproducts. The amount of methane and carbon dioxide in the produced biogas are typically in the 45–60% and 36–41% range respectively [Kauriinoja, 2010]. A typical AD plant consists of different parts, the design of which depends on intended application. Typical components include (Figure 18):

- A digester where the microbes digest the organic matter releasing biogas following the process described in formula . Inside the digester, the environment is monitored and controlled in order to optimize the process. The technology of a digester can vary according to the AD system, and it typically includes a heating system, to maintain the optimum temperature for the digestion process, a mixing mechanism, if separation is to be avoided, a biogas collection system and a drainage system for the extraction of the digestate.
- A control unit, where the necessary key aspects for a correct functioning of

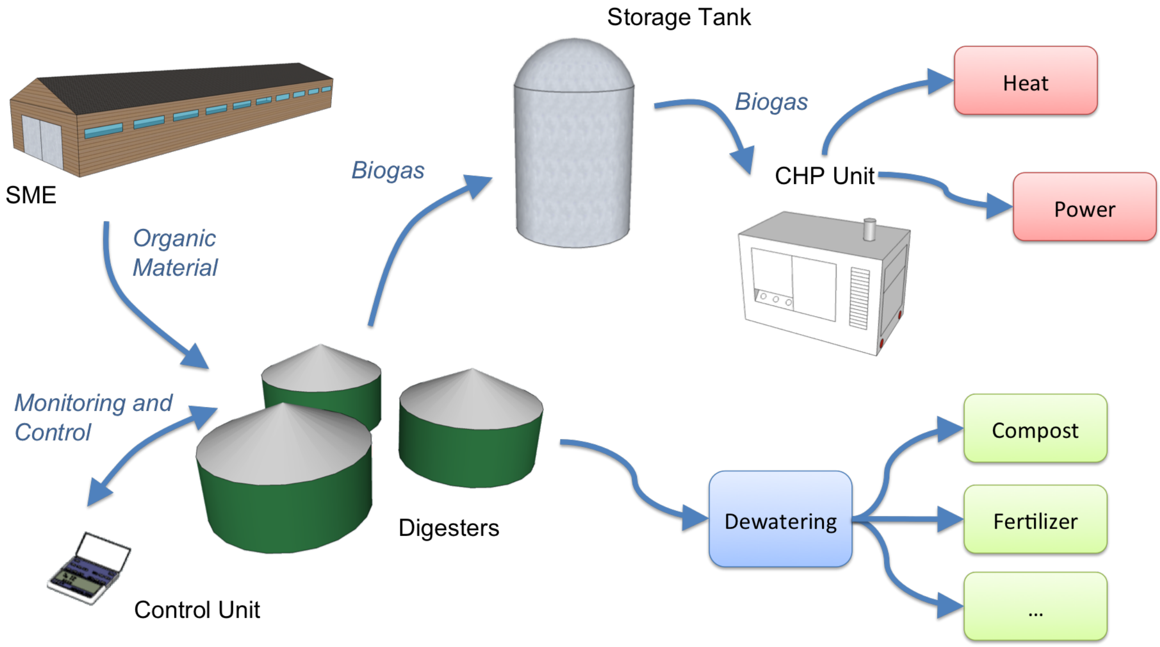


Figure 18: Schematic representation for the anaerobic digestion process and its components.

the system are monitored and managed. The available sensor technology allows the role of the control unit to span across a broad range of possibilities [Vanrolleghem, 1995] and it strongly depends on the typology of the AD plant; typical monitoring includes temperature, liquid level and fluids' flows.

- Storage tanks.
- A combined heat and power (CHP) unit.

A more detailed description of the AD process and the technical specifications of the corresponding digesters goes beyond the scope of this work and the interested reader can find the required information in the indicated references ([Kauriinoja, 2010] and references therein, [Waste-to-Energy Research and Technology Council, 2009]).

Depending on the design of the AD unit, water and biomass can be recovered and locally reutilized. For what concern the energy flow, biogas can be used to sustain the AD process (in which case the plant would include a CHP unit as shown in the figure) and/or to directly contribute to the energy budget of the facility.

More informations can be found in [Kauriinoja, 2010] and references therein.

4.3 Energy Storage

Energy can be stored in different form and stages of the energy chain: as primary source (i.e. fuels, biomass, etc.) or as secondary source (i.e. heat, mechanical and chemical energy, etc.). For most practical applications, stored energy can be understood as stored electrical energy, especially for any deployment intended for on-grid application. Nevertheless, it is important to stress the key difference between energy storage commonly viewed as a sort of large battery for houses vs. energy storage device. The second necessarily imply a broader range of available technologies such as the waste-to-energy solutions mentioned in section 4.2 which produce biogas that represent a primary source of energy.

The possibility to storage energy helps mitigating the energy supply demand ratio fluctuation; as we already mentioned (Sec. 4.1.1 and 4.1.2), this is a very important aspect especially when using wind and solar power where supply uncertainties are not related with end user choices or behavior.

Characteristics of different energy storage technologies and, therefore, their possible practical applications, can be defined primarily in terms of discharging time and storage capacity. Currently, available options can be categorized by high-power and high energy storage technologies: High-power solutions can supply large power, for a limited time (usually up to seconds or few minutes). High energy applications can provide smaller amount of power but it can be sustained for much longer period of time. High-power applications are typically dedicated to issues such as voltage level

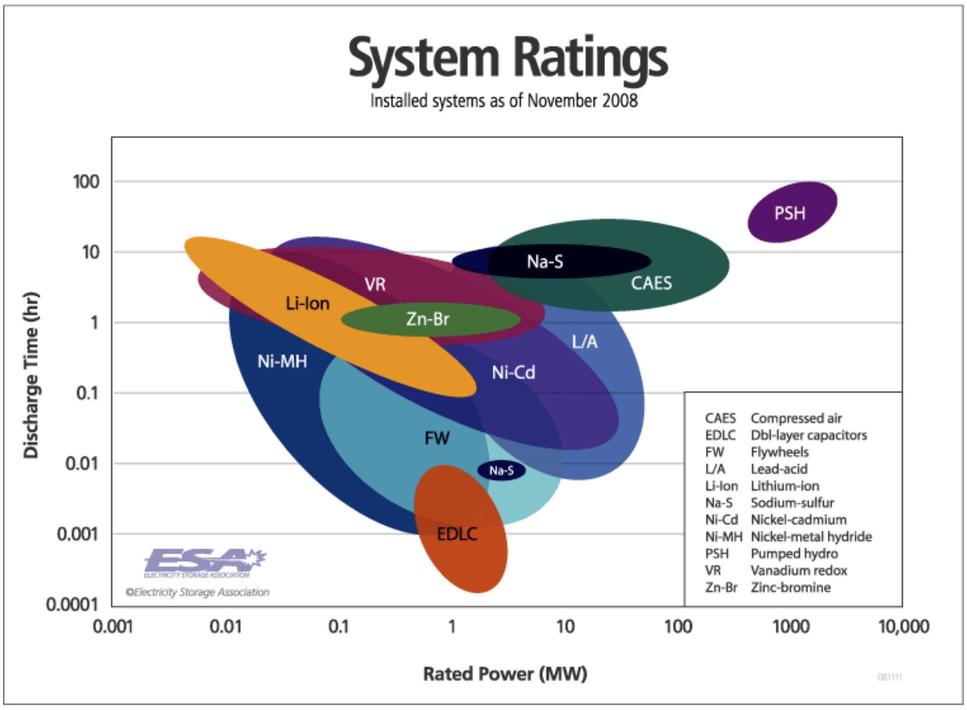


Figure 19: Rating of different energy storage technics based on their discharge-rated power ratio. Picture from [Electricity Storage Association, 2009]

maintenance, while high-energy applications include sustained electricity production in case of power shortages.

A schematic summary of the available energy storage technology, their characteristics is reported in Figure 19 and Table 3. A detailed description of the technical aspects of these technologies goes beyond the scope of this work; the interested reader can refer to [Electricity Storage Association, 2009] and references therein

4.4 Predictability and Controllability

In the near future, the spread of small and medium scale DES dedicated primarily to energy and heat production for local needs can have a series of consequences, especially on the low voltage (i.e. distribution) network, that needs to be considered. From a technical point of view, the expected benefit of a decentralized energy

Table 3: Comparison between different energy storage technologies. Table reproduced from [Electricity Storage Association, 2009]. Abbreviations and symbols: PSH = Pumped Storage Hydro; CAES = Compressed Air Energy Storage; SMES = Superconducting Magnetic Energy Storage; DSMES = Distributed Superconducting Magnetic Energy Storage; ☼= Technology fully capable and reasonable; ⛅= Reasonable for the indicated application; ☁= Feasible but not practical or economical; 🌧= Not feasible or economical.

Storage Technology	Advantage (Relative)	Disadvantage (Relative)	Power (App.)	Energy (App.)
PSH	High capacity. Low costs.	Special site requirement.	🌧	☼
CAES	High capacity. Low costs.	Special site requirement. Gas fuel required.	🌧	☼
Flow batteries (PSB, VRB, ZnBr)	High capacity (Independent power and energy ratings).	Low energy density	⛅	☼
Metal-Air	Very high energy density	Difficult electric charging	🌧	☼
NaS	High power and energy density. High efficiency	High production costs. It requires special charging circuit	☼	☼
Li-Ion	High power and energy density. High efficiency	High production costs. It requires special charging circuit	☼	☁
Ni-Cd	High power and energy density. Efficiency		☼	⛅
Other advanced batteries	High power and energy density. High efficiency	High production costs	☼	☁
Lead-Acid	Low capital costs	Limited life cycle when deeply discharged	☼	☁
Fly-wheels	High power	Low energy density.	☼	☁
SMES, DSMES	High power	Low energy density. High production costs.	☼	🌧
E.C. Capacitors	Long life cycle. High efficiency	Low energy density.	☼	⛅

system can be determined in terms of redistribution of peaks loads and the overall flattening of the total power demand curve. The negative aspects of an integrated decentralized energy production can be formulated in terms of control; the decentralized energy production can be characterized by a strong seasonal variation; each plant depends on the needs and preferences of the single users and furthermore some of the production units are subjected to weather and climate conditions. All these components of uncertainty are making the efficient management of demand-response mechanisms an essential part of future of the smart grids.

Notwithstanding wether based on a centralized or decentralized model, the monitoring and control of the grid not only opens the possibility for future economic development for the energy market, but it is likely to shift its entire center of mass. Examples of delocalized energy productions based on the idea of energy as a service rather than energy as product, are already been developed.

An example is provided by the showcase residential area project developed by the Finland based company Fortel Components Oy [Fortel Componenents Ltd, 2010a] in Kempele, near Oulu. Loosely translated ”eco block” in English, Ekokortteli [Fortel Componenents Ltd, 2010b, Matikainen, 2010] is completely unplugged from the public electricity network; the area includes ten single family houses a CHP unit run using biogas and a small wind turbine [Haapakoski, 2011]. The project has been developed with the idea of energy efficiency and self sufficiency while still maintaining a traditional lifestyle. Costumers that purchased a lot in the area were free to plan and built their own house. The only technical requirements concerned the compatibility with the area's district heating, underfloor heating, a mandatory option for a wood sauna and a maximum installed power of 10 kW. The built houses present extra insulation and energy efficiency solutions (i.e. the use of led lights for illumination), consuming approximately 40% less energy compared to the average detached house of the region. The average total power consumption of the

Ekokortteli residential area is approximately 20 kW, corresponding to approximately 400 m^3 of wood chips per year. The CHP unit runs using syngas produced by a wood gas generator using wood chips. The power generator has a capacity of 100kW and it is able to provide for the area heating system. In case of excess power production, the control system automatically begins to charge the 2600Ah battery plugged into the system. The excess production of heat is used for the drying of the woodchips, a process that guarantee a lower percentage of humidity of the wood and therefore a higher efficiency in the gasification process. The use of the small wind turbine is primarily dedicated to show the versatility of the system, which is able to work with virtually any form of energy production.

The possibility to further develop these models by connecting these independent systems to the grids – without changing the economical drivers – gives the possibility to fully exploit the economic potential leaving to the energy utility the new role of network administrators.

In this context, the development and application of intelligent functions for the data analysis and prediction of power loads is becoming increasingly important in order to guarantee the necessary adaptability, efficiency and reliability characteristics that the future energy grid is required to present.

The application and development of intelligent methods for system analysis applied to the management of DES based grid represent an interesting and valuable option for this project future development but it goes beyond the scope of this thesis work and it is not further discussed.

Experimental Part

5 Smarter energy system: an example

The simulator discussed in this section is intended to provide a realistic example of the possibilities to use the previously described technologies, and their interplay. Furthermore, the considered examples are meant to demonstrate how the potential of these applications can be evaluated not only in terms of efficiency and, on the medium term, in economical benefit, but also in terms of profound transformation in the way the energy market – understood as the complex interplay between production, transmission, distribution and consumption of energy – is conceived.

