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Department of Process and Environmental Engineering
Centre of Northern Environmental Technology

Master's thesis

Smart buildings to improve energy efficiency in the residential sector

Simulation of a detached house in Oulu

In Oulu, 16.08.2012

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Abstract of Thesis

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Abstract

Energy consumption in Finland doubled since the 1970's and, at the same time, peak power levels have increased by 330 %. The objective of this work was to demonstrate that the development of smart buildings integrated in a smart grid would reduce total energy consumption in the residential sector, and also cut peak consumption levels.

The theory part underlines that legislation should promote small-scale renewable energy production systems. Standardizing smart buildings will enhance and accelerate the deployment of such technology. The role of end-users to realize the energy efficiency potential is highlighted and different feedback strategies are presented. In order to facilitate data exchange between the home and the grid, communication technologies must be developed. To this end, data safety and data privacy are of major concern as well as the ownership and access to data.

In the experimental part, a detached house was modelled using MatLab/Simulink, in order to simulate the energy flux. The house is modelled to be located in Oulu, and climate data (temperature, wind speed, wind frequency, solar radiation data) are available on an hourly basis for the last 10 years. The house model details the lighting system and includes twenty-one appliances with different power rates. The variables used where also the number of inhabitants and bedrooms, and potential small-scale energy production systems (wind turbine, photovoltaic panels and fuel cell). Three levels of user responses were evaluated from 'green' to 'brown' users. The feedback methods assessed were self-comparison, inter-comparison, and a target based system. Automatic control for some appliances was also integrated, in order to optimize the system.

The results indicate a potential of 30 % reduction of energy consumption, using energy efficient appliances (A/B label) over regular appliances (C/D label). Applying a smart meter resulted in 2-8 % reduction, depending on the user response. Delaying the use of appliances from the day to the night resulted in the flattened of the mean daily energy consumption profile. Cutting the peaks reduced energy consumption by 18 % during the day and increased it by 47 % during the night in average. It was concluded that an hourly pricing system calls for the development of an iterative model and would also require interaction between the house and the grid. It is expected that the deployment of smart buildings will be an essential part of a smart grid system, and a key element of improving energy efficiency in the residential sector.

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Tiivistelmä

Energiankulutus on kaksinkertaistunut Suomessa 1970-luvun jälkeen, samalla kun energiakäytön huipputaso kohosi 330 prosentilla. Tämän työn tavoitteena on ollut osoittaa, että älykkäisiin sähköverkkoihin integroidut älykkäät rakennukset vähentävät asuintalojen energiankulutusta.

Teoriaosiossa korostetaan lainsäädännöllisten toimien tärkeyttä pienen mittakaavan uusiutuvien energiatuotantotapojen tukemisessa. Älykkäiden rakennusten standardoinnilla voidaan edesauttaa ja tehostaa tällaisten teknologioiden käyttöönottoa. Loppukäyttäjien merkitys energiatehokkuuden saavuttamiseksi käy ilmi eri käyttöstrategioista, joita on myös esitetty. Jotta tiedonvaihto kotien ja sähköverkon välillä olisi mahdollista, tulee viestintäteknologioita myös kehittää. Tietoturva ja -suoja-asiat ovat keskeisessä asemassa tässä, kuten myös omistusoikeudet ja pääsy tietoihin.

Kokeellisessa osiossa on mallinnettu MatLab/Simulink -ohjelmaa käyttäen Oulussa sijainneen omakotitalon energiankulutusta. Mallin käyttämät ilmastotiedot (lämpötila, tuulennopeus ja -toistumistiheys, auringonsäteilytiedot) ovat olleet saatavilla tunneittain kymmenen viime vuoden ajalta. Mallitalossa on käytössä valaistus ja 21 erilaista sähkölaitetta. Muita muuttujia ovat olleet asukkaiden ja huoneiden määrä, sekä mahdollisuus pienenmittakaavan energiantuotantoon (tuuliturbiini, aurinkopanelit ja polttokenno). On tutkittu myös eri käyttäjien (”vihreistä” ”ruskeisiin”) vaikutusta energian kulutukseen. Arvioidut palautemetodit olivat itsevertailu, keskinäinen vertailu ja tavoiteperusteinen järjestelmä. Joidenkin laitteiden kytkentä oli myös automatisoitu, jotta niiden käyttö voitaisiin optimoida.

Tulosten mukaan energiankulutusta on mahdollista vähentää 30 prosentilla käyttämällä energiatehokkaita (A/B) laitteita tavallisten (C/D) laitteiden sijaan. Älykkään mittarin käyttäminen vähensi kulutusta 2-8 prosenttia, riippuen käyttäjän toiminnasta. Laitteiden käyttäminen yöllä päivän sijasta johti energiankäyttöprofiilin tasoittumiseen. Tämä laski energian kulutusta päivisin 18 prosentilla ja lisäsi energian kulutusta öisin 47 prosentilla keskimäärin. Älykkäiden rakennusten kehittäminen on keskeisessä asemassa älykkäitä sähköverkostoja kehitettäessä ja on erittäin tärkeä tekijä asuintalojen energiatehokkuuden lisäämisessä.

Tutkimusta on rahoittanut Pohjoista Voimaa Ympäristötili.

Säilytyspaikka
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Muita tietoja

Content

EXPERIMENTAL PART

List of Figures and Tables

List of Abbreviations

CEN	European Committee for standardization
CENELEC	European Committee for Electrotechnical standardization
DHW	Domestic Hot Water
EC	European Commission
EDPS	European Data Protection Supervisor
ETSI	European Telecommunications Standards Institute
EU	European Union
HMI	Human-Machine Interface
IHD	In-Homes Display
ISO	International Organization for Standardization
MP	Members of the Parliement
MS	Member States
NZE	Nearly Zero Energy
OPEC	Organization of the Petroleum Exporting Countries
PbD	Privacy by Design
PEB	Positive Energy Building
PEMFC	Proton Exchange Membrane Fuel Cell
PET	Privacy Enhancing Technology
PLC	Power Line Communication
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RTM	Real-Time Monitors
SFS	Suomen Standardisoimisliitto (Finnish Standard Organization)
SME	Small and medium- sized enterprise
UNFCCC	United Nations Framework Convention on Climate Change

List of Symbols and Units

°C	Celsius
AM	Air Mass
bps	Bytes per second
C_w	Week action response
DH_{pm}	Detached house monthly price
$E_{overall}$	Cumulated energy
E_{wd}	Mean energy consumption for a given day
G(0)	Global horizontal solar radiation
HHV	High Heating Value
I_{sc}	Short Circuit Current
kg $CO_{2\ eq}$	kilogramme of carbon dioxide equivalent
kVA	kiloVolt Ampere
kW	kilowatt
$kWh/dw.y^{-1}$	kilowatthour per dwelling per year
$kWh/m^2.y^{-1}$	kilowatthour per square meter per year
kWh/y	kilowatthour per year
$kWh_{pe}/m^2.y^{-1}$	kilowatthour primary energy equivalent per square meter per year
Lux	illuminance
m^2	Square meter
NOCT	Nominal Operating Cell Temperature
P_{dh}	Hourly electricity purchase price
P_m	Maximum power
P_p	Hourly purchase price
P_{pm}	mean monthy purchase price
rad	Radian angle
R_d	Daily random generation number
R_h	hourly random number generation
S_p	Hourly selling price
stp	time step
V_{oc}	Open Circuit Voltage
$W.m^{-2}$	Watt per square meter
W/K	Watt per Kelvin
γ_s	Solar Altitude
δ	Declination of the sun
δ_{Eh}	Cumulated and mean daily energy consumption ratio
δ_h	Hour in a day ratio
Θ_{zs}	Solar Zenith
μ_0	Daily limit of energy consumption
Ψ_s	Solar Azimuth
ω	Solar angle

Forewords

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Oulu, August 2012

Jean-Nicolas Louis

THEORETICAL PART

1. Introduction

In a world where changes have never been occurring fast, energy security is one of the main concerns for the future. Fossil fuel resources are decreasing in quantity, while prices of fossil fuel are increasing more rapidly than predicted. Today, barrel price is around 120 US$/b (OPEC, 2012), whilst it was predicted to be around 71,88 US$/b at this time (Capros et al., 2009). Today's oil overall stock is estimated at 1 467 billions barrels across the world while the daily consumption of oil was around 88 millions barrels in 2008 (OPEC, 2011). Based on the projections of daily oil consumption until 2035, the Organization of the Petroleum Countries (OPEC) deduced that the world would run out of oil by 2050. Similar projections can be made for natural gas, whereas by 2045 we would have consumed the world's known natural gas reserves (OPEC, 2011; CIA, 2012). Thus only three decades are between present days and the day where world fossil fuel reserves will be depleted.

Another transformation that is occurring very rapidly is climate change. This phenomenon may be explained by different factors such as environmental (solar radiation, atmospheric composition and motion, land cover, ...) but can also be attributed to human activity (IPCC, 1997). Since the industrial revolution (1750 - 1850 (Dean, 1979)), fossil fuel based energy has been used in such intensity as if it was infinite. Fossil fuel based energy (coal, oil, natural gas) is now known as a highly polluting source of energy. This is now understood at the international level and 192 nations have adopted the Kyoto protocol in 1997, in which all ratifying countries committed to increase the energy efficiency in buildings and industry, and carrying out research on the use of renewable energy and the capture of CO_2 as well as a wide range of other topics related to agriculture or greenhouse gas emissions (UNFCCC, 1998).

The European Union (EU) has established a roadmap to achieve the Kyoto protocol's commitments. The EU published a green paper to introduce the 20-20-20 target that is now one of the key drivers of EU energy policy: reducing the greenhouse gas emissions by 20 % below 1990 levels, 20 % of EU energy consumption to come from renewable resources and 20 % reduction in primary energy use through improvement in energy efficiency (COM(2006) 105 final, 2006).

Considering that 30 % of the current energy generation capacity will diminish by 2020 due to end of the installations life span, one of the solution to overcome this problem is to adapt to renewable energies. The European market consists of five different electricity grids between Ireland (RG Ireland), the United Kingdom (RG United Kingdom), Nordic countries (RG Nordic), Western European countries (RG Continental) and the Baltic countries (RG Baltic) (ENTSOE, 2012). The Energy 2020 strategy advises (COM(2010) 639 final, 2010) controlling the whole energy chain, from the production to the final consumption phase. Currently, it is evident that the grid infrastructure is unprepared for integrating renewable energies and thus the coming years' main focus should be on smart grid development.

Smart grids have been defined by the European Smart Grid Task Force as "*an electricity network that can cost-efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety.*" (EU Commission Task Force for Smart Grids, 2010). The main idea of a smart grid consists of building up links between dwellings, companies, which can both be consumers and producers depending on their configuration, and the energy suppliers. As illustrated in Figure 1, the smart grid is set in a complex structure where different layers occur from the national grid (transmission lines) to local grids (distribution lines). Exchange of energy happens within the distribution grid and between the distribution lines and the transmission lines. Part of the energy comes from the energy suppliers and the production is centralized in parks (wind, solar, bio, nuclear, gas, oil, coal, hydro). This energy is directly fed to the transmission grid and is re-distributed to the different distribution lines and act as a backup when the distribution cannot be self-sufficient. In other words, the smart grid handles the energy flux between the distribution grids and aims to shorten the electricity travelling distances to lower losses (heat losses) and increase its energy efficiency. Another view on smart grids focuses on the information flux. Each producer is able to record climatic data that can be transmitted to other facilities via a communication device. Other data such as energy consumption, can be retrieved down to very low resolution for handling the network and anticipate peak production and avoid them. Finally, smart grids are considered as the main way for implementing renewable energy and reach the legislative targets set by the EU (COM(2011) 202 final, 2011).

The development of smart grids must take into account the parallel development of the energy production mode. Reducing the emissions from energy production is one of the targets of the Energy 2020 strategy. The Finnish Ministry of Environment foresees (Ministry of the Environment, SITRA, TEKES, 2010) the development of a decentralized electricity production from renewable energies such as wind, solar or bio, in order to support centralized production. Considering the size of the market and the multiplicity of energy production area, the grid will need information from the producers in order to handle the traffic. This should be done by using a two ways communication device: a smart meter. Smart meters should work in order to receive information from the grid as well as retrieving some specific and pre-defined data to the grid whilst keeping in mind the most fundamental rules of privacy.

Peak power demand is one of the main concerns of energy management. In Finland, the

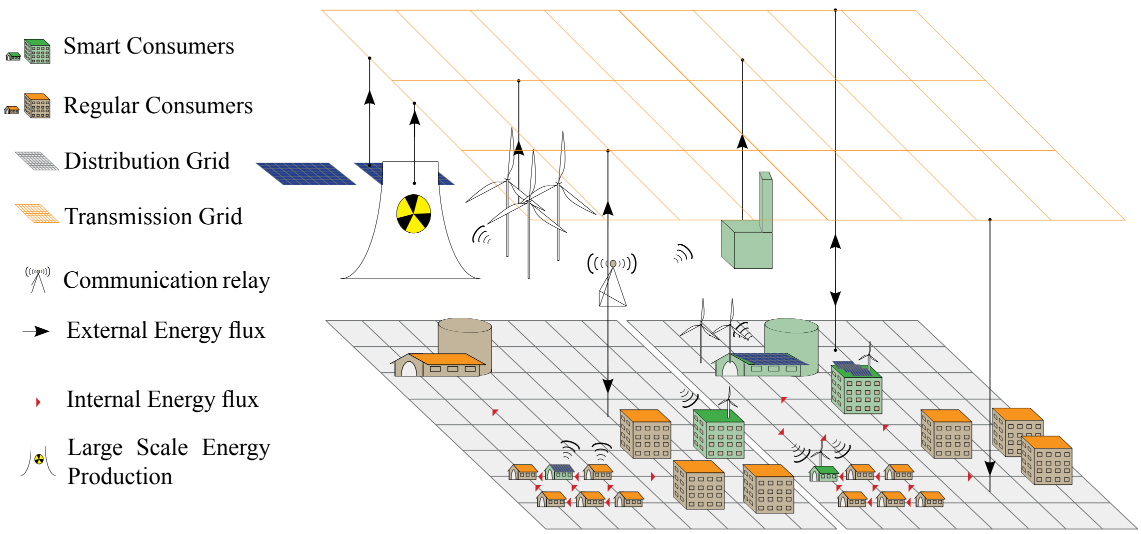


Figure 1. Simplified Smart grid schematic

instantaneous peak power level has increased some 40 % compared to 1990 and, similarly, the weekly average peak power has increased by 38 % (Statistics Finland, 2011). Compared to 1970, these levels have increased by 330 %, which denotes a huge increase in power demand but also requires stronger power lines to handle such increase. Therefore, power production meets an efficiency failure and cost issue. Efficient power production will be reached when an even amount of power will be produced throughout the day, meaning that the load curve will not have the present high consumption peaks at 8 am and 7 pm. Surveying households consumption allowed to estimate the improvements that could be made in the energy residential sector. Indeed, Finns are one of the top electricity consumers at their homes when looking at the appliances and lighting electrical consumption (EEII, 2012) with an energy consumption of 4 237 kWh/dw/y, while the average European dwelling uses 2 607 kWh/dw/y and in the neighbour country Sweden is at a rate of 3 738 kWh/dw/y. A similar figure can be drawn for the overall energy consumption per dwelling where Finland is consuming around 21 216 kWh/y, while the average European energy consumption per dwelling is 14 353 kWh/y and in Sweden is 16 414 kWh/y. It expresses an indubitable margin of potential progress in reducing the energy consumption in Finnish homes. Moving from regular buildings to smart buildings via the implementation of smart meters is of major importance to create a smart grid.

This research has been conducted in order to investigate the potential of smart buildings over regular buildings and how those facilities should interact with the grid that should turn smart, because a structure cannot be fully smart if it cannot interact with the grid. Furthermore, buildings will tend to have a lower heat demand per square meter used in the coming years due to the European legislation. On the other hand, the living surface area per person will increase, which will not necessarily result in the diminution of the overall energy consumption. Therefore, scenarios will be considered to investigate the potential of a smart house in the future, and its role to improve energy efficiency and reduce energy consumption.

2. Energy efficiency in buildings through policy

One of the key driver when changes must occur widely is through regulations. Each European country has their own national regulation, however, the main streamlines are drawn at the European level. Three types of legislation can be distinguished depending on how the members of the parliament (MP) want to apply new rules and to whom they apply: regulation, directive and decisions. Whilst regulations and directives apply to all Member States (MS), decisions may be addressed to a specific MS or company. European regulations do not need to be transcribed into national legislation but apply directly to MS. The time for applying the regulation is usually set to four years after the publication of the regulation in the official journal of the European Union. On the other hand, Directives need to be transcribed into national legislation. The EU set the main lines for implementing a legislation but considering the difficulties to implement a common law for all MS, the European Parliament prefer giving directives to the MS and then each of the MS can adjust the legislation to the existing legislation.

Energy efficiency in buildings is most probably the cornerstone for reducing the energy consumption of citizens considering that the life span of buildings can be between 40 to 120 years (IEA, 2010). In other words, buildings quality will define the energy consumption in buildings of tomorrow knowing that today's share for energy consumption in buildings represent 43 % of the overall European energy consumption (Statistics Europe, 2011).

2.1 European strategy

At the moment, the Directive in force driving energy efficiency in buildings in Europe at the moment is the Directive 2002/91/EC (2002/91/EC, 2002) of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings revised by the Directive 2010/31/EU (2010/31/EU, 2010) of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings

Directive 2002/91/EC was valid until February 1st 2012. The directive 2010/31//EU needs to be transposed into national legislation within 4 years after the publication of the directive in the official journal. Nevertheless, MS of the European Union might obtained some delay to put in place the next energy efficiency in building directive from July 2012 to 2015 for some articles of the directive 2010/31/EU.

Directive 2010/31/EU is the result of the Energy 2020 strategy (COM(2008) 780 final) and therefore, no more actions have been carried out in energy efficiency in buildings. However, a new call has been released in order to write the next energy action plan where new targets for building efficiency should be made.

While energy positive buildings (buildings producing more energy than they consume) already exist either as prototypes, conceptual architecture designs or show cases, they aim to be standard in the horizon of 2020 in some countries, such as France. Such buildings are not bounded yet by international legislation but they are already taken into account in some national legislations such as the French thermal regulation RT 2012 (Legifrance 2010).

2.1.1 Directive 2002/91/EC

The objective of this directive was to promote energy efficiency in buildings taking into consideration the indoor and outdoor climates as well as the thermal comfort in those buildings. As it is mentioned in Article 1 of the Directive, this European directive had set up a framework for MS for a common methodology of calculation in order to have the same basis for working. Therefore this will enable the comparison of the results of energy efficient building in Europe. It included also minimum requirements in terms of energy performance. Finally, to be able to spread the behaviour of having more efficient houses, this directive started the certification for buildings' quality and inspection of the heating system as well as the air conditioning system has been set.

2.1.2 Directive 2010/31/EU

This directive is replacing the one presented in section 2.1.1. It will be used in a near future as the base legislation in terms of energy efficiency in building throughout Europe. In principle, the Directive 2010/31/EU has the same goal (aiming to improve the energy efficiency in buildings), however, major differences can be drawn.

Firstly, this directive does not apply only to houses but also to every new part that can be built within an existing house. Secondly, it is aiming to promote nearly zero-energy buildings. Finally, the inspections try to be in accordance with other European regulations (such as the F-Gas regulation in the case of the inspections of air-conditioning systems).

In the Article 1, the definition for a nearly zero-energy house is a house with a very high thermal performance and which use mostly renewable energy to cover the low amount of energy needed for the different systems in use.

Methodology (Art. 3 + Annex I)

MS need to set their own methodology in accordance with Annex I that states what has to be taken into account in order to calculate the energy performance of buildings. New characteristics appear such as the internal load (production of heat from humans for instance).

- Thermal characteristics (Thermal capacity, insulation, passive heating, cooling elements and thermal bridges);
- Heating installation as well as the hot water production including their respective insulation;
- Air conditioning system;
- Natural and mechanical ventilation;
- Lighting;
- Design, positioning, orientation of the building;
- Passive solar installations as well as solar protection;

- Thermal comfort, and
- Internal loads.

Minimum requirements (Art. 4)

Requirements to be defined by MS will make a differentiation between old and new buildings as well as the type of building or the end-use.

Requirements shall take into account the economical aspect for building up the house. Buildings that are intended to be used less than 4 months and buildings with a consumption of less than 25 % per year are excluded from these requirements. The concept of an economically viable project has to be taken into account when making renovation or building a new house. This new rule is explained in Article 5.

Cost-optimal level of minimum energy requirements (Art. 5)

For every project the minimum requirements can be reached by using different techniques but the cost effective concept should be used. Methodology of comparison has to be set between MS and shall take into account the age of the building and the end-use of the building. It takes into account:

- Outer climate;
- Investments cost;
- Maintenance and running costs;
- Benefits during the running time, and
- End-of-life costs.

New Buildings and Existing Buildings (Art. 6 and 7)

Every new building shall fulfil the requirements and the following generators should require a special attention when designing a new house: Cogeneration; District heating; Heat pump

When renovating an existing building, the requirements defined in article 4 shall be respected as much as possible.

Nearly zero-energy (NZE) Building (Art. 9)

This is a new concept that is implemented in this directive. The purpose of this article is mostly to prepare MS for the future legislation on energy efficiency in buildings. By 2021 every new building for private owner should be NZE.

Inspection of heating and air-conditioning systems (Art. 14 and Art. 15)

As the title indicates, we do not speak anymore about boiler inspection but heating system inspection in order to add other systems in the future.

The accessible part of the heating system should be regularly inspected. As in the previous Directive (section 2.1.1), it targets only generators with a rated output above 20 kW.

Alternative for replacing the existing installations should be made available to the owner.

The scope of the air-conditioning systems (or Air to Air heat pump) does not change and stay for equipment with a rated output above 12 kW. In additions, the study of the energy efficiency of the system, combined with its sizing should be carried out.

2.2 Finnish regulation

The Finnish legislation is presented for reviewing two aspects that will influence the actual and future system and the development of smart houses. The thermal legislation will tend to get more frequent updates due to the renovation of European legislation. The tax legislation will influence the rate of renewable energy devices that will be implemented in the future Finnish buildings.

2.2.1 Thermal legislation in buildings

Finnish legislation must be based on the European legislation, which sets the minimum requirements but they can be taken further. Low energy buildings are complicated to design and build. It requires end users to follow hundreds of pages of legislation in order to meet the requirements set by the state (the French building regulation is over 1500 pages). For these reasons, a short overview about what is important in reducing energy usage in buildings and thus meet an energy efficient house is to be introduced. However, the reader should keep in mind that building regulation is extended to ventilation rate, thermal comfort, indoor air pollution, lighting etc.

The Finnish legislation is divided into many codes but only the ones directly impacting the building thermal performances are going to be reviewed (D series, C3 and C4) (Finnish Ministry of Environment, 2012).

Compared to most advanced countries in this field (Denmark, the Netherlands and France), the requirements are not set in terms of $kWh/m^2/y$ but is given in terms of using materials with a minimum thermal resistance.According to Building Code C3 of the Finnish legislation and its previous versions, the minimum requirements for the insulation of the house must fulfil criteria detailed in Table 1.

Table 1. Minimum technical requirements evolution in the building regulations and its effect throughout the years

Reference Value for maximum heat loss	Year					
	1976	1978	1985	2003	2007	2010
Wall, U-Value [$W/m^2.K$]	0,40	0,29	0,28	0,25	0,24	0,17
Roof, [$W/m^2.K$]	0,35	0,23	0,22	0,16	0,15	0,09
Floor, [$W/m^2.K$]	0,40	0,40	0,36	0,25	0,24	0,16
Window, [$W/m^2.K$]	2,1	2,1	2,1	1,4	1,4	1
Door, [$W/m^2.K$]	0,7	0,7	0,7	1,4	1,4	1
Air Tightness, n50 [h^{-1}]	6	6	6	4	4	2
Yearly exhaust air heat recovery efficiency	0 %	0 %	0 %	30 %	30 %	50 %
Thermal transmittance [W/K]	2017	1905	1879	1367	1353	917
Change 1976 = 100	0 %	-6 %	-7 %	-32 %	-33 %	-55 %
The EPBD-effect	-	-	-	-	-1 %	-33 %

The area of windows must be at least 15 % of the total floor area but cannot exceed 50 % of the mentioned surface. Also, windows must be designed, sized and oriented to get as much profit as possible of the solar radiation.

In the Finnish regulation, the design temperature used for sizing the engines is 21°C for winter time and 23°C for summer time where the base temperature for designing vary from -26°C for the southern region of Finland to -38°C for the northern region of Finland (-32°C should be used for Oulu municipality) and +25°C for summer design.

2.2.2 Legislation supporting renewable energies

Different methods have been used across Europe; from the Green certificate system which is used in Sweden, to the feed-in tariff system which is used in most of the countries supporting renewable energies and has been popularized by Germany. Energy companies buy the energy produced by a local producer at a guaranteed fixed price which is higher than the selling price on the market. Finland has put in place a feed-in tariff system (1396/2010, 2010), which support medium-sized systems. Wind turbines are supported, among other conditions, if the rated power output is 500 kVA, as well as biogas power plants. Wood chip power plant are financially supported from a 100 kVA power output. Considering that such systems cannot be installed in a dwelling or an apartment building, the current Finnish legislation is not in favour of developing small-scale renewable energies knowing that small-scale wind turbine are defined in the literature as a device with a rated power from 0 - 100 kW spread in Micro Wind 0 - 1,5 kW, Small Wind 1,5 - 15 kW and Small Medium Wind 15 - 100 kW (BWEA, 2011).

However, lines are moving according to the Managing director of the Finnish Wind Power Association (Mikkonen, 2012) when seeing that "...a consultant is drafting a proposal for net-metering-system for Ministry of Employment and Economics. In my opinion the net-metering is a feasible way to support the small scale turbines that are connected to the grid...".

2.3 Local regulation: the case of North-Ostrobothnia, Oulu Council

The local regulation of the North-Ostrobothnia region for saving energy in buildings is not specific and follow the national guidelines, although efforts are put into building architecture (City of Oulu, 2012). On the side to the regulation, there are also the intentions coming from the city of Oulu to keep the image of being on the Top Seven Intelligent Communities of the Year 2012 (Invest in Finland, 2012) by investing time into developing Oulu as a smart city.

2.4 Current Legislation and On-going legislative work for implementing smart buildings

To reinforce the existing energy performance in buildings' directive, additional measures are necessary for implementing new technologies that will enhance a reduction in energy consumption in the building fields. Directive 2009/72/EC ruling the internal electricity market has introduced in its Annex I the implementation of smart meters throughout the European Union by 2020 where 80 % of the households should be equipped. In Finland, the decree 66/2009 has set the rule of 80 % smart meter penetration by January 2014 and where hourly data should be retrieved from 2012 for smart meters already deployed.

