Energy Efficiency Potential of the European Building Stock

A Case Study of France

Master's Thesis within the Sustainable Energy Systems programme and the Industrial Ecology programme

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ABSTRACT

The building sector in France represents 44% of the national total final energy consumption and 25% of the carbon dioxide (CO_2) emissions. Therefore, this sector is of great importance when aiming for the globally recognised 2°C target, where a reduction in energy demand and CO_2 emissions account for two of the three main goals related to climate change.

By applying ten different energy saving measures (ESMs) on the building sector using the *Energy, Carbon and Cost Assessment for Building Stocks* model (ECCABS), this thesis assesses potential energy savings, CO_2 emissions mitigation and cost-effectiveness of each ESM.

The energy, CO_2 emissions and cost-efficiency assessments should not be implemented individually, but rather evaluated in parallel looking at each of the building archetypes. However, for summarising, the biggest savings potentials are found in single-family dwellings and the main energy and emissions savings are shown to be connected to insulation measures.

Due to the high share of low emissive electricity used for space heating and the comparably high carbon intensity of heat production in France, there is a complex relationship between electricity, space heating and the CO_2 emissions created by some of the measures. For example, by increasing the efficiency of appliances and lighting devices, the CO_2 emissions tend to rise.

The ESMs give a cost-effective saving potential of around 150TWh and $20MtCO_2$ annually, i.e. a reduction of 20% and 24%, respectively. An annual investment of €59 billion would potentially save 329TWh, representing 50% of the present energy consumption in the French building sector, as well as $51MtCO_2$ (56%) per year.

This thesis verifies the technical potential’s accuracy of the ECCABS model and its transferability to different building stocks. The model is a relatively quick tool for investigating different energy saving measures and can be used for rough evaluations of contemplated energy policies’ cost-efficiency.

Key words: energy simulation, French building stock, energy demand, bottom-up modelling, carbon dioxide emissions, cost-efficiency

Energieffektiviseringspotential för det europeiska fastighetsbeståndet
Fallstudie av Frankrike
Examensarbete inom masterprogrammen *Sustainable Energy Systems* programme *and the Industrial Ecology programme*
TRI-CANG DINH, HANNA LUNDEVALL
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SAMMANFATTNING

Byggnadssektorn i Frankrike utgör idag 44 % av landets totala slutenergianvändning och står för 25 % av landets koldioxidutsläpp (CO_2). Detta gör byggnadssektorn till en viktig faktor i det nationella arbetet mot klimatförändringar där en minskning i energianvändning och koldioxidutsläpp står för två av de tre huvudmålen.

Det här examensarbetet utvärderar potentiella energibesparingar, minskade koldioxidutsläpp och kostnadseffektiviteten för tio olika energibesparingsåtgärder implementerade inom byggnadssektorn via en simuleringsmodell kallad *Energy, Carbon and Cost Assessment for Building Stocks* (ECCABS).

Undersökningarna av energibesparingar, koldioxidutsläpp och kostnadseffektivitet bör inte appliceras individuellt, utan snarare utvärderas parallellt med varandra för respektive byggnadstyp. För att summera kan dock sägas att den största besparingspotentialen återfinns i enfamiljshus och att isoleringsåtgärder står för den största besparingspotentialen för energi och koldioxidutsläpp.

På grund av den franska elektricitetens låga kolintensitet och den jämförelsevis höga kolintensiteten hos fransk värmeproduktion, skapas en komplex relation mellan elektricitet, rumsuppvärmning och koldioxidutsläpp hos några av energibesparingsåtgärderna. Om man till exempel ökar effektiviteten hos en apparat eller en glödlampa, så ökar koldioxidutsläppen till följd av det ökade behovet av rumsuppvärmning.

Energibesparingsåtgärderna ger en kostnadseffektiv besparingspotential på cirka 150TWh och $20MtCO_2$ per år. En årlig investering av 59 miljarder Euros skulle potentiellt kunna spara 329TWh per år, vilket är 50 % av dagens energikonsumtion i den franska byggnadssektorn, liksom 51 megaton koldioxid (56 %).

Examensarbetet styrker riktigheten i ECCABS-modellens resultat vad gäller teknisk potential, liksom modellens tillämpbarhet inom olika nationers fastighetsbestånd. Modellen är ett relativt snabbt redskap vid undersökning av olika energibesparingsåtgärder och kan användas för grova utvärderingar av kostnadseffektiviteten hos tilltänkta energipolicys.

Nyckelord: energisimulering, franska fastighetsbeståndet, energibehov, bottom-up modellering, koldioxidutsläpp, kostnadseffektivitet

Contents

Preface

The thesis has been carried out from January to June 2013 at the Department of Energy and Environment, Energy Technology, Chalmers University of Technology, Sweden.

The work is performed by master students Tri-Cang Dinh and Hanna Lundevall, with PhD student Érika Mata as supervisor. All work has been carried out in the offices of the Department of Energy and Environment at Chalmers University of Technology. The project has included thoroughly collaboration between Dinh and Lundevall and thus no distinct individually conducted parts may be defined.

We would like to thank Tillman Gauer for his co-operation and involvement. Special thanks to Érika who has guided us through our work.