The presented simulator has been built using the Simulink © package [MathWorks Inc., 2011].

5.1 System Architecture

5.1.1 General considerations

The considered scenario for the studied cases consists of a small- or medium-size enterprise (SME) located in a semi-urban environment in the northern periphery. This allows the possibility to consider electrical grid and district heating network connections.

The built model, shown in Figure 20, consists of a number of components:

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

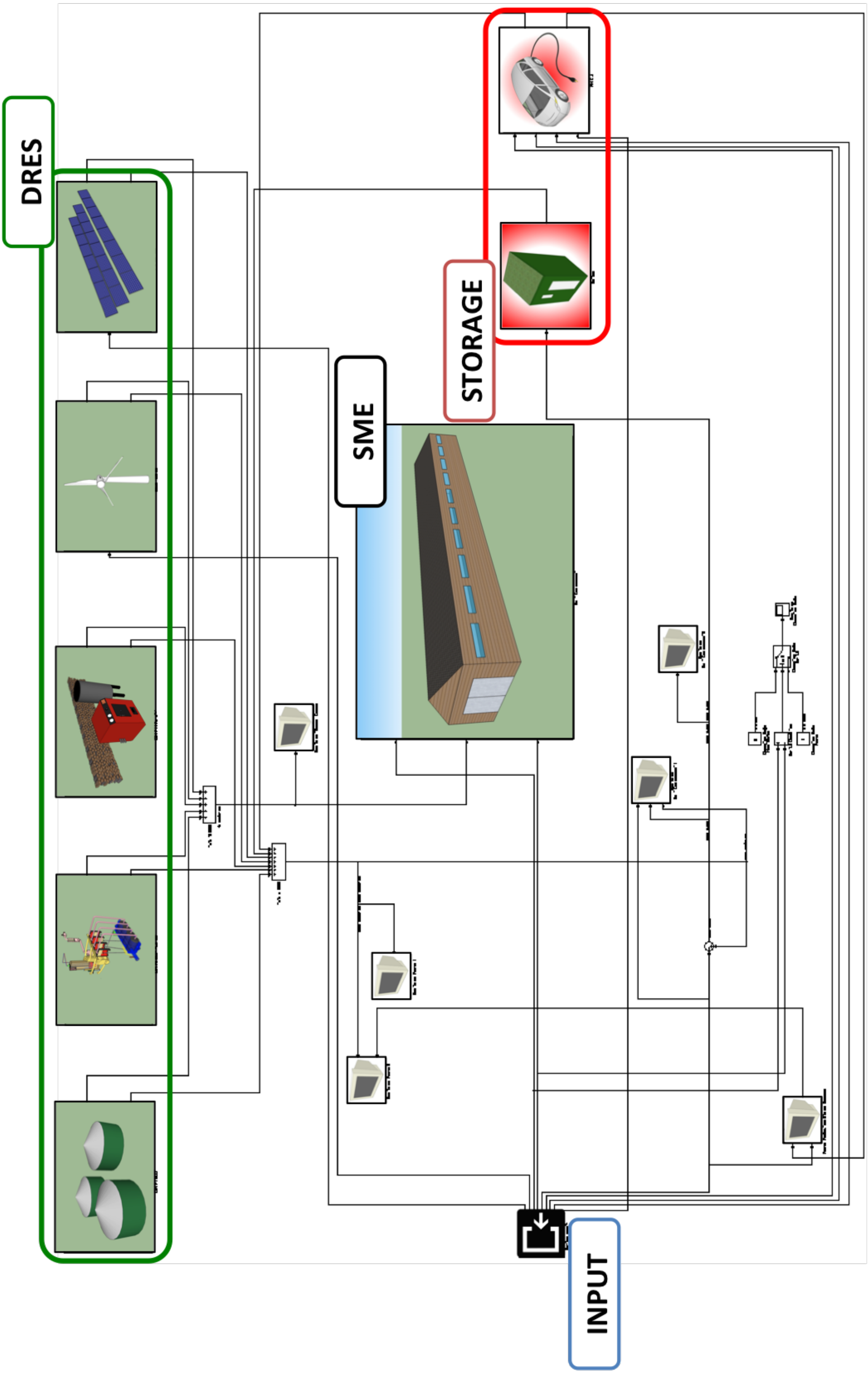


Figure 20: Overview of the system architecture. Monitors mark data collections points.

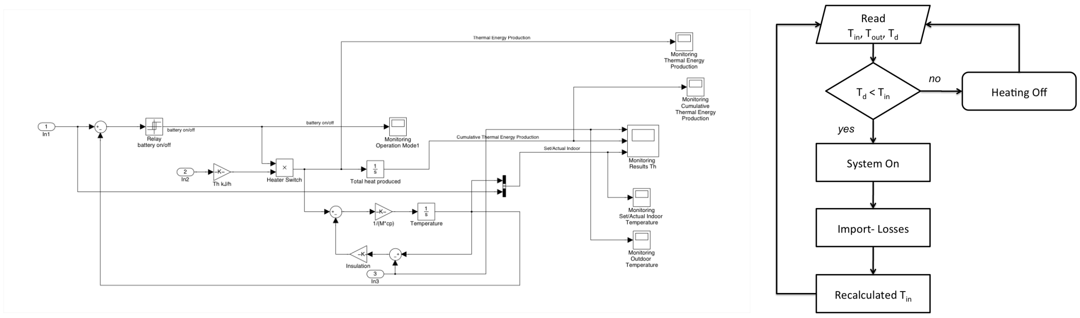
- The Input block providing the necessary environmental and system information.
- The distributed renewable energy sources (DRES) block with the description of a number of selectable energy production systems, some of which related to the environmental data.
- The Storage block describing the electric 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.

Simulations run utilizing hourly environmental and system inputs. Each run considers a period of one calendar year (365 days corresponding to 8760 hours) from the zero hour of the 1^{st} of January to the midnight of the 31^{st} of December 2010. Energy flows are calculated in kW and no attempt has been made for a detailed description of the electric and hydraulic systems necessary for correct functioning of the considered components. As the system is to be considered connected to the main electric grid and district heating network, although not clearly indicated, unmatched energy requirement resulting in negative values on the energy balance outputs are to be considered automatically supplied from the common networks.

Furthermore, the described system includes a number of deliberate simplifications reflecting choices that the author made taking in consideration of the available resources and the scope of this work.

5.1.2 The built environment

The elements contained in the SME subsystem are shown in Figure 21a. The considered model for the built environment is of a medium size building. The specifications for the considered built environment (size, U-values, etc.) are described in



a b

Figure 21: (a) SME block architecture and (b) flowchart of its operation.

more detail in Appendix A.1.1. The thermal and electrical energy requirements of the structure are considered to be independent: buildings include underfloor water heating systems; the electricity needs are related to the SME activities and no electric heating or thermal effects due to the illumination or the electrical appliances are considered.

The flowchart showing the algorithm followed by the system is shown in Figure 21b. The set indoor temperature is compared with the actual indoor temperature at one hour interval. The relay then switch 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 (kJ/h) and, once heat loss have been considered, the new temperature is calculated.

5.1.3 System and environmental inputs

The input block (Figure 22) contains the system and environmental information required for a realistic functioning of the simulator. The first set of data includes the chosen indoor temperatures and the environmental conditions (temperature, wind, cloud cover and PV system performance). Changing the geographical location of the considered model is likely to affect the overall performance of the system as the outdoor temperature and the environmental condition have strong influence on the

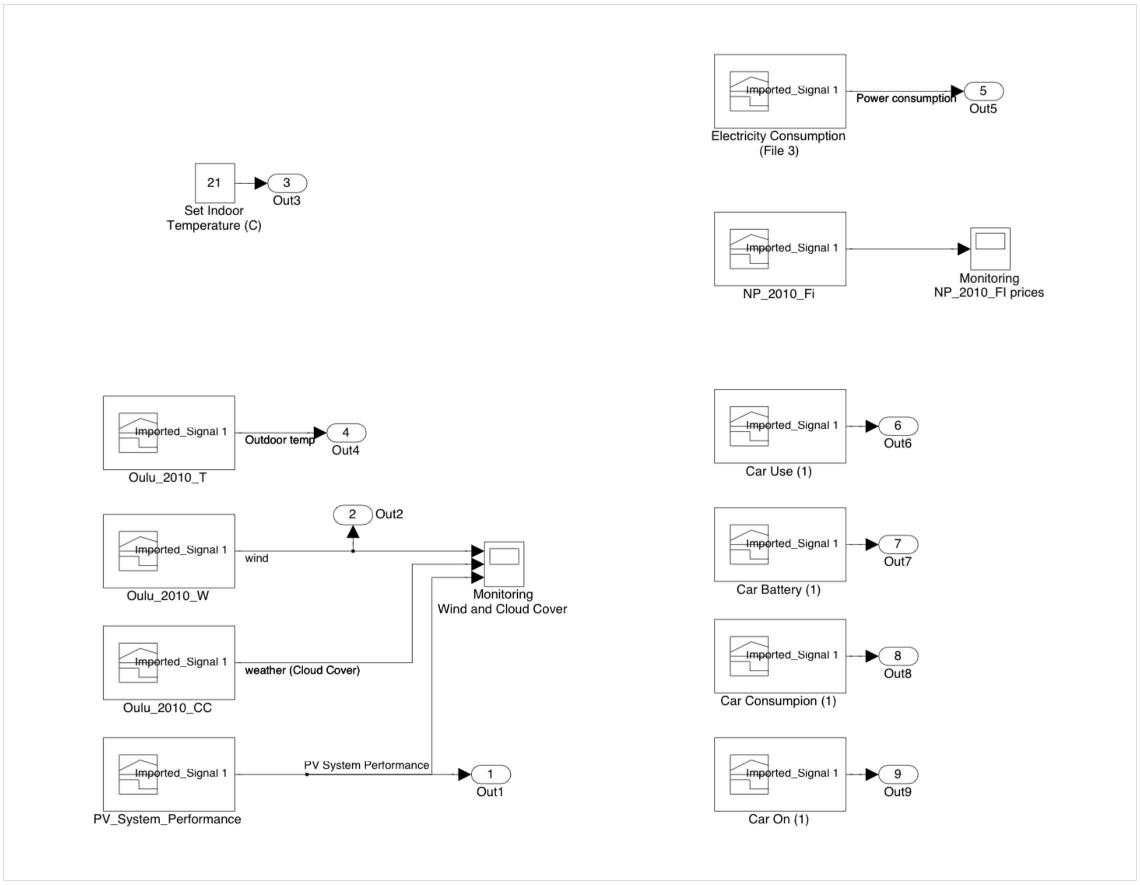


Figure 22: Architecture of the Input block.

requirements of the heating system and on the performance of RESs (respectively), in particular wind and solar power generation.

The NPS electricity prices for the corresponding locations are included. Even though these prices indicate the electricity cost at retailer level, prices at end user level can be approximated to vary reflecting the retailer costs, providing then a basic comparative evaluation on the economic performance of the system.

The last set of input data is related to the use of the plug-in hybrid electric vehicle (PHEV). The four blocks include the car and battery usage, the battery consumption and the time the car is actually plug and connected to the system. Most of this input data are randomly produced following a predetermined statistical distribution.

A more detailed description of the characteristics of the input signals is reported in

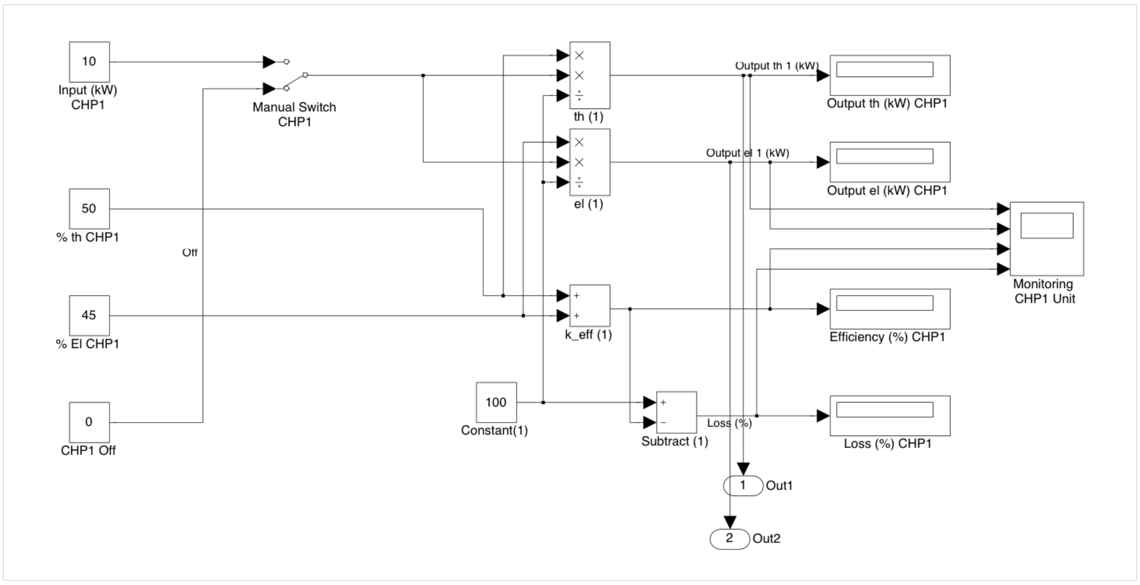


Figure 23: CHP units model architecture.