The next step for implementing smart buildings among the whole European Union will require a set of rule that will frame the use of smart meters since a certain amount of drawbacks raised e.g. data privacy, remote control, communication technology. A task force is the only existing lever at the moment and take the role of surveying the available technology, technical challenges and mapping the road for standardizing and regulating smart technology i.e. smart grids and smart meters. In parallel, the European Commission is developing a directive proposal for energy efficiency where the implementation of smart meters are taken into account as well as the electricity market for supporting smart grids (2011/0172(COD), 2012). It indicates that smart metering can only be used for surveying the energy savings from consumer behaviour and not as a proof of energy saving coming from the installation. It uses In-Home Display (IHD) or internet interface for retrieving the data and should enhance a better control and decrease of the energy consumption. Two-way communication devices shall be installed in order to have an interactive behaviour with a “real time” pricing system. Historical consumption should be made available, on request from the building holders, under five different format: Day by day historical consumption on a period of seven days, last complete week, last complete month, same complete month of the previous year and the complete previous year. Communication between devices and a smart meters is set as a minimum requirement. The directive draft point out the fact that smart meters should be installed with no additional cost compared to regular meters. Energy production from cogeneration should be facilitated in the framework of smart grid implementation but other sources are not mentioned. However, every country should assess their energy efficiency potential including the implementation of micro- and small-scale energy generators. Privacy concern is mentioned by referring to the European regulation on data privacy. However, concerns have been brought up by the European Data Protection Supervisor (EDPS) and are highlighted in section 2.1.

3. Building types

Buildings can be categorised by their mean of attendance (tertiary, residential, industrial, etc...) or/and by their design defining their energetic performances. An other category exist naming the materials used for the construction and the way of building up the structure e.g. Green buildings but is not taken into account in this section.

In this second category, a numerous number of sub-categories can be listed depending on their conceptual definition:

- High-energy buildings;
- Medium-energy buildings;
- Low-energy buildings (Sørensen, 2011): Ultra-low energy buildings, Passive houses, Zero-energy buildings (Net zero site energy use, net off-site zero energy use, net zero source energy use, net zero cost, net zero emission and off-grid buildings), Energy-plus buildings, Autonomous buildings.

This section will introduce the basic concept of these three categories, focusing more on the low-energy buildings being seen as the future design in the future regarding the legislation (see section 2).

3.1 High-energy buildings

High energy buildings refer to the thermal use of energy for heating or cooling of the structure, thus excluding any energy use from the appliances existing in the building. Different level of high-energy buildings can be found in the literature depending on the country, however a classification using the energy labelling system (see section 2.1) exist and set the high energy buildings above an annual energy consumption of $kWh_{pe}/m^2/y$. It usually applies to retrofitting buildings.

3.2 Medium-energy buildings

Medium-energy buildings see their thermal energy consumption between 91 $kWh_{pe}/m^2/y$

up to 231 $kWh_{pe}/m^2/y$. It is considered to be buildings made before 2010 (Effinergy, 2012).

3.3 Low-energy buildings and other definitions

Low-energy buildings have the widest range of building definition and are considered to have a thermal energy consumption below 91 $kWh_{pe}/m^2/y$ (Effinergy, 2012). This limit will vary depending on which category the building belongs to.

Low-energy buildings are already implemented in many western countries and are named differently depending on the countries (e.g. Bâtiments Basse Consommation - BBC in France, low-energy building standard in Switzerland or Germany). These buildings have an energy consumption from 45 to 80 $kWh_{pe}/m^2/y$ (Effinergy, 2012) including heating, cooling, lighting, ventilation and domestic hot water systems. The evolution of low-energy buildings are called ultra low-energy buildings and see their energy consumption below 15 $kWh_{pe}/m^2/y$ (Effinergy, 2012). Below the ultra low-energy buildings comes the category wide of zero-energy buildings that include six sub-categories as defined in (Marszal et al, 2010).

Sørensen (Sørensen, 2011) defines the Net zero off-site energy use as buildings taking its energy entirely from renewable energy and are defined as net zero site energy use buildings when the energy comes from the site itself. These buildings do not necessarily have a balances energy between the energy used and the energy produced. Buildings with a balanced energy used are called net zero source energy use and produce the same amount of energy than the energy consumed on-site including the transmission and transportation losses (Gray and Zarnikau, 2011). Another type of building that produces energy from renewable energies is called the net zero cost building where the energy produced and sold to the energy providers balance the energy bought from the provider. This type of building is dependent on the contract signed with the energy providers and thus may have different energy system structure. Other buildings can refer to their environmental impact and are called net zero energy emissions when the carbon emissions coming from on-site or off-site energy sources is balanced by the amount of renewable energy produced on-site. The last definition of zero energy buildings is presented for off-grid buildings. These buildings are not connected to the main power grid and act as stand-alone structure. Thus, the entire energy production must be carried out on site and imply an efficient energy storage system to overcome the lack of energy production when the energy course is unstable e.g. wind, solar.

Coming after the zero energy buildings are the positive energy buildings or energy plus buildings (Kolokotsa et al., 2010). Positive energy buildings produce on a yearly basis more renewable energy than they consume. Those are seen as the next generation of buildings in Europe after 2020 (ECEEE, 2011). Consultants must skilfully play with the building design using and its relative orientation to the sun, the insulation of the building that will minimize the use of heat during the winter and the use of cold during the summer and reduce the use of lighting combined with a production of energy coming from renewable energy sources.

4. Smart buildings

Smart building can be defined as an integrated and advanced automation system for different purposes such as lighting, temperature, multimedia, openings (windows/doors) (Markovic et al., 2011), health recording. Smart buildings cover a wide range of applications. Thus, it is possible to classify them in different categories according to the purpose of the smart system implemented:

- "Energy" smart system: this smart system is defined as a smart system handling the energy distribution within the building including both electricity and heat consumption. (Kok et al., 2009)
- "Health" smart system: they will look into the well-being of the people and can be developed in two more categories whether it is a private building or a hospital. Principle of this type of smart building is to survey the inhabitant's health and advice them on taking medication and so on. It would be possible to combine this type of smart building with the energy smart system by making them interacting with each others such as anticipating thermal comfort requirements of elderly and sedentary people. (Chan et al., 2009)
- "Everyday life handling" smart system: it includes a bench of information based on technology such as handling the food content of the fridge or the cupboards by analysing the bar codes for instance. Such systems can also be applied to Hi-Fi system in order to make them working together (i.e. Smart phones). (Friedwald et al., 2004)

This thesis considers only energy smart systems.

Smart energy houses ought to be the future if the energy flux within a house needs to be controlled. As mentioned in section 2.1, the next step in the building construction will be to achieve nearly-zero energy buildings (NZE) by 2020 and the final target is to have positive energy buildings (PEB). "Passive house" is nowadays a well-known concept among professional building consultants. However, passive houses are different from PEBs and NZEs concepts (Passive House Institute, 2012). Passive houses suggest that the building does not need active energy system operating in the building whereas PEBs and NZEBs have an active energy systems running. The overall energy flow should be respectively nul or positive meaning that buildings produce energy equally or more what it consumes. Small and medium-scale energy production equipment will arise and energy flux will have to be controlled in order to handle the energy coming in and out of the building. As an extent, energy in existing buildings can be controlled to meet the requirements set for flattening the everyday energy flow curve. Creating smart buildings with existing infrastructures will be one of the main challenge of the coming years considering that almost 80 % of the overall building park of Oulu has been erected before the year 2000 (Statistic Finland, 2012). Smart energy house can be regarded under two different views which will always imply a user action: a feedback information to increase the awareness of householders about energy consumption and a direct access to some of the machines in the house to switch them on and off remotely.

A declination of smart energy buildings can be found in the literature and no common trend is found in the physical architecture. However, a common element that is found in smart buildings is the smart meter. Furthermore, smart buildings have common targets to achieve and are described in the Smart Energy-Efficient Buildings for Smart Energy Grids research project (SEBEG, 2011):

- Collecting real-time data enabling intelligent automation,
- Data management infrastructure allowing consumption and production of energy,
- Data platform,
- Energy user preferences for flexible feedbacks,
- Supporting the grid operators enabling smart grid infrastructure,
- Enabling producers and consumers interaction and have a dynamic energy market,
- Reducing maintenance using the cloud system,
- Energy display in the building, and
- Improving the billing and payment system.

4.1 Feedback strategy

Feedback to the end users is an essential part of smart homes. Energy efficiency and decreased energy consumption cannot be met without the will of the householders. Thus, educating and informing householders on energy efficiency and energy reduction must also be done through different actions.

The first feedback testing was carried out in 2004 (Roberts et al., 2004) by informing householders of their energy consumption on paper. It demonstrated a disparity of end user responses. Some customers had no trust in the feedbacks, others had little motivation, etc. The downside of paper-based feedback is also that users need to read them, and not throwing the papers away. In addition, real time information cannot be displayed and it contributes to unnecessary paper consumption.

Internet based feedback display is widely used today but implies externalizing the data to make them available on the web. This method does present a certain cost advantage because it does not require investing in any new technology. However, drawbacks are also found: risks of being hacked allowing to trace if a house is empty, following the house owners habits can be used for marketing purposes. This can decrease the willingness of the people to use this technology, bringing technical limitation in controlling the different features that a smart meter. In addition, the internet based method has presented low impact on the reduction of the energy consumption; between 5 % - 8,5 %, in households when some 20 % reduction have been achieved with other methods (Ehrhardt-Martinez et al., 2011). As well, studies did not show a flattening of the energy consumption profile but an evenly distributed decrease of the energy consumption over the day using this method.

Therefore, the focus will be centred on In-Homes Display (IHD), which consists of a screen interface accessible to the user at any time. It will provide different datasets depending on the configuration (number of rooms), the year of construction of the building (e.g. for scaling the heat demand) and the technology installed in the house (e.g. Overall or single appliance energy reading).

A first set of possible data that could be displayed has been highlighted by Karjalainen (2010) for directing the attention to the energy consumption within a building and Ehrhardt-Martinez (Ehrhardt-Martinez et al., 2011) for organizing the billing system. In addition, a possible way of combining energy consumption data with the energy production data need to be added in order to create a synergy of the energy flux in a building. Figure 2 presents a modified matrix from Karjalainen, where feedback information can be selected. Different combinations of objectives, units, scale, time scale and retrieved format can be arranged in order to highlight the data.

Regarding what affects people's behaviour, points of view differ in the literature. Ehrhardt-Martinez shows that comparing consumption to other users is beneficial for improving the energy saving through fair competition. Other studies are more doubtful and recommend further study to really prove the beneficial effect of inter-comparison (Jain et al., 2011) and recommend historical self-comparison. Achieving goals may be useful for challenging the inhabitants although a reward action plan could be emphasized by the energy company as Jain explains (Jain et al., 2011) to motivate people in their action. Jain also

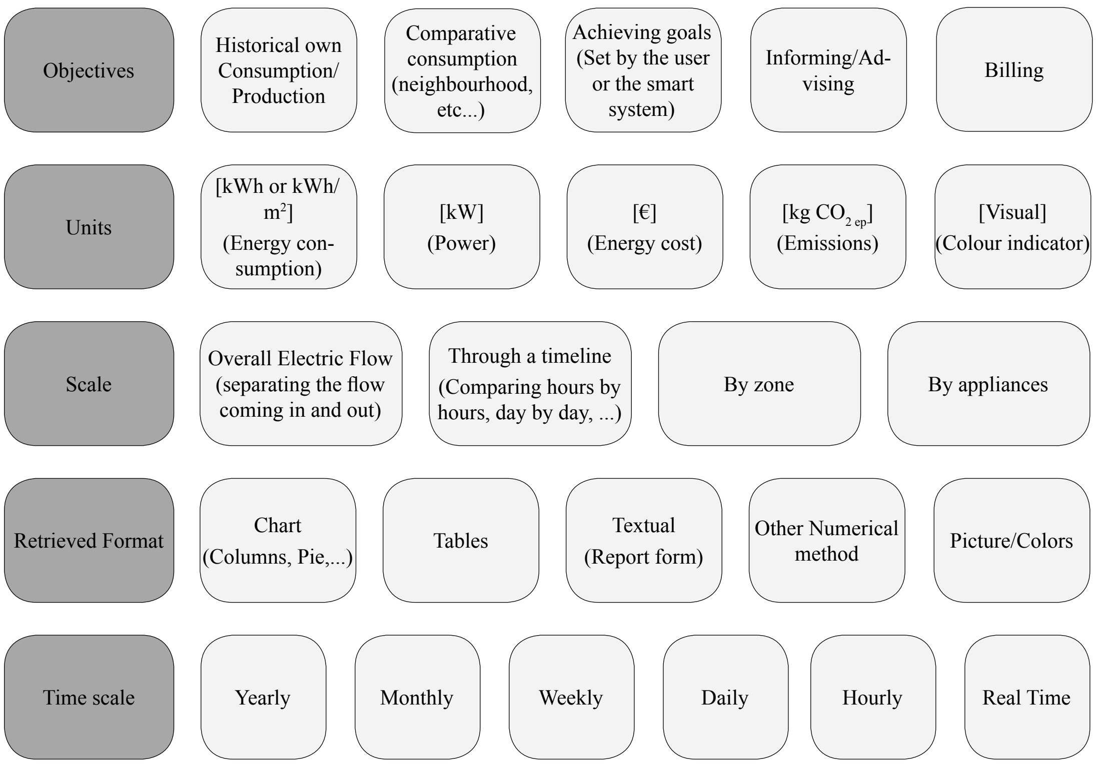


Figure 2. Matrix of optional data to be retrieved and under which form; energy consumption and energy production feedback
(Based on Karjalainen, 2010)

dismisses the penalization system saying that it was counterproductive. Another objective is the advising/informing scheme where owners may receive recommendations on what device to turn off or pointing out the inefficiency of some machines if they are overconsuming, according to international standards of energy efficiency. Informing about the most suitable time to operate certain devices may also be delivered.

Previous studies may differ in their recommendations but a general conclusion can be drawn (Hargreaves et al., 2010 ; Bonino et al., 2011): Using energy units [kWh] is more accepted but less understood by the end-users, thus power unit [kW] should be preferred because it is a better indicator for evaluating the technical limitation of the building. Emission unit [$kgCO_{2\,eq}$] is not well understood and does not influence much on the behaviour of the householders. Monetary units are usually the most effective, mostly because people find their motivation in saving energy for financial purposes (Hargreaves et al., 2010 ; Ehrhardt-Martinez et al., 2011). However, a proper time-scale should be defined to have a real effect on consumer behaviour. Visual response of the energy consumption is probably the most pedagogical and simple method to warn people about potential overload on the network or in the house, pointing out which appliances or zones are the most energy intensive for further actions.

Scaling the feedback format is highly building dependent and has to be put in correlation with the privacy issue as mentioned in section 2.1. Large scale (e.g. monthly data vs. hourly data) feedback is safer in terms of privacy and gives the main overview of the energy consumption of the building. This scale may be appropriate for owners who do not pay or do not want to pay too much attention to the feedback and are unwilling to spend their time for surveying the energy flux of their building.

Hargreaves (2010) defines four categories of users based on their characteristics:

- Financial;
- Environmental;
- Curiosity, and
- Technological.

Providing feedback for each individual appliance may be interesting for at least two categories of people; to those who like having as much information as possible in order to extract the data and post-process them, and those who are interested in technology such as smart phones and similar technologies. Appliance-specific data also sheds light on the inefficiency of certain devices and make inhabitants realize that a fridge or a kettle may have a high nominal power leading to high energy consumption.

The retrieving format is a little bit unclear and has not been the subject of sociological study. Karjalainen (2010) conducted some research on the topic but results do not appear statistically viable for extrapolations. In his studies, participants had a preference for getting the feedback through a written form in a table, where each appliance is detailed with their energy consumption over a certain period. On the other hand, this study showed that historical consumption under the form of bar chart did not have any success, while other studies have shown potential of having historical comparisons (Jain et al., 2011).

Time scale of the feedback will depend on the use of the feedback and by whom the feedback will be used. In case an active role should be played by the inhabitants of a building, real-time data should always be on screen, while monthly or yearly data will support and highlight the efforts that people made during a long period.

As pointed out in the beginning of this section, feedbacks have a role of training and informing the population about energy efficiency and the need to reduce our energy consumption. However, this method finds its limits in the inhabitants' availability. While the environmentally and the technologically interested people may carry on their investigations and use the feedbacks for improving their performances, the other part of the population may lose its eagerness and interest in using this technology (Faruqui et al., 2009). Thus, feedbacks should be drawn for each building where a standard version and an advanced version of the retrieved data are available. The standard version gives only the basic and meaningful information and have an access to the overall building. The advanced version giving more precise data allowing the follow up and instant actions on a specific device or zone if available from the HMI.

4.2 Smart meters

Smart meters can be defined as the technological means for turning a regular building into a smart facility (Shekara et al, 2011). Smart meter is a two-way communication device allowing the transfer of information to and from the smart meter. Some important points must be taken into account when designing/selecting a smart meter, related to the used communication technology, the data privacy and the security level of the smart meter. There is also need for standards to regulate the communication systems between smart meters.

In this work, smart meters are assumed to have a separate communication interface between the building and the grid. Thus, those two sides of the smart meter cannot access each other and a bridge must be built between the two interfaces to control the type of data that needs to be transferred to the grid and vice versa. This is to avoid intrusion within a building and third party remote control (e.g. System operators, hackers).

4.2.1 Communication systems within the building and building/grid

Communication within the building of the different information is crucial for future of smart houses. Depending on how the technology needs to be implement, two main options are possible to have: wired communication system and wireless communication system. Wired communication system has many advantages over the wireless system in terms of privacy safety or signal wave from wireless communication. However, wired system can get expensive (Markovic et al, 2011) when implemented in existing building due to the massive retrofitting work needed. As well, if new equipment need to be connected to the smart meter, it may become complicated and costly to implement a new wire from the new device to the smart meter. However, wire technologies exist to tackle the cost issue (Zuberi, 2003), either by using the home phone networking or the powerline technologies, but are not widely used. Wireless communication systems do not have this problem and are flexible considering the evolution of the equipment in time.

Selecting a technology will require answering questions such as the cost of such systems, the speed rate for transferring the data from the smart meter to the system operator or to the In-Home interface, the acceptance of having such technology at home.

A wide range of solutions and combinations can be created. However, this work does not target a full description of the communication system within a building because a highly detailed literature already exist on this topic (OPENmeter, 2009a, 2009b, 2009c, 2010).

Table 2 presents the different communication protocols that may be used to interact inside the building or with the grid.

Table 2. Communication systems characteristics within a building or the grid

Wired Technologies	
PLC (Power Line Communication)	***Technologies***: Narrowband PLC (A, B and C), Broadband PLC, up to 1 km (needs of repeaters for longer distances) ***Application***: Power grid control, Building interconnection through wires, High/Medium/Low voltage network application, ***Cost***: Unknown ***Limitations/advantages***: Can be applied to existing buildings, ***Data rate***: Narrowband → Few thousands bps, Broadband → up to 2 Mbps, ***Power required***: Unknown
Wireless Technologies	
Unlicensed Radio Technology	***Technologies:*** Io-Homecontrol, Z-Wave, EnergyAxis, Evolution, OpenWay. Range of 100 m ***Application***: **AMI** (Advanced Metering Infrastructure), **AMR** (Automatic Meter Reading), Home comfort, Centralized Management, remote control ***Cost:*** Low cost ***Limitations/advantages:*** Security issue due to share frequency bands (free-licensed), Free licence ***Data Rate***: 10^{th} of kbps ***Power required***: < 0,2 W
IEEE 802.15.4	***Technologies:*** low-rate wireless personal area networks, Peer-to-peer networks, Range of 10 to 75 m ***Application***: AMR, Home automation, Industrial remote control communications, WPAN (Wireless Personal Area Network), Sensor networks ***Cost:*** Very low cost ***Limitations:*** Unlicensed ***Data Rate***: 20, 40, 100 and 250 kbps ***Power required***: 3 W
IEEE 802.11	***Technologies:*** Service equivalent to Ethernet layer 2 wired connectivity, Range of 100m ***Application***: Wireless LAN access (Local Area Network), Ethernet networks bridges, ***Cost:*** Low cost ***Advantages/Limitation:*** Unlicensed, plenty of retailers, interoperability, subject to humidity, interference due to free frequency, easily hacked unless WPA2 encryption ***Data Rate***: 11 000- 54 000 kbps ***Power required***: 3 W
IEEE 802.16	***Technologies:*** 802.16d has range of 75 km and 802.16e has range of 2-4 km ***Application***: Wireless LAN/WAN (Wide area network) access ***Cost:*** 300 € for individuals ***Limitation/advantages:*** Licensed/Unlicensed, main competitor of 3G ***Data Rate***: 15 000, 75 000 kbps ***Power required***: 3 W

Zigbee	***Technologies:*** Uses the IEEE 802.15.4 standard, formed by an association of companies, Range of 100 m ***Application***: WPAN, Mesh sensor networks, wireless control and monitoring application, Smart lighting, advanced temperature control, Water/power sensors, smart appliances, energy monitoring, mobile services (e-payment, remote control ...), smart metering. ***Cost:*** Very low cost if high volume of application ***Limitation/advantages:*** Unlicensed, low power, smaller battery, joining/leaving a Zigbee network, assign addresses to devices, Network synchronisation, Advanced Encryption Standard (AES), must be part of the Zigbee alliance for using this technology ***Data Rate***: 20 - 250 kbps ***Power required***: < 0,2 W
Wireless M-Bus (Message Bus)	***Technologies:*** Range of 100 m, Internet technology based, based on EN13757-4 ***Application***: Application components communication, remote reading of consumption meters (water, gas electricity and heat) sensors and actuators, AMR ***Cost:*** Low price due to simple architecture ***Limitation/advantages:*** Unlicensed, no self-configuring nor self-healing for smart, flexible, reliable and efficient management over many years operation, can be combined with a building controller, individual meter reading, possible remote reading, easey post-processing of the data ***Data Rate***: 16 - 66 kbps ***Power required***: < 0,2 W
Wavenis	***Technologies:*** Range of 100 m, FHSS (Frequency-hopping spread spectrum) technology ***Application***: Metering, Sensor Networks, Fixed network monitoring ***Cost:*** Low cost ***Limitation/advantages:*** Unlicensed, enable wireless communication in hard-to-reach devices, high sensitivity, strong robustness against interferers (industry suitable), work in cycles, recommended as a complementary technology ***Data Rate***: 5 - 20 kbps ***Power required***: Very low power
WiFi (Wireless Fidelity)	***Technologies:*** Range of 100 m, based on IEEE 802.11 ***Application***: Wireless LAN access ***Cost:*** Price of the membership and certification, may be high. ***Limitation/advantages:*** Unlicensed, must be a member of the WiFi alliance, ***Data Rate***: 11 000 - 54 000 kbps ***Power required***: 3 W
Bluetooth	***Technologies:*** Radio (broadcast) communications system, Range of 10 to 100 m, open wireless protocol, Bluetooth standard, ***Application***: PAN, Phone connection, fixed and mobile technology ***Cost:*** Low cost technology, price for the bluetooth certification ***Limitation:*** Unlicensed, open wireless protocol, refreshable encryption ***Data Rate***: 1 000 kbps ***Power required***: < 0,3 W
GPRS (***2G***) (General Packet Radio Service)	***Technologies:*** Operator coverage area, GSM system, IP-based service ***Application***: WAN Access, remote file and data exchange, Remote office access for nomadic users, Remote metering data collection ***Cost:*** Mobile network subscription (operator dependent) ***Limitation/advantages:*** Licensed, not available in Japan, Network owned by the mobile operator, 0,5 to 2 second latent response, security protocol may be based on IPSec or TLS/SSL, ***Data Rate***: 9 to 60 kbps downlink, 9 to 40 kpbs uplink ***Power required***: < 1 W
UMTS (Universal Mobile Telecommunication System) (***3G***)	***Technologies:*** Operator coverage area, evolution of the 2G network ***Application***: WAN Access, Remote office access for nomadic users, File exchange, Substitute of xDSL where no cable infrastructure available/deployable, Video messaging / telephony, Remote metering. ***Cost:*** high cost of 3G deployment, more expensive than GPRS in the near future, operator contract cost ***Limitation/advantages:*** Licensed, urban areas ***Data Rate***: 384 - 7 200 kbps ***Power required***: < 1,5 W

TETRA (Terrestrial Trunked Radio)	***Technologies:*** Operator coverage area ***Application***: WAN Access, design for governmental services (police, fire departments, ambulance, rail transportation, oil and gas, military) ***Cost:*** high cost due to low expansion, could be competitively used against GSM ***Limitation/advantages:*** Licensed, All traffic is normally encrypted, can transmit and receive simultaneously, can be used in rural and urban areas, high security level ***Data Rate***: 20 - 700 kbps ***Power required***: < 1 W
WiMAX (Worldwide Interoperability for Microwave Axess)	***Technologies:*** Range of 20 km, based on IEEE 802.16 ***Application***: Wireless LAN/WAN Access ***Cost:*** Certification raise the price ***Limitation/advantages:*** Licensed/Unlicensed, only WiMAX forum member companies can certify WiMAX products, interoperability, ***Data Rate***: 15 000 - 75 000 kbps ***Power required***: 3 W
EverBlu	***Technologies:*** Bi-frequency, long-range 300 m, wireless mesh technology, use Radian protocol ***Application***: Metering, AMR, multi-energy (water, gas, electricity and heat), ***Cost:*** Limited infrastructure investment, lower operation cost ***Limitation/advantages:*** Unlicensed, suitable for rural, suburban and rural areas, 1 million modules already installed, WAN communication infrastructure (e.g. GPRS) ***Data Rate***: 10 kbps ***Power required***: < 0,3 W

4.3 Privacy concerns

The notion of data exchange is of major importance for connecting the different elements composing smart houses and smart grid together. However, data can be sensitive information whether for the householders or the energy operators. The European Parliament has framed the data privacy in its regulation (95/46/EC, 1995) and the flexibility that companies can have when transmitting such data. This covers a first aspect of data privacy which consists of avoiding the use of the personal information by companies that would use it for surveilling and controlling their customers. A second aspect is described by the independence of individuals over the distribution operator and extendedly to the energy operators to take control of any building for any reason (political, commercial, economic, energetic) and plug a whole building or industry off the grid. A third aspect of data privacy is found within the technological limitations of data transfer. Transferring data through an open media such as the Internet has found its limitation in the form of hackers who can access all personal data either on a personal computer or on the company's servers. Finally, data could be used by the state and the tax offices to prove or find out if the declared building is registered as a secondary or main residence. By extension, tax offices could survey the energy consumption of the unemployed population and penalize them for the excess use of energy.