Göteborg May 2013

Tri-Cang Dinh

Hanna Lundevall

Notations and Definitions

Roman upper case letters

AC	Abatement cost for mitigating CO_2 emissions
Ac	Average constant heat gain from appliances; i.e. electricity consumption
$Bbio$	Energy efficiency of a building regarding heating, cooling, lighting, insulation, solar transmittance and air permeability
CE	Unit cost per energy saving
CI	Carbon intensity
Cp	Heat capacity of the building envelope
Ef	Efficiency of certain device
EP	Energy price
$H\mathrm{Re}cEff$	Efficiency of Heat recovery System
Hw	Energy demand for hot water production
HyP	Energy consumption of hydro pumps
Lc	Average constant heat gain from lighting; i.e. electricity consumption
N	Time period of scenario
n	Lifetime of investment = lifetime of measure
Pc	Response capacity of the cooling system
Pfh	Heat losses of the fan
Ph	Response capacity of the heating system
P	Percentage (share) of a certain device
P_Sh	Percentage of a certain device used in space heating
R	Interest rate of investment
r	Discount rate of investment
Sc	Maximum hourly capacity of the cooling system
SFP	Specific Fan Power
Sh	Maximum hourly capacity of the heating system
$Sdoor$	Total door surface
$Sfloor$	Total external floor surface (Sbg)
$Sroof$	Total external roof surface (Sr)
Sw	Total window surface
$Swall$	Total external wall surface (Sag)
$T\max$	Maximum acceptable indoor temperature
$T\min$	Minimum acceptable indoor temperature
Ts	Window solar transmittance coefficient
Tv	Natural ventilation; tint for opening of windows
U	Mean U-value for the whole building
$Udoor$	U-value for door
$Ufloor$	U-value for floor (ground)
$Uroof$	U-value for roof
Uw	U-value for window
$Uwall$	U-value for wall
Vc	Sanitary ventilation rate
Vcn	Natural ventilation rate
W	Weighted; all buildings of each subtype are included

Abbreviations

$ECCABS$	Energy, Carbon and Cost Assessment for Building Stocks

The residential subsector’s subtypes:

$R1 = SFD$	Single Family Dwelling
$R2 = \Pr ivMFD$	Private Multi Family Dwelling
$R3 = PubMFD$	Public Multi Family Dwelling

The tertiary subsector’s subtypes:

$NR1 =$	Offices
$NR2 =$	Commercial
$NR3 =$	Education
$NR4 =$	Health
$NR5 =$	Sport, Culture, Leisure

Definitions

99 Building archetypes
3 residential subtypes x 18 building archetypes = 54 residential building archetypes
5 tertiary subtypes x 9 building archetypes = 45 non-residential building archetypes

H1, H2 and H3
France’s three climatic winter zones

Metropolitan France
The area of France located in Europe; does not include the overseas territories.

Residential sector
Buildings where >50% of the gross area is used for dwelling (households).

Non-residential sector = tertiary sector
In this thesis, the word non-residential only includes the tertiary sector. They represent buildings where <50% of the gross area is used for dwelling and do not include industrial or agricultural buildings, nor warehouses. In this thesis, no dwellings are assumed in the tertiary sector.

Primary energy
The energy of raw fuels arriving at the energy plant

Delivered energy = Final energy
The energy arriving at the building

Net energy
The energy that is theoretically consumed by the building

1 tonne of oil equivalents (toe) = 1 tonne d'équivalent pétrole (tep) = 42GJ

1 Introduction

This master's thesis is being a part of a European project focusing on the energy saving potential of the European building stock and addresses the building stock of metropolitan France. The following chapter presents the background, context, aim and structure of the thesis.

1.1 Background

With today's economic and population growth leading to increasing energy use and greenhouse gas (GHG) emissions, the 2°C target of climate change as well as fuel security is a worldwide challenge. The EU has agreed upon its climate target for the year 2020, where it shall:

- decrease its carbon dioxide (CO_2) equivalent emissions by 20% in relation to year 1990
- extract 20% of the energy from renewable energy sources
- increase its energy efficiency by 20%

From the European Commission, these targets are translated into the following figures for France (EC, 2011):

- decrease its CO_2 emissions by 14% in relation to 1990[1]
- extract 23% of the energy from renewable energy sources
- reduce its energy use by 34 million tonnes of oil equivalents (Mtoe)[2]

In 2010, France had decreased its CO_2 emissions by 7% (Eurostat, 2012c), but in order to reach its 14% target as defined in the first goal above, there is a need for further measures to be taken. By looking at the CO_2 emissions released by the French electricity and heat production, respectively, the focus for future measures should be on reducing the heat consumption of the country, see Figure 1.

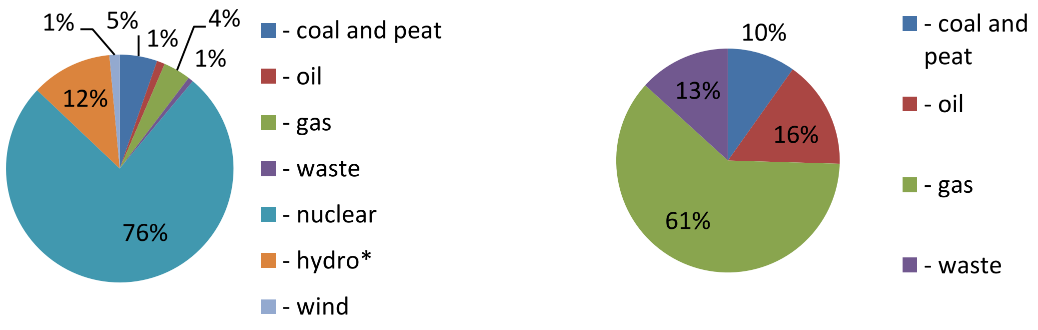

Figure 1 Electricity production in France 2009 (left); 542TWh (IEA, 2009). *Includes production from pumped storage plants. **Figure 1b Heat Production in France in 2009 (right); 44,4TWh (IEA, 2009)**

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[1] Emissions covered by the Emissions Trading System (ETS) shall be reduced by 21% compared to 2005 levels

[2] 34Mtoe = 1428PJ = 397TWh ≈ 20% reduction from today's energy use

Since almost 90% of the electricity is produced from nuclear and hydro power, it may be considered as low-emissive. On the other hand, the heat is produced mainly from carbon intensive energy sources such as gas and oil.