Appendix (A.1.2).

5.1.4 Energy Source

The energy source block contains five selectable elements representing the technologies described in Chapter 4. The first 3 included elements describe CHP units (Figure 23) using small-scale combustion (using pellets as fuel), gasification and anaerobic digestion as described in section 4.2. Energy outputs have been arbitrarily chosen based on the information from [OPET Network, 2002] and [Kirjavainen et al., 2004].

The last two elements are set to reproduce the energy performance of a small wind turbine and a small PV system. The architecture of the core elements of these units (Figures 24 and 25 respectively) is the same as for the previously described CHP units with no thermal energy output. Both units have their actual output calculated considering the installed power and the environmental conditions. More detailed information on the modeled wind and solar power units are presented in section A.1.3.

The chosen medium size wind turbine is a common 3 palettes model with a power curve. The PV system is set to work in a similar fashion as it filters the installed output using the data from PV system performance signal. More details concerning wind turbine specifications are reported in the Appendix A.1.3.

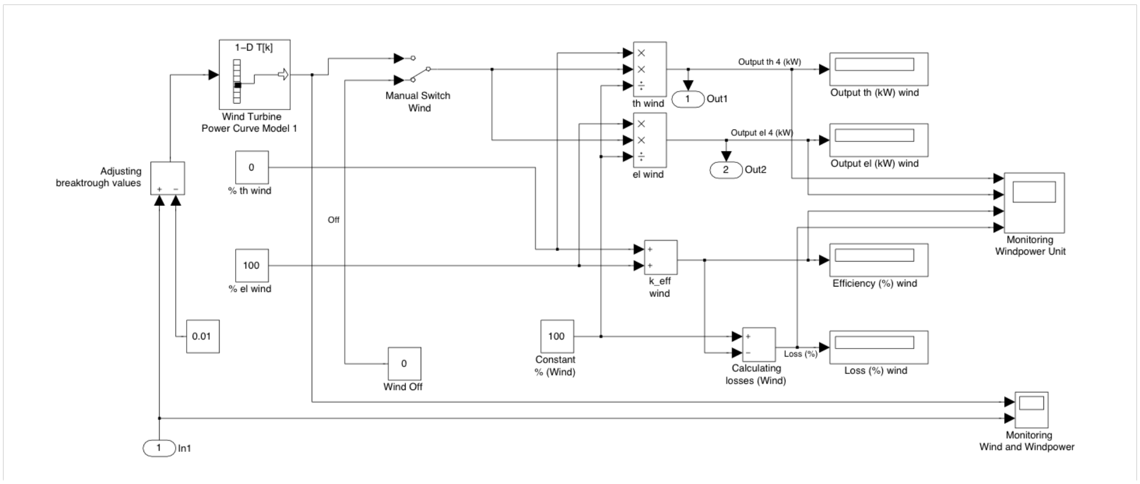


Figure 24: Wind power generation unit model architecture.

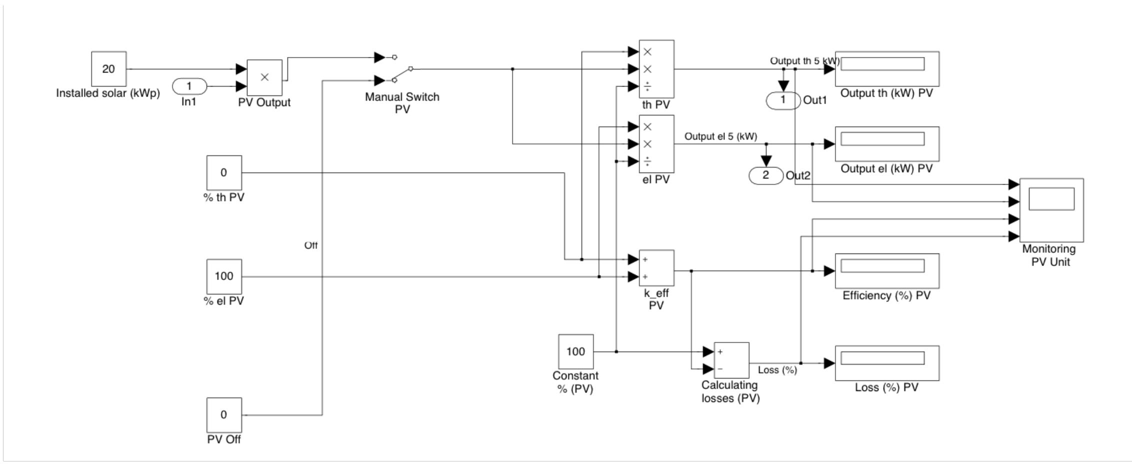
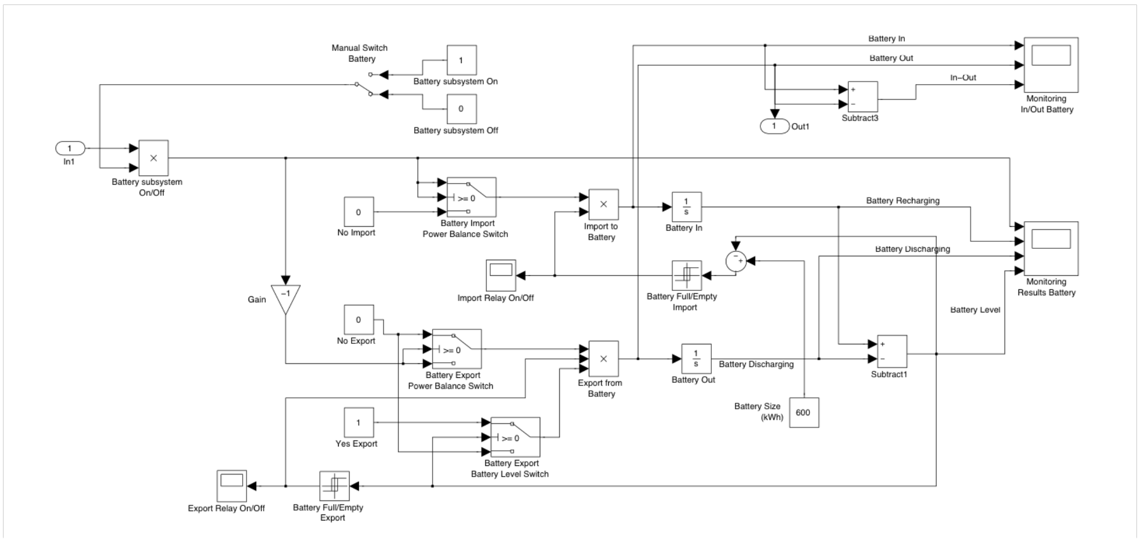


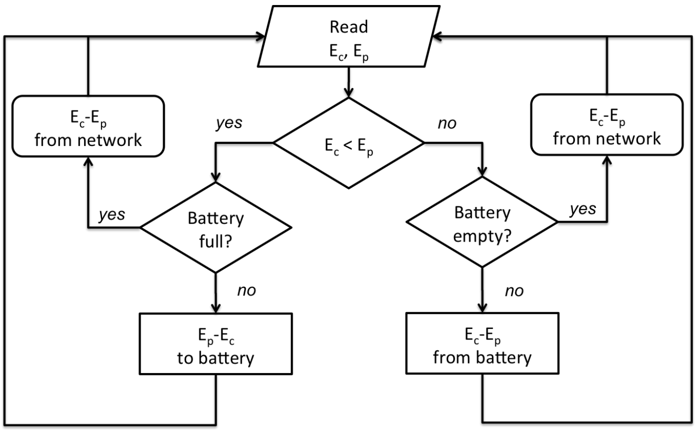
Figure 25: PV unit model architecture.

5.1.5 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); both elements are selectable.



a



b

Figure 26: (a) Storage block architecture and (b) flowchart of its operation.

The fixed electric energy storage and the flowchart of the followed algorithm are showed in Figures 26. On an hourly base, the power balance is monitored and if the produced power exceed the needs, the battery is loaded. In case of power need, energy is drawn from the battery. The size of the battery can be selected from the user, together with the upper and lower limits (in %) allowing battery recharging and discharging respectively; the variation of these values are likely to affect the number of battery cycles and partial load, in some cases affecting quite significantly the battery life and therefore the economic performance of the system.

The second element of the storage block describes the PHEV (Figure 27). The rules regulating the behavior of the battery for the PHEV are the same as those described before for the fixed battery. Additional elements take in consideration if 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.

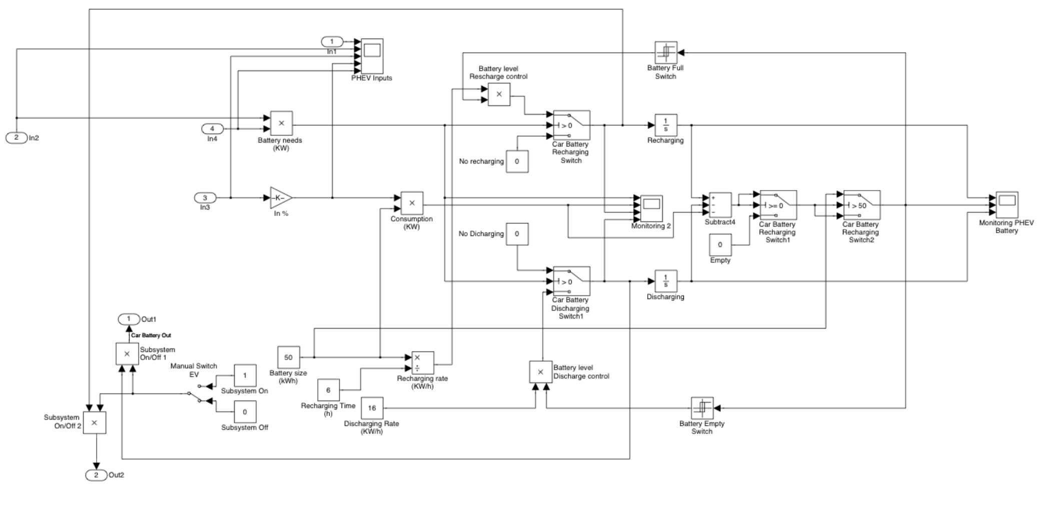
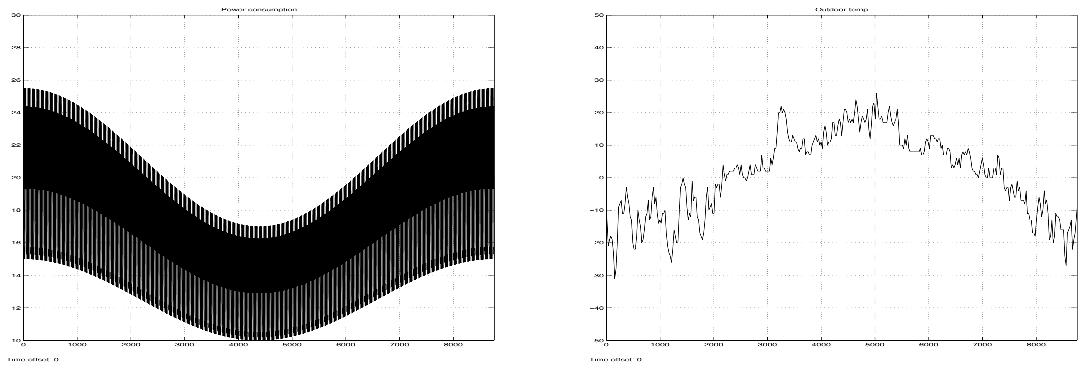


Figure 27: PHEV units model architecture.

6 Simulation results

The results from the simulation are collected in Appendix A.2. All the considered scenarios are based on common power and thermal energy requirements described in the previous section and shown in the Figures 28. All the reported data cover a period of one year, from the zero hour of the 1st of January to the midnight of the 31st of December 2010, displayed on the horixzontal axis on a hourly based scale. The electrical energy consumption as been modeled following a cos^2 trend in



a b

Figure 28: The common input signals for the energy requirements used in all the presented simulations include the electrical energy consumption (a) and the thermal energy consumption modeled on the actual recorded outdoor temperature (b).

order to mimic the seasonal variation of power consumption. The thermal energy requirements are represented by the outdoor temperature assumed to be directly proportional to the total thermal energy needs. This assumption can be justified by using the SME block architecture and the flowchart of its operations in Section 5.1.2. The actual indoor temperature and the need of thermal energy are determined by the heat losses of the previous hour, in turn directly proportional to the indoor/outdoor temperature gradient. Consequently, the outdoor temperature can function as a reliable indicator of the thermal energy needs. More detailed information on the input signals are described Appendix A.1.2.