Under a legal frame, we enter in a paradox where two European laws have to interact as explained by Knyrim and Trieb (2011): the Electricity Directive (2009/72/EC, 2009) and the Data Protection Directive 95/46/EC. In the first one, data should be freely given to the energy operators when an explicit contract has been signed (Annex 1, paragraph h of the directive). In the second one, private data can be released only for a "*specific and legitimate*" goal and should not excess this limitation. As long as the Data protection law is a European Directive, the Personal Data Act 523/1999 prevails in Finland.

McKenna et al. (2011) have illustrated the controversial use of data. Data are not intrinsically sensitive but the time frame in which data are collected is. Collecting data in a monthly basis should be enough for establishing the data, while hourly data would indicate the users habits which could be used in different ways such as forbidding the use of certain devices to some building because they use large amount of electricity at a given time. It would take away the freedom of people of doing what they want and when they want. A parallel issue with detailed data in time and space can occur within a building itself in a second level (the first level being the power that companies can have over the building holders). Imagining that the energy data are retrievable on a remote device such as a phone, parents could have access to all the activities in a house and thus we enter in the "big brother" era where every move is watched and controlled. If, on top of that, machines are controllable remotely, it would be possible for the householder to switch off the whole building or part of the building and could be seen as a punishment of the children. This could destroy the trust between humans. On the other hand, controlling remotely a building can be seen as a technical advantage for warming up the building after a long time of non-use of the building for instance.

To overcome the privacy issue, a solution is proposed by Cavoukian and Winn (2012) called Privacy by Design (PbD). The concept is declined by 7 principles (Cavoukian and Winn, 2012) and recommends, among other principle, the default full security setting and data can be retrieved only by a physical action of the householders to communicate its private data. The PbD concept is also recommended by the European Data Protection Supervisor (EDPS) in its paper regarding the roll-out recommendations of smart meters in EU (EDPS, 2012).

The EDPS has set a list of recommendations (EDPS, 2012) regarding the future Energy Efficiency Directive and has pointed out concerns that should be raised at the legislative level. The EDPS sees smart-metering as a high intrusive system enabling tracking any actions within a building and could profit a large number of sectors such as marketing (including oriented advertisement), the tax authorities, governmental agencies (e.g unemployment office), insurance companies, landlords, employers and also hackers and the crime organisations. The EDPS recommends also to extend the responsibilities to the whole chain of energy from the energy suppliers to the providers of value-added data and not only to the network operators (over 90 distribution network operators in Finland (EMV, 2012)). The EDPS insists on the fact that data should be retrieved only with the clear consent of the householders for the energy provision, the billing system, fraud detection and the grid maintenance. It implies that every owners should have the choice to accept or not to have a fully operational smart metering system in their homes. Another point of the EDPS is the restriction of taking out data from the household using Privacy-Enhancing technologies (PETs).

In summation, it can be stated that data privacy has a key role in the development of smart metering and smart grid system.

4.4 Standardization

As presented earlier, a common communication language is key for smart houses. Standards play a role in this matter for having a harmonized industry of smart houses. This is crucial when changes must be achieved on a large scale. Different organizations exist and, in the case of Europe, three levels can be distinguished: the national level (SFS, Finnish Standards Association), the European level (e.g. European Committee of Standardization CEN, European Committee for Electrotechnical standardization CENELEC) and the international level (ISO standard). In Europe, a wide range of standards are already available for the communication systems, the building performances and the energy systems. The work of the European standards is to create a new standard to regroup and combine different standards as well as setting rules for standardized smart houses. So far, there are no standards for smart houses available. It is in this matter that the mandate M/441 has been enforced. To enable the inter-operability of utility meters, understand smart meters (Mandate M/441, 2009).

CENELEC started the work of creating a standard for smart houses and surveyed the existing standards for communication systems in its roadmap for smart houses (CENELEC, 2011). Concerning the second organisation, the CEN has launched the Technical Committee 294, with five working groups for writing communication standards related to heat and electric meters (CEN, 2012). The third and last organisation, ETSI, has already published four communication standards for smart meters (ETSI, 2012) and were on the framework of M2M project (Machine to Machine).

Although performance of buildings does not exactly match the scope of smart houses, it will be one of the buildings' cornerstone in the future, and smart houses will have to be developed considering the development of building energy performances. Building performances are regulated by national legislation (see section 2). However, standards exist to provide a framework of building performance such as the ISO 7730 for evaluating the thermal comfort, the EN 15251 for setting the environmental criteria for evaluating the energy performance in the building, and the ISO 13790 on the "*Energy performance of Buildings – Energy use for space heating and cooling*".

Finally, systems also have their standards for calculating their performances. A non-exhaustive list of building standards is compiled in APPENDIX A. By combining all standards, it will be possible to set up rules for high performance smart buildings as well as smart buildings in the retrofitting sector.

Most recent news have stated on-going discussion in China to set up standards frame-works for smart grids and smart houses where the China Standards Authority should have organized the signature of the "one m-to-m" document making the foundation of future standardization in the field of smart systems (EurActiv, 2012).

4.5 On-going projects

The Annex I of the directive 2009/72/EC indicates that 80 % of the households should be equipped by a smart meter by 2020. Every country has undertaken work that will allow to achieve this target. In Finland, ten projects have been accounted so far for implementing smart meters. Although most of them are located in southern Finland (e.g. Helsinki, Espoo, Vantaa), three projects have been already finished in Haukipudas, Tornio and Kemi. The singularity of those three projects is that it uses the same technology from the same company Landis + Gyr. This singularity is actually extended to other projects around Finland such as Jyväskylä, Tampere, Vaasa, Kainnu, Espoo and Helsinki area (Smart Electric News, 2009).

Oulun Energia has also started an implementation project of smart meters with the same company. 26 000 smart meters are going to be deployed in the City of Oulu with an extension to 62 000 meters that will cover 90 000 consumers. The operation and maintenance service is covered by the same company than the above mentioned project.

The Oulu University of Applied Sciences (OUAS) participates to a Northern Periphery Programme project on the Opportunities for Community groups Through Energy Storage (OCTES) (NPP, 2011). OUAS is surveying detached houses around the City of Oulu and collect the data. The smart meters collect the overall energy consumption from the building (OCTES, 2012) but is not able to differentiate appliances. Energy production cannot be measured either. The data can be retrieved on an internet interface and indicates the spot price market as well as the energy consumption of the house.

Table 3 presents projects that are active around the municipality of Oulu.

Table 3. Smart meter project around Oulu

Tornion Energia	11,000 metering points in the Tornio region. Uses the advanced metering management (AMM) technology from Landis + Gyr (Toshiba) on the recommendation of the Finnish Energy Industry (Energiateollisuus) (Energycentral, 2007). **Communication systems**: GPRS TCP/IP **Enables**: Hourly reading of the electrical consumption. Displayed on internet. Remote connection and disconnection of a building to the grid.
Kemin Energia	15 000 metering points in the Kemi area. Uses the advanced metering management (AMM) technology from Landis + Gyr (Toshiba) AMM technology (Metering, 2008). **Communication systems**: GPRS TCP/IP **Enables**: Improve meter reading. Improve the invoices process as well as the customers services
Haukipudas Electricity Cooperative	9 000 meters have been installed from 2008 to 2011. Uses the advanced metering management (AMM) technology from Landis + Gyr (Toshiba) (Metering, 2007). **Communication systems**: GPRS TCP/IP **Enables**: Hourly reading of the electrical consumption. Displayed on internet. Remote connection and disconnection of a building to the grid.
Oulun Energia	28 000 meters are or will be installed by the end of 2012. Uses the advanced metering management (AMM) technology from Landis + Gyr (Toshiba) (Metering, 2011). The final target will be to install 62 000 smart meters in Oulu region (Landys&Gyr, 2012). **Communication systems**: GPRS TCP/IP **Enables**: Hourly reading of the electrical consumption. Displayed on internet. Remote connection and disconnection of a building to the grid.
Oulu University of Applied Sciences	Smart meter project within the Northern Periphery Programme (NPP). Partner University. OUAS is surveying detached houses around the City of Oulu. The project is using the Cost EnviR smart meter bought from Current Cost company. **Communication systems**: Wireless and 433 MHz bandwidth **Enables**: Retrieve the data every 15 minutes. Displayed on a Android tablet. Can receive information from 9 transmitters. Survey only the electricity (Current Cost, 2011)

EXPERIMENTAL PART

5. Model description

The model developed in this work has been built in the MatLab/Simulink Environment. It integrates different parts of the building from energy production systems to energy consumption specifications.

The model integrates a detached house that can be located geographically by its latitude and longitude. The type of user, aiming to characterize the user response, can be set from *Green* to *Brown* users. The number of inhabitants may vary from 1 to 6 as well as the number of bedrooms in the house. The building automatically integrates a bathroom, living room and a kitchen in addition to the bedrooms. A choice of appliances is given and integrates twenty one appliances from radio to sauna. The type of bulbs used in the building are either incandescent or low consumption. For each appliance, its power rating can be selected. Finally, a metering system must be defined which will set the frame for handling the energy flux depending on the energy consumption and the energy price.

The model uses climatic data of Oulu, obtained from free licensed climatic data website and the Finnish Meteorological Institute.

5.1 Scenarios

Different scenarios are drawn to describe a set of behaviours and architectures for the three types of building (SMEs, Dwellings, apartments' building). The first set of scenarios described will set the architecture of the smart building. Five case scenarios are described between section 5.1.1 and section 5.1.2 which covers the retrofitting buildings and buildings that will be built in the coming years. Practical issues, such as the need of inverters to transform the electric signal from DC to AC, are not considered in the following scenarios.

Table 4 summarizes the different smart systems architecture

Table 4. Smart houses matrix

[a)] Optional energy production. This is house dependent. By Law, those buildings do not have the obligation to install energy production. Possible obligation may happen in future legislations when renovating those buildings.

[b)] Optional energy production in case of passive houses (PH). Nearly-zero energy building (NZEB) do not have nay obligation either but in order to be near zero, it is foreseen that those buildings, as well as positive energy buildings (PEB) will have to install (an) energy production system(s).

	Information Flux								
Case	Energy production → the house or grid	Energy production → the smart meter	House → the smart meter	Smart meter → the grid	Smart meter → HMI	Smart meter → smart meter	HMI → House	Grid → the house	Grid → the smart meter
Existing Building with single output -> Overall electricity consumption	-	The energy flow goes through the smart meter before being dol to the grid	Overall energy consumption and production	Overall energy consumption; Overall energy production. Monthly sample	-	-	-	Instant consumption via internet	-
	a); Energy directly used in the house	-	Overall energy consumption	Overall energy consumption. Monthly sample	-	-	-	Instant consumption via internet	-
	a); Energy directly sold to the grid	-	Overall energy consumption	Overall energy consumption. Monthly sample	-	-	-	Instant consumption via internet	-
Existing Building with single output -> Overall electricity consumption	-	a); The energy produced goes first to the smart meters allowing a direct reading before integrating the grid	Overall energy consumption	Overall energy consumption; Overall energy production. Monthly sample	Electricity price from the grid; Instantaneous overall consumption	-	Graphical energy price variation; Instantaneous consumption; Advise on the best time to switch on/off high consumption devices; Warn if consumption is high while the electricity price is high; General feedbacks (Billing services)	-	Instantaneous electricity price; 24h electricity forecasted prices
Existing Building with multiple output (appliances or Zone)	-	a); The energy produced goes first to the smart meters allowing a direct reading before integrating the grid	The energy consumption is read by appliances via "smart plugs" or by zone (2 or more zones within the building)	Overall energy consumption; Overall energy production. Monthly sample	Electricity price from the grid; Instantaneous consumption by zone or by appliances	-	Graphical energy price variation; Instantaneous consumption; Advise on the best time to switch on/off high consumption devices; Warn if consumption is high while the electricity price is high per zone; Warn on which zone the energy consumption is high → allows identifying the high energy device running; General feedbacks (Billing services)	-	Instantaneous electricity price; 24h electricity forecasted prices
PH or PEB or NZEB with multiple output -> Global Electrical consumption, Global energy production	-	b); The energy produced goes first to the smart meters allowing a direct reading before integrating the grid	Overall energy consumption	Overall energy consumption; Overall energy production. Monthly sample	Electricity price from the grid; Instantaneous overall consumption	Exchange of climatic data; Average a delimited zone energy consumption for comparison.	Graphical energy price variation; Instantaneous consumption; Advise on the best time to switch on/off high consumption devices; Warn if consumption is high while the electricity price is high per zone; Warn on which zone the energy consumption is high → allows identifying the high energy device running; General feedbacks (Billing services)	-	Instantaneous electricity price; 24h electricity forecasted prices
PH or PEB or NZEB with multiple output -> Electrical consumption by zone or by appliances, Energy production by type of energy	-	b); The energy produced goes first to the smart meters allowing a direct reading before integrating the grid	The energy consumption is read by appliances via "smart plugs" or by zone (2 or more zones within the building)	Overall energy consumption; Overall energy production. Monthly sample	Electricity price from the grid; Instantaneous consumption by zone or by appliances	Exchange of climatic data; Average a delimited zone energy consumption for comparison.	Graphical energy price variation; Instantaneous consumption; Advise on the best time to switch on/off high consumption devices; Warn if consumption is high while the electricity price is high per zone; Warn on which zone the energy consumption is high → allows identifying the high energy device running; General feedbacks (Billing services)	-	Instantaneous electricity price; 24h electricity forecasted prices

5.1.1 Smart systems in existing buildings

Two different smart system architectures can be described for existing buildings depending on the structure of the building. The first case represents existing buildings which are not controlled. The buildings are connected to the grid to which energy production systems can be added (Figure 3, Figure 4 and Figure 5). The second case is grid-dependent meaning that those buildings will appear only if the grid evolvement includes the exchange of data feature (Figure 6).

Scenario 1 - the present Finnish case

Figure 3 presents the present situation of Finland where it is possible to implement on-site energy production systems but it is not possible to sell it to the grid for small scale energy production according to the Finnish legislation (see section 2.2.2) (1396/2010, 2010). Therefore, all the energy production must be consumed on site by the owners. The energy is thus going directly into the building, used on site, and information about the consumption is retrieved to the smart meter that is able to send all consumption information to the grid. The grid has then different possibilities for processing the data. First of all, the grid informs the energy operators remotely for calculating the electrical bill. Secondly, the data set can be made available to end user by the energy providers. The energy operator needs to store the data in a computing centre and use cloud computing technology to handle the data. Then, the energy operators have the possibility to make the data accessible to the end-users through an internet interface which is user related. Each user is able to survey their consumption remotely from a computer or a phone that has an internet connection.

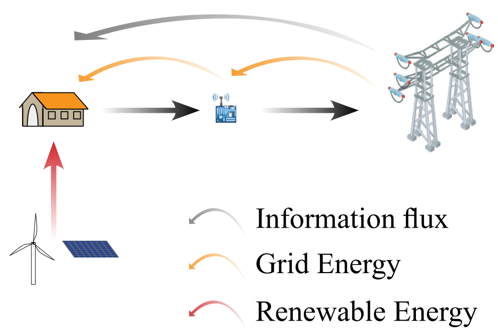


Figure 3. Scenario 1: A Finnish smart house today

Scenario 2 - A general European case scenario

Figure 4 is very similar to the previous case. The difference stands in the energy flux. In case an energy production system is added up to the building, it does not go through the house but is sold to the grid at a fixed price, also called the feed-in tariff. The user is not equipped with a smart meter that is able to control the energy flow coming in and out but it only reads the energy consumption of the house. Similarly to the previous case, the energy operators have the possibility to make data available for the end user through an internet interface or data can be confined within the building. The householders are able to read their energy production via a deported reading system that is not connected to the smart meter.

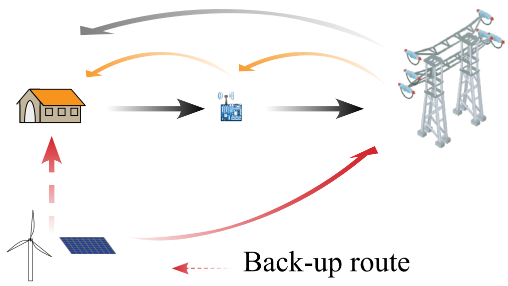


Figure 4. Scenario 2: A general European case

Scenario 3 - Simple evolution of the European scenario

Another type of architecture is presented in Figure 5 where the smart meter is able to survey the energy flow from the dwelling to the grid and vice versa. In the three cases presented above, smart meters have the possibility to return an instantaneous response of the end user bill as an indication using a Human-Machine Interface (HMI) as a data notifier (also called In-Home Displays IHD or Real-Time Monitors RTM).

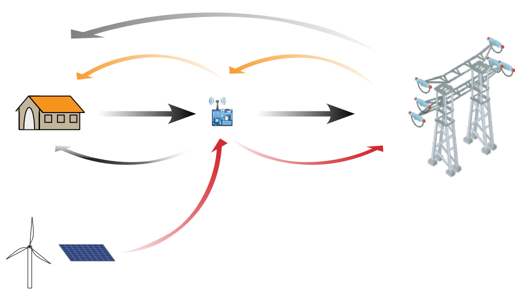


Figure 5. Scenario 3: A simple European case evolution

Scenario 4 - Advanced evolution of the European scenario

A smart meter evolution (Figure 6) is thought to exchange more data with the grid and the building. Comparably to some of the previous meters, this evolution is able to analyse the energy flux between the building and the grid. However, the smart meter stands as the only interface between the building and the grid and is able to control the flux of information and energy in this configuration. More options are added up to the previous technological version. In this new structure, smart meters are able to send data to the grid (and to the energy operators) and inform of the energy consumption and the energy production of the building. Nonetheless, they have also the possibility to receive information from the grid such as the instantaneous electricity price and the 24 hours forecasted prices in case an hourly pricing is put in place. Two types of construction are considered in this structure: the first one suppose no distinction in the energy consumption. The energy consumption information arrives as one consistent pack to the smart meter that is able to process it to send instructions to the grid and to the house via its HMI. The HMI is able to retrieve graphical energy price variation, the instantaneous global energy consumption of the house and may advise what sort of devices may be switched off in case of high consumption when the market price is high or when the power used is going to reach the technical limit. The second one enables the detection of the so called "smart plugs" in case of renovation of the existing building. In addition of reading specific plugs such as the oven plug, the washing machine plug or the sauna plug, this system is able to detect any plugs within a building. This feature allows the reading of the electricity consumption for a specific device and give the advantage to have a precise knowledge about the source of electricity consumption and electrical leakage in case of an over-consumption of any appliances.

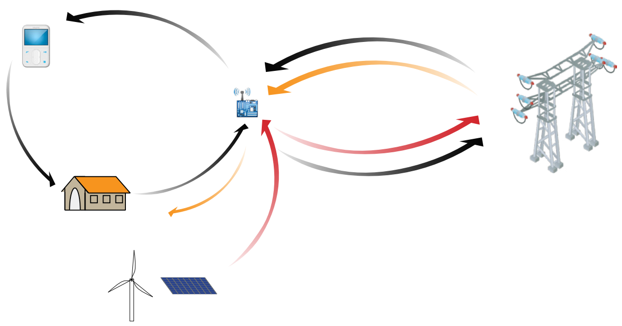


Figure 6. Scenario 4: An advanced European case evolution

In all the cases presented above, the energy operators should have access to the smart meter's core in order to update the processor or upgrade it to the next generation of smart meter.

5.1.2 Smart systems in tomorrow's buildings

Smart systems in tomorrow's buildings will consist of handling the energy flow to and from the grid. It is somehow similar to the systems described in the previous section except that smart meters are able to communicate between each other. The information exchanged between smart meters can be various: from home independent data such as climatic data that are recorded from the power production installed, to home dependent data such as the energy production and the energy consumption that can be displayed as percentages. On one hand, retrieving information for building up a competition between similar buildings would result in a decrease in the energy consumption (Ehrhardt-Martinez, 2011). On the other hand, such information should not reveal the identity of a particular consumer but should be an average energy consumption of the similar buildings. Thus, a building would be able to know if it is overconsuming comparing to other buildings with a similar architecture and could also compare the different appliances that would help to find out which machine makes the difference in plus or minus.

Another aspect of tomorrow's smart house lays in the control of the house rather by the smart system if it is preset as such or by the building owner by default. In the default configuration, the smart meter is able to read the consumption of each appliance and communicate through the HMI. In case of an overconsumption or any other alert such as high price on the electricity market, the user is able to remotely control some devices. Security control would prevent switching off necessary devices such as freezer which cannot be switched on and off regularly. Other devices that have their own control system such as the energy production devices (heat pump, gas burner, electric heaters, etc.) are not directly controlled by the user. The user can adjust variables manually and the information is sent to the devices. The devices receiving the information will then control the heat flux. In the case of controlling the electricity flux, gas burner can be put aside for a moment. The information language used should be harmonized to enable a communication between the smart meter and the different devices that have their own language and depend on manufacturer preferences. Thus, the smart meter is able to replace the existing HMI for the basic command but the existing HMI should still be in place because a wide panel of information are dependent on the device and the manufacturers, each of them offering different advanced control on their machine (especially for technical maintenance).

So far, heating systems are controlled by temperature sensors which regulate the water flow or the air flow within the heating system to maintain a constant temperature within the building. In tomorrow's smart buildings, temperature settings will not be fixed anymore but can be adjusted considering the price of the energy on the network. For instance, a temperature set at 21°C can be adjusted to 19°C when the electricity price is high for a certain time and when the electrical or heat (in case of district heating) network come back to a normal load, the setting points returns to 21°C. This setting point can be manually adjusted by the user but requires an active role which may not necessarily be the most current case, semi-automatic adjustment when the end-user addresses predefined setting points in the control system or automatic adjustment where the control system take the lead on defining the setting point temperature. A similar approach can be drawn for the district heating network. Figure 7 illustrates that future buildings' architecture will have interconnection, in order to work with other infrastructures. It can be noticed that the smart meter plays a central role in the energy/information/control flux. So far, Internet communication system was used to retrieve all the information to the In-Home Display. In tomorrow's building, only a certain amount of information could be retrieved via internet to the energy operators. Data are confined within the smart meter and only preset data can reach the energy providers. The other part of the data integrates a closed loop between the building and the smart meter. It implies that the smart meter is able to process all the data and thus integrates a processor with a trashing system to optimise the data processing speed as well as the size of the processor and its internal memory.

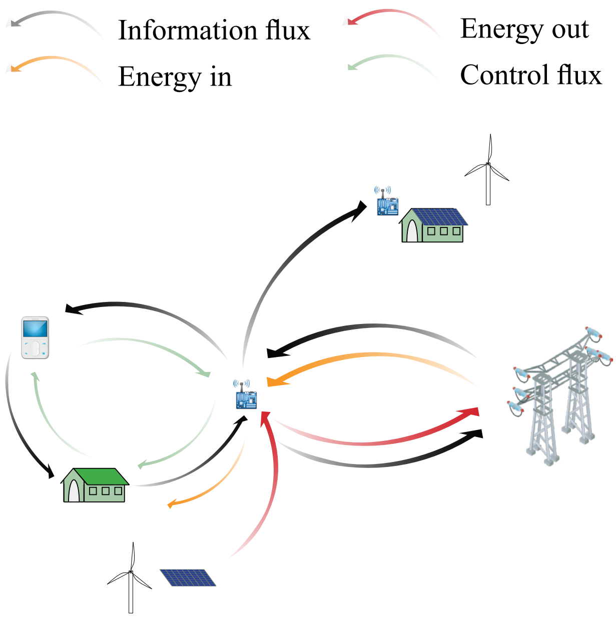


Figure 7. Smart system in future buildings - an Energy and Information flow schematic

Home dependent data are controversial considering the data privacy of the consumers (see section 4.3). In this work, two communication means are going to be used: communication inside the building (smart meter to In-Home display, and vice versa and smart meters to devices) and communication with the grid. In the first case, the information does not get out of the building but stays inside and can be passed through a hard wire system (PLC) or remotely via radio wave, Bluetooth or internal network (see section 4.2.1) depending on the preferences of the customer. Using this method, sensitive information circulates in the building without being transferred outside. Considering the communication with the grid, it can use the internet network or the mobile phone network as it is in place at the moment. Internet secured access would allow retrieving the monthly energy data for establishing the bill and archiving the data because the bill itself can be generated from the real-time pricing and the energy consumption. However, both parties should agree on the price to paid for every month and thus cross-checking the data. Detailed information can be found in the next section.

5.2 Smart meters

The smart meter developed in the model is a two-way communication device that integrates two types of control systems: an energy related control system and an energy price control. As long as the control system acts only on the electric part of the building, it is complicated for the control system to take over the decision of the owners although appliances such as the washing machine and the dishwasher use could be delayed to the time slot where the energy is cheaper or the energy demand on the network is low. The smart meter can receive data from the local neighbourhood that will be used for inter-comparison. It can receive price information from the grid for the instant price but also the forecasted price for the next 24 hours that enhances the energy planning for the next day. The latest functionality of the smart meter can work only in the case of a dynamic electric grid where price is adapted according to the technical limit met by the power network. The logic of the model integrates the user response depending on the acceptability of doing an action or not and depending on the user type from brown to green, low positive response and high positive response respectively. The user type may affect the time of use of an appliance or delay an action to a more appropriate time (energy or financially related).

This section investigates the control system modelled and highlights the algorithm used for setting up targets that influence the user response. Input and output data to the control system are detailed. Finally, a method for creating an hourly pricing system based on the spot market price is introduced as well as the algorithm to take into account the hourly pricing system in the controller is presented.

5.2.1 Control system

The control system integrates the price system and the energy systems. Both combine an automatic control over a given appliance and an indirect control modelled by the user response, which can be:

- Self comparison based on historical data;

- Inter-comparison based on mean energy values of the neighbourhood, and

- Target based logic.

The user response is directly dependent on the user type which is divided into three categories: green, orange and brown users.

User category

Three categories of users can be found in the model. They are characterized by colour type, whereas the “green” user is the most respondent, the “orange” user has an average response and the “brown” user has a low positive response to changes. As a 100 % positive response for an action is highly improbable, 70 %, 50 % and 30 % positive responses have been selected for the respected categories mentioned earlier.

The reduction of the time of use of an appliance is also dependent on the user category. A device can see its time of use decreasing by 15 %, 10 % or 5 % for the above mentioned user categories.

Self-Comparison

The self-comparison system evaluates the mean energy consumption over a given period and compares it to the actual electric energy consumption over the same period. Depending on where the real energy consumption is located compared to the mean energy consumption, user response will vary.

Four time periods were chosen to be compared: Weekdays, Week, Month and Year.