In 2011, the total final energy consumption of France was 157,7Mtoe[3] and the country was ranked 11th in the world when it comes to total primary energy consumption; 3160TWh (EIA, 2013).

1.2 The building sector in France

While in Europe, the objective is to reduce the GHG emissions by a factor of 2 to the year 2050, the French government has committed to divide its GHG emissions by 4 (with 1990 as baseline); an environmental commitment called "Factor 4".

With 70Mtoe[4] of primary energy consumed per year, the building sector in France represents 44% of the total final energy consumption of the country, see Figure 2, and is therefore of great importance when it comes to energy saving measures (ESM). Furthermore, 120Megatonnes of CO_2 is emitted from the building sector each year, which equals to 25% of the national emissions.

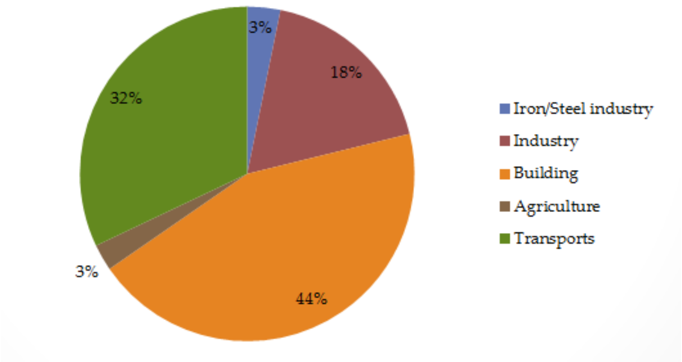

Figure 2 Share of final energy consumption in France in 2011 (Chiffres clés de l'énergie, 2012).

The French building sector is known for being slow to evolve, especially due to high construction costs. While the existing building stock accounts for around 30 million dwellings, only 350 000 dwellings, or about 1%, are constructed each year[5]. For the tertiary sector which today accounts for 814Mm^2 of heated area, only 22Mm^2 of heated area, less than 3%, are built annually (ADEME, 2011). Further, over 18 million of the existing dwellings were established before 1975; date of the first thermal regulation, and represent a significant potential for energy savings. Thus, the building sector is today considered the key for achieving the Factor 4 goals, with a growing focus on the existing stock (Charlot-Valdieu & Outrequin, 2011). The *Plan Bâtiment Grenelle* scheme was established in 2007 and aims at reducing the primary energy consumption of the existing building stock by 38% by the year 2020 (with 2008 as baseline). *Plan Grenelle* includes measures such as retrofitting of buildings but also specific regulations (Mission Plan Bâtiment Grenelle, 2011), see Chapter 2.3.

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[3] 157.7Mtoe = 1840Twh

[4] 70Mtoe = 816TWh

[5] In Sweden, this figure is about 0.5% (SCB, 2012)

In Table 1, the features of the French building stock are summarized.

Table 1 Features of the French building stock (ADEME, 2011), (Charlot-Valdieu & Outrequin, 2011).

Residential	***Non-Residential***
• Final energy consumption: 423TWh • In 2011, oil and gas prices increased by 29% and 12%, respectively • 63% of final energy use allocated to heating (mostly electricity, gas and oil); 12% for hot water production (mostly electricity, gas and oil) • Decreasing consumption of oil and gas; increasing electricity use • 96% of dwellings; centralized heating system • Stagnation of solar thermal collectors sales • Decrease of heat pumps sales	• Offices, commercial and education sectors represent >60% of heated area • Final energy consumption stable around 225TWh/yr; significant share of electricity

The most recent French political incentives related to the building sector are focusing on increasing the new construction rates. Further, they force a two years pause onto the introduction of new construction norms, since these have largely increased the costs and prolonged the construction time for new buildings. When it comes to reducing the energy demand, the focus is on the residential sector, where the plan is to increase the thermal renovation of multi-family dwellings by a factor of four to reach an annual renovation rate of 120 000 dwellings in 2017. Also, a subsidy for thermal renovation of dwellings will enter into force in 2014.

1.3 Context of the thesis

The international project called *Pathways to Sustainable European Energy Systems* started in 2007 and is collaborations between academia and industry for assessing and evaluating different options to meet targets set on energy efficiency, CO_2 emissions and renewable energy sources by the year 2020. The work is conducted on a long-term basis and its goal is to define and illustrate possible pathways towards a sustainable future.

As a part of the work package No. 4, *Households and Services*, future energy use scenarios of the European building stock are assessed. Since France has one of the six biggest building stocks in Europe, it is of interest to evaluate its energy saving potentials. Apart from France, six additional countries are being assessed in the project; Sweden, Germany, Italy, Poland, Spain and the UK. In 2009, these six countries accounted for about 70% of the energy consumption by residential, commercial and public services in the EU-27 region (IEA, 2009).

Chalmers University of Technology is taking part in the EU project by assessing the possibility of creating a code for evaluating the energy saving potential of a country’s building stock. A bottom-up model was developed by Érika Mata, namely the Energy, Carbon and Cost Assessment for Building Stocks (ECCABS), and was first implemented on the Swedish building stock for which it gave satisfying results (Mata, 2011). Previous master's theses have examined the availability of data for the French building stock (Gravalon, 2007), (Martinlagardette, 2009) and gathered the baseline parameters for evaluating its present energy consumption and CO_2 emissions (Ribas Portella, 2012).