Figure 29 shows a representative excerpt of the simulation results with data for the electrical and thermal energy displayed on the left and right respectively. The scenario considered in this example includes all the available elements: 3 CHP units, wind turbine, PV system and 2 electricity storage units (one of which is the PHEV battery).

Figure 29a shows the power production which 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. The Figure (29c) shows the power balance calculated as the difference between the power production and consumption, with the positive values indicating a surplus of energy production while negative values indicate a deficit of energy. The Figure at the bottom (Figure 29e) shows the cumulative power balance: a growing trend indicates a surplus of energy while a decreasing trend indicates a deficit of energy; the cumulative power balance allows the monitoring of the overall energy budget over one year period, providing information complementary to those obtained by the monitoring of the power balance which provides information on the energy budget at a certain moment but has no memory for the earlier periods.

Figure 29b shows the set and the actual indoor temperature of the built environment. The figure below, Figure 29d, shows the total thermal power production which includes the contribution from all the CHP units operative at a certain time. The last Figure 29f shows the cumulative thermal energy production in the same way it was described earlier for the production of electrical energy.

In the reported example, 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

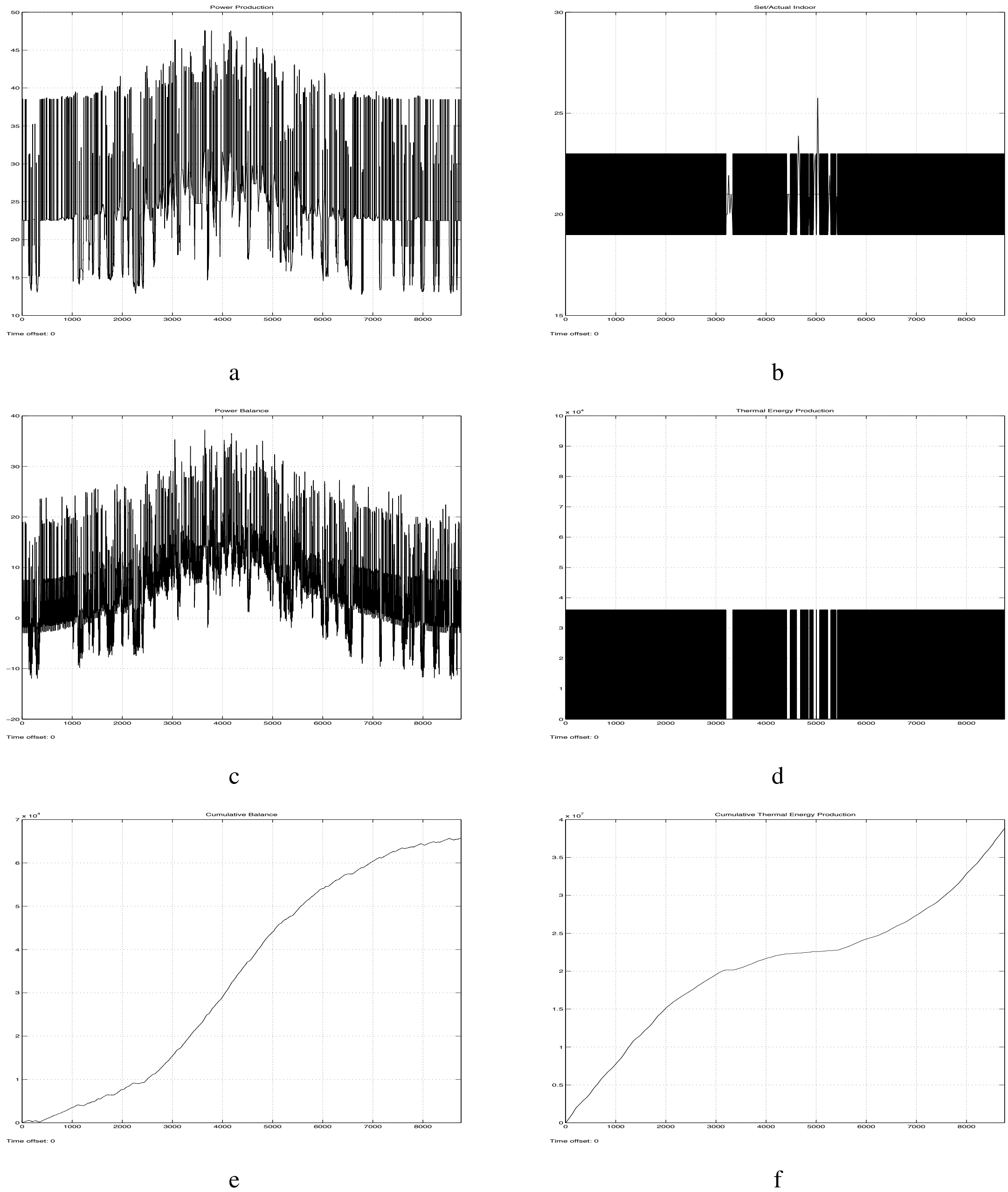


Figure 29: Summary of the results obtained in the simulation run including all the elements described in 5. The included graphs present (see text for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal 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). These results are reflected in the shape of the cumulative power balance graph that shows a constant growing trend with the summer month, characterized by a lower power consumption and a higher power production, showing the fastest growth.

For what concern the thermal energy production, it is immediately possible to notice how the system is fully capable to maintain the indoor temperature near the selected value. The oscillations are a consequence of the relay settings which are activating and deactivating the system every time the indoor temperature falls below 2°C or rise above 2°C of the set values. These oscillations are in direct connection with the variations shown in the thermal energy production (Figure 29d). Depending on the hourly temperature reading the heating system is switched on/off, with a constant and regular thermal energy production reflecting the combined production of all the CHP units. The cumulative thermal energy production graph (Figure 29e) shows a profile indicating a constant surplus of energy except for the warmer months when, as the system is deactivated for longer periods due to warmer outdoor temperatures, the energy production is strongly reduced showing little growth on the cumulative energy production graph.

The results showed in Appendix A.2 allow the possibility to single out, by comparison with different scenarios, the contribution of each element.

The exclusion of the photovoltaic system (Figure 36), consistently with the previously results, eliminates the strong seasonal variation of energy production 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. As expected (no thermal power production has been assigned to the PV system), no variations can be noticed on the thermal energy aspect of the system.

Assessing the performance of a system without the small wind turbine system (Figure 37), 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 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 parto f 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 (Figure 38) 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 consequence of the difference between system power demand and supply (varying consistently over the year), and the battery limits: the battery storing capacity and 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 (Appendix A.1.2) which in this case they have been randomly distributed.

The description of the previous case is consistent with the results obtained if also all the storing devices are excluded from the system (Figure 38). 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. Also in this case no variation on the thermal energy aspect of the system. Still there are no variations and on the thermal energy aspect of the system as all the excluded components have an exclusive power contribution. If only the CHP units are left operational the relation between the power production and the power balance is straightforward as the power production of the system is constant. Still there are no variation and on the thermal energy aspect of the system as all the excluded components have an exclusive power contribution.

Scenarios excluding one of the CHP units (Figure 39 and Figure 40) have also been considered. It is easy to see how the overall result in these cases is the reduction of the power production of a 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 staied unchanged, the outcome is a scale but similar result as on the previous cases.

As the last set of results include the system without any of the previously described elements, an important aspect of the modeled system, by comparison with all the other cases (Figures 41-43), can be pointed out. In Figure 44 it is easy to notice how the power balance is constantly negative and, as expected, the specular image of the power consumption input signal described in the beginning of this section. One element that can be noticed is also how the power demand, now entirely depended on the common network, is varying quite significantly between winter and summer seasons, oscillating between 15 kW and 25 kW in the colder months and between 19 kW and 17 kW in the warmer months. If the actual values of the electricity demand depends 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 on the other hands shows important contributions in these aspects. In every case 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. For the reason mentioned earlier and in Section 4.4 this is a very important outcome for the future possible development of a smart energy grid system.

7 Conclusions

In this work, different aspects that contribute to define the potential for the development of smart energy grids in the NP territories has been discussed. It was seen how these territories, and the Nordic Countries in particular, present significative 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. At the same time, it has been mentioned how the technological means for the development of an energy network based primarily on distributed energy production is technologically mature, in both what we called the classical RES and waste-to-energy RES. Furthermore, an example has been provided showing how 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 7). As it was mentioned in Chapter 3 and shown in Chapters 5 and 6, the new liberalized and decentralized energy market would include not only a number of new elements (i.e. PHEV) and a new way to asses the energy needs basically based on an on-demand local energy production scheme, but it stresses the needs for the energy providers to redefine their role in the energy market.

The traditional energy system system, if already environmentally and socially unsustainable, is likely to become economically unsustainable as well, as the economical benefits of the end user have the specular counterparts on the energy providers which, eventually, will reach a breaking point where energy efficiency and effectiveness would translate into lower income. At the same time the new envisioned system requires a number of energy services currently either not available or shared among a number of market players in a non user-friendly way. For example, in Chapter 5 it was mentioned that there was no attempt in this work to assess issues related to the development of the electric and hydraulic networks required for the correct functioning for the modeled system. Nevertheless these networks are to be installed and maintained. This is not a secondary aspect, especially in regions characterized by sparsely populated areas and harsh climate where these kind of services include 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. Beside a number of administrative and political aspects, that stretch beyond the aspects considered in this work, there are a number of technical obstacles that need to be overcome, while, at the same time, there are a number of possibilities currently available in the NP. 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 thesis, it could be used to, at least partially, 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.

These aspects are of primary importance: as it was described in Section 2.3, the energy prices are defined on a demand/offer equilibrium. The foreseeable effects of these described solutions is, in time, the flattening of the energy demand profile. As mentioned earlier this has two important consequences: on the environmental side it contributes to the reduction of GHGs emission while on the other side it provides economical benefits for the market which translate in reduced expenses for the transmission and distribution of energy. This would create the economical mean for further investments in the development of a smart energy network while, at the same time, rationalize the energy consumption on a number of levels, including the end user that would probably not reduce the overall energy consumption but would quite simply redistribute over time.

It was already mentioned how the model described in this thesis presented a number of limitations and simplifications. It is in the interest of the author to further develop this model and to include a number of aspects that could much improve the usefulness of its analysis. Possible improvements cover a wide range of elements and aspects of the considered model, and only a highlight of the considered modifications is mentioned here. It would be interesting to include the NPS energy prices in the system's decision making process. Energy storage infrastructure could include natural gas, transforming in this way the power storage component in energy storage component, with the possibility to fuel, for example, the already considered PHEV. The models for the inclusion of the electric vehicles can be further developed and its usage more carefully considered and analyzed, including the benefits and the challenges from the mobility point of view that such a system implies. Finally, the inclusion of a sophisticated built environment model could be developed. This latter element could include not only a proper description of the infrastructure but it would also consider the inclusion of an energy management system, its decision making process and its inclusion and role in the development of the energy network functioning.

A Appendices

A.1 System specifications

A.1.1 Built environment

The built environment structure considered in the simulations is represented in figure 30. The size of the structure takes in consideration the possibility of a small enterprise accommodating the necessary space for the business and a living area. These environments can be easily thought to constitute separated – and possibly more complex – structures than the one reported. For sake of simplicity, a basic shape has been chosen under the assumption that a broad range of possibility can be adequately studied with the proper choice of parameters (average desired temperature, U-values, space, etc.) properly averaged and weighted.

No structural details have been considered for the estimation of the heat losses. The used U-Values are those considered by the European Insulation Manufacturer Association for sustainable buildings [EURIMA, 2008]. In this case U-Values change according to the location, primarily reflecting different environmental conditions. Values for the Nordic Countries are reported in the Table 4.