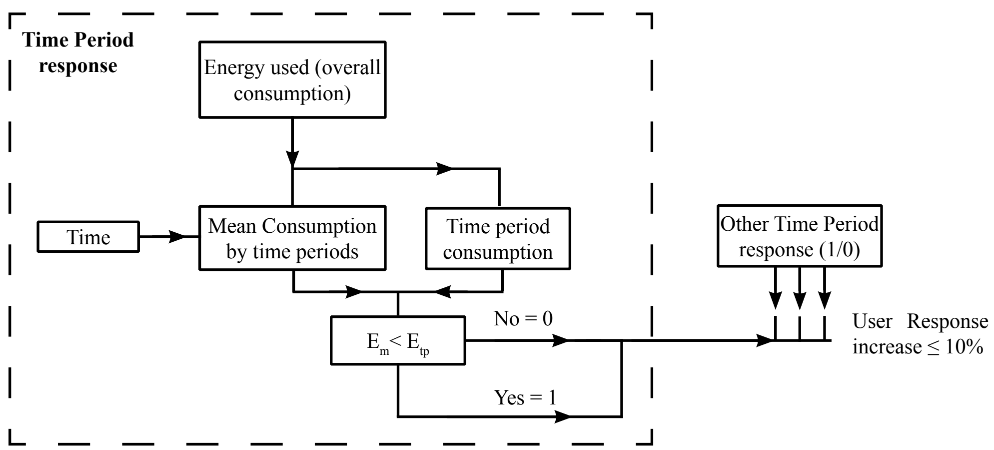


Figure 8. Self-Comparison logic diagram

For each time period, a 1/0 output is provided depending on the correlation between the mean and the real value. By combining the four time periods, the user acceptance may gradually increase up to 10 %. Figure 17 represent the logic diagram for modelling the self comparison control system.

I*nter-comparison*

The inter-comparison control system needs an outside input. This input may come from a specific neighbour. However, a mean value of the neighbourhood should be taken in this case in order to avoid conflicts (see section 4.1). Other strategies may be used such as a comparison between building types, family type, etc.

A monthly time period has been selected as a base. The user response increases when 120 % of the monthly mean energy consumption of a given building goes over the comparative value. The value of 120 % has been arbitrarily chosen for taking into account an inaction of the user in the range of 100 % to 120 %. When the comparison becomes true, the user response increase by 10 %.

Target control

The target controller influence the user response by setting targets for lowering the overall building energy consumption. Targets are set by the controller itself and are based on the mean energy consumption of a specific day in the week. The primary strategy was to influence the user response based on the energy consumed over a whole day, meaning that the user response may be influenced only at the end of the day when the cumulated energy consumption over the day gets close to the mean value.

Thus, a second strategy has been adopted by using a percentage (δ_{Eh}) of the cumulated hourly energy used compared to the mean daily energy consumption (equation (1) and (2)). This percentage differs from the time of the day as a percentage (δ_h) where a gradual decrease of a 10 % excess is applied for allowing the user a certain flexibility over the day.

$$\delta_{E_h} = \frac{\mu_0 \times \overline{E_{wd}}}{\sum_0^h E_{overall}} \tag{1}$$

For $0 < n \leq 24$,

$$\delta_{h_n} = \frac{stp}{24} \cdot n \times \left[1.1 - \frac{stp}{240} \cdot n\right] \tag{2}$$

Where, μ_0 is the daily limit [%], $\overline{E_{wd}}$ is the mean energy consumption for a given day [kWh], $E_{overall}$ is the cumulated overall energy over the day [kWh], stp is the time step [-] and x is the step during the day [-].

δ_{Eh} and δ_{hn} are then compared. The comparison influences the user response at each step and evaluate the target to be set for the next same day in the week. The model considers that when the previous target (μ) has been achieved, a lower (-2.5 %) target for the next week must be met whilst a higher (-5 %) decrease of the energy consumption is excepted if the target point is not reached. Figure 9 represents this decrease compare to a linear limit represented by stp/24.

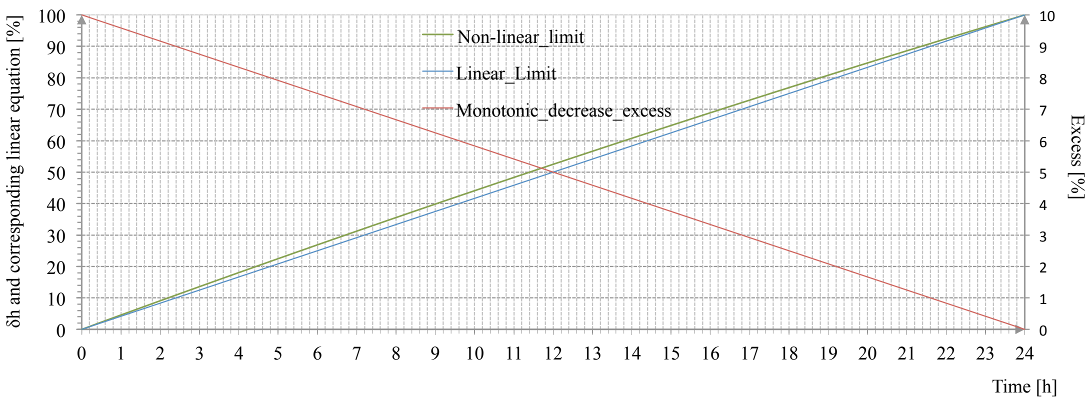


Figure 9. Progressive target limit δ_h over a day

Figure 10 illustrates the logic diagram for modelling the target control system. The comparison between the two percentage value influence the user response by 10 % depending if the targets is being reached or if the consumption at a given step is higher than the expected target.

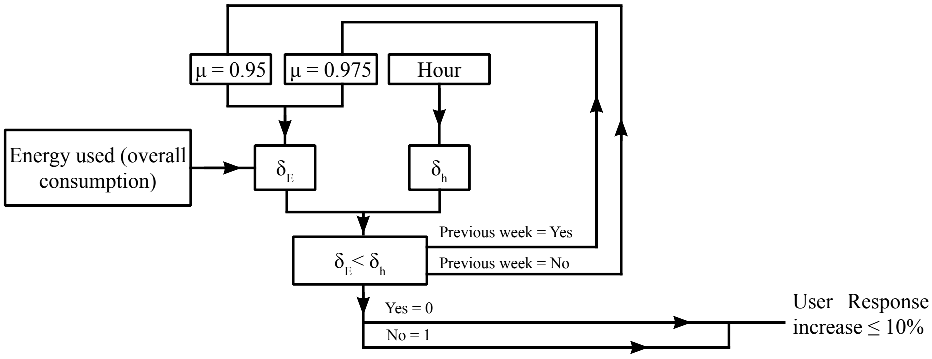


Figure 10. Target system logic diagram

5.2.2 Input data

The input data required for running the controller are listed in Table 5.

Table 5. List of the input data for the controller

Control system	Input Data
Self Comparison	- Time (hour, week number, weekday, month year) - Appliance consumption
Inter-Comparison	- Mean monthly energy consumption - Comparative value (from a neighbour or the neighbourhood)
Target	- Mean weekly energy consumption - Time (hour)

It can be seen that five input are necessary to run statistics and achieve the targets mentioned in section 5.1.1. In order to achieve the inter-comparison target, it is necessary to have access to a comparative value from the neighbour, which implies that smart meters are able to communicate between each other within a given area. In case a cloud computing system is operating, it will be possible to integrate a function that reads the type of detached house (by year of construction, surface, number of inhabitants, location) that is able to compare the “Comparative value” from other location within a municipality.

5.2.3 Output data

The output data are variables that are stored within the smart meter and will be used for evaluating the three control system options. Table 6 summarizes the different output depending on the control system employed.

Table 6. List of the output data for the controller

Control system	Output Data
Self Comparison	- Mean activity of the previous day in the week - Mean weekly activity - Mean monthly activity - Mean yearly activity - User response
Inter-Comparison	- Binary output
Target	- Binary output

The "self comparison" control system produces the most valuable output for enabling the "inter-comparison" and "target" control system. The "inter comparison" and "target" control system output a binary signal that indicates if the goals were achieved or not and both need the "self comparison" control system in order to perform their objectives. They can be retrieved to the end user by using a feedback strategy using a colour index.

5.2.4 Pricing system

In the model, the current pricing system established of Oulun Energia is used. Table 7 summarizes the contracts offered by Oulun Energia (Oulun Energia, 2012)

Table 7. Oulun Energia electricity price by contract type

	Varmavirta	Vihreävirta	Tuulivirta
Winter/Weekday - 7-22 h	7.21 € cent	7.36 € cent	7.51 € cent
Winter/Weekend - 7-22 h	6.58 € cent	6.73 € cent	6.88 € cent
Winter/WE\WD - 22-7 h for both	6.58 € cent	6.73 € cent	6.88 € cent
Summer/Weekday - 7-22 h	6.86 € cent	7.01 € cent	7.16 € cent
Summer/WE\WD - All the time\22-7 h	6.30 € cent	6.45 € cent	6.60 € cent

The model allows choosing one of the contracts that is possible to get from the energy provider. It represents the primary approach to integrate the economical aspect of having a smart house. However, limitation arises quickly because there is no flexibility in the pricing system. A real-time pricing system applied to the Nordic countries has been introduced by Kopsakangas-Savolainen and Svento (2012), however a price vector needed to the model was missing. Therefore, a tool to create a vector for a "real-time" pricing (on an hourly basis) has been developed. The calculation is based on the grid market price where hourly selling (S_p) and purchasing (P_p) price is available at the network level. Data are handled by Fingrid.

To evaluate what would be the potential hourly price at the dwelling level, historical data about the electricity price (DH_{pm}) have been used (EMV, 2012) by distinguishing the building type. Ten different building architectures are defined where three "single house" categories are differentiated. Equations (3) and (4) are used to link the market price and the electricity price at the building level to draw an hourly vector of electricity price for purchasing and selling. A plot illustrating the variation of P_{DH} throughout a 12 months period is available in APPENDIX F.

$$P_{DH} = DH_{pm} \times \frac{Max(10; P_p)}{\overline{P_{pm}}} \tag{3}$$

Similarly, the selling price S_{DH} is calculated as

$$S_{DH} = DH_{pm} \times \frac{Max(10; S_p)}{\overline{S_{pm}}} \tag{4}$$

Where, P_{DH} is the hourly electricity purchase price of a detached house [€ cent/kWh], $\overline{P_{pm}}$ is the mean monthly purchasing price at the network level [€/MWh], P_p is the hourly purchasing price at the network level [€/MWh], DH_{pm} is the monthly purchasing price at the building level [€ cent/kWh]. The constant 10 is added for setting the minimum purchase price at 10 €/MWh because the data contain negative values for some hours, meaning that people were paid to use electricity.

This method allows calculating a purchasing price for every hour, based on the historical price data at the network level. This method can be used at the building level and find its usefulness in a direct, dynamic and simple way to provide a price vector. However, this method sees its limits at the grid level when speaking about smart grid because the grid price would evolve with the electric flow. In case the grid is able to read the energy consumption of a house or a given location instantly, it would be possible to influence the end-user by changing drastically the price of electricity on a given period. This period may vary from building to building and is handled by the grid in order to reduce the peak consumption. For modelling such behaviour, it is necessary to have a set of buildings connected in a micro grid. Although the model could already integrate such architecture, the iterative model for integrating price variation at the grid level does not exist. Thus, the method used in the model does not influence the grid price while, when studying a smart grid, the influence of building energy consumption will influence the grid price.

5.2.5 Hourly pricing delay control

Having an hourly time pricing system allows delaying an action to a given time of the day where the price is the cheapest. The algorithm works with the forecasted pricing system of the next day. In order to avoid low price peak followed by a high price peak that would have a negative impact on the bill, a three hours time slot is selected to evaluate the most appropriate time slot over. Equation (5) is used to calculate any three hours time slot:

$$P_{sl} = P_{for-t+22} + P_{for-t+23} + P_{for-t+24} \tag{5}$$

Where P_{sl} is the time slot cumulated price [€ cent] and $P_{for\text{-}t+n}$ are the forecasted prices at different hours [€ cent].

Two time slots are evaluated, the first one covers the first half of the day (from 0 am to 11 am) and the second the other half of the day (from 12 am to 11 pm). In other words, a three hour time slot is elected for each half of the day. Once the three hour time slot is evaluated, the actions are delayed to occur during this time slot.

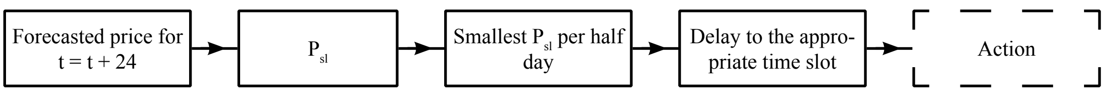


Figure 11. Hourly pricing system, delay logic diagram

5.3 Climatic Data

Climatic data collection has been done through several stages, and half hourly vectors have been drawn for wind speed, outside temperature, wind direction, atmospheric pressure and relative humidity of the air. Data were collected from Weather Underground (World meteorological data database, 1995) website for the period starting from January 2000 to March 2012. Data are plotted in Figure 30 and Figure 31 available in APPENDIX B.

The climatic data have been processed to assess data quality. There were missing data especially in the early years. An algorithm was built and interpolated linearly the climatic value when no more than 6 hours in a row were missing. If more values were missing, a mean affine equation between two half hour data was calculated taking the year before and the year after the reference year and was applied to the reference year to create the missing data and having a general variation trend from the year framing the reference year, using equation (6)

$$y_{year-n} = \left(\frac{a_{year-n+1} + a_{year-n-1}}{2}\right) \times x + \left(\frac{b_{year-n+1} + b_{year-n-1}}{2}\right) \tag{6}$$

Where a is the first coefficient of the affine equation and b the second coefficient.

This method was applied to the entire February of the year 2002 and few days throughout the dataset.

Solar radiation data were collected on an hourly basis from the Finnish Meteorological Institute and preprocessed by them for Revonlahti (2003 - 2012) and Vihreäsaari (2006 - 2012). Few hours were found missing and needed to be added in order to have a monotonic vector. Since it was only few hours throughout the entire period and never more than 4 hours in a row, the same method as described before was applied extrapolating from the days before and after. Solar radiation data are plotted in Figure 32, available in APPENDIX B.

5.4 Energy production systems

Small scale energy systems can be implemented in every building depending on the energy need of each building. Renewable energy is dependent on its surrounding environment, such as wind power depends on wind availability, solar power will depend on solar availability. This section introduces the different types of energy that could be used in dwelling, apartment building and SMEs (Small and Medium-Sized Enterprise) as well as the different techniques to produce domestic hot water (DHW) within a building. An introduction to the different energy sources is already available (Caló, 2011) for wind power, solar power and its physics but excluding the thermal solar energy and bio-energy which does not require to be repeated in this work. Thus, only the logic diagram used in the model is given for those energy production systems.

5.4.1 Wind power

Small-scale wind turbine may have different scales but the definition of the British Wind Energy Association will be given: small-scale wind turbine has a power rated from 0 - 100 kW spread in Micro Wind 0 - 1,5 kW, Small Wind 1,5 - 15 kW and Small Medium Wind 15 - 100 kW (BWEA, 2011).

The model developed in this work is a modified version of an existing wind turbine block developed by MatLab/Simulink (MathWorks, 2012a). By adjusting the characteristics of the wind turbine such as the pitch angle of the blade, the wind turbine efficiency as well as the cut in wind speed, it creates the power profile for a wind turbine as shown in Figure 12.

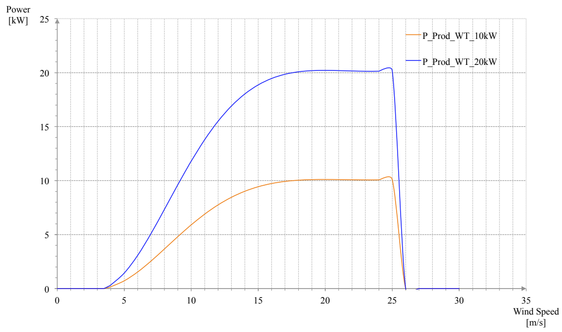


Figure 12. Modelled wind turbine power profile

The wind turbine model does not produce energy from 0 m/s to 3.5 m/s. Once the minimum wind speed allowing the energy production is reached, the wind turbine has an increasing output power from the interval 3.5m/s to 18 m/s. Above this limit, the energy production system limits its output power in order to maintain a proper rotational speed of the rotor that could potentially harm the rotor in case of too high speed. The limited power level is set as the nominal power of the wind turbine. Above a wind speed of 25 m/s, the wind turbine blocks the rotor in order to avoid damages from high mechanical stress. The power output above the limit wind speed is, therefore, 0.

Figure 13 illustrates the energy production of a 10 kW wind turbine over 8 years (2004 to 2011). Although a seasonal variation is hardly noticeable, an average production of 26 000 kWh/yr is expected to be delivered from a 10 kW wind turbine which represent an efficiency of approximately 30 % at the nominal power.

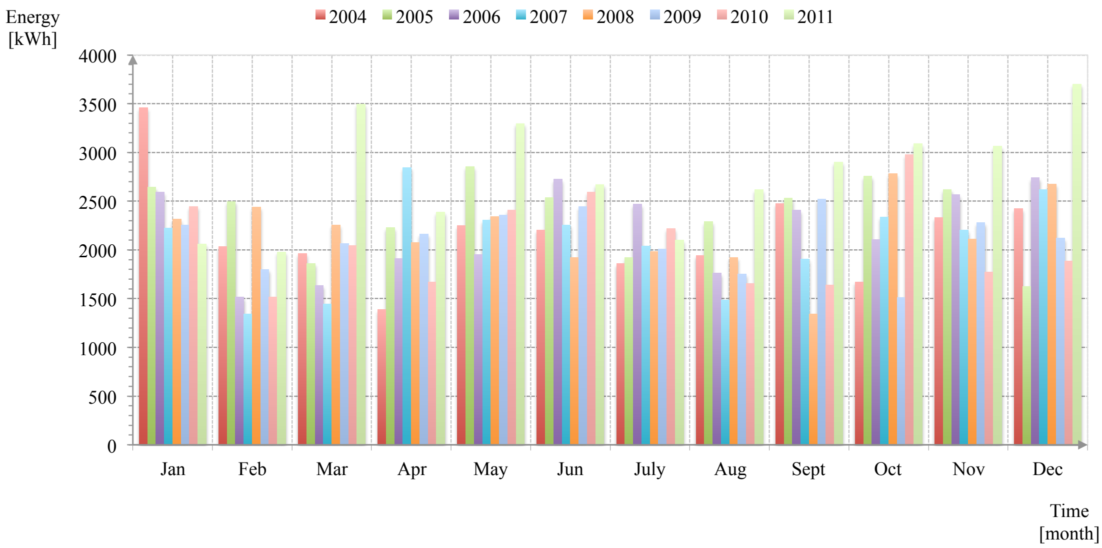


Figure 13. Monthly energy production of the modelled wind turbine

5.4.2 Solar Photovoltaic System

Solar photovoltaic system covers a wide range of technologies for inorganic solar cells (as opposed to organic solar cells defined as flexible thin film solar cells). The technology considered in this work is mono-crystalline solar cells (silicon-based). Studying the solar geometry is necessary in order to evaluate the power output coming form the photovoltaic (PV) system. Three configurations are considered in the model: fix-on-the-roof, 1-axis system and 2-axis system. These three systems are characterized by their respective aspect (orientation of the panel on a N-S axis where 0° indicates the North and 180° the South) and tilt (Orientation of the panel compared to the ground where 0° means that the panel is on the horizontal relatively to the ground). Fix-on-the-roof system has a fixed aspect and tilt throughout the simulation, 1-axis system sees its tilt angle varying with the time (relatively to the sun geometry) when its aspect stays constant and the 2-axis system has its aspect and tilt varying simultaneously in order to have the best orientation to the sun. A short introduction to the solar physics can be found in the previous study conducted by Caló (2011).

The angles used in the model are the solar azimuth (ψ_S), the solar altitude (γ_S) and the declination of the sun (δ). Symbol used are taken from (Luque et al., 2003). The solar declination is used to calculate the sunset time, the sunrise time but also the angles previously named (γ_S, ψ_S). Other variables are fundamental for calculating the direct and the diffuse components from the global irradiation e.g. The Air Mass (AM), the solar angle (ω). Knowing the sun geometry throughout the years enables the re-calculation of the solar irradiation on a given surface from the global irradiation on a horizontal surface. Solar radiation data have been collected by the Finnish Meteorological Institute since December 2003 for Revonlahti location and since August 2006 for Vihreäsaari location on an hourly basis. The data were not complete and needed to be processed for missing hours (< 0.5 % of the total 123 332 data). A model taking into consideration the performances of a solar cell has been achieved and allows the calculation of a given solar module (possibly in array) by knowing the solar cell characteristics (open circuit voltage V_{oc}, short circuit current I_{sc}, peak power of the module P_m, the length and width of the solar module, nominal operating cell temperature NOCT). The model has been built in such a way because manufacturers' data are available for most of the companies on Photon Magazine website. Photon Magazine website keeps a database of solar cell and solar module manufacturers, and the required values for the variables used in the model are available online (Photon Magazine, 2012). Characteristics by default are set for a 200 W module from ITC Innotech Solar.

To take into account the power required in the 2-Axis and 1-Axis technology, an arbitrary value of 35 W is used for running the printed circuit as well as the motor enabling the rotation of the modules.

Figure 14 shows the energy production from a 2-Axis system throughout the year 2004.

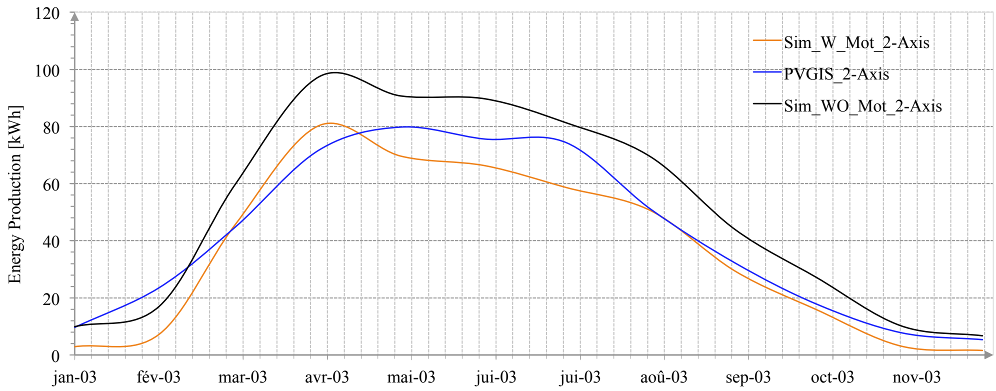


Figure 14. Energy production of a 400 W module in 2004 - PVGIS vs. Model

In order to validate the model, the energy production calculation has been carried out using the Photovoltaic Geographical Information System (PVGIS) online software. Differences can be noticed and explained by several factors. First of all, the solar radiation data used are different. While in this model, measured data from a meteorological station have been used, the PVGIS project uses average values derived from Meteosat satellite by the European Solar Radiation Atlas. The European Solar Radiation Atlas has been developed by the Ecole des Mines de Paris/Armines, Center for Energy and Processes (Helioclim, 2001)and solar radiation data can be found from the Solar Energy Services for Professionals portal (SoDa, 2004). Moreover, missing values were reprocessed in their model, thus creating more uncertainties. Secondly, the model proposed in this work uses cells efficiency by evaluating the current and the voltage depending on a particular cell specificities. In addition to this work, a cleanness index is used with a module cleaning every six months. The model proposed by the PVGIS uses an empirical equation to calculate the efficiency of a module directly which allows the calculation of the power output of a power rated module. More differences exist between those two models, however results found are following a similar trend when using the present model with a motor of 35 W and the model developed by the PVGIS.

Figure 15 illustrates the monthly production of electricity from 400 W modules in series using the proposed model.

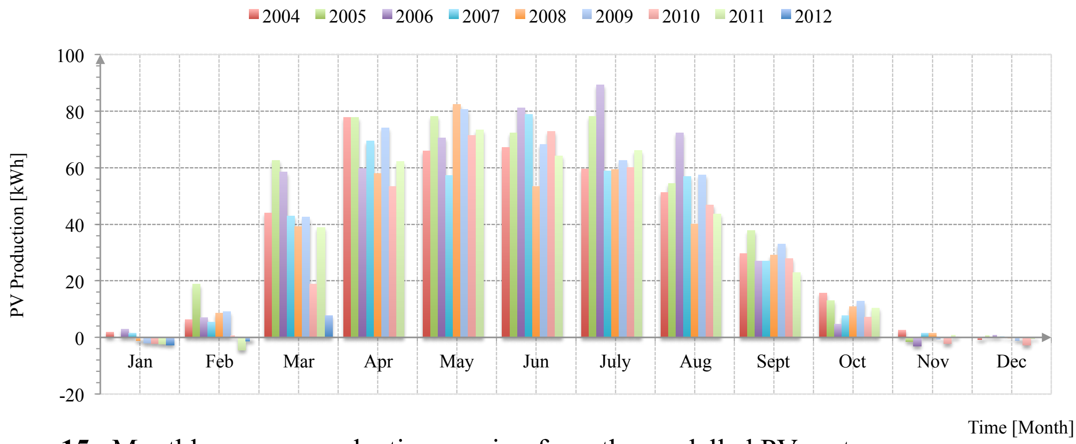


Figure 15. Monthly energy production coming from the modelled PV system

It can be seen that during the winter month, negative values appear meaning that more energy has been used for orientating the panels than the actual energy production from these panels. In case the peak power rate would have been higher (e.g. 1 kW installed), these negative values would not appear because the balance would be in favour of the energy production side.

5.4.3 Solar thermal

Three main technologies can be found on the market that enable the production of hot water: flat plate solar thermal panel, evacuated tube collector and thermodynamic solar panel (which can also be used for electricity production). Solar thermodynamic is considered as industrial technology and will not be taken into account in this thesis work and only flat plates and evacuated tubes technology are considered (Duffie and Beckman, 1980). Flat plate is considered due to its low price and simple technology enabling a widespread of solar energy and the second one for its high efficiency in cold climate (Adsten et al., 2001).

Figure 16 a illustrates the flat plate solar thermal technology which is widely used in warm and sunny climate (Kalogirou, 2004).