1.4 Aim of the thesis

This thesis investigates the potentials and costs for energy savings and CO_2 emissions reductions in the French building stock, based on previous work which described the French building stock using archetype buildings. A secondary aim is to validate the applicability of the ECCABS model to all EU countries. The work aims specifically at:

- Identifying and assessing different energy saving measures (ESM) with respect to the measures presented in the European Pathways project and to today's French regulation
- Evaluating the ESMs' potential to reduce the energy demand and to mitigate the CO_2 emissions of the building sector; the so called technical potential
- Evaluating the ESMs' cost-effectiveness; the so called techno-economic potential

1.4.1 Boundary conditions

This thesis only addresses net and final energy demands. Primary energy is not taken into consideration and therefore some ESMs that would be possible to implement in a wider scope are not investigated.

Only the existing building stock is investigated and therefore construction and demolition is not considered. Moreover, national protected monuments are not being separated from regular buildings even though this may affect the possibility of implementing a certain ESM.

Only CO_2 emissions are considered. Emissions created from producing and implementing the measures is not included.

When the measures are assessed separately, synergies are not being further considered.

Cooling demand is not considered in this thesis' simulations; only heating demand.

Behavioural issues and life style changes as well as rebound effects are not taken into consideration in the simulations and are subsequently not being further investigated in this thesis.

Effects on the potential application of measures caused by expected future changes in climate are not considered.

1.5 Structure of the report

The report structure starts with an introduction of the main sources and references used for gathering the data required. In Chapter 3, the concept and usage of the ECCABS model is defined. Methodologies for selecting input parameters for the ESMs, prices and CO_2 emissions data respectively are explained.

In Chapter 4, the results from running the ECCABS model are presented. A sensitivity analysis in Chapter 5 is presenting the most critical parameters found when running the model with respect to their effect on the cost-effectiveness of each measure. Here, the energy prices and the discount rate are assessed respectively.

Chapter 6 includes the discussion part, where the results and their relation to other literature data are being assessed.

Finally, Chapter 7 gives overall conclusions as well as some advices regarding further work in the field.

2 Data Sources

This chapter presents the main data sources used in this thesis and what input data are taken from each source. The sources are presented in alphabetical order.

2.1 Institutions

The institutions consulted are:

- **Agence de l'Environnement et de la Maîtrise de l'Energie, (French Environment and Energy Management Agency), ADEME**

  ADEME is a French public agency engaging around 820 employees and is answering to the Ministry for Ecology, Sustainable Development and Energy; and the Ministry for Higher Education and Research. The agency focuses on coordinating and supervising the management and protection of energy and the environment within its main priority areas; energy, air, transport, waste, noise, polluted soil and environmental management.

  ADEME is the source to the background data of hot water production and lighting measures. Also, it is used as reference when assessing the accuracy of the simulations results for insulation measures (roof, walls and windows).

- **Agence nationale de l'habitat, (National Housing Agency), ANAH**

  Created in 1971, ANAH is a public State institution that works with enforcing the national politics regarding development and amelioration of the private building stock. The agency is granting subsidies to landlords, tenants and part-owners, thereby creating possibilities to help citizens with the least means. ANAH works on a local level and is represented in each department.

  The costs for insulation are found in the ANAH source.

- **Centre National de la Recherche Scientifique, (National centre for scientific research), CNRS**

  The CNRS is a French public institution conducting technical, scientific and societal research under the Ministry of Higher Education and Research. With its 34 000 employees and a budget of around €3.4 billions, its 10 institutes are present in all of the major disciplines of research. The cooperation between the CNRS and the university responds to the demands and needs of the society and the economy. One of the main interdisciplinary fields with which the CNRS is working, is Environment, Energy and Sustainable Development.

On the CNRS website, the French Working Norm NFX_35-1211 is found from which the minimum acceptable indoor air temperature, Tmin, is taken.

- **Centre Scientifique et technique du Bâtiment, (Scientific and technical centre for buildings), CSTB**

  Formed in 1947, CSTB is a public institution under the guardianship of the Minister of Housing and the Minister of Ecology, Sustainable Development, Transports and Housing. The main focuses are research, expertise, evaluation and the communication of knowledge across the international building sector, covering construction products, buildings as well as their integration into the surrounding society. With national, European and international partners, CSTB has got 909 collaborators working for ameliorated quality and security of the buildings.

  In this thesis, the CSTB is consulted when defining the potential electricity savings from lighting measures; Lc.

- **Federation of European Heating, Ventilation and Air-Conditioning, REHVA**

  REHVA represents a pan-European network of more than 100 000 engineers and 26 different nations. The organisation works for the improvement of health, comfort and energy efficiency in buildings and different communities.

  The potential savings from introducing heat recovery units are connected to this source.

- **International Energy Agency, IEA**

  The IEA was founded during the 70’s to help countries with their oil supply during the oil crisis in 1973-74. The agency is a sovereign organisation and has 28 member countries. Its main areas of focus are: energy security, economic development, environmental awareness, and engagement worldwide. France joined the IEA in 1992.

  IEA was consulted when gathering information on the energy sources for electricity and heat production in France. Further, the potential savings referring to appliances are also taken from this source.

2.2 Databases

The databases consulted are:

- **Database on Energy Saving Potential, ESP**

  This database offers energy saving potentials for EU Member States, Croatia, Norway, Iceland and Liechtenstein. It is created by a project team including Enerdata; ISIS; Fraunhofer; Science Centre North Rhine-Westphalia; Wuppertal Institute for Climate, Environment and Energy; and Energy Economics group.