The heat losses Q_{loss} have been calculated as follow:

$$Q_{loss} = U \cdot A \cdot \Delta T \tag{A.1}$$

where A is the exposed surface area and ΔT is the indoor/outdoor temperature

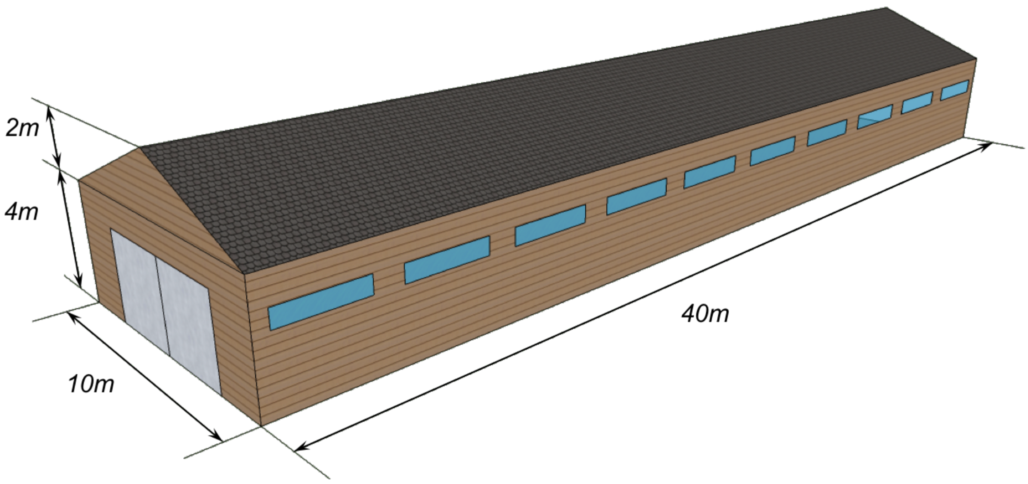


Figure 30: Structure shape and size utilized in the simulation See text for further details.

Table 4: U-Values used for the simulations. [EURIMA, 2008]. See text for further details.

	Wall		Roof		Floor	
	Low	High	Low	High	Low	High
Finland	0.25	0.25	0.16	0.16	0.25	0.25
Sweden	0.18	0.18	0.13	0.13	0.15	0.15
Norway	0.18	0.22	0.13	0.18	0.15	0.18

difference. Using the reported data it has been possible to calculate, for each case, the final heat transfer $Q_{tot}$and corresponding temperature as follow:

$$T = \frac{Q_{tot}}{m \cdot c_p} \tag{A.2}$$

where m is the total mass – of air – and c_p is the specific heat. The used values for air density and specific heat are:

$$\rho = 1.205kg \cdot m^{-3} \qquad c_p = 1.005kJ \cdot kg^{-1}K^{-1} \tag{A.3}$$

A.1.2 Input data

Looking at the system architecture (Figure 20), the input subsystem includes a number of input signals. The first one is the selectable indoor temperature, in this case, set to be constant across the simulation run time.

The following group collects the environmental information required by the model: the historical records of temperature, wind and cloud cover for the considered location . Data have been obtained from the internet weather service "Weather Underground" ©[Weather Underground Inc., 2011] for each day and extrapolated to an hourly base. The reported temperatures, measured in °C, refer to the average daily temperature. Wind data, measured in m s^{-1} are produced in the same way. Cloud cover data, extrapolated as in the previous cases, are measured on a scale from 1 to 8, indicating clear sky and overcast weather respectively. Cloud cover data have been utilized to estimate the performance of the PV system, together with the monthly averaged insolation data from the GAISMA database [Tukiainen, 2011] concerning the selected locations:

$$P_{PV} = \frac{8 - cc}{7} \cdot In \cdot R \cdot 0.75 \cdot \frac{1}{24} \tag{A.4}$$

where P_{PV} is the average hourly output of the installed PV system, with assumed 75% performance, cc is the previously described cloud cover coefficient, In is the average month insulation (measured in kWh m^{-2} day^{-1}) and R is the ratio of beam radiation for the selected location as described in section 4.1.2. As the necessary data to perform the calculation illustrated in equation 4.16 were not available, a value of R was performed by comparing the data reported in figures 4.15a and 4.15b as follow:

$$R = \frac{\text{Output at optimum angle}}{\text{Output at 0°angle}}. \tag{A.5}$$

The final results were collected in the input signal block "PV System performance".

The following input block describe the yearly electricity consumption on a hourly base. The electricity consumption profile was described considering a double peak model (Figure 31 left). The differences between a more demanding winter profile and a less demanding summer profile were approximated to differ by a simple scale factor. The winter-sumer-winter profile transition was set to follow a $\cos^2$ shape (Figure 31 right).

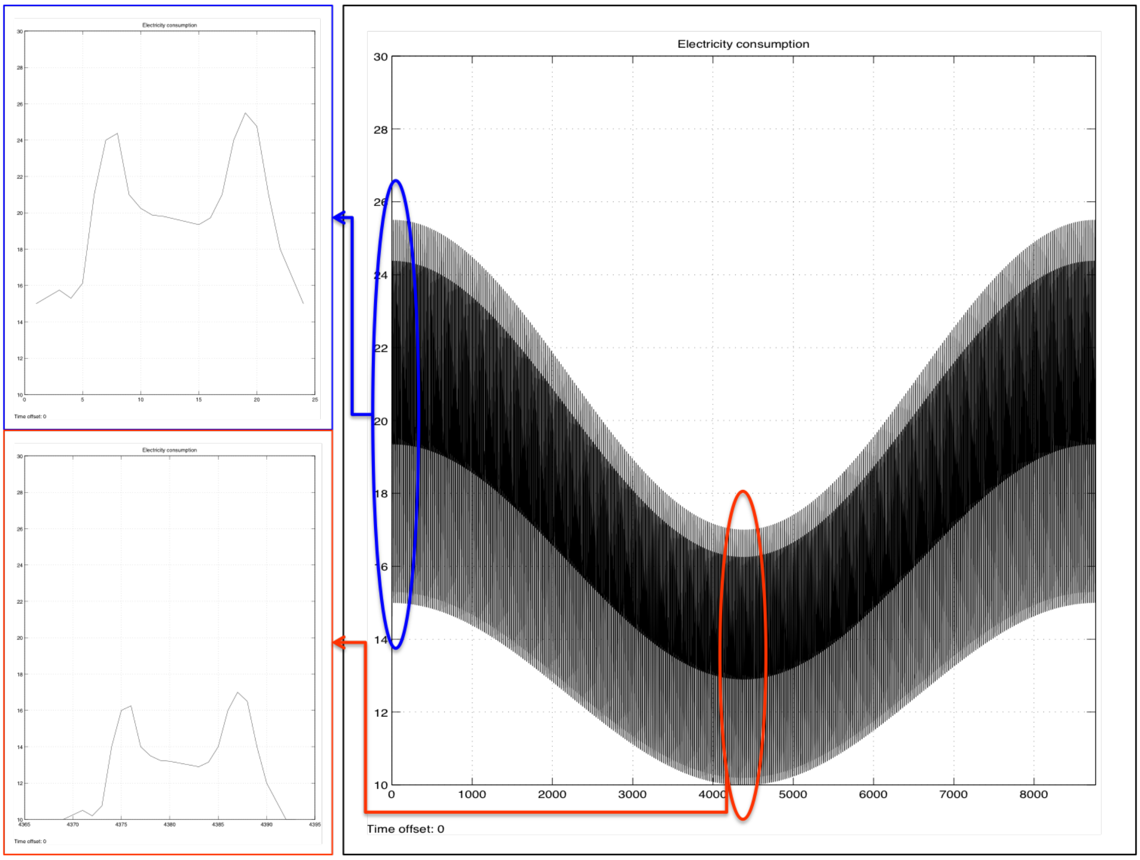
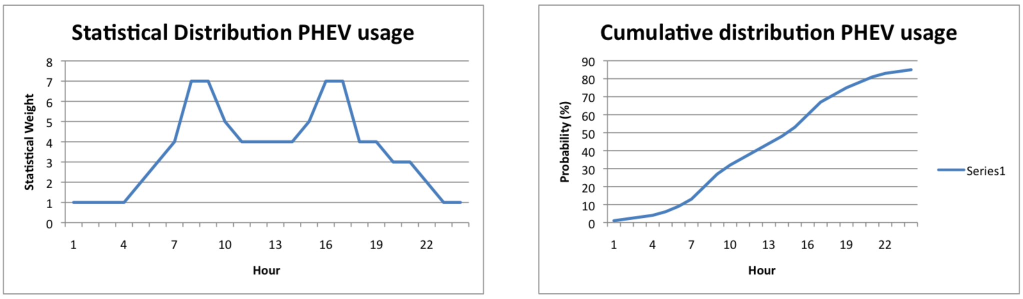


Figure 31: Electricity consumption profiles used in the simulations. The winter (upper left) and summer (bottom left) electricity consumption differ for a 2/3 scale factor. The yearly consumption is built using a linear combination of the winter and summer profiles (see text for further details).

The input block marked "NP_2010_FI" collects the electricity cost for Finland in the year 2010 as reported by the NordPool Spot energy market website.

The last four input blocks collect all the necessary informations for the simulation of a PHEV which can share the energy stored in the vehicle battery to contribute to the energy needs of the built environment. The four input signal report on the car usage, the battery usage, the energy consumption and the car availability. The first input signal has been random generated considering different statistical weight for the usage of the car in different hours of the day (Figure 32). The second input indicates for how long the vehicle (specifically its battery) is used. The third signal communicates the battery status once the vehicle is again plugged into the domestic system. These last two signals, randomly generated, allow to consider possibilities of vehicles usage (in time and intensity). The last input signal is simply communicating to the system whether the vehicle (and therefore its battery) is plugged or not.



a b

Figure 32: PHEV usage modeled distribution (a) and cumulative distribution (b). The probability for car usage has been arbitrarily considered to be 85%, corresponding approximately to 6 days a week.

A.1.3 Energy production systems

The wind power generation subsystem (Figure 24) considers a 3 blade wind turbine whose power curve is shown in figure 33.

The generated power output depends from the wind speed. Historical data concerning the daily mean wind speed in the Oulu area have been obtained from dedicated databases [Weather Underground Inc., 2011] and then extrapolated to an hourly base. No corrections due to different wind direction has been considered; further-

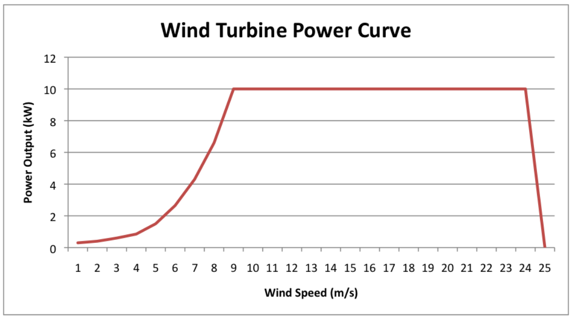


Figure 33: Power curve of the modeled wind turbine system.

more, as the wind data from the Oulu weather station are reported from an altitude of 12m, they were assumed compatible with the height of a small wind turbine, therefore no wind speed correction (section 4.1.1) has been considered. The input signal for the wind turbine subsystem is shown in figures 34. It is easy to verify how the wind speed statistical distribution follows a Weibull profile as mentioned in section 4.1.1.

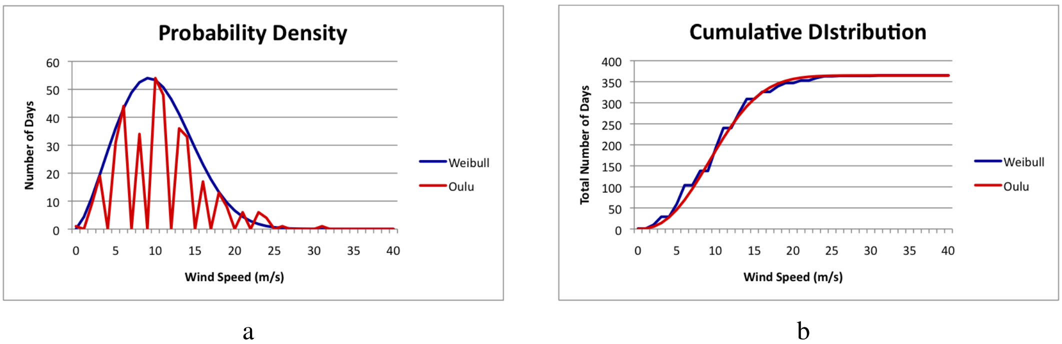


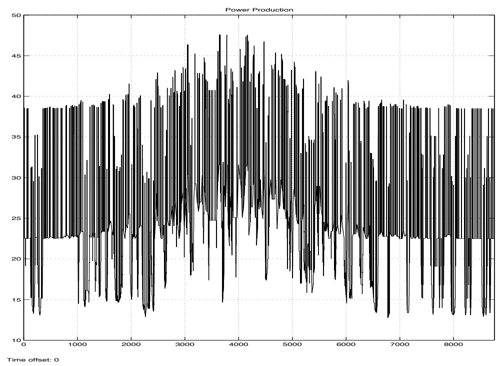
Figure 34: Comparison between the historical wind data for the Oulu area in 2010 and the Weibull probability density (a) and cumulative distribution (b) functions. The represented data fit a profile with α = 2.4 and β = 1.15 (See section 4.1.1 for further details).