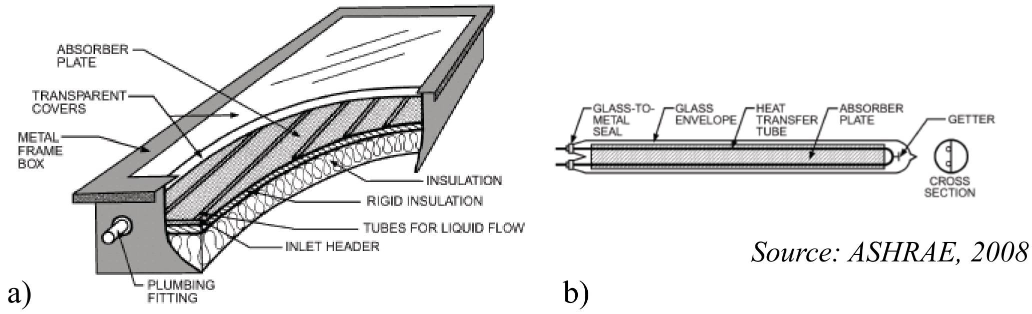


Figure 16. Solar Thermal technology a) Flat plate, b) Evacuated tube collectors

It consists of a tube on a black absorber which is insulated on the bottom and protected with a glass window on the top to avoid forced convection which could cool down the plate. A wide technological set of flat plate thermal collectors are used with different design (Kalogirou, 2004) (flexible absorber, with/without glass window, insulated/not insulated, integrated in the roof/fixed on the roof, etc...). Thus, a general case will be taken for implementing the model.

Figure 16 b presents a tube of a vacuumed tube collector. Similarly, a wide set of designs exist and a general one will be described in the model. It consists of a U-tube inserted in a glass envelop which is further sealed and air-tight (ASHRAE, 2008). It enables the sun rays to reach the water circulating in the U-Tube and insulating the water network from the outside air temperature. This technology has proved to be efficient in cold climate (Adsten et al., 2001) and drawbacks are found when used in hot climate such as high water temperature leading to high pressure and damaged material. However, this technology happens to be more expansive than the flat plate design and is considered as an advanced alternative to the flat plate technology.

5.4.4 Fuel cells

Fuel cell is an electrochemical technology using a chemical process for producing electricity. A gaseous fuel is used on one side of the fuel cell and is connected to the anode. A oxidant is used on the other side (e.g. air) connected to the cathode. In between, a membrane is used for transferring the atom while the electrons are extracted and transferred to a power load (EG&G Services Parsons Inc., 2004). Figure 17 is a schematic representation of a Proton Exchange Membrane fuel cells (PEMFC) fuel cell with its basic components.

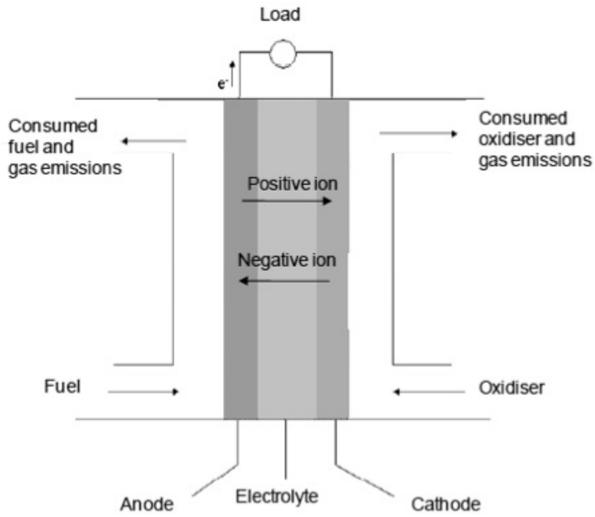


Figure 17. Fuel Cell schematic

A number of fuel cell design are available and their specificities will vary according to the material used for forming the electrolyte, the type of fuel used and the electrolyte's chemical composition.

Considering the scale of energy production in this thesis, PEMFC has been selected to be implemented in the model. A mathematical model (Larmini and Dicks, 2003) for simulating PEMFC is available in APPENDIX C. Shortly, PEMFC uses hydrogen as a fuel and air as an oxidant. The working temperature is around 65°C but varies depending on manufacturers. The PEMFC's efficiency is calculated using the higher heating value (HHV) of hydrogen combustion.

5.5 Energy Consumption

The electrical energy consumption profile of a building represents an important challenge within this work and sets the foundations for enabling the smart controller. Considering that the simulation was done on an hourly basis, the daily energy profile represents the reference for determining the accuracy of the model and will be presented in this section. The energy profile shall be flexible to integrate multiple buildings having the same characteristics e.g. Type of appliances, number of inhabitants. Thus, the work was divided into three sections:

- Flexible energy profile generation;
- Appliances function and use definition;
- Potential connection with other sources than appliances

In this model, the building does not take physically electricity from the grid but assumes that all electricity is available at the building level and generates an output as electricity consumption that can be used for further processing at the controller or the network level.

5.5.1 Appliances

Twenty-one appliances are taken into account in the model. They are split into categories which represent different zones in the building. The five zones defined in the building are:

- Kitchen area, includes: Washing Machine, Dish Washer, Hobs, Mirco-Wave, Fridge, Kettle, Coffee maker, Electric oven, Toaster and Waffle/Crêpes maker
- Living Room area, includes: Television and Stereo
- Bathroom area, includes: Shaver, Hair dryer, Electric heater and Sauna
- Bedroom area, includes: Radio, Laptop and Telephone charger
- Cleaning tools area, includes: Vacuum cleaner and Iron.

Power rating

Each appliance has three power ratings based on the European energy labelling principle. Table 8 details the power rate for the different appliances.

The greyed areas are values diverted from the EuP task reports, and highlight the mean energy consumption per year for a given appliance and a given number of working hours within a year. Three of the appliances (e.g. hobs, electric heaters and sauna) do not have varying power rating; therefore, average power has been taken into account.

Table 8. Appliances power rate set for the simulation

House zone	Appliance	A/B Category [kW]	C/D Category [kW]	E/F Category [kW]	Stb power [kW]	Use for Lighting Control
Kitchen	Washing machine	0.306	0.410	0.520	N/A	✗
	Dish Washer	0.929	1.250	1.600	N/A	✗
	Hobs		4.000		N/A	✗
	Kettle	2.000	3.000	4.000	N/A	✓
	Electric Oven	4.000	5.000	6.000	0.005	✗
	Micro-Wave	0.950	1.200	1.400	0.005	✓
	Coffee Machine	0.600	0.800	1.000	N/A	✓
	Toaster	0.800	1.300	1.600	N/A	✓
	Waffle/Crêpes	0.900	1.200	1.500	N/A	✓
	Fridge	0.300	0.400	0.600	N/A	✗
Bedroom	Radio	0.005	0.008	0.010	0.001	✗
	Laptop Active	0.060	0.080	0.120	N/A	✗
	Laptop Sleeping mode	0.003	0.005	0.010	N/A	✗
	Laptop off mode	0.002	0.003	0.006	N/A	✗
	Telephon charger	0.010	0.015	0.020	N/A	✗
Bathroom	Electric heaters		1.500		N/A	✗
	Shaver	0.010	0.015	0.020	N/A	✗
	Hair dryer	1.000	1.200	1.500	N/A	✓
	Sauna		6.000		N/A	✗
Living Room	Television	0.125	0.150	0.200	0.005	✓
	Stereo/Hi-Fi	0.080	0.100	0.120	0.001	✓
Cleaning Tools	Iron	1.000	1.300	1.500	N/A	✓
	Vaccuum cleaner	0.700	1.200	1.400	N/A	✓

Based on the European Energy Label

Regarding the hobs, usually four electric plates of different power are installed resulting in a mean nominal power for the four electric plates.

Illuminations are not mentioned in Table 8 but are also split into two categories of power rating: low consumption bulbs and incandescent bulb. The power rates are given in $W.m^{-2}$ and thus is dependent in the size of the building.

Low consumption bulbs have a power rate of 1.1 $W.m^{-2}$ and incandescent bulbs have a power rate of 6 $W.m^{-2}$ corresponding to 1 installed bulb per 10 m^2.

Household habits

Every appliance can be utilized following different patterns depending on the end-use. EuP reports detail some common trend, the average use and time of an appliance per person (Okopol, 2012). Strategy for each appliance is detailed in APPENDIX E.

5.5.2 Energy profile model

The energy profile model uses a uniformly distributed random number generation method. Uniform random number generation uses a rectangular distribution with a constant probability function distribution (MathWorks, 2012b):

$$p = F(x \mid a, b) = \frac{x-a}{b-a} I_{[a,b]}(x) \tag{7}$$

This block generates random numbers between 0 and 1 and is characterized by the seed given as an input meaning that for a given seed, the random generation number will have the same pattern.

Figure 18 presents the logic diagram for generating random number for generating an action for a given hour and a given day.

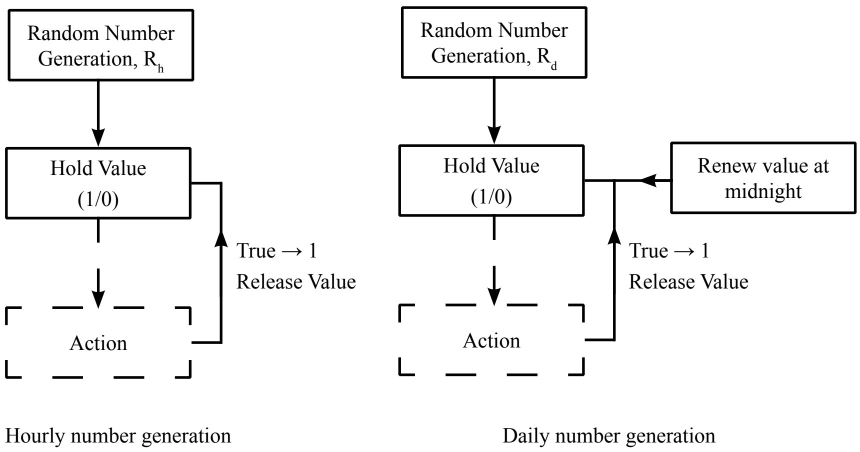


Figure 18. Random number generation logic diagram

Separate random generation determines a time and a day at which an action will occur. Regarding the hourly number generation block, at the first step, the value generated is dependent on the seed given and pass through the "hold block". At the second iteration, if an action occurred at the studied hour, the value 1 is sent to the "hold block" which release the next random number. If no action occurs, the block retains the value until an action arise. The daily number generation block has a similar logic except that it integrates the fact that the "hold block" retain a value no more than a day, meaning that at least everyday a random number is generated. This is to avoid to be on a Monday with a random number pointing out that the next action will occur during the weekend. By default, it implies that the given action cannot occur for the next five days and must reach the weekend to occur. Note that the link between the hold block and the action block is dashed because intermediary actions pop in and are explained later in this section.

Daily Action

At every time step, the hourly random number generated is sent to the hourly distribution

Table 9. Hourly distribution of appliances use for any day of the week

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Total
Washing Machine	0.5%	0.5%	1.0%	1.0%	2.0%	2.0%	3.0%	3.0%	4.0%	3.0%	3.0%	3.0%	3.0%	2.0%	2.0%	3.0%	4.0%	10.0%	12.0%	15.0%	10.0%	7.0%	4.0%	2.0%	**100.0%**
Dish Washer	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	3.0%	5.0%	5.0%	2.0%	2.0%	10.0%	10.0%	2.0%	1.0%	1.0%	5.0%	5.0%	10.0%	15.0%	15.0%	5.0%	0.5%	**100.0%**
Hobs	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	5.0%	10.0%	15.0%	3.0%	15.0%	10.0%	3.0%	1.0%	1.0%	3.0%	8.0%	11.0%	7.0%	3.0%	0.5%	0.5%	**100.0%**
Kettle	0.5%	0.5%	0.5%	0.5%	0.5%	1.0%	1.0%	8.0%	5.0%	5.0%	3.0%	3.0%	8.0%	8.0%	3.0%	2.0%	8.0%	8.0%	8.0%	9.0%	9.0%	5.0%	2.0%	1.5%	**100.0%**
Oven	1.0%	0.5%	0.5%	0.5%	1.0%	2.0%	3.0%	4.0%	8.0%	10.0%	13.5%	10.0%	6.0%	5.0%	2.0%	2.0%	4.0%	6.0%	8.0%	6.0%	3.0%	2.0%	1.0%	1.0%	**100.0%**
Micro-Wave	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	4.0%	8.0%	10.0%	8.0%	8.0%	3.0%	10.0%	8.0%	3.0%	2.0%	2.0%	2.0%	5.0%	10.0%	8.0%	3.0%	2.0%	1.0%	**100.0%**
Coffee Machine	0.5%	0.5%	0.5%	0.5%	0.5%	2.0%	5.0%	12.0%	14.5%	7.0%	1.0%	1.0%	10.0%	10.0%	3.0%	3.0%	8.0%	10.0%	5.0%	2.0%	1.0%	1.0%	1.0%	1.0%	**100.0%**
Toaster	0.5%	0.5%	0.5%	0.5%	0.5%	2.0%	8.0%	12.0%	15.0%	10.0%	5.0%	2.0%	4.0%	5.0%	5.0%	2.0%	1.0%	1.0%	6.0%	10.0%	6.0%	2.5%	0.5%	0.5%	**100.0%**
Waffle/Crêpes	0.5%	0.5%	0.5%	0.5%	0.5%	1.5%	3.0%	10.0%	12.0%	10.0%	4.0%	2.0%	1.0%	1.0%	1.0%	1.0%	2.0%	2.0%	2.0%	15.0%	12.0%	10.0%	4.0%	4.0%	**100.0%**
Fridge	an be modelled independently from the user point of view																								
Radio	1.0%	1.0%	1.0%	1.0%	3.0%	5.0%	5.0%	20.0%	20.0%	14.0%	5.0%	3.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	5.0%	5.0%	2.0%	1.0%	1.0%	**100.0%**
Laptop	1.0%	0.5%	1.0%	1.0%	1.0%	3.0%	4.0%	5.0%	7.0%	7.0%	6.0%	5.0%	7.0%	7.0%	4.0%	3.0%	3.0%	3.0%	4.0%	5.0%	7.0%	7.0%	5.0%	3.5%	**100.0%**
Electric heaters	1.0%	1.0%	1.0%	1.0%	1.0%	6.0%	15.0%	20.0%	15.0%	10.0%	5.0%	2.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	5.0%	5.0%	2.0%	2.0%	**100.0%**
Shaver	1.0%	1.0%	1.0%	1.0%	1.0%	5.0%	12.0%	15.0%	15.0%	12.0%	5.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	8.0%	6.0%	5.0%	3.0%	**100.0%**
Hair dryer	1.0%	1.0%	1.0%	1.0%	1.0%	5.0%	12.0%	15.0%	15.0%	12.0%	5.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	8.0%	6.0%	5.0%	3.0%	**100.0%**
Television	1.0%	1.0%	1.0%	1.0%	1.0%	2.0%	5.0%	8.0%	7.0%	7.0%	3.0%	2.0%	5.0%	6.0%	4.0%	1.0%	1.0%	3.0%	7.0%	10.0%	10.0%	8.0%	4.0%	2.0%	**100.0%**
Stereo	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	1.0%	4.0%	4.0%	5.0%	4.0%	3.0%	2.0%	3.0%	5.0%	5.0%	12.0%	15.0%	10.0%	8.0%	7.0%	6.0%	2.0%	1.0%	**100.0%**
Iron	0.5%	0.5%	0.5%	0.5%	0.5%	2.5%	4.0%	6.0%	8.0%	4.0%	2.0%	1.0%	1.0%	3.0%	5.0%	5.0%	8.0%	10.0%	12.0%	10.0%	8.0%	4.0%	3.0%	1.0%	**100.0%**
Vaccuum cleaner	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	4.0%	5.0%	6.0%	8.0%	6.0%	3.5%	4.0%	6.0%	8.0%	8.0%	4.0%	7.0%	8.0%	8.0%	5.0%	4.0%	2.0%	0.5%	**100.0%**
Telephon charger	4.0%	4.0%	4.0%	3.0%	3.0%	4.0%	4.0%	4.0%	2.0%	2.0%	2.0%	2.0%	1.0%	1.0%	1.0%	2.0%	2.0%	3.0%	5.0%	7.0%	10.0%	15.0%	10.0%	5.0%	**100.0%**
Sauna	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	8.5%	18.0%	23.0%	23.0%	18.0%	0.5%	0.5%	**100.0%**

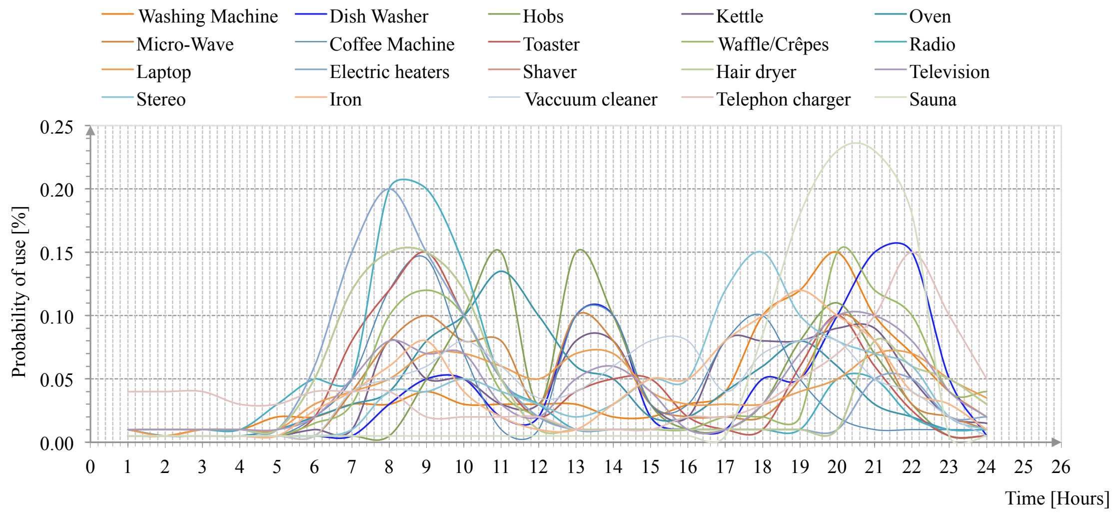


Figure 19. Hourly distribution of appliances use for any day of the week

block which defines at which time of the day an action is most probable to occur. It follows a given distribution and every appliances have their daily distribution as illustrated in Figure 19 and Table 9, except the fridge and the light (see section 5.5.3 & 5.5.4). At this stage, an action is validated only based on the probability that a given action will occur. However, certain actions cannot occur several time within a day e.g. 5 washing per day with 2 inhabitants is highly improbable to happen. Therefore, a daily limitation is set to define under different levels if:

- An action is going to happen during the weekday or the weekend (C_w), or
- An action can be repeated several times depending on the weekly average use of the given device (see APPENDIX E for the weekly average use)

These two levels generate a daily and a weekly acceptance that will validate the previously validated action.

Figure 20 represents the logic diagram that allows an action to happen at a particular time. The output value is a 1/0 signal and will be used also in the next step for calculating the energy consumption of a given device. The “Action” block has a three layer validation process. The first layer evaluates R_d with the daily allowance C_w. In case $R_d < C_w$, it means that an action is not authorized for the present day and thus the “Action” block directly output 0. On the contrary, if $R_s > C_w$, then it triggers the second layer which will look at the past activity. The second layer compares the mean activity of the previous weeks with

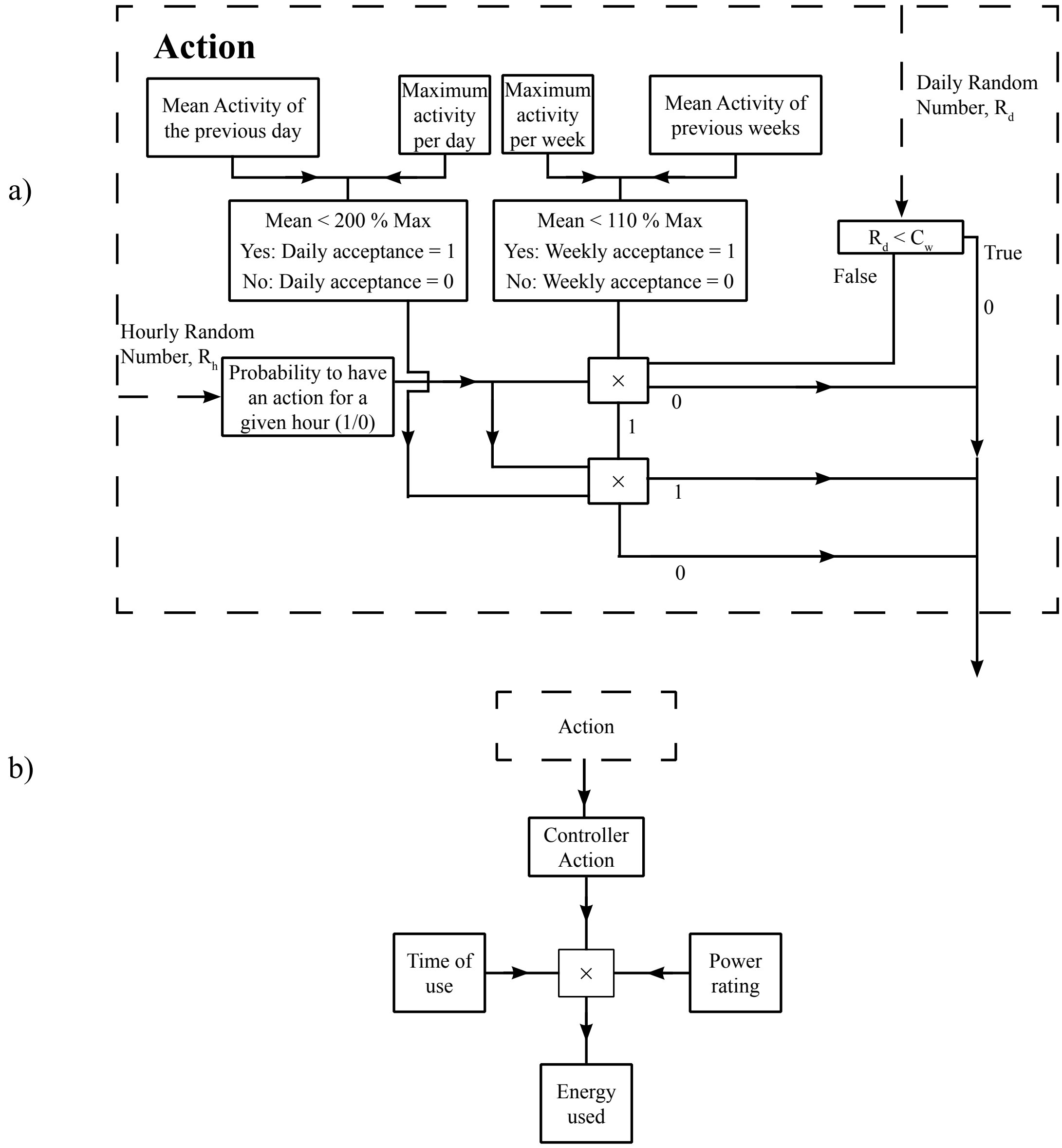


Figure 20. a) “Action” block activation logic diagram. b) From action to energy, a logic diagram

the maximum activity per week allowed (as defined in APPENDIX E). In case the average weekly activity is 1.1 times higher than the maximum allowed activity, the “Action” block will directly output a 0 signal, otherwise it will validate that an action can occur during the studied week and will look at the hourly probability that an action can take place. If for a given hour, the probability that an action appears then the “Action” block will output 0. In the second case, the third layer is activated and will look at the daily allowance. This is the final layer and validates an action for every days. This third layer prevents the fact that an actions is activated several times during the same day. At most, an action can be approved no more than two times the maximum daily allowance (based on 1/7th of the maximum weekly activities defined in APPENDIX E). In case the number of actions gets over two times the daily allowance, then the “Action” block output a 0 signal. In case the number of actions is still under the daily allowance limit, it will look at the probability that an action is confirmed for a given hour. In case the studied hour does not take the action, then the “Action” block output a 0 signal, otherwise, the “Action” block output a 1 signal. This is only from the third layer that an action can be triggered from the “Action” block.

Energy Consumption

Once the output from the stage presented above is available, the time of use of the studied appliance must be defined following the “time of use” distribution. Each appliance can be used differently, depending on the user or the user mode, which will affect the duration of use of an appliance. The distribution used for each appliance can be found in APPENDIX E. In the second time, the rated power of the device must be known. The different power rate can be found in section 5.5.1. The energy used is calculated by multiplying the three factors together. As illustrated in Figure 20, an intermediary step before the calculation of the energy used is carried out involving a controller. It involves three types of control depending on the settings chosen for the building. The controller can delay an action of several or one hour(s), and/or reduce the time of an action depending on the user response. In reality, the time reduction is not carried out by the controller but by the user himself. This point is developed in section 5.2.1.

5.5.3 Lighting model

Modelling the energy consumption used for illumination is dependent upon three main factors:

- Climatic → Natural light luminosity
- Building activity → Presence of persons in the building
- Building design → Orientation of the building, openings, natural shadows (from surrounding environment), artificial shadows (solar protections), surfaces colours etc...

Building design does not take part in the lighting model in the present simulation for practical reasons regarding the degree of specifications that it requires. However, the climate influence and the building activity are fully integrated into this model.

No measurement was made in order to calculate the natural light luminosity. However, models exist to calculate the natural light luminosity depending on the global solar irradiation. Yokoya and Shimizu (2011) use an empirical model developed by Igawa et al. (1999, 2009) that can give the natural light luminosity from the global solar radiation:

$$Evg = (8.86\Theta_{ZS} + 210.12)\,G(0)^{0.9} + \left(-10.98\Theta_{ZS}^4 + 54.16\Theta_{ZS}^3 - 102.31\Theta_{ZS}^2 + 90.21\Theta_{ZS} - 29.24\right)G(0)^{1.1} \quad (8)$$

Where Evg is the global horizontal illuminance [lux], G(0) is the global horizontal solar radiation [W/m^2] and Θ_{ZS} is the solar zenith angle [rad].

The natural luminosity range from 0 to 100 000 lux for overcasting weather knowing that an average luminosity of 300 lux is required in average for living (dependent on the type of work and the comfort conditions). Figure 21 presents the logic diagram used in the model.

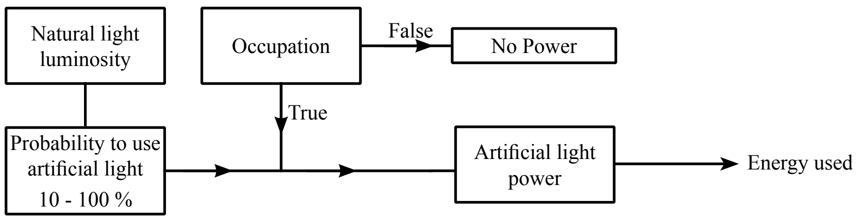


Figure 21. Lighting logic diagram

The model integrates the variable “luminosity” by comparing the natural light luminosity value with the average luminosity required for allowing light comfort. The output is a probability number between 10 % to 100 % chances of using artificial light when the building is occupied. A value of 10 % represents the probability of switching on the lights on a very clear day whereas a value of 100 % is the probability of using artificial light when the natural light is nonexistent.

The occupancy scenario is based on the use of appliances that require the active participation of the householders. The list of the appliances taken into account for defining the occupancy scenario can be found in Table 8 in section 5.5.1.