  ESP was consulted to assess the accuracy of the simulation results when it comes to ESMs including ventilation upgrading; appliances; lighting; and boilers, respectively.

- **Eurostat**

  Eurostat was established in 1953, is a Directorate-General (DG) of the European Commission and is the statistical office of the European Union. Eurostat is providing the European Union, the Commission, EMU, other DGs and other European institutions with statistical figures and reports.

  In this report, Eurostat is chosen as data source for the energy prices.

- **Eurelectric**

  Eurelectric, the Union of the Electricity Industry, is a sector association representing the whole electricity industry at a pan-European level. The members are today representing 32 European countries and the work is carried out in expertise working groups, supervised by five committees. The major focuses of Eurelectric are to enlarge the share of carbon neutral electricity in Europe; to ensure a cost-efficient and reliable supply; and to mitigate the climate change by developing the demand side in a sustainable manner. The work of the association is presented in policy papers and reports; at debates and at conferences.

  One of the 30 working groups, Eurprog, is chosen as a source for the carbon intensities used in this thesis.

- **Odyssee**

  Energy efficiency data and indicators for the 27 European Union member states plus Norway and Croatia are assembled in the Odyssee database by the European Commission and 26 European national efficiency agencies. The around 150 sources include for example statistical institutions, governmental ministries, associations and research institutes.

  The Odyssee database was consulted for the stock and electricity consumption numbers of the appliances; Ac.

2.3 Policies and regulations

Below follows a review of the policies and regulations that are being used in this thesis. New residential buildings were subject to the regulations in 1974, while non-residential buildings are regulated since 1977.

- **Code de l'Environnement, CE**

  The CE gathers juridical texts regarding French environmental laws and is being regularly updated. The code consists of seven different books, the first five being: *Dispositions communes* – Shared environment; *Milieux physiques* – Physical environment; *Espaces naturels* – Natural spaces; *Faune et flore* – Fauna and Flora; *Prévention des pollutions, des risques, et des nuisances* – Prevention of pollution, risks and disturbances.

  The sixth book is applicable in New Caledonia, French Polynesia, Wallis and Futuna, the Southern and Antarctic French territories and at Mayotte.

  The last book deals with the protection of the Antarctic environment (French gouvernment, u.d.).

  From the Environmental Code, the minimal performances for boilers are being used when calculating the energy demand for hot water production, Hw.

- **EC Directive 66/2003**

  The 2003 European Commission Directive No.66 has been used for defining the efficiency potential of energy consumption in new appliances, Ac.

- **EC Directive 641/2009**

  The 2009 European Commission Directive No.641 has been used for defining the operational regulations for hydro pumps, HyP, so called circulators.

- **EC Regulation 327/2011**

  The 2011 European Commission Regulation No.327 has been used when finding new figures for the specific fan power, SFP, and the heat losses of the fan, Pfh.

- **Energy Efficiency for Buildings — Standard economic evaluation procedure for energy systems in buildings**

  This European Commission report was used for defining lifetimes of the measures as well as additional maintenance costs (EU, 2006).

- **Le Grenelle de l'Environnement, (Grenelle Environment Forum)**

  This forum was initiated by the French president Nicolas Sarkozy, with the goal to define the main pathways for the governmental policies regarding ecological and sustainable development. In 2007, four round tables gathered civilian and public service representatives, represented by the state, unions, employers, NGOs and local authorities. In 2010, the Parliament adopted the engagements denoted by the forum reports (Ministry of Ecology, 2013).

  The Grenelle Environment Forum has added to the information on the environmental situation of and future goals for France.

- **Réglementation Thermique 2000, RT 2000**

  This thermal regulation was taken into practise in June 2001 and concerns all new construction permits regarding residential and services buildings. It aims at reducing the energy consumption by 20% in the residential sector, and by 40% in the services, non-residential, sector. Also it focuses on improving the indoor climate in non-air conditioned buildings during summer season. Thus, it imposes three requirements: maximum energy consumption; maximum indoor temperature during summer season; and minimum performances of a series of building components (e.g. insulation, heating system etc) (CSTB, u.d.).

  The heat recovery efficiency figures, HRecEff, are taken from this regulation.

- **Réglementation Thermique 2005, RT 2005**

  This thermal regulation was being enforced in September 2006 and is a continuation to the RT 2000. The regulation is applicable to both residential and services buildings and embraces three issues concerning the construction of buildings; the global, social and economic matters. The global issue concerns the goals set by the Kyoto protocol and the RT 2005 implements the Climate Plan of 2004 "*le Plan Climat 2004*", which regulates the energy performance and specifies the objectives of the thermal regulations for new buildings. These objectives include an improvement of energy performance of new buildings of at least 15%; limitations concerning air conditioning; and the control of electricity demand. Further, there are three requirements set for new buildings; energy efficiency; climatic comfort during summer; and some specific “safeguards” (Developpement Durable, 2006), (RT bâtiment, u.d.).

The RT 2005 has been used for updating lighting electricity consumption, Lc, and U-values.

- **Réglementation Thermique 2012, RT 2012**

The objective of this thermal regulation is to limit the primary energy consumption of new buildings constructed after October 2011; the maximum limit of primary energy consumption is set to $50kWh/m^2$,yr. The new buildings should also from now on comply with the following requirements: significant technical evolution of building components and appliances; high energy systems quality; and a technical and economic equilibrium between energy being used for heating and for hot water production, respectively. The RT 2012 was influenced by and obtained in parallel with the Grenelle Environment Forum (RT bâtiment b, u.d.).