Concerning the input signal for the PV subsystem, the theoretical description of data processing has been described in section. Data for monthly insolation and clearness from [Tukiainen, 2011] have been used to estimate the monthly insolation for the Oulu area as

$$\text{In} = \frac{\text{Monthly Insolation}}{\text{Clearness}}. \tag{A.6}$$

For each month then, the insulation values have been calculated including the cloud cover data as described in formula A.4. The validity of these calculations has been verified by comparing the obtained yearly sum of insulation with the values reported in figures 15. For the Oulu area the yearly sum of global insolation were ∼840 kWh/m^2 on the horizontal plane (Figure 4.15a) and ∼1068 kWh/m^2 on a 46° inclined plane facing south (Figure 4.15b).

A.2 Simulations Results



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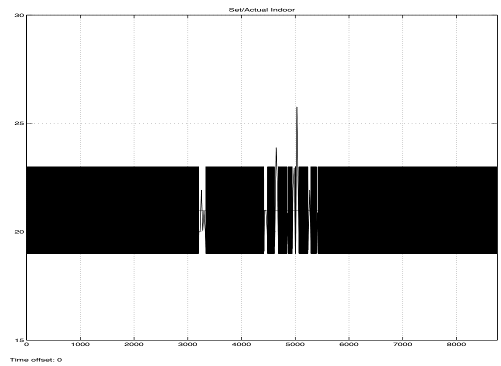

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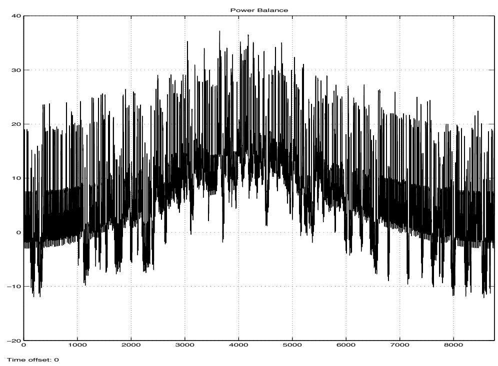

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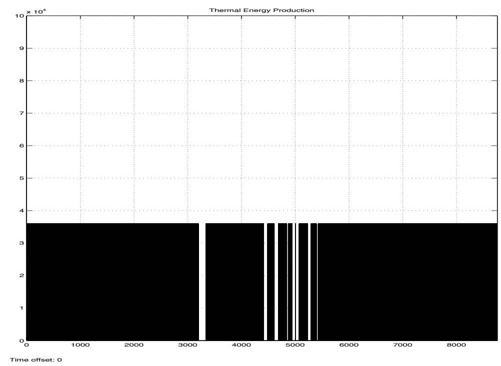

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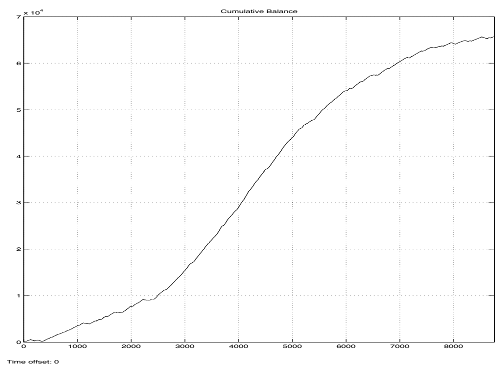

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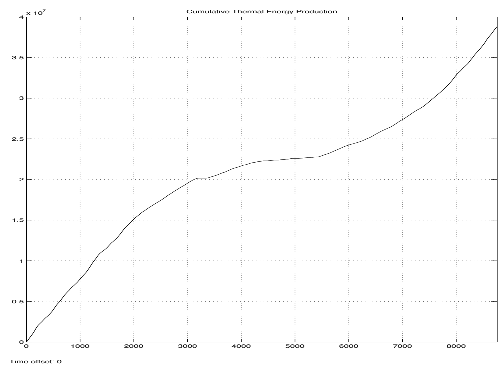
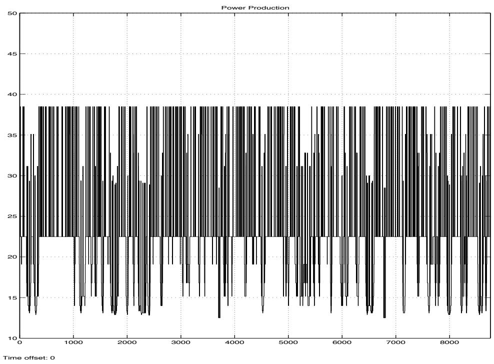


f

Figure 35: Summary of the results obtained in the simulation run including all the elements described in chapter 5. The included graphs present (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.



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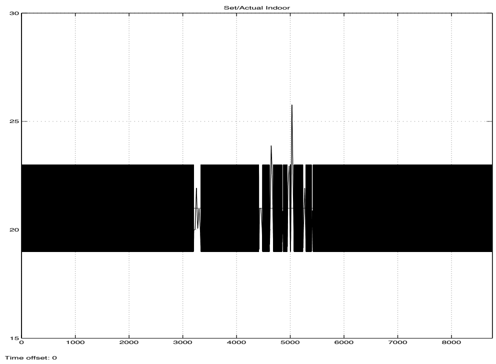

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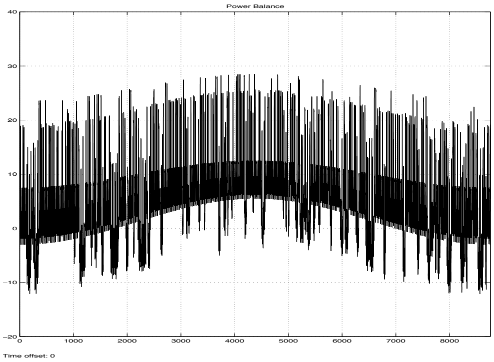

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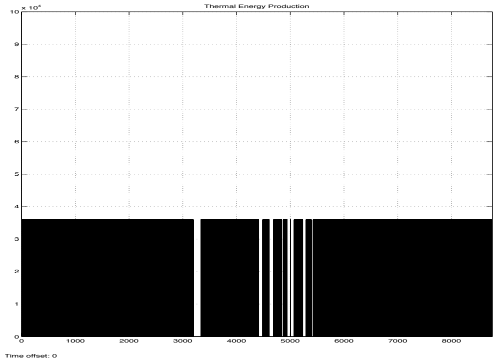

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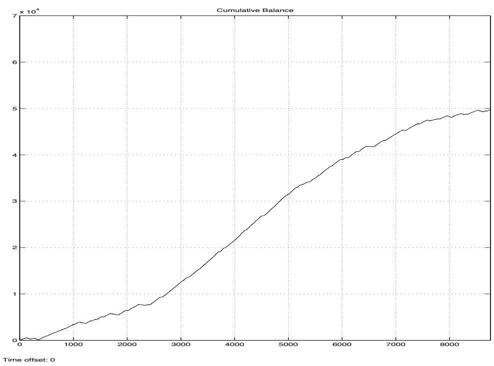

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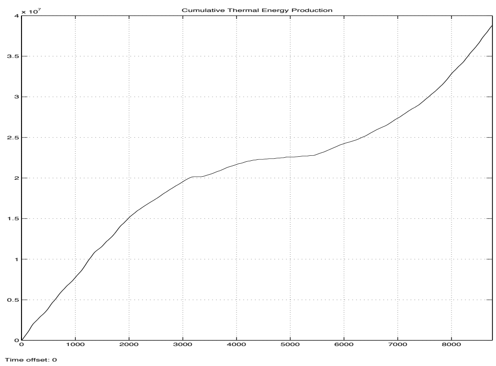


f

Figure 36: Summary of the results obtained in the simulation run excluding the PV element (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

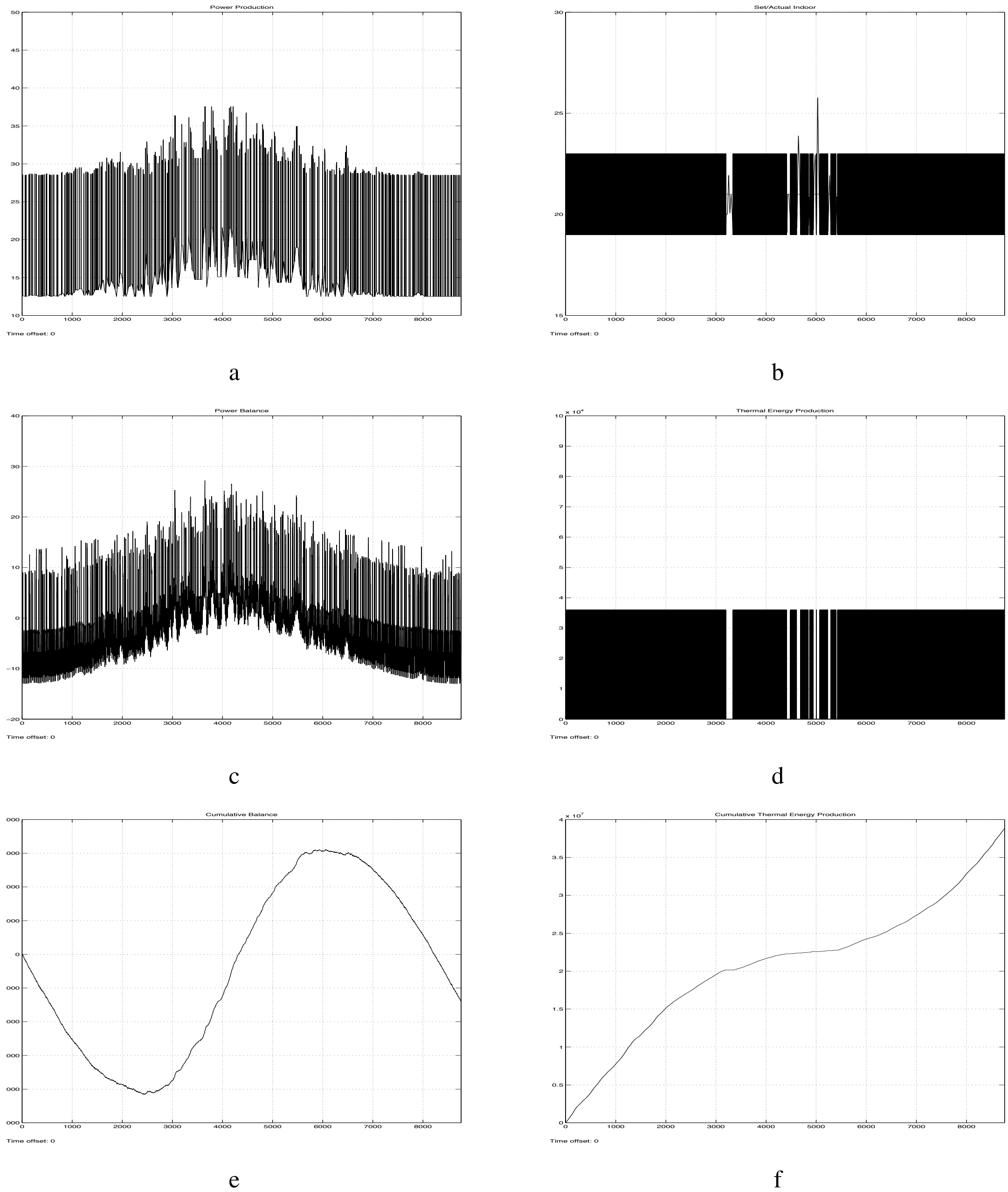


Figure 37: Summary of the results obtained in the simulation run excluding the wind turbine element (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