This indicates that when at least one of the above appliances is active, the building is occupied and vice versa.

Figure 22 presents the results found using such model.

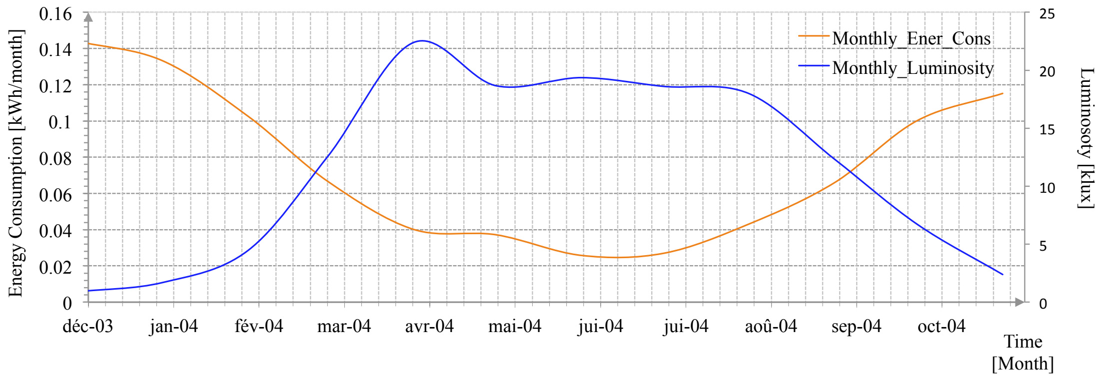


Figure 22. Energy consumption due to the use of lights compared to the outside luminosity for the year 2004

As expected, the energy consumption coming from the lighting is higher in winter than summer and follow approximately the reverse curve of the natural light luminosity.

5.5.4 Fridge model

The fridge model (Figure 23) follows a repeating pattern with a succession of two off-hours and one on-hour.

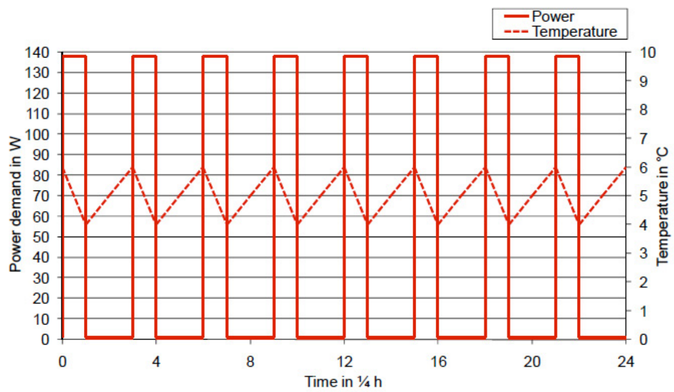


Figure 23. On/off sequence of a fridge

The model is taken from the Intelligent Energy Europe report (Stamminger and Friedrich-Wilhelms, 2008).

As mentioned in section 5.5.1, the maximum power is between 300 and 600 W, whereas a 140 W value is used in the Figure 23.

5.5.5 Overall energy consumption

After modelling all the appliances and the lighting, an overall energy consumption profile can be drawn without any specific control for a full year. As stated in the introduction, the overall energy consumption for a dwelling is around 4 237 kWh/dw/yr.

Figure 24 illustrates the energy consumption evolution throughout a 12 months period from December 2003 to December 2004.

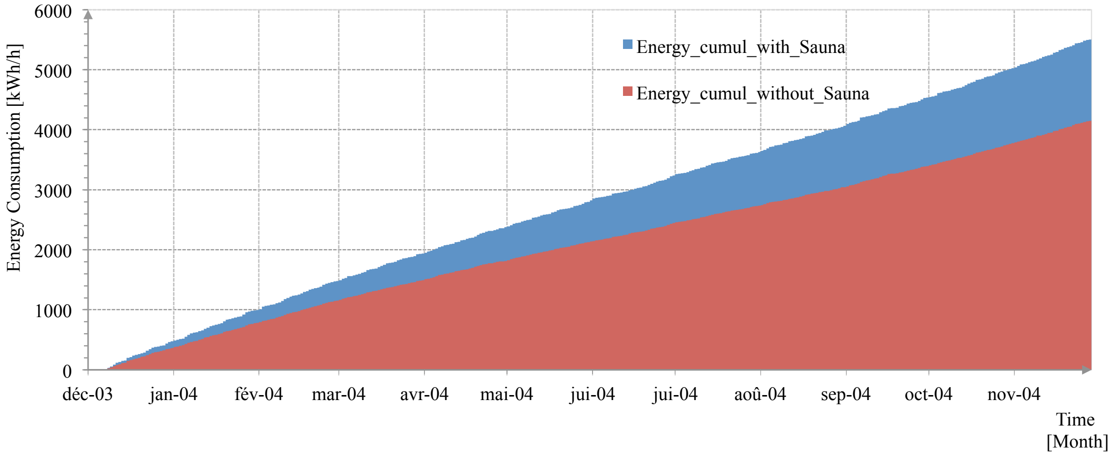


Figure 24. Cumulative energy consumption of a dwelling with and without sauna
Green User category, incandescent bulbs with and without sauna, without control system, 4 persons family with 3 bedrooms.

Two cases have been modelled using the same building characteristics and number of appliances, considering a four person dwelling, with three bedrooms with and without an electric sauna.

In case of an installed sauna, the modelled dwelling has a yearly electric consumption of 5 514 kWh/yr and the building that does not have a sauna has an overall electric consumption of 4 158 kWh/yr. It can be considered that the overall energy consumption is rather accurate and follows the general trend given in the literature seeing an average consumption of 4 836 kWh/dw/yr.

It can be noticed from Figure 24 that the energy consumption throughout a 12 months period is linearly increasing. Seasonal variation is not noticed because the model considers only the energy consumption coming from the appliances. Although it could be assumed that some end users may use more the appliances during a given season because of the increase of an activity. However, no common trend has been found in the literature showing that the electric consumption of the appliances has a seasonal variation. Thus, no differentiation has been made in the model to take into account the seasons in the weekly usage of appliances.

However, the daily energy profile needs to be accurate as well. The daily energy profile needs to be coherent regarding the model and its daily distribution. Daily distribution of the time of use of an appliance has been detailed in Figure 25, illustrating the electric energy used after using the model for the appliances and the lighting model.

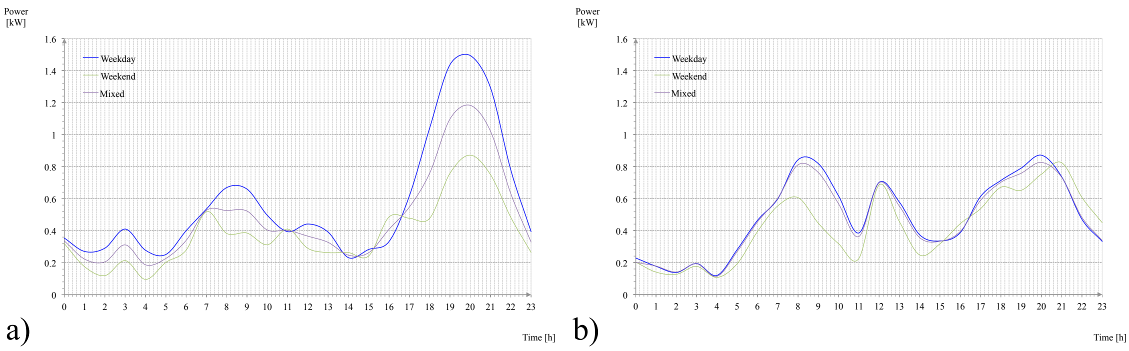


Figure 25. a) Daily mean power demand with sauna. b) Daily mean power demand without sauna

Sauna has a high influence on the daily energy distribution, as it can be seen from the peak at 19-20. The y-axis represents the energy in kWh but the plots represent mean values, thus the high peaks when using the sauna (6 kW) do not appear on the figure.

5.6 Thermal modelling

A thermal model of the building has been created but not investigated in depth. The main reason lays in limiting the scope of this work. The factors that were left out of this investigation are the solar gain, passive energy gain from the appliances and people living in the building as well as the relative humidity due to activities within the building.

Therefore, the thermal model used in this model is a simplified model of energy balance. The house is to be on one level and cannot have any shape except rectangular or squared. The tilt of the roof can be set in order to calculate the heat losses through the roof. All thermal resistance constants must be set by the user, from the windows, to the floor, door, roof on each side of the cardinal points. It would allows the calculation of the heat losses by conduction. The heat losses by convection are not taken into account. The heat losses by ventilation are calculated by using the number of air change per hour. Summing up the heat losses by conduction and the heat losses by ventilation, it is possible to have the relative heat loss value for the house expressed in W/K. This result must be multiplied step by step by the temperature difference between the room temperature and the outside temperature for a given hour. Figure 26 illustrates the hourly consumption of a 110 m^2 detached house having the thermal performance mentioned in Table 1 for 2010.

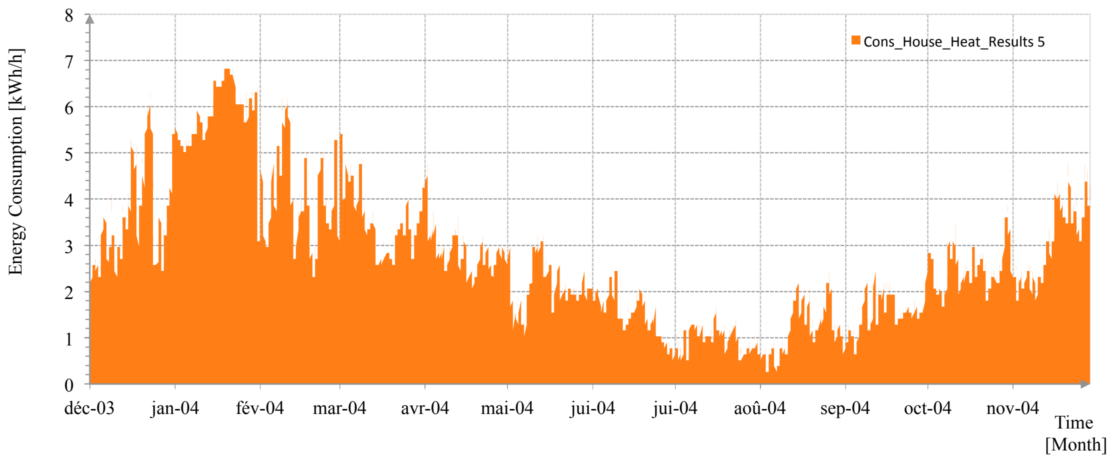


Figure 26. Thermal energy need for a 110 m^2 detached house in Oulu

The energy profile varies throughout the seasons and sees a peak consumption in February. Energy consumption occurs over the summer time because the passive solar gain is not taken into account in the calculations, resulting in a heat demand during this period. The modelled detached house has an yearly heat demand of 20 941 kWh/yr. This result can be compared with data collected from (EEII, 2012) where Finland sees its detached houses having an energy consumption of 16 979 kWh/dw/yr.

As the thermal model of the house is not considered in this study, only this simple model has been sketched.

6. Results and discussion

The results presented in this section are based on data from 2004. Results are given with their code and always having the form ***Results XX***. The description of these results can be found in APPENDIX G. All the simulations were made for a 4 persons detached house with 3 bedrooms and an hourly step simulation time.

Although the simulations provided a multitude of data, results have been selected to look at the energy consumption fluctuation, the effect of smart buildings on the daily energy profile, the influence of the smart meter, user behaviour and the impact on the electrical bill every month and at the end of year.

The Figure 27 illustrates the monthly energy consumption for 4 scenarios.

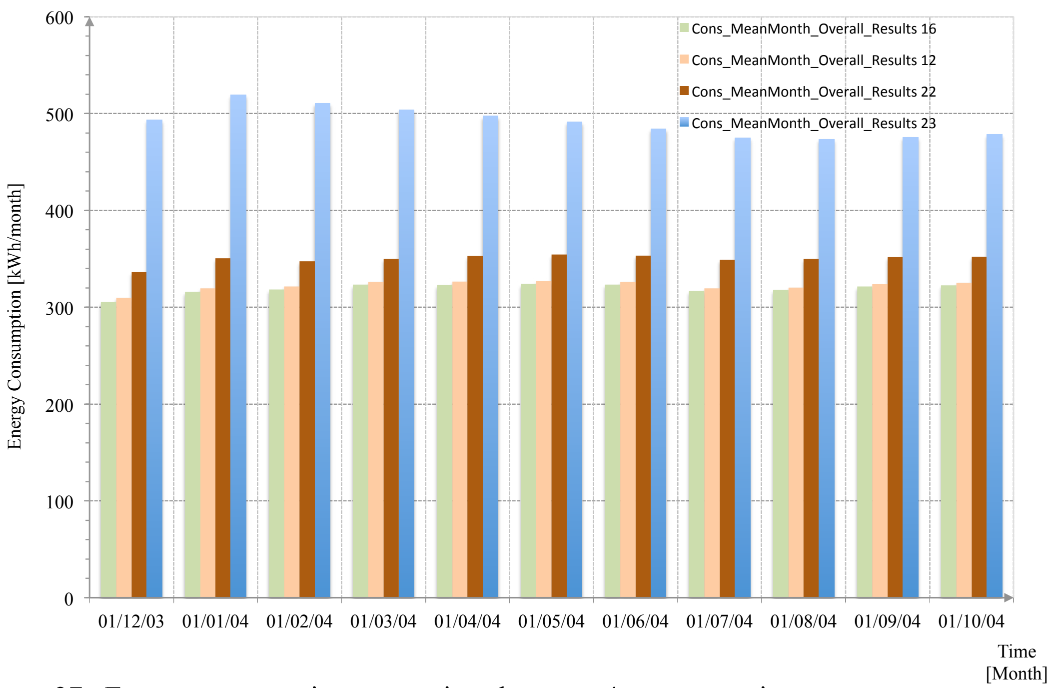


Figure 27. Energy consumption comparison between 4 case scenario

All the appliances and lighting are integrated in the building. The four scenarios presented in Figure 27 illustrate the evolution of the house from a regular building with an average technology to a smart building with high technology standards throughout a 12 month period. The 1st scenario (*Results 23*) represents the detached house, without control system, with the energy efficiency of appliances ranked as average (C/D label). The next three scenarios integrate an upgrade of the appliances from C/D label to A/B, and feature a user response categorised “green”. The 2nd scenario (*Results 22*) represents the technology upgrade where the detached house integrates high technology standard. The 3rd scenario (*Results 12*) is an evolution of the second scenario where a smart meter is added (as presented in Figure 6), which allows retrieving data and influence user behaviour. Finally, the 4th scenario (*Results 16*) features an upgraded controller from the 3rd scenario, where the dishwasher and washing machine are delayed to work at the hours when electricity is cheap. The results show a 30 % reduction of the energy consumption between the 1st and the 2nd scenario. An energy reduction of 8 % was observed between the 2nd and the 3rd scenario. An average improvement in the energy consumption by 1 % was seen between the 3rd and the 4th scenario.

Adding a basic smart meter will reduce the energy consumption by 8 %. This result correlates with the findings of Ehrhardt-Martinez et al. (2011), where an appropriate feedback strategy reduced the energy consumption by 4 to 15 %.

Having an advanced smart meter (such as presented in Figure 7) that would entirely control the starting time of the washing machine and the dish washer has a similar impact whatever type of user is living in the house (*green*, *orange* or *brown*) when comparing *Results 12* and *28* with *Results 16* and *29* respectively (from user-based action to automatic control of the appliances). A reduction of the monthly energy consumption of 1 to 1.5 % is to be expected. This is explained by the fact that the user is by default decreasing its use of washes because multiple washes over the same day is not possible to reach knowing that the action will be automatically postponed during the night time.

Upgrading a building from its regular state with a smart meter that is able to retrieve information and advices to the residents will allow lowering the energy consumption depending on the type of users (Figure 28). *Green users*, with a 70 % positive response, will see their energy consumption decreasing by 7.5 % (*Results 7*), while *Orange users*, with a 50 % positive response, will see their energy consumption decreasing by 4.5 % (*Results 1*). Finally, Brown users with their 30 % positive response will have a decrease of 2.5 % (*Results 10*) compared to a regular dwelling without control system (*Results 5*).

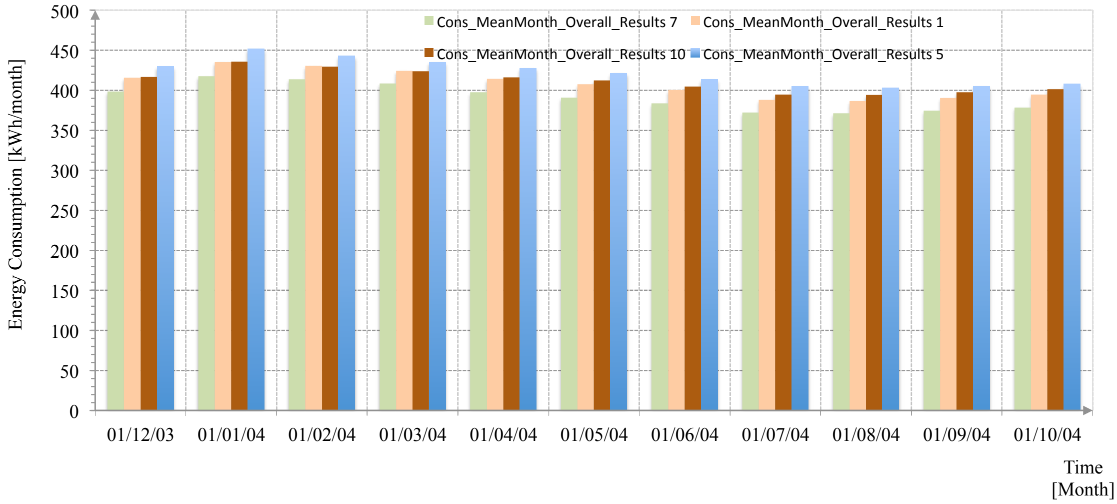
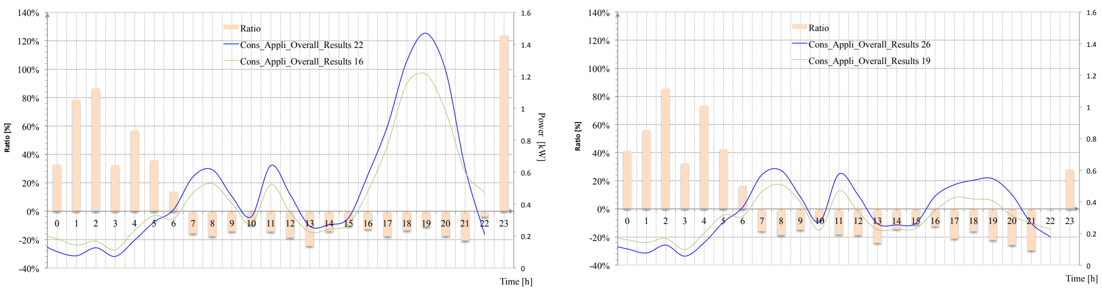


Figure 28. User response impact on their energy consumption

Another purpose of having a smart building is to contribute to the flattening of the energy consumption profile of the day at the network level. This simulation was made only on one building and was not used for interacting with other buildings in a micro grid (as presented in Figure 7). However, by using a basic smart meter that influence the end user in their way and time of using appliance showed results in the daily energy profile as presented in Figure 29.



a) b)

Figure 29. Daily energy profile in 2004, a) With Sauna, b) Without Sauna

By upgrading the building into a smart building, it is possible to transfer some activities to another time when the energy consumption or the energy price is low. Using this system allowed to decrease the energy consumption over the day time (7-22) and transfer it to the night time. The results presented include only the appliances in the house but do not take into account the thermal energy or the energy used for the domestic hot water. A mean increase of energy during the night time of 47 % has been noticed while a mean decrease of the energy consumption over the day of 18 % was found. These results do not show as much of a flattening energy consumption profile as would have been expected. However, as mentioned earlier, the effect of having multiple buildings in a grid has not been studied and depending on the information given by the grid, it is expected that the sum of buildings in series would results in a flatter energy consumption profile at the network level.

Upgrading a traditional home with low consumption bulbs allowed reducing the energy consumption by 8 % from 4 221 kWh/yr to 3 885 kWh/yr.

Finally, the impact of having an hourly pricing system of the energy have been studied for the appliances. In order to compare fairly similar data, the year 2011 has been selected to draw the hourly price vector and compare it with the actual available contracts from Oulun Energia. The results were not conclusive in a way that it seemed that energy consumption was not transferred to the time slot where the electricity price was the cheapest. The algorithm used was price based, and thus was selecting the delaying time depending on the forecasted price. It was not meant to flatten the daily energy profile but choosing the cheapest time slot for the coming day based on the forecasted prices in order to lower the energy bill at the end of the month. However, neither the daily energy profile nor the bill has shown improvements. It can be explained by a set of different factors influencing the energy price: the price variation is based on the network price evolution and it appeared that for some hours the electricity price could reach 10 €/kWh which can greatly influence the monthly bill although some actions have been delayed because of the high price.

7. Conclusions

This thesis followed up a previous study on smart grid systems (Caló, 2011), where the built environment was considered as a non-modular entity. The primary objective was to model the dwelling, and evaluate the potential of smart systems at the building level. Different scenarios were set up where end-user choices were taken into account in the decision making process of the building through a human-machine interface. An energy price monitoring system was installed in the smart system, in order to take into account the spot price system as well as the feed-in tariffs. The final objective was to carry out an energy flux comparison between a building equipped with a smart system and one without it.

In this thesis, a detached house in Oulu was modelled based on the MatLab/Simulink environment. As an input data, 10 years climatic data were extracted an processed on an hourly (all) and half-hourly basis (all except energy price and solar radiation). In order to build a modular living environment, the model implemented twenty one appliances in the different house zones. Three small-scale energy production systems were added to the system; PV-panels, a wind turbine and a fuel cell. Three types of end-users were modelled in order to implement their choices. The controller developed allows having three different feedback strategies that will influence user response. The feedback strategies included in the controller are self-comparison, inter-comparison and a target based system. The control system is able to integrate an hourly pricing system and the forecasted prices of the spot price market. Two management systems for controlling the appliances are available. The first one does not take a direct control of the house and takes its orders from the end-user. The second one can fully take control of two appliances; the washing machine and the dishwasher. Finally, a set of scenarios were created to allow a comparison between a house without a control system and different architectures of smart houses.

This thesis showed that smart buildings can contribute to reducing the energy consumption in the residential sector, although this study was focusing on the energy consumption from appliances and lighting only. Finland has a large potential for reducing energy consumption in buildings, considering their energy use intensity. Smart meters are essential part of smart houses. Energy is not well understood by non-specialists and, therefore, retrieving the information from the smart meter in the right way is critical. Adding too many control tools to a building could result people losing their interest in this technology. A reduction of energy consumption from the appliances and the lighting were found to be between 2 to 8 %, depending on the end-user response. Further studies on the retrieved layout should be made on a large scale, taking into account the awareness of the users. Another way of doing it would be to have a flexible retrieving format device. Work has been carried out on augmented reality for representing an exact 3-D model of any building using cameras. This could be used to navigate inside a building to identify the appliance or a sector where improvements can be made.

One of the cornerstones for the deployment of smart buildings lays in the security transfer of data. Different opinions exist in the energy sector, ranging from retaining all the data, through companies handling the data, to implementing cloud computing. Data confinement induces that there is no possible way of extracting raw data from the building. This will answer to the privacy issue, by blocking illegal access to data. From a technical point of view, reducing the flow of information would require a stronger telecommunication system, if the all the residential areas of Oulu were to be equipped. This thesis was considering a built-in system that does not communicates all information outward. The only data accessible was the overall energy consumption for different time slots (monthly, daily), in order to implement the inter-comparison system and billing end-users.

The model built within this work was thought to be used in a smart grid architecture, and was meant to facilitate interacting between buildings. While energy consumption directly impacts on the bill, the daily energy consumption profile was of primary importance for the grid, which is looking for a way to flattening the electricity demand peaks. Since the grid level was not modelled in this work, it was not possible to verify the impact of smart buildings on the energy demand profile of the grid. However, results indicate that the controller allowed to somewhat reduce the peaks of energy consumption at the house level.

Considering the current pricing system offered by Oulun Energia and its price based on the time of the day, it was shown that a decrease from 5 % to 25 % of energy consumption were achieved from 7 to 22 O'clock. An increase of the energy consumption over the night time varied from 15 % to over 100 %. The controller did not allow having a completely flat energy distribution plot over the day. It is expected that the impact on the network can be significant considering multiple buildings equipped with such a system in parallel, and in series. Further development should consider a fully integrated system. In addition, the development of other building types could be considered such as apartment's buildings and SMEs. The three types of energy user profiles were chosen arbitrarily, but there is potential of developing an index based on existing standards such as the ISO 7730 where PPD/PMV index could be calculated. This method has been developed for thermal comfort and could be transposed for user response regarding the energy used. This far, research focused on building energy profiles for the appliances and lighting at home. Another major component to be integrated is the thermal use of energy, and having the building interact with the district heating system. This would also include heating of domestic hot water, which is one of the critical points in energy losses. Other thermal losses such as the ventilation system should also be included, and including thermal energy recovery by air-to-air heat exchangers. Notwithstanding, this work can be seen as the first step toward developing an optimizing method for smart energy buildings.

The hourly pricing system used in the model did not show conclusive results because it requires an iterative model with the grid for re-calculating the energy price depending on the energy demand.

Toward developing smart buildings, people's habits will be key concern. Major differences were seen when users did not respond positively, because smart building do not necessarily mean fully automated buildings. Therefore, it is hoped that consumers would take an active role in reducing their energy consumption. In this matter, there can be debates about how automated should a smart building be, especially considering thermal energy. Although today's control systems can regulate the energy consumption depending on outside and inside temperatures, other variables such as the energy price could also be considered to temporarily reduce the temperature setting and thus reducing the energy consumption.

Succeeding in developing smart grid systems will necessarily involve the deployment of smart buildings. A number of projects are under way across the world, which will bring field experience as well as technological improvements in different engineering fields. Indeed, employment opportunities and challenges will increase for information and communications technology engineers, control system engineers as well as building design engineers/architects. Therefore, a great potential is seen in the development of smart buildings that will, ultimately, reduce energy consumption and meet legislative targets for buildings. To this end, Oulu as the smartest city in Europe will have an important role to play.