The RT 2012 was used when defining new values for the lighting energy consumption, Lc, as well as the window solar transmittance, Ts.

3 Methodology

This chapter presents each of the energy saving measures assessed. Each subchapter includes a brief literature review on the components of the measure; the last chapters presenting the costs needed for implementing it.

3.1 The ECCABS model

The modelling tool used in this project is called *Energy, Carbon and Cost Assessment for Building Stocks* (ECCABS) and is based upon a MATLAB code and a Simulink model. The Simulink model solves the heat balance equations and formulas describing the building's characterisation factors, while the MATLAB code handles the input and output data. For the input data see Appendix A.

For a more detailed description of the models used see (Mata & Kalagasidis, 2009) for the Simulink model and (Mata, et al., 2012) for the ECCABS model. The output of the ECCABS model run with baseline figures, i.e. today's characterisation figures, shows the net energy and the final energy demand as well as the CO_2 emissions released. The output of the ECCABS model using our new input figures, presents values on net energy and final energy saved, as well as CO_2 emissions avoided. The ECCABS model also gives the direct cost and reflects the cost-efficiency related to each of the measures and building archetypes assessed.

Concisely, the simulation part of the thesis consists of an adaptation of the model to comply with the French building stock's characteristics and changes made in the Excel input files, followed by an analysis part where the Excel output files are being assessed in comparison to the baseline values.

3.2 Baseline

The baseline year of this thesis is based on previous master's thesis (Ribas Portella, 2012). However, the baseline's result for final energy consumption of this thesis is differing somewhat compared to the result of Ribas Portella (2012). This is due to several changes made in the baseline input values, amongst other depending on new values in the French regulation *Code de l'Environnement* (Republique Francaise, 2013). Input parameters that have been changed in relation to Ribas Portella's baseline input data are the following:

- Energy efficiencies of different boilers
- CO_2 emissions from each energy source, see Table 2
- Energy prices of 2012, see Chapter 3.5
- Heat losses of the fan, see Chapter 3.3.2

Still, the difference in baseline result of this thesis compared to other reference sources such as ADEME and CEREN can be considered as adequate, see Table 3.

Further, the same fuel shares were used for space heating as for hot water production.

The baseline maintenance cost is set to zero.

CO_2 emissions

The electricity production in France emitted 369.7gCO_2/kWh in 2009, a small increase compared to the 2008 figures (368.47gCO_2/kWh). The Eurelectric website Power Statistics and Trends, explains this trend as follows:

"*A possible explanation could be the increasingly flexible operation of the fossil-fired fleet enforced by the deployment of variable RES* (Renewable Energy Sources, authors' comment). *Faced with more frequent starts and stops as well as more frequent part-load operations, thermal power plants become less efficient and emit more CO_2*" (Eurelectric, 2011)

The carbon intensities are assumed to be constant over time and are estimated using two sources:

- Statistics for the union of the electricity industry Eurelectric (EURPROG, 2007)
- The official law text (Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)

For district heating, an average value of carbon intensity has been calculated according to the values provided for each French region in the law text, Appendix 7, Table "*Évaluation du contenu en CO_2 des réseaux de chaleur et de froid*" (Ministry of Ecology, Sustainable Development, Transports and Housing, 2012).

Table 2 Carbon intensities per energy carrier for France in 2012 in [kgCO_2/kWh]. NB. The Carbon intensity for other sources, CIa, is a calculated average value. *See explanation below.

	Description	*Carbon intensities*	*Source*
$CIEl$	Carbon intensity of Electricity	0.057*	(EURPROG, 2007)
CIo	Carbon intensity of Oil	0.300	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
CIg	Carbon intensity of Gas	0.230	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
$CIbw$	Carbon intensity of biomass + waste	0.013	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
CIc	Carbon intensity of coal	0.342	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
$CIdh$	Carbon intensity of district heating	0.172	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
CIa	Carbon intensity of other fuels	0.176	Calculated average value

*The electricity production in France in 2005 emitted 31 100 kilotons of CO_2. The same year, 549.8TWh of electricity was produced (EURPROG, 2007). This means that the carbon intensity (CI) of electricity in 2005 was:

$$\mathrm{CI}_{\mathrm{el}}^{2005} = \frac{31100 * 10^{6}\,[\frac{\mathrm{kgCO_2}}{\mathrm{yr2005}}]}{549.8 * 10^{9}[\frac{\mathrm{kWh_{el}}}{\mathrm{yr2005}}]} = 0.057\,[\frac{\mathrm{kgCO_2}}{\mathrm{kWh_{el}}}] \qquad \text{Equation 3.1}$$

According to the official law text from Feb 7 2012; "*Journal Officiel de la République Française*", the carbon emissions produced by electricity from non-renewables range between 0.180 and 0.040kgCO_2/kWh. Thus, our new figure in Equation 3.1 seems adequate if assuming that only 11%[6] of the French electricity is produced by non-renewable fuel sources which would then result in 0.0554kgCO_2/kWh (IEA, 2009).

Baseline results

The baseline results are presented in Figure 3. These figures show the energy consumption in the French building stock with no energy saving measures implemented.