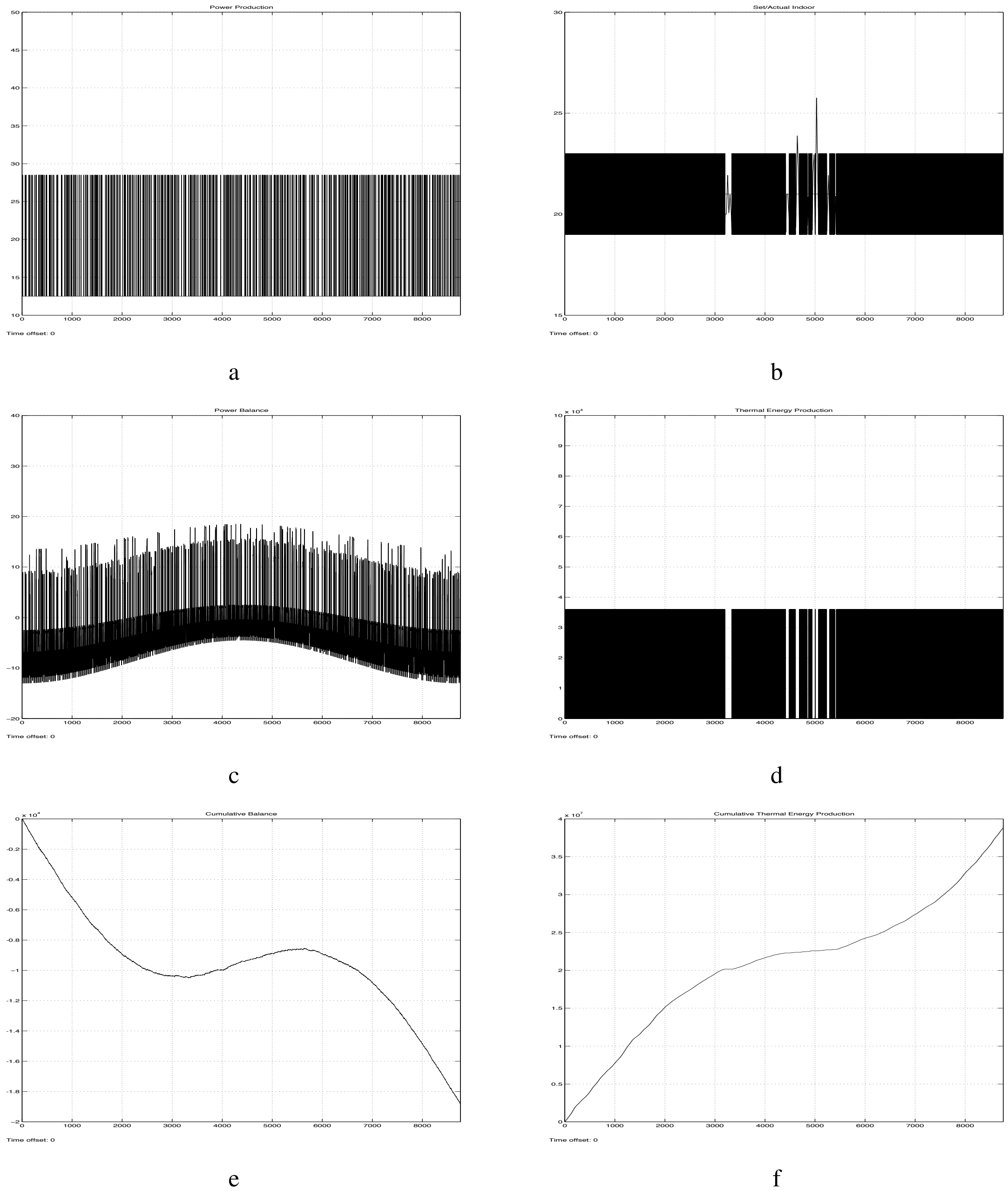
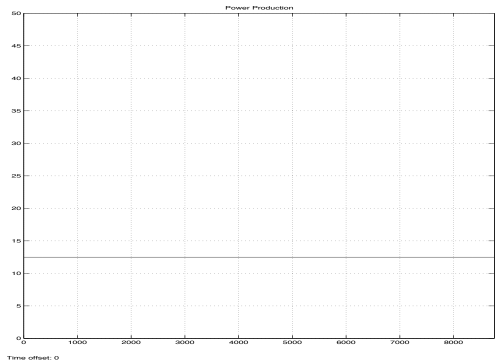


Figure 38: Summary of the results obtained in the simulation run excluding the PV and the wind turbine elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.



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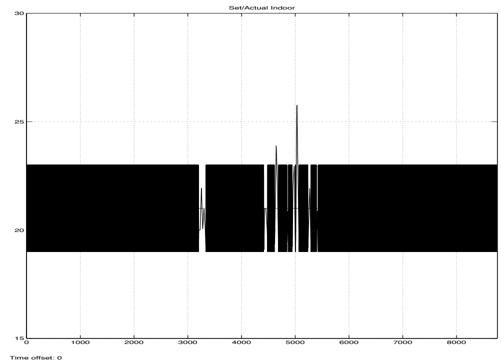

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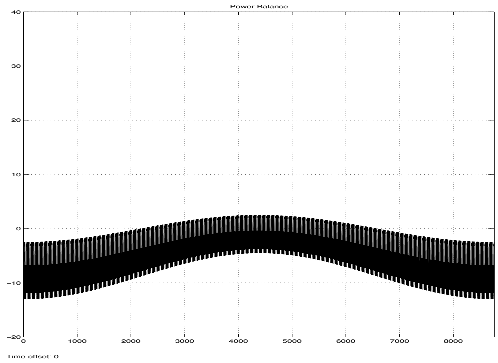

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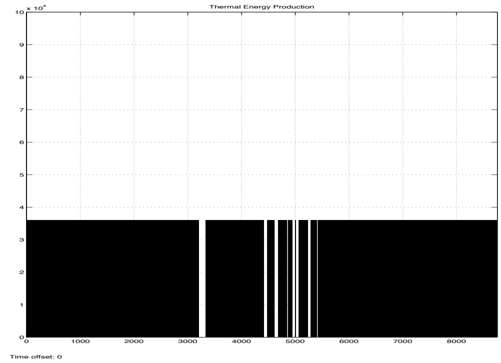

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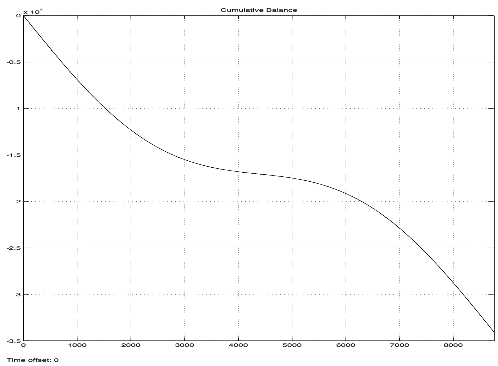

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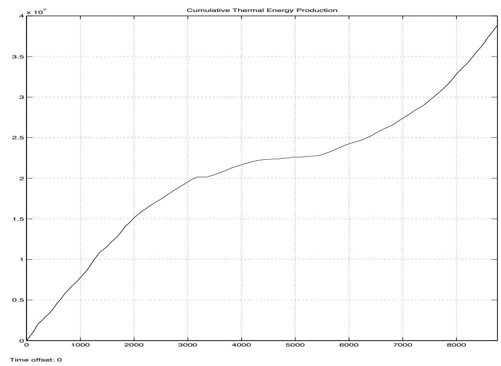


f

Figure 39: Summary of the results obtained in the simulation run excluding the PV, the wind turbine and all the power battery elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

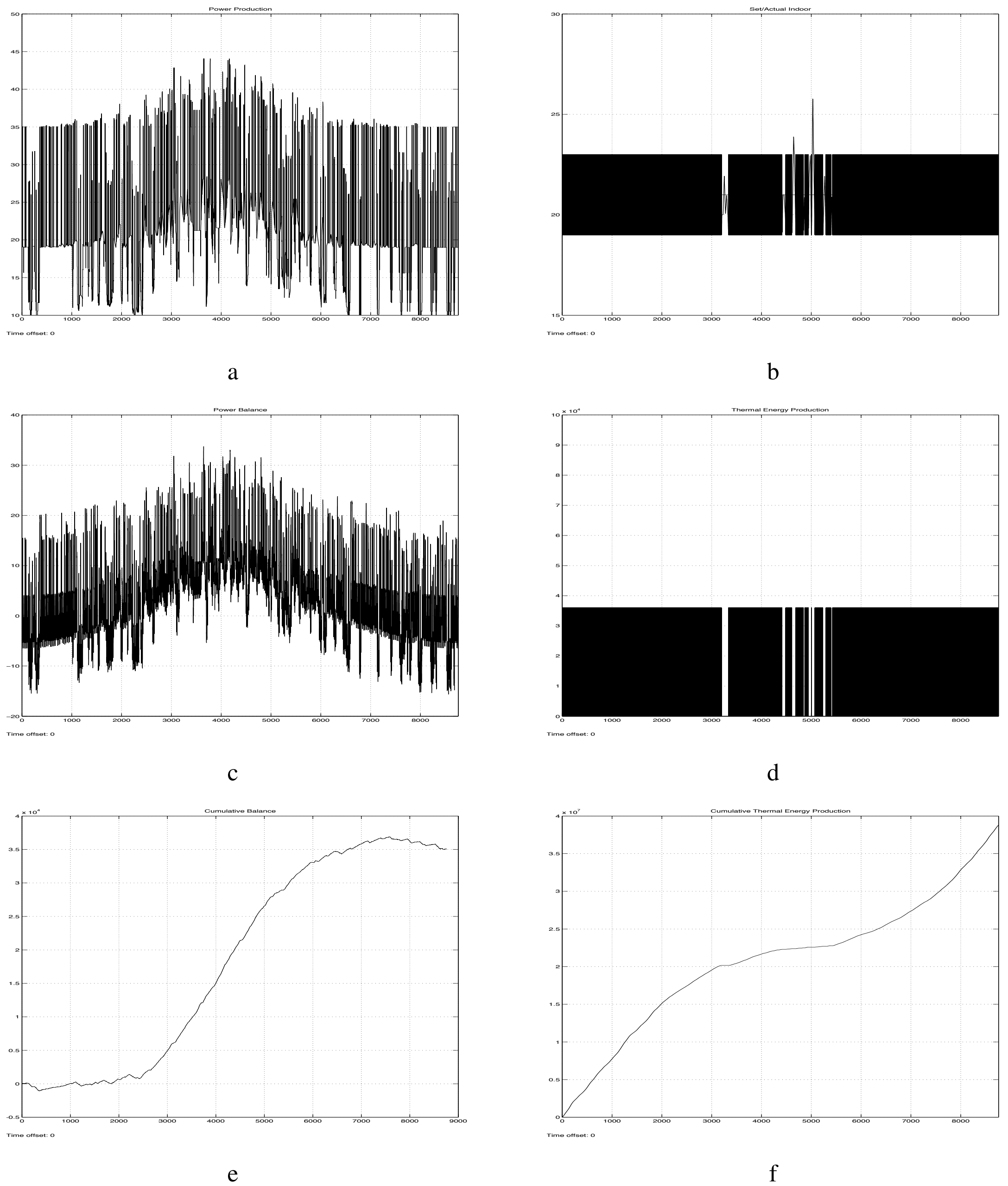


Figure 40: Summary of the results obtained in the simulation run excluding one of the CHP units (pellet) elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

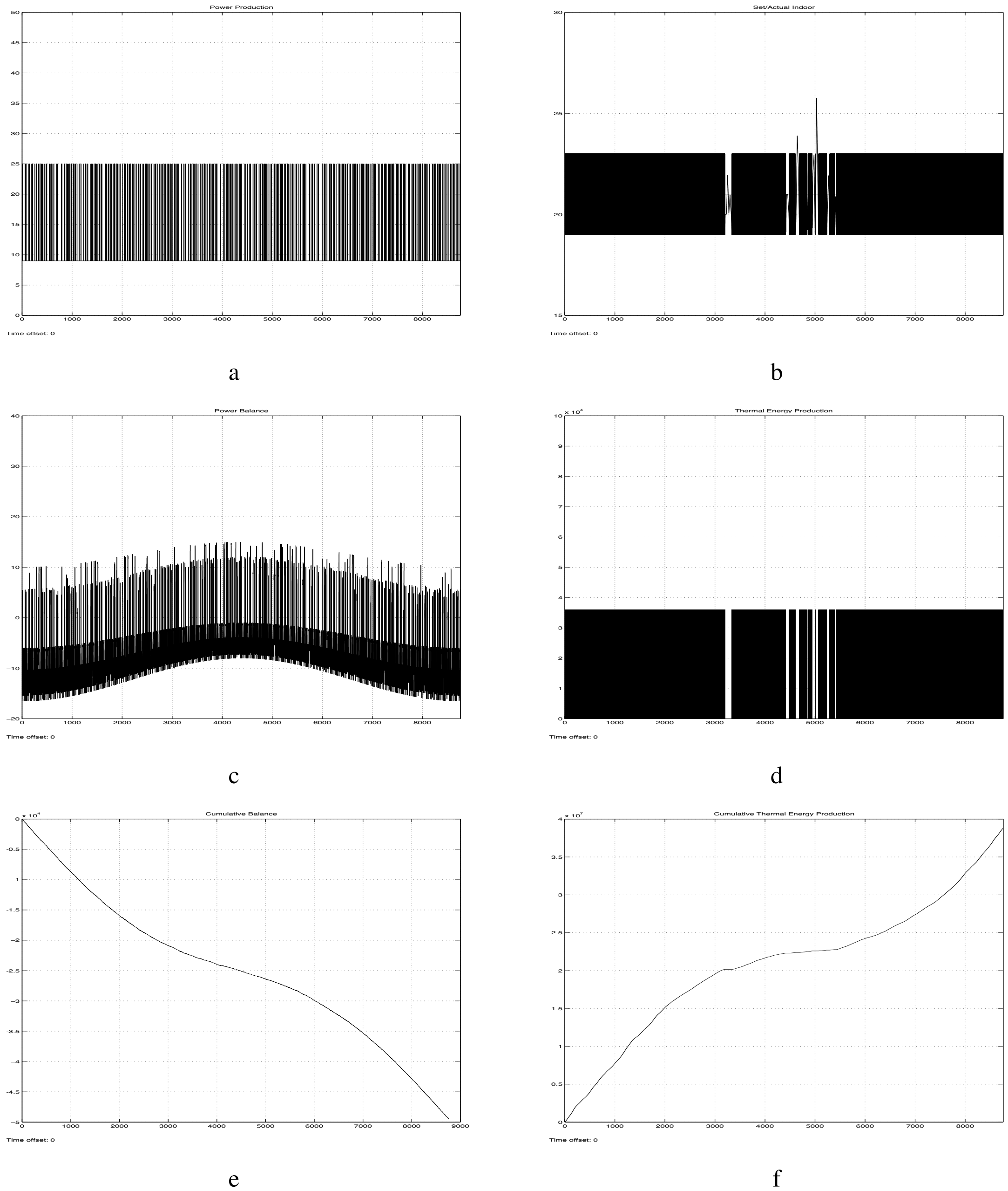


Figure 41: Summary of the results obtained in the simulation run excluding the PV and the wind turbine elements as well as one of the CHP units (CHP2) elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