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APPENDIX A Non-exhaustive list of standards for buildings and energy systems

EN 832	Thermal Performance of Buildings - Calculation of Energy Use for Heating - Residential Buildings
EN 1264 series	Floor heating - Systems and components (5 parts)
EN 12412 series	Thermal performance of windows, doors and shutters. Determination of thermal transmittance by hot box method (4 parts)
EN 12831	Heating systems in buildings - Method for calculation of the design heat load
ISO 13370	Thermal performance of buildings - Heat transfer via the ground - Calculation methods
EN 13465	Ventilation for buildings - Calculation methods for the determination of air flow rates in dwellings
EN 13829	Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method
EN 13947	Thermal performance of curtain walling. Calculation of thermal transmittance
EN 14336	Heating systems in buildings - Installation and commissioning of water based heating systems
EN 14337	Heating Systems in buildings - Design and installation of direct electrical room heating systems
EN 15026	Hygrothermal Performance Of Building Components And Building Elements - Assessment Of Moisture Transfer By Numerical Simulation
EN 15242	Ventilation for buildings - Calculation methods for the determination of air flow rates in buildings including infiltration
EN 15243	Ventilation for buildings — Calculation of room temperatures and of load and energy for buildings with room conditioning systems
EN 15251	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
EN 15255	Energy performance of buildings - Sensible room cooling load calculation - General criteria and validation procedures
EN 15265	Energy performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures
EN 15316 series	Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies
EN 15377 series	Heating systems in buildings - Design of embedded water based surface heating and cooling systems (3 parts)
EN 15450	Heating systems in buildings - Design of heat pump heating systems
EN 15459	Energy performance of buildings - Economic evaluation procedures for energy systems in buildings
ISO 6946	Building components and building elements — Thermal resistance and thermal transmittance - Calculation method

ISO 7345	Thermal insulation - Physical quantities and definition
ISO 7730	Ergonomics of the thermal environment - Analytical determination and interpretation of thermal confort using calculation of the PMV and PPD indices and local thermal comfort criteria
ISO 10077 series	Thermal performance of windows, doors and shutters — Calculation of thermal transmittance (2 parts)
ISO 10211	Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations
ISO 13732 series	Ergonomics of the thermal environment - Methods for the assessment of human responses to contact with surfaces (3 parts)
ISO 13786	Thermal performance of building components - Dynamic thermal characteristics - Calculation methods
ISO 13788	Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods
ISO 13789	Thermal performance of buildings - Transmission and ventilation heat transfer coefficients - Calculation method
ISO 13790	Thermal performance of buildings - Calculation of energy use for space heating
ISO 15927 series	Hygrothermal performance of buildings - Calculation and presentation of climatic data (6 parts)
P 52-612/CN	Heating systems in buildings - Method for calculation of the design heat load - National addition to NF EN 12831 - Default values for the calculations in clauses 6 to 9

APPENDIX B Climatic Data figures

B.1 Temperature Data

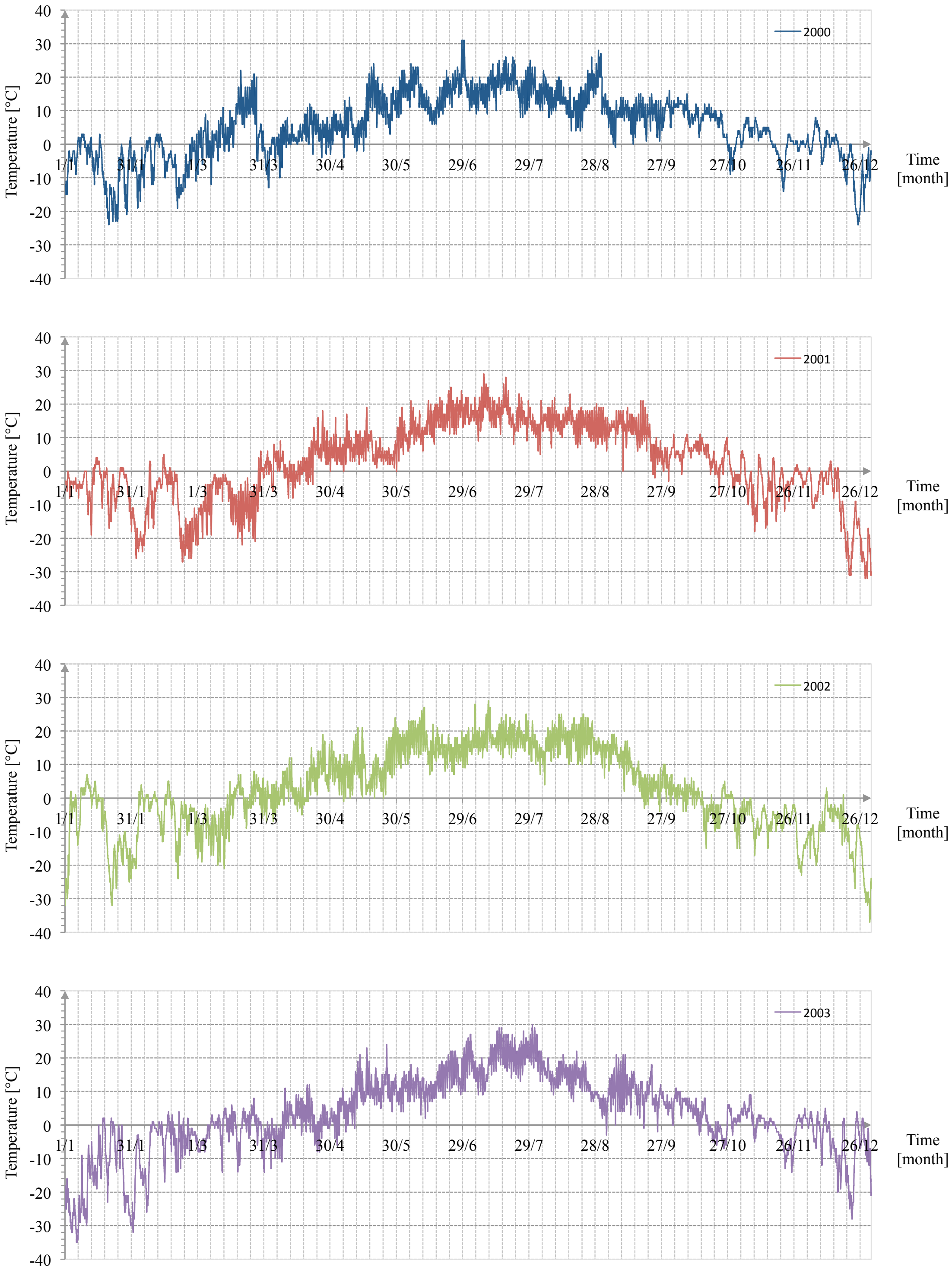


Figure 30. Temperature variation for Oulu arranged by years from 2000 to 2012

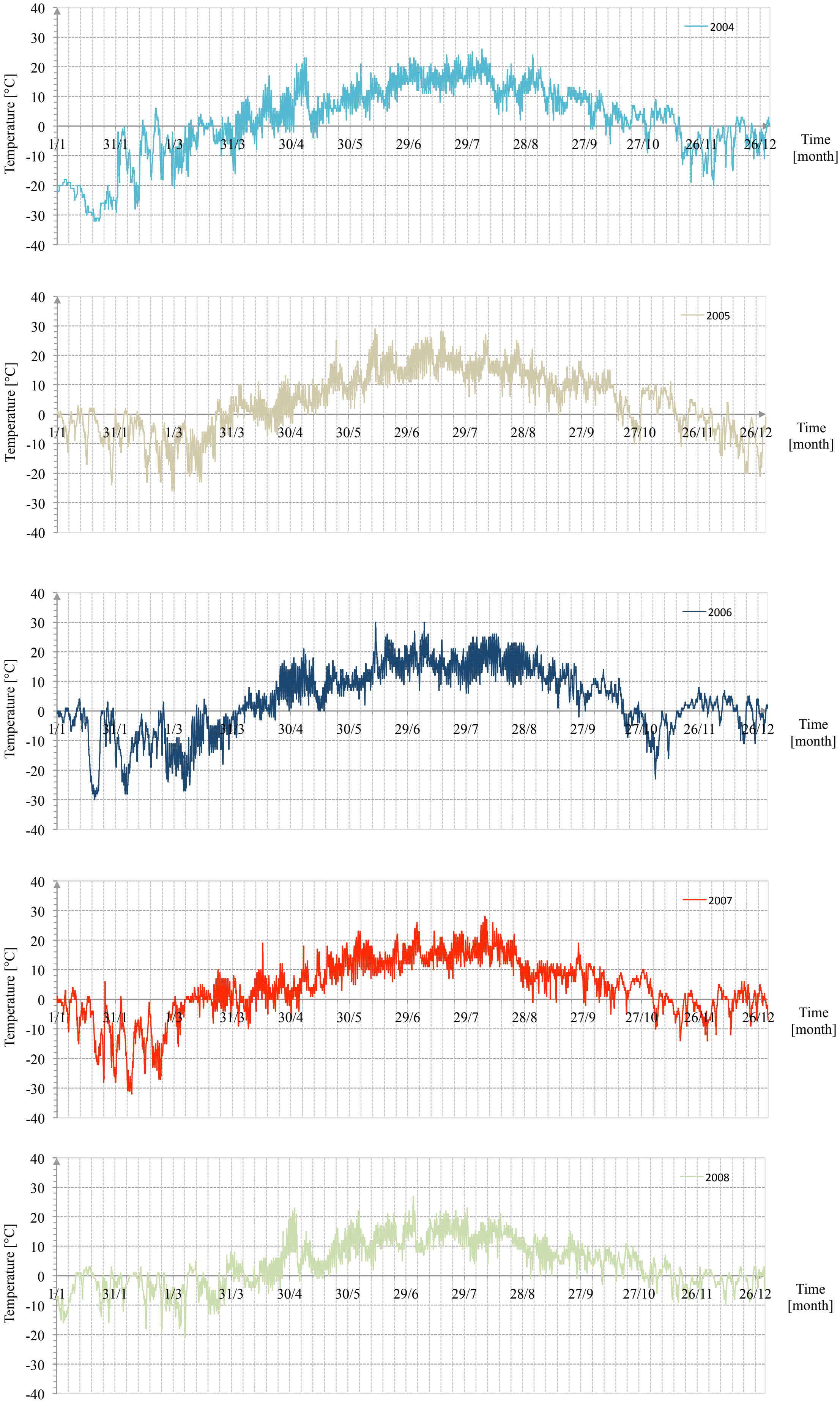


Figure 30 (continued)

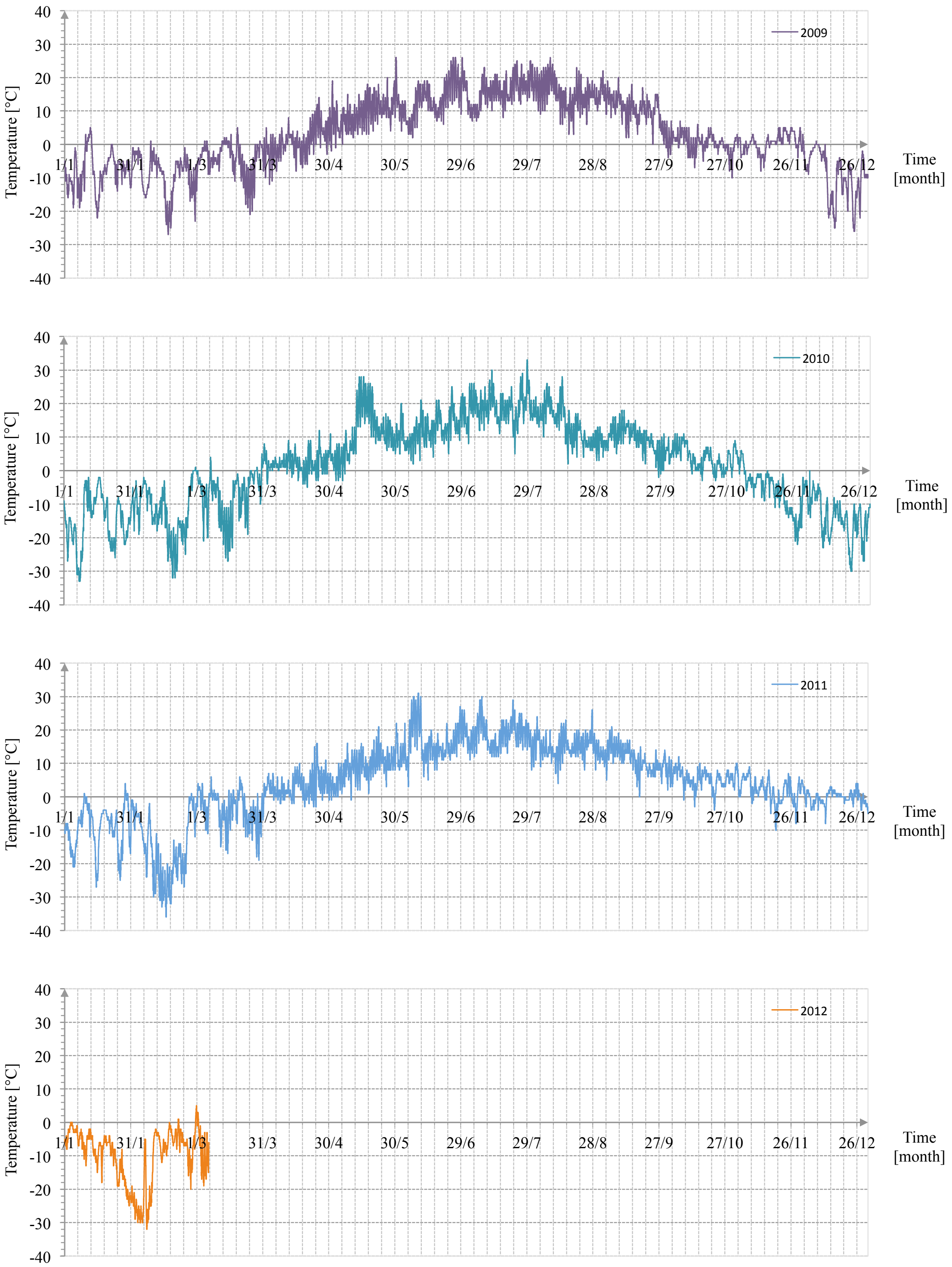


Figure 30 (continued)

B.2 Wind Speed

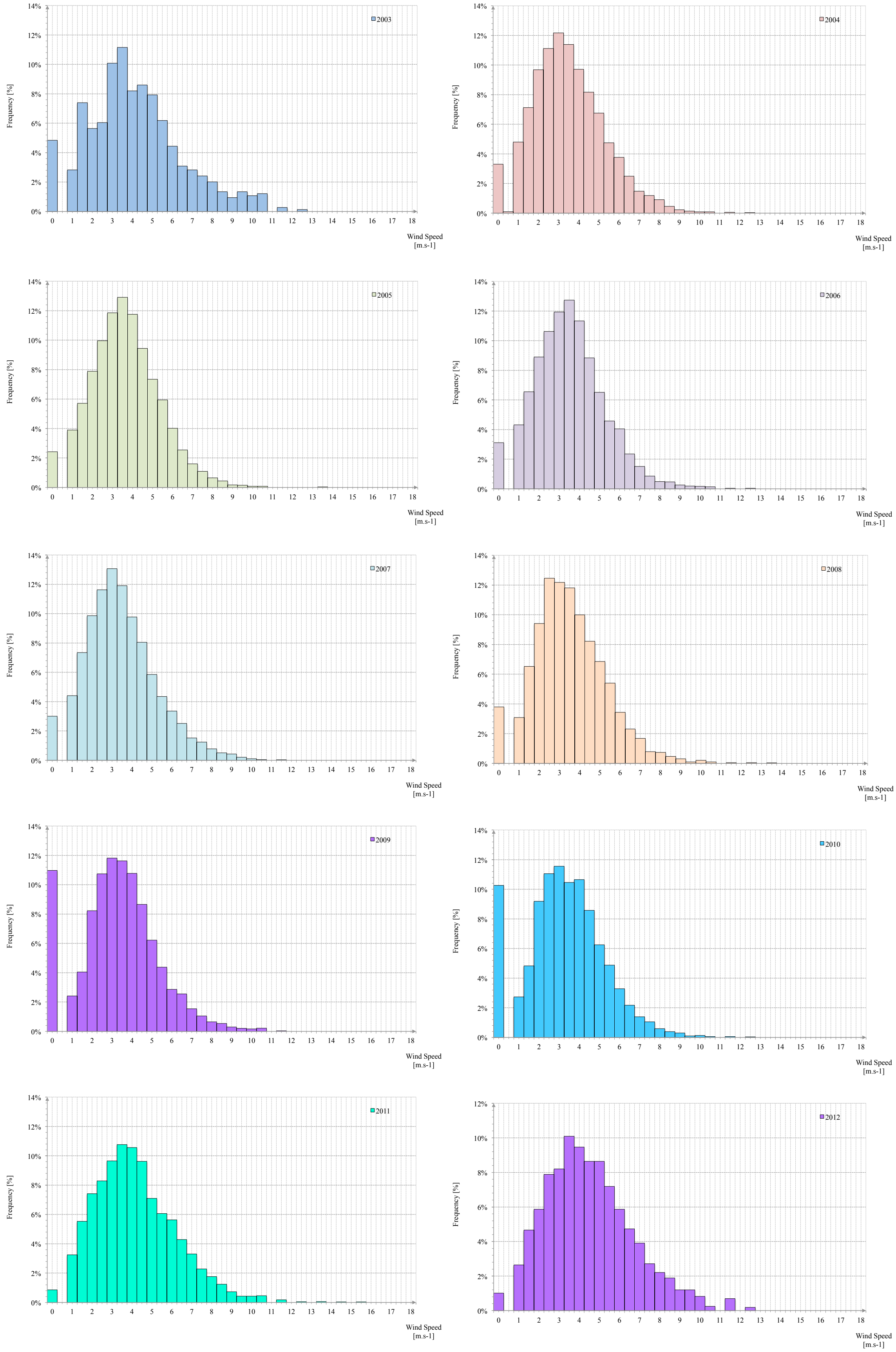
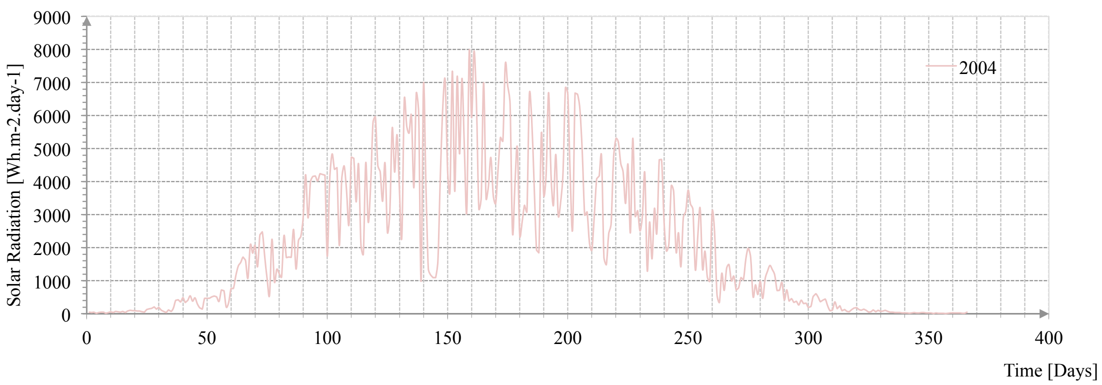


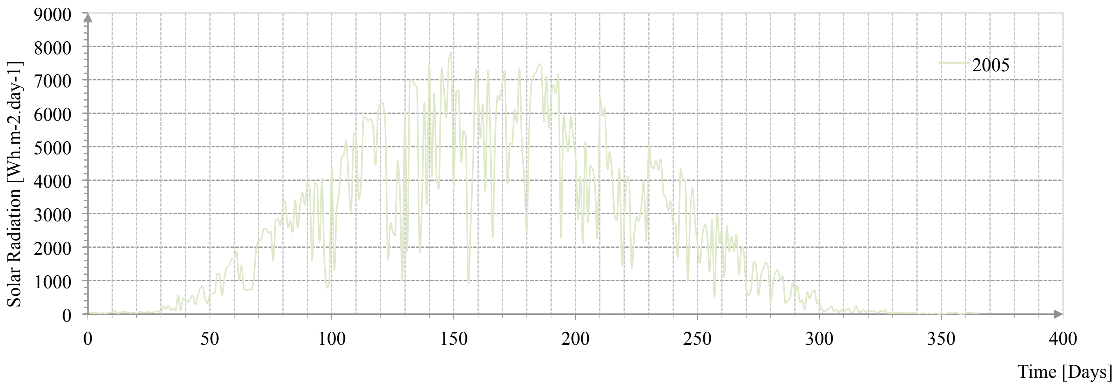
Figure 31. Wind frequency throughout the years 2003 to 2012, Oulu Finland

Figure 31 (continued)

Figure 31 (Continued)

B.3 Solar radiation data





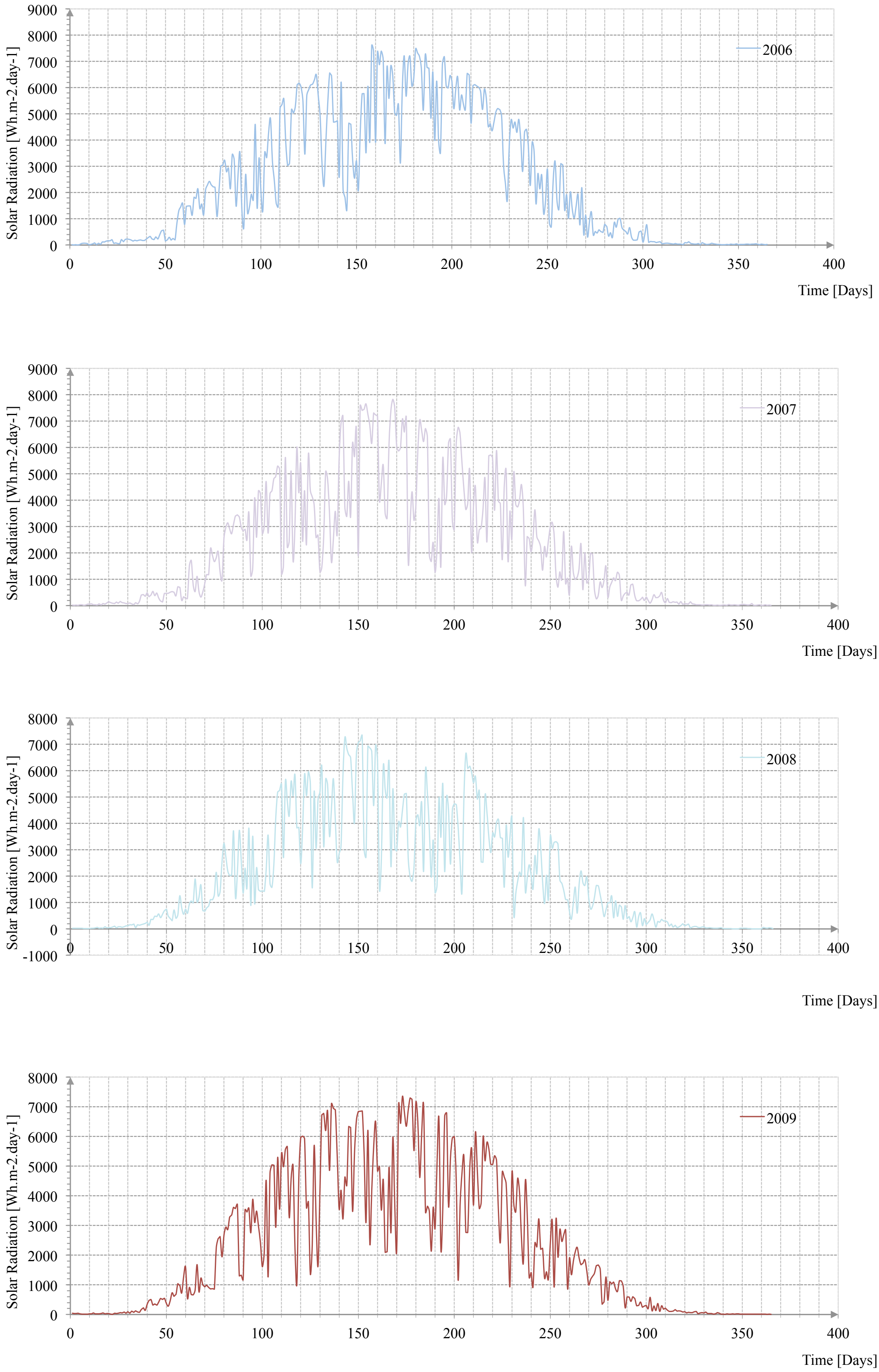
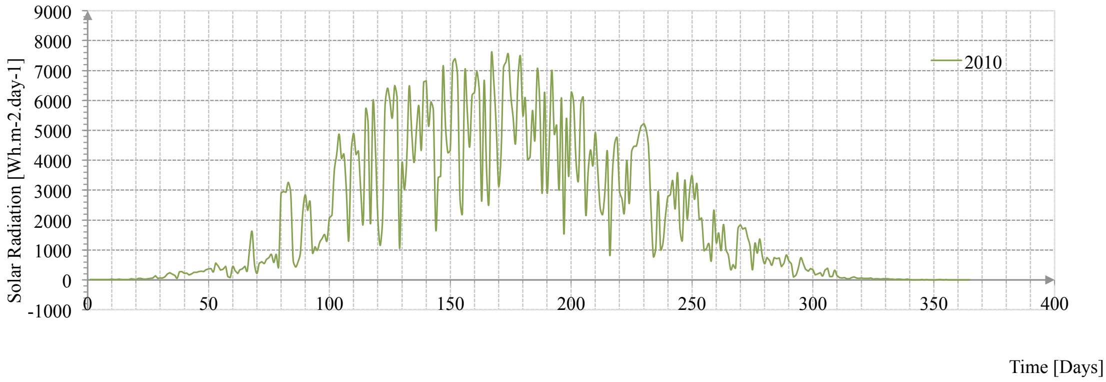
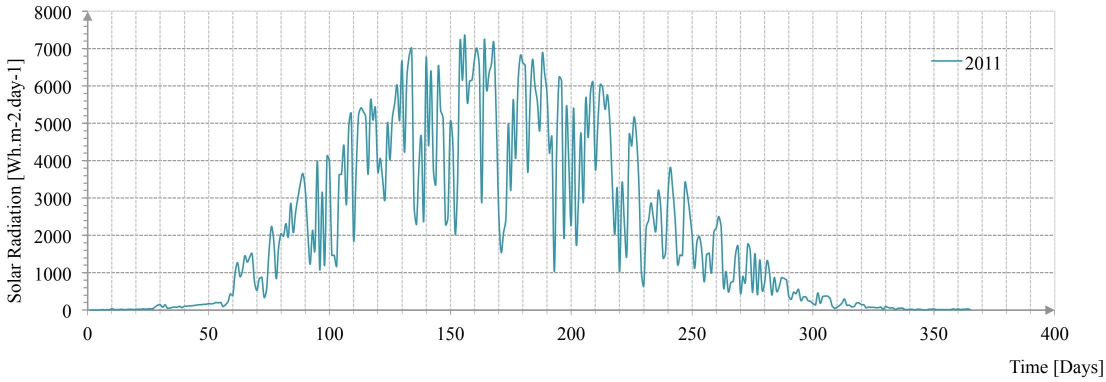


Figure 32. Mean daily solar radiation in Oulu region from 2004 to 2012





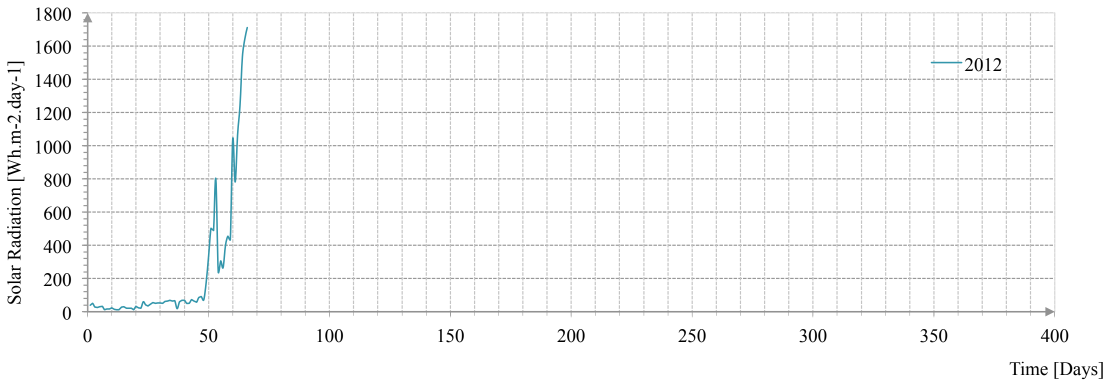


Figure 32 (continued)

APPENDIX C Fuel Cell Mathematical model

C.1 Introduction

This Annex is meant to help understanding the fuel cell model developed on Simulink.