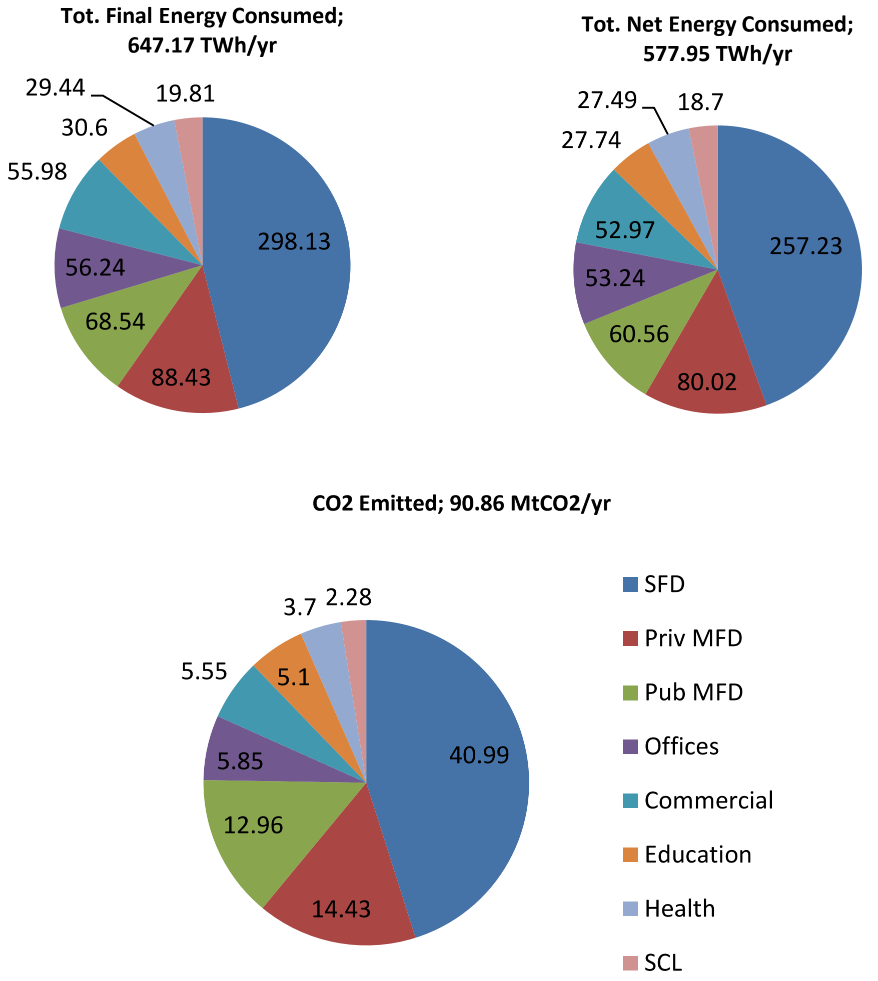

Figure 3 Baseline energy consumption and CO_2 emissions with updated input values.

The net energy figures are corresponding with the ones presented in previous thesis, while the total final energy consumption of the residential sector gives a 6.1% difference (Ribas Portella, 2012). For the non-residential sector this difference is 3%.

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[6] See Figure 1a.

Below 5% is seen as adequate. The figure for the residential area can be seen as accurate since comparing with the ADEME source referred to by Ribas Portella (2012) gives a difference of only 2.8% (Ribas Portella's value differs with 8.7% compared to ADEME), see Table 3. The variations are probably due to the changes mentioned in Chapter 3.2, as well as changes made in the MATLAB code, see Appendix H.

Table 3 Annual total final energy consumption for both residential and non-residential sector, according to each specific source, see (Ribas Portella, 2012). A variation of less than 5% is seen as acceptable.

Source	***Residential*** *[kWh/m²]*	***Difference to old Baseline of***	***Non-residential*** *[TWh]*	***Difference to old Baseline of***
New Baseline	205.2		191.75	
Ribas	192.7	6.1%	186.3	3%
ADEME	211.1	2.8%		
CEREN			188.3	2%

The residential sector's final energy use; 455.1TWh, correlates by 2.2% with the 2011 figure of Enerdata; 445TWh (Enerdata, 2013).

If summing up the total final energy consumption of both residential and non-residential sectors; 646.85TWh/yr, it goes well in hand with the figures presented in Table 1, Chapter 1.2, which gives a sum of 648TWh/yr.

CO_2 emissions from the building sector reached 92Mt in 2009 (Charlot-Valdieu & Outrequin, 2011), which correlates by 1% difference with the emissions obtained in this thesis's simulations; 90.86MtCO_2.

3.3 List of ESMs assessed

To give a clear overview, the energy saving measures applied in the thesis are listed below, see Table 4.

Table 4 Energy Saving Measures extracted from (Mata, et al., 2013) and related abbreviations of parameters affected in the further work of this thesis. The insulation measures only refer to the external building envelope. [a] Regulation of working schedule.

ESM	***Description***	***Input parameters affected***
1	Insulation of floor	Ufloor
2	Insulation of roof	Uroof
3	Insulation of walls	Uwall
4	Replacement of windows	Uw, Ts
5	Upgrading of ventilation system	SFP, Pfh
6	Introduction of heat recovery units in households	HRecEff, SFP
7	Appliances efficiency	Ac
8	Lighting efficiency	Lc
9	Hot water production; efficiency	Ef_O, Ef_W
	Hot water production; energy source	P_Sh_O, P_Sh_W, P_Hw_O, P_Hw_W
10	Upgrading of hydro pumps[a]	HyP

To define the most efficient ESMs, new figures are needed as input data for the Excel input files of the ECCABS model. In each of the subsequent chapters, the input parameters presented in Appendix A are assessed and possible changes are being addressed. In the following presentation of the input data to the ECCABS model, the parameters are allocated into the ESM categories presented in Table 1. There are two different types of measures; one reducing the energy demand; and one increasing the efficiency. ESMs 1-4 are reducing the demand for energy, while ESMs 5-10 are increasing the efficiency of the device assessed.