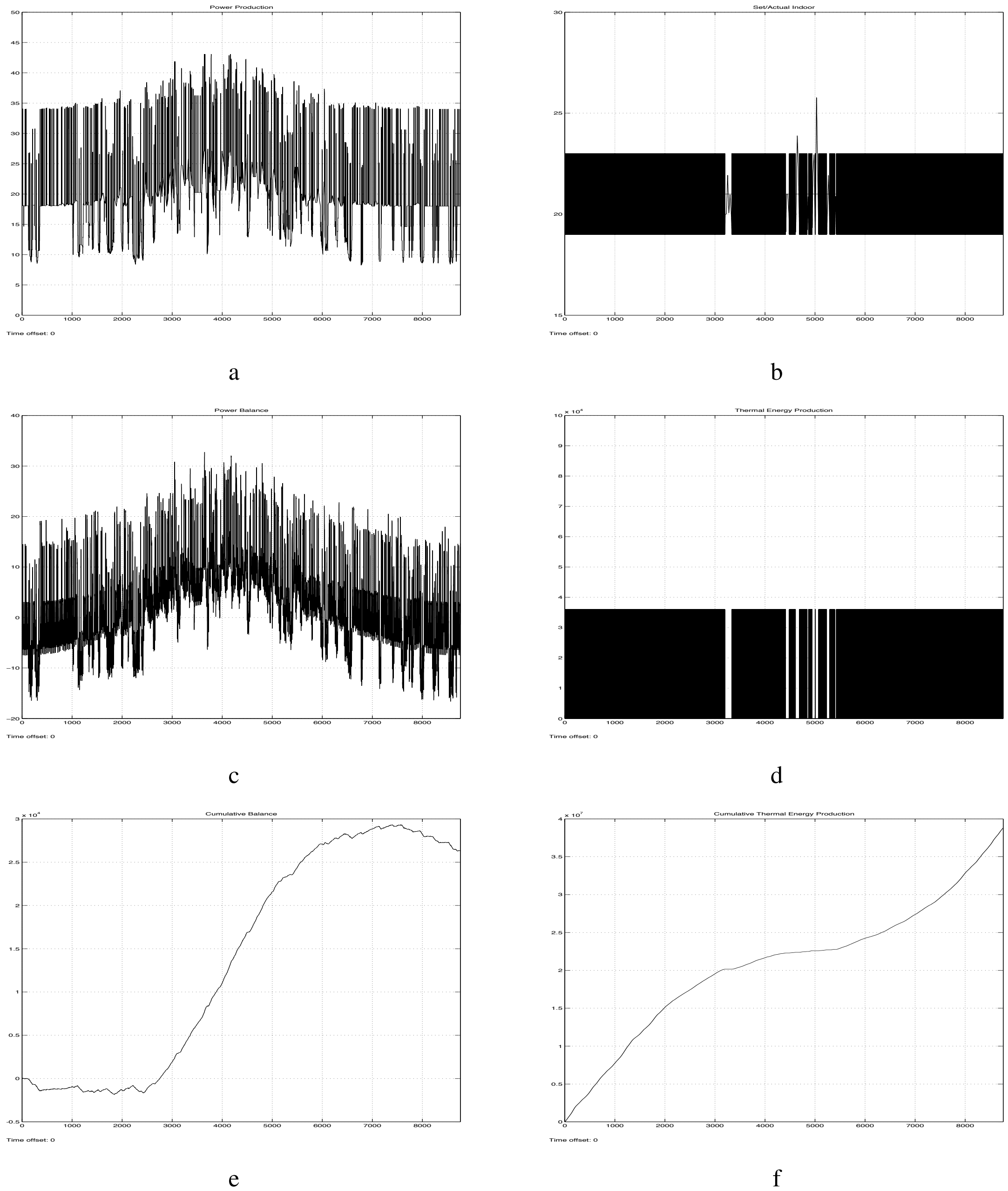


Figure 42: Summary of the results obtained in the simulation run excluding one of the CHP units (AD) elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

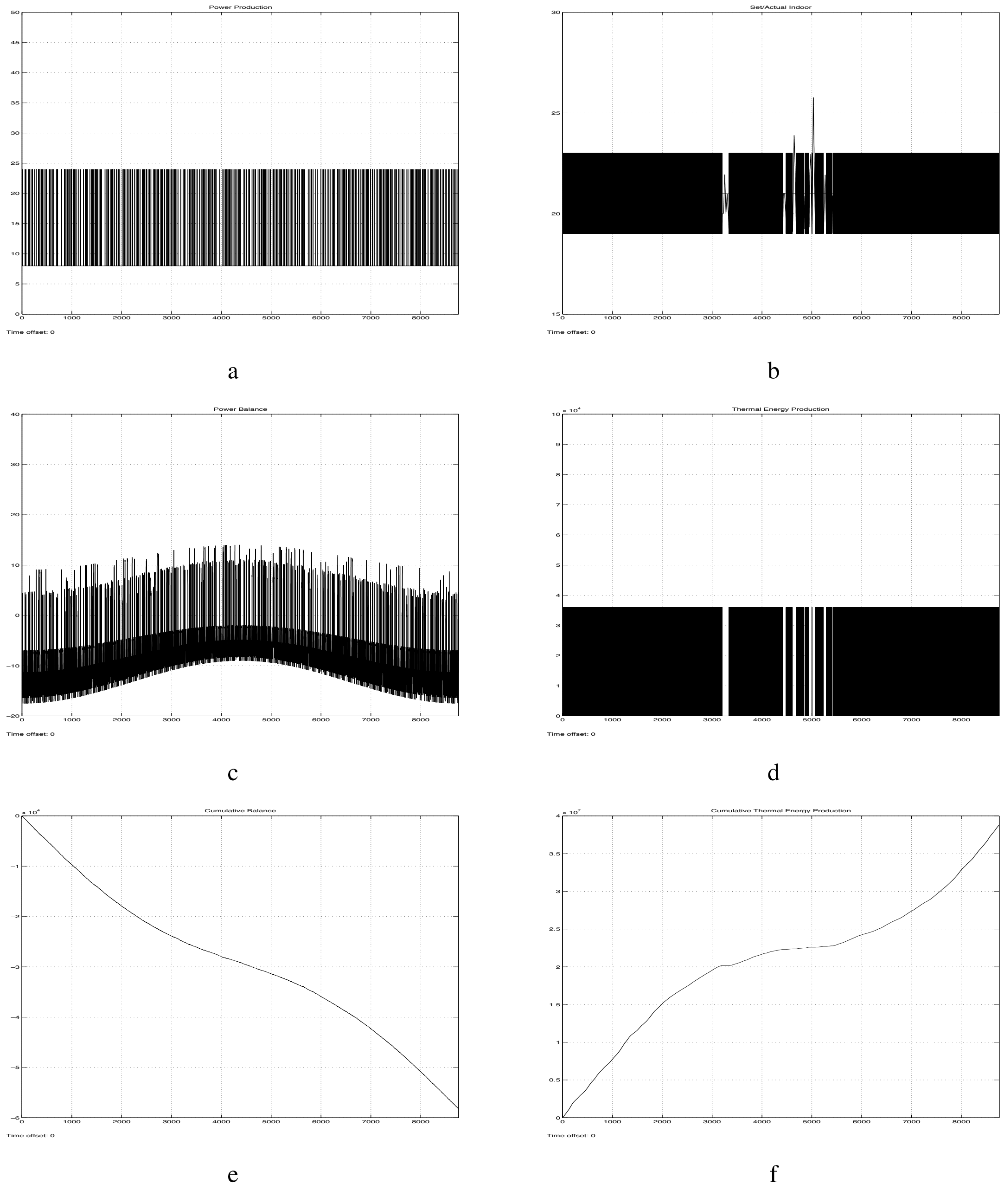
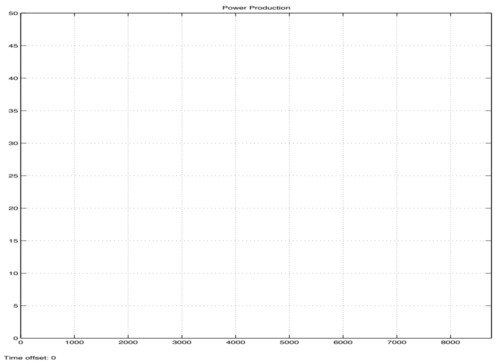


Figure 43: Summary of the results obtained in the simulation run excluding the PV and the wind turbine elements as well as one of the CHP units (CHP1) elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.



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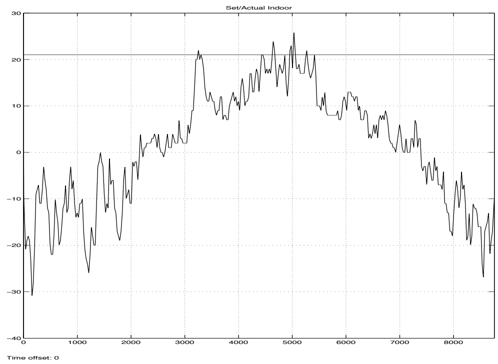

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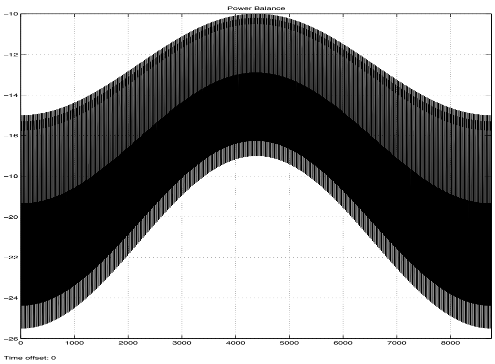

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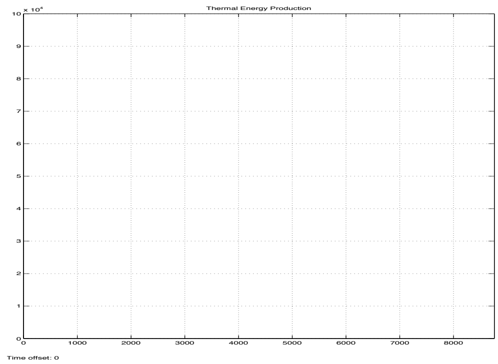

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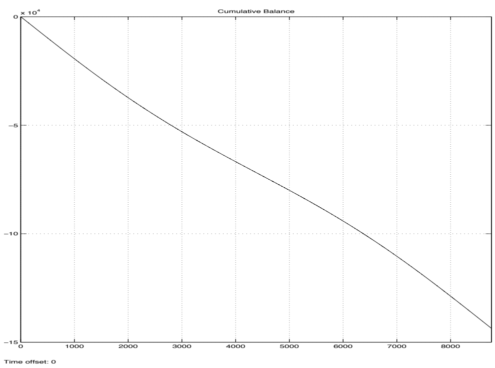

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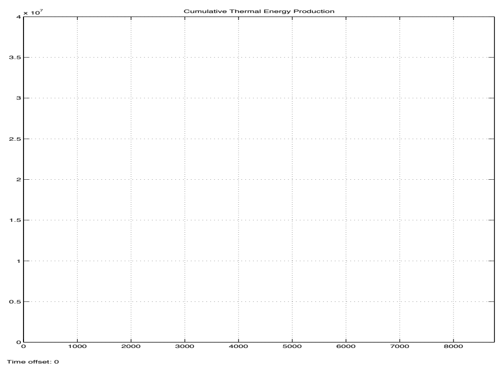

f

Figure 44: Summary of the results obtained in the simulation run without including any of the energy production or storage elements (See chapter 6 for further details): (a) Power Production; (b) Set and actual indoor temperature; (c) Power balance; (d) Thermal energy production; (e) Cumulative power production; (f) Cumulative thermal energy production.

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