C.1.1 Theoretical voltage

The first step is calculate the theoretical voltage output of the fuel cell. The work is based on (Larmini and Dicks, 2003) and all data comes from this handbook.

First of all, a set of constant are defined such as in the table below:

	h_f [J/mol]	s [J/mol.K]
H_2O liquid	-285838	70,05
H_2O gas	-241827	188,83
H_2	0	130,59
O_2	0	205,4

where, h_f is the enthalpy of formation per mole

s is the entropy per mole

From the values given above, it is possible to calculate the enthalpy and the entropy of formation at a given temperature T.

$$\overline{h_T} = \overline{h}_{298,15} + \int_{298,15}^{T} \overline{C}_p dT$$

$$\overline{s}_T = \overline{s}_{298,15} + \int_{298,15}^{T} \frac{1}{T} \overline{C}_p dT$$

Each value can be calculated (H_2, O_2 and H_2O). After developing the equation, we have:

For H_2O,

$$\overline{s}_T = \overline{s}_{H2O} + \int_{298,15}^{T} \frac{1}{T} \times \left(143,05 - 58,04x^{0,25} + 8,2751x^{0.5} - 0,036989x\right) dT$$

$$\overline{s}_T = \overline{s}_{H2O} + 143,05 \cdot [lnx]_{298,15}^{T} - 58.04 \cdot \left[\frac{x^{0,25}}{0,25}\right]_{298,15}^{T} + 8,2751 \cdot \left[\frac{x^{0,5}}{0,5}\right]_{298,15}^{T} - 0,036989\,[x]_{298,15}^{T}$$

For O_2,

$$\overline{s}_T = \overline{s}_{O2} + \int_{298,15}^{T} \frac{1}{T} \cdot \left(37,432 + 0,000020102x^{1,5} - 178570x^{-1,5} + 2368800x^{-2}\right) dT$$

$$\overline{s}_T = \overline{s}_{O2} + 37,432 \cdot [lnx]_{298,15}^{T} + 0,000020102 \cdot \left[\frac{x^{1,5}}{1,5}\right]_{298,15}^{T} - 178570 \cdot \left[\frac{x^{-1,5}}{-1,5}\right]_{298,15}^{T} + 2368800 \left[\frac{x^{-2}}{-2}\right]_{298,15}^{T}$$

For H_2,

$$\overline{s}_T = \overline{s}_{H2} + \int_{298,15}^{T} \frac{1}{T} \cdot \left(56,505 - 22222,6x^{-0,75} + 116500x^{-1} - 560700x^{-1,5}\right) dT$$

$$\overline{s}_T = \overline{s}_{H2} + 56,505 \cdot [lnx]_{298,15}^{T} - 22222,6 \cdot \left[\frac{x^{-0,75}}{-0,75}\right]_{298,15}^{T} - 116500 \cdot \left[x^{-1}\right]_{298,15}^{T} - 560700 \left[\frac{x^{-1,5}}{-1,5}\right]_{298,15}^{T}$$

In a similar way, it is possible to write down the same equations for h_f.

It is then necessary to calculate Δs_t and Δh_f the difference in entropy and in enthalpy of the product and the reactant respectively.

$$\Delta\overline{s} = (\overline{s})_{H2O} - (\overline{s})_{H2} - \frac{1}{2}(\overline{s})_{O2}$$

A similar equation is used to calculate Δhf. The results will be used to calculate the change in Gibbs free energy of formation per mole Δgf.

$$\Delta\overline{g}_f = \Delta\overline{h}_f - T\Delta\overline{s}$$

The EMF voltage of the fuel cell can be calculated by using the following equation,

$$E = \frac{-\Delta g_f}{2F}$$

Where F is the Faraday constant [96 485 C]. Note that the voltage (EMF) calculated is a value without any losses and thus represents the theoretical maximum voltage output of the fuel cell. In reality, the fuel cell will have losses and in the model four types of losses are integrated: the activation voltage losses, the fuel crossover and internal losses, the resistance losses (which is mostly caused by the electrolyte) and the mas transport or the concentration losses. All those losses are integrated one by one into the EMF calculation in order to provide the theoretical voltage output of the cell.

$$V = EMF - A \cdot ln\left(\frac{i + i_n}{i_0}\right) - i \cdot r - m \cdot e^{i \cdot n}$$

Where, i is the internal density current in [mA/cm^2], i_n is the value of the internal density current, i_0 is also a current density and represents the exchange current density with a typical value of 0,04 mA/cm^2, A is a constant [V] and has usual value of 0,06 V, r is the area specific resistance [$k\Omega/cm^2$] and has a typical value of 0,000245, m and n are constants with typical values of 3×10^{-5} V and 8×10^{-3} cm^2/mA respectively.

A typical graph that can represent the performance of a fuel cell is given below with on the x-axis the value of the current density in mA/cm2, on the right y-axis the power in W and on the left y-axis the voltage of a single cell in V.

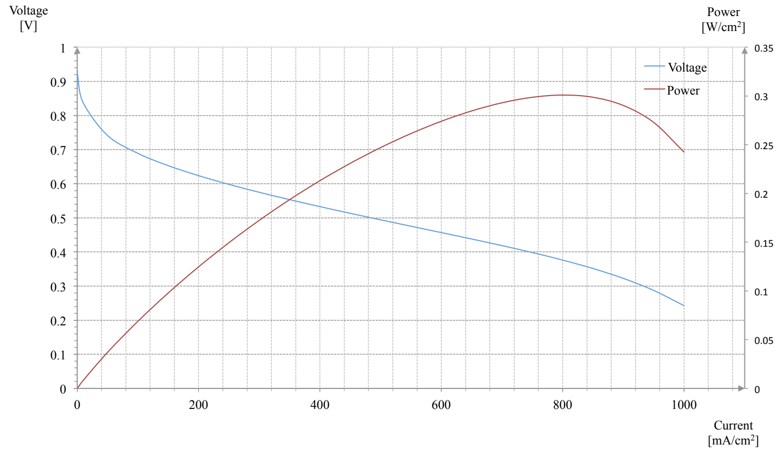


Figure 33. Performances of the modelled Fuel Cell

C.2 Energy variation

C.2.1 Electrical production

The model will have one input for the hydrogen flow rate, most probably expressed in [l/min]. According to (Larmini and Dicks, 2003), it is possible to evaluate the available electrical power depending on the hydrogen flow rate. However, equations are using mass flow rate, thus conversion from volume flow rate to mass flow rate must be done,

$$\frac{\rho_{H_2} \times \dot{q}_V \, [l/min]}{60\,000} = \dot{q}_m \, [kg/s]$$

Where, ρ_{H2} is the hydrogen density and is taken equal to 0,084 kg/m^3 at NTP (Normal Temperature and Pressure). The electrical power delivered by a fuel cell can then be calculated for a given mass flow rate,

$$P_e = \frac{\dot{q}_m \times V_c}{1,05 \times 10^{-8}}$$

Where, V_c is the voltage of one cell (calculated in Eq ...), P_e is the electrical output [W], and the constant $1,05 \times 10^{-8}$ is related to the Faraday constant. From now on, calculating the air mass flow rate and evaluating the amount of water produced can be processed. This has been done in an Excel spreadsheet and still have to be evaluated in order to rank the relevance of such information in the model.

C.2.2 Heat production

In parallel, heat is produced from the fuel cell. The heat produced during the electrical generation can be calculated according to the current and the voltage generated (Larmini and Dicks, 2003) and follow the equation,

$$Q_{heat\,loss} = P_e \cdot \left(\frac{1,25}{V_c} - 1\right)$$

Common electrical knowledge allows calculating the current in each cells,

$$i = \frac{P}{n \times V_c}$$

Where i is the current in one cell [A] and n is the number of cells in the fuel cell.

C.2.3 Heat rate

As mentioned in the previous paragraph, heat is produced during the active phase of electrical production. On the other hand, the fuel cell sees its temperature rising. It can be assumed that the temperature rise in the fuel cell is mostly due to the production of heat during the chemical reaction (Khan & Iqbal, 2004).

$$\frac{dT}{dt} = \frac{Q_{heat} - Q_{cool} - Q_{loss}}{C_t}$$

Where Q_{cool} is the heat flow rate of the cooling system [J/s], Q_{loss} is the heat flow rate through the stack surface [J/s], C_t is the thermal capacitance and is assumed equal to 17 900 [J/°C] and $\frac{dT}{dt}$ is the variation temperature of the cell stack [°C/s].

C.2.4 Cooling system

Cooling system model can be found in literature (Khan and Iqbal, 2004) but it uses water to cool down the system and it is not matching with the model presented in this work. Fuel cells used in the model are using air as a cooling medium. The power extracted with an air cooling system can be calculated by using the difference of enthalpy between the air fed and the air rejected,

$$Q_{extracted} = \dot{q}_m \left(h_{out} - h_{in}\right)$$

Where h_{out} is the enthalpy of the air rejected [kJ/kg], h_{in} is the enthalpy of the air fed [kJ/

kg], q_m is the air mass flow rate [kg/s] and $Q_{extracted}$ is the power extracted [W]. The enthalpy is usually read on a psychrometric chart, however it needs to be modelled in order to calculate the energy in the air. Literature provides us the following equations,

$$h = h_a + xh_w$$

Where h_a is the specific enthalpy of dry air [kJ/kg], x is the humidity ratio [kg/kg] and h_w is the specific enthalpy of water vapour [kJ/kg]. The specific enthalpy of dry air can be calculated by using the specific heat capacity of air at constant pressure Cp_a [kJ/kg.°C] and the air temperature,

$$h_a = Cp_a \times T_{air}$$

Where T_{air} is the temperature of the air studied [°C]. Cp_a varies the temperature in a nonuniform way, however it has been possible to establish a polynomial equation that allows the calculation of Cp_a,

$$Cp_a = -7,357 \cdot 10^{-10} \times T_{air}^3 + 7,0394 \cdot 10^{-7} \times T_{air}^2 - 6,618 \cdot 10^{-6} \times T_{air} + 1,004$$

The specific enthalpy of water vapour is calculated using the specific heat of water vapour at constant pressure Cp_w and is usually taken equal to 1,84 [kJ/kg.°C], the evaporation heat of water at 0°C h_{we} equal to 2 501 [kJ/kg] and the air temperature,

$$h_w = Cp_w \times T_{air} + h_{we}$$

Finally, the humidity ratio x can be calculated using the vapour partial pressure method consisting in evaluating the humidity ratio by using the atmospheric pressure of moist air P_a [Pa] and the partial pressure of water vapour in moist air P_w [Pa] which is function of the saturation pressure of water vapour P_{ws} [Pa].

$$x = 0,62198 \times \frac{P_w}{P_a - P_w}$$

$$P_w = P_{ws} \times RH$$

$$P_{ws} = \frac{e^{\left(77,345 + 0,0057 \times T_{air} - \frac{7235}{T_{air}}\right)}}{T_{air}^{8,2}}$$

Note that those equation, the air temperature must be expressed in kelvin in order to have the right result. When processing the equation evaluating the extracted power, the flow rate used is a mass flow rate, however flow rate is usually expressed in volume [m^3/s], it is then required to know the air density. The air density is calculated on the extracted air characteristics. At constant pressure, the air density varies with the air temperature. Similarly to the specific heat capacity of air, the air density varies in an nonuniform way and a polynomial equation has been established,

$$\rho_{air} = -2,835 \cdot 10^{-8} \times T^3_{air-ex} + 2,016 \cdot 10^{-5} \times T^2_{air-ex} - 5,598 \cdot 10^{-3} \times T_{air-ex} + 1,2996$$

The air volume flow rate is taken equal to 8,6 m^3 and has been set from literature (Meyer and Yao, 2006). With all the data previously calculated, it is possible to calculate the extracted air temperature.

C.2.5 Cooling Control system

A control system of the fuel cell's cooling system has been implemented assuming that the fan used for the cooling system has a fixed speed and thus the volume air flow rate cannot be controlled but the system will switch on and off the system in order to keep an optimum temperature set at 55°C (Riascos and Pereira, 2009). According to manufacturers, PEM fuel cells see their limit temperature at 65°C (see section 3). As long as it has been set that the optimal temperature of the fuel cell is around 55°C, it has been decided that the cooling system is not working until the fuel cell's temperature reaches 55°C. The target being to keep a 55°C average temperature throughout the working period. A control system has been implemented in order to stop the fuel cell energy production when the fuel cell temperature reaches 65°C and restart once the fuel cell temperature gets below 55°C. This is modelled by using a relay. Thus, the fuel cell's control system is sending a message to the hydrogen tank not to send any hydrogen while the fuel cell is cooling down.

C.3 Integrating real technology

It is important to integrate in the model not only theoretical calculations of the performance of a cell but compare them with values given by manufacturer (Fuel Cell Store Inc., 1999). In order to continue the model, it has been decided to pick up three different fuel cells model available on the market. As long as those fuel cells should be used rather in domestic building or in a larger scale in a SME, three fuel cell power have been selected: one of one kW power capacity, one of three kW power capacity and one of five kW of power capacity. The details of those fuel cells are given in the table below:

Table 10. Technical specifications of PEM Fuel Cell

Type of fuel cell	PEM 1 kW	PEM 3 kW	PEM 5 kW
Number of cells	72	72	120
Rated power	1000 W	3000 W	5000 W
Performance	43V @ 23,5A	43.2V @ 70A	72V @ 70A
H2 Supply Valve Voltage	12V	12V	12V
Purging Valve Voltage	12V	12V	12V
Blower Voltage	12V	12V	12V
Reactants	Hydrogen and air	Hydrogen and air	Hydrogen and air
External temperature	5-35°C	5-35°C	5-35°C
Maximum stack temperature	65°C	65°C	65°C
Composition	99.999% Dry H2	99.999% Dry H2	99.999% Dry H2
Hydrogen pressure	7.9-9.4 PSI	7.9-9.4 PSI	7.9-9.4 PSI
Humidification	Self humidified	Self humidified	Self humidified
Cooling	Air (integrated cooling fan)	Air (integrated cooling fan)	Air (integrated cooling fan)
Weight (with fan and casing)	4200 g	11 000g	17 000g
Dimensions	32,4cm x 22,0cm x 12,2cm	38,0cm x 16,0cm x 28,0cm	38,0cm x 16,0cm x 46,0cm
Hydrogen flow rate	14 l/min of hydrogen at maximum power	42 l/min of hydrogen at maximum power	84 l/min of hydrogen at maximum power
Start up time	Immediate	Immediate	Immediate
Stack efficiency	40% at 43V	45% at 43.2V	45% at 72V
Controller	450g	1000g	1000g
Low Voltage Shut Down	36V	36V	60V
Over Current Shut Down	30A	70A	70A
Over Temperature Shut Down	65°C	65°C	65°C

APPENDIX D Wind turbine Mathematical model

The general formula for the kinetic energy is defined as:

$$E_k = \frac{1}{2}mv^2$$

Where E_k is the kinetic energy [J], m is the mass [kg] and v is the wind speed [m/s]. The derivative of this equation allows calculating the power present in the wind:

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

Where P is the available power in the wind [W], A is the area of the rotor [m^2] and ρ is the air density [kg/m^3]. Considering different factors such as the design of the blade and its related flow dynamic properties. A theoretical coefficient defining the maximum extractable power from the wind has been set and defined as the Betz's limit.

APPENDIX E Strategy for the use of appliances

E.1 Kitchen

Washing machine

	Nbr of wash/week
1 person	2.1
2 person	3.4
3 person	4.9
4 person	6.4
5 person	6.3
6 persons	7

Start time delay

Never	36%
Once a month	19%
Once a week	24%
every time	21%

Temperature

		Time [min]
Cold	2%	35
30°C	9%	40
40°C	49%	45
50°C	7%	50
60°C	27%	60
90°C	6%	70

Dish washer

	Nbr of wash/week
1 person	1.4
2 person	2.8
3 person	4.2
4 person	5.6
5 person	7
6 persons	7

Temperature

		Time [min]
35°C	5%	45
55°C	38%	60
65°C	45%	80
70°C	12%	90

Hobs

	Nbr of use/week
1 person	1.4
2 person	2.8
3 person	4.2
4 person	5.6
5 person	7
6 persons	7

Temperature

		Time [min]
Short cooking	30%	10
Medium cooking	38%	20
Med-Long cooking	22%	45
Long cooking	10%	80

Micro-Wave

Average time 2.6 minutes/cycle
3.28 cycle/day

	Nbr of use/week
1 person	5
2 person	10
3 person	15
4 person	23
5 person	27
6 persons	30

	Time [min]
Time per cycle	2.6

Kettle

	Nbr of boiling/week
1 person	7
2 person	10
3 person	15
4 person	20
5 person	30
6 persons	40

Boiling Time		Time [min]
1	30%	3
2	20%	6
3	20%	9
4	10%	12
5	10%	15
6	10%	18

Coffee maker

	Nbr of coffee/week
1 person	7
2 person	14
3 person	17
4 person	20
5 person	30
6 persons	30

	Time [min]
Coffee maker use	60

Electric oven

	Nbr use/week
1 person	1
2 person	1
3 person	1.5
4 person	2
5 person	3
6 persons	3.5

		Time [min]
Short cooking	60%	30
Medium cooking	35%	60
Long cooking	5%	120

Toaster

	Nbr use/week
1 person	4
2 person	6
3 person	6
4 person	7
5 person	7
6 persons	8

		Time [min]
Toasting time	100%	15

Waffle

	Nbr use/week
1 person	0.5
2 person	0.5
3 person	0.5
4 person	1
5 person	1
6 persons	2

		Time [min]
Recharging time	100%	70

E.2 Bedroom

Radio

	Nbr of radio/week
1 person	7
2 person	7
3 person	14
4 person	21
5 person	21
6 persons	30

radio listening time		Time [min]
Wake-up clock	90%	30
Random clock	10%	10

Laptop

	Use/week
1 person	7
2 person	14
3 person	17
4 person	20
5 person	30
6 persons	30

		Time [min]
Active mode	16%	60
Sleeping mode	33%	60
Off mode	51%	60

Telephone charger

	Nbr use/week
1 person	3
2 person	6
3 person	9
4 person	12
5 person	15
6 persons	15

		Time [min]
Recharging time	100%	300

E.3 Bathroom

Shaver

	Nbr of recharge/week
1 person	1
2 person	1
3 person	1
4 person	2
5 person	2
6 persons	2.5

	Time [min]
Time per recharge	480

Hair Dryer

	Nbr of drying/week
1 person	4
2 person	7
3 person	9
4 person	10
5 person	12
6 persons	15

	Time [min]
Time per recharge	20

Electric heater

	Nbr use/week
1 person	5
2 person	5
3 person	7
4 person	7
5 person	7
6 persons	7

		Time [min]
Time per user	100%	20

Multiply by the number of user

Sauna

	Nbr use/week
1 person	0.5
2 person	0.5
3 person	1
4 person	2
5 person	2
6 persons	3

		Time [min]
Time per user	100%	120

E.4 Living room

Stereo

	Nbr of stereo hearing/week
1 person	10
2 person	10
3 person	15
4 person	15
5 person	25
6 persons	25

		Time [min]
Information	20%	60
Music	80%	120

Television

	Nbr of time use/week
1 person	8
2 person	16
3 person	24
4 person	32
5 person	40
6 persons	48

	Time [min]
Time per person	96

E.5 Cleaning Tools

Vacuum cleaner

	Nbr use/week
1 person	1
2 person	1
3 person	2
4 person	2
5 person	3
6 persons	4

		Time [min]
Fast cleaning	20%	30
Medium cleaning	50%	60
Long cleaning	30%	90

Iron

	Nbr use/week
1 person	1
2 person	1
3 person	2
4 person	3
5 person	5
6 persons	7

		Time [min]
Fast ironing	40%	15
Long ironing	60%	70

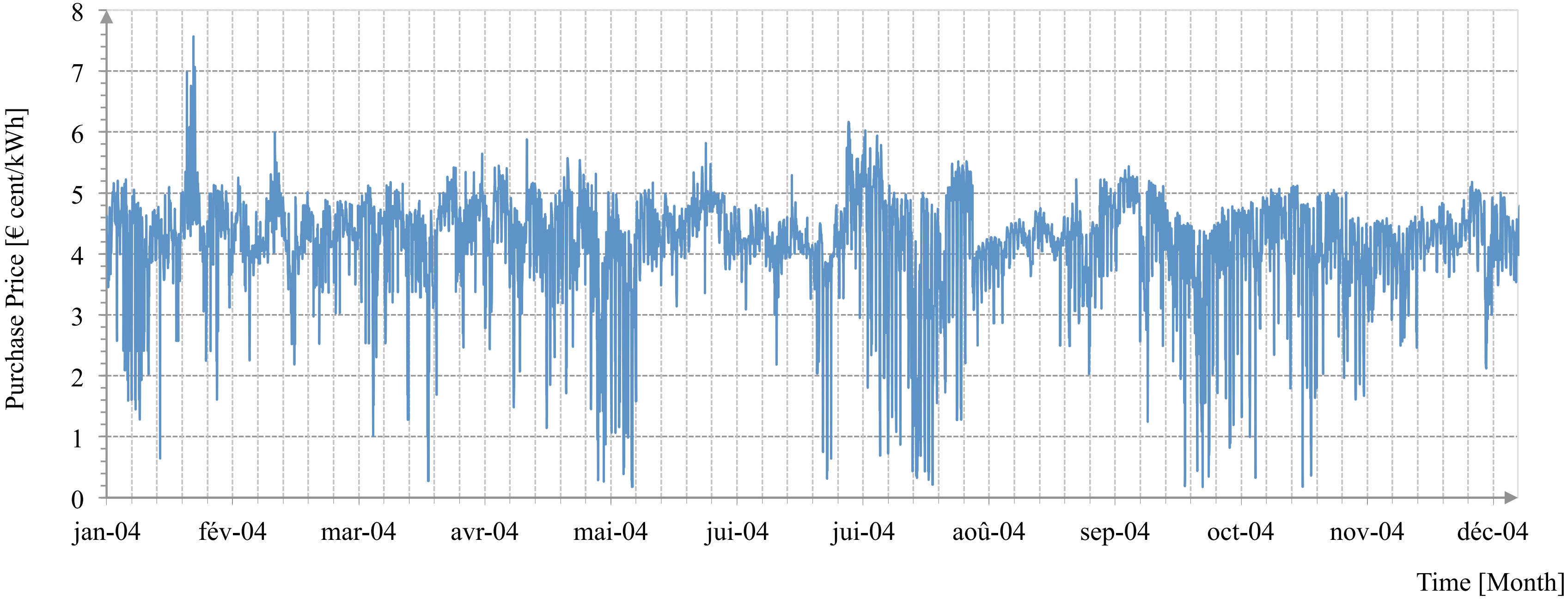


Figure 34. Purchase electricity price variation using the method stated in section 5.2.4.

While the mean purchase price of electricity at the building level for a single house with 3 × 25 A fuses is around 6.93 € cent/kWh, the method gives a mean electricity price of 6.94 € cent/kWh over the year 2004. Similar results are found for the following years.

Results 1	With Controller With Sauna Orange User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract All Control
Results 2	Without Controller With Sauna Orange User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 3	Without Controller Without Sauna Orange User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 4	With Controller Without Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract All Control
Results 5	Without Controller With Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 6	With Controller With Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract Only Delay
Results 7	With Controller With Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract All Control
Results 8	With Controller Without Sauna Brown User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract All Control
Results 9	Without Controller With Sauna Brown User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 10	With Controller With Sauna Brown User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract All Control

Results 11	Without Controller Without Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 12	With Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract All Control
Results 13	With Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract Only Self Control
Results 14	With Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract Only Inter Comparison
Results 15	With Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract Only target control
Results 16	With Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract All Control Automatic Control
Results 17	With Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	Hourly pricing All Control Automatic Control
Results 18	With Controller Without Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract All Control Automatic Control
Results 19	With Controller Without Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract All Control Automatic Control
Results 20	With Controller Without Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	Hourly pricing All Control Automatic Control

Results 21	With Controller Without Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	Hourly pricing All Control Automatic Control
Results 22	Without Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 23	Without Controller With Sauna Green User	Incandescent bulbs No Energy Production All App C/D	VarmaVirta Contract
Results 24	With Controller With Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract Only Self Comparison
Results 25	With Controller With Sauna Green User	Incandescent bulbs No Energy Production All App A/B	VarmaVirta Contract Only Target Control
Results 26	Without Controller Without Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract
Results 27	Without Controller With Sauna Green User	Low Consumption bulbs No Energy Production All App A/B	Hourly pricing All Control Automatic Control
Results 28	With Controller With Sauna Brown User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract All Control Automatic Control
Results 29	With Controller With Sauna Brown User	Low Consumption bulbs No Energy Production All App A/B	VarmaVirta Contract All Control