In the report article (Sadineni, et al., 2011), different ways of retrofitting the building envelope and components are investigated and compared to their respective energy saving potentials. Furthermore, different measures are divided into active or passive strategies, respectively. On the one hand, energy saving measures that improve energy efficiency in relation to heating, ventilation, air conditioning systems (HVAC), electrical lighting and appliances are named “active strategies”. By these measures, the consumers can influence their own energy consumption. On the other hand, measures for improvement of the building envelope are classified as “passive strategies”, i.e. the energy demand of the building is decreased without any direct influence of the consumers. This same division is used to describe the ESMs assessed in this thesis. Hence, ESMs 1,2,3,4 are related to insulation and thus passive measures, while the rest are active measures.

Today's renovation situation in France's residential sector is illustrated in Figure 4, where the shares of each of the retrofitting measures are presented. Here one can see that today's focus of the households is on passive measures (72%) with windows representing the biggest share.

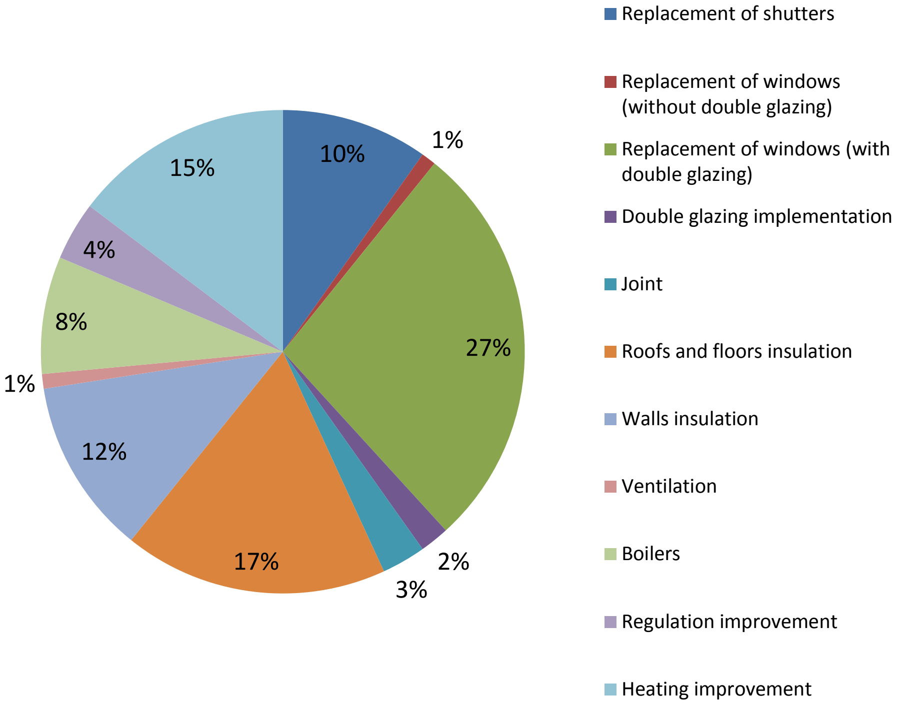


Figure 4 Share of retrofitting measures in the French residential sector (ADEME, 2011)

3.3.1 Retrofitting building envelope by insulation

The ESMs for insulation assume an upgrade of the U-values as given in the thermal regulation RT 2005.

According to ADEME, walls make a significant part of the building envelope and they provide noise and thermal insulation associated with the aesthetics of the building. After the roof, walls have the second biggest energy losses; the ones facing the north are to be prioritized as they are less subject to solar radiation. In France, internal insulation for walls is mostly used when retrofitting is needed. Insulation of the ground is essential, especially when situated above a non-heated basement, since around 8% of the heat losses take place through the floor (ADEME, 2008), see Figure 5.

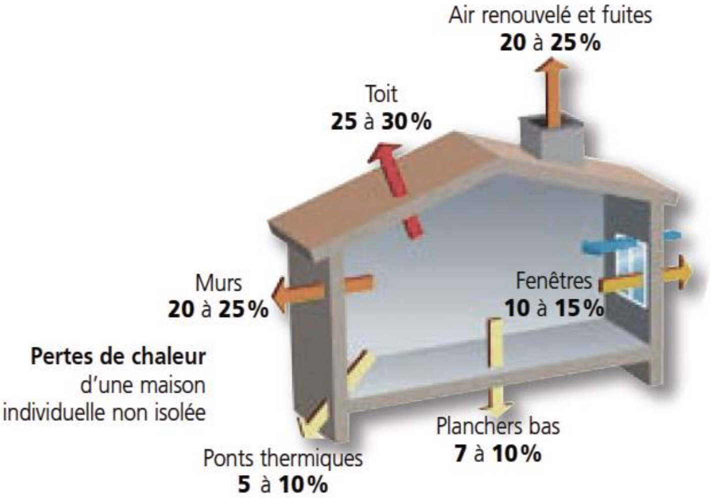


Figure 5 Heat losses in an SFD (ADEME, 2008). *Toit* (roof), a*ir renouvele et fuites* (exhaust air and leakage), fenêtres (windows), *planchers bas* (ground), p*onts thermiques* (thermal bridges), m*urs* (walls).

The French thermal regulation RT 2012 does no longer use the U-value parameter, but only takes into account the insulation of the building envelope. Instead, the new regulation replaces the U-values by another parameter called "B_{bio}". B_{bio} is a point system which rates the energy efficiency of the building regarding heating, cooling, lighting, insulation, solar transmission and air tightness. In order to be consistent with previous thesis and to comply with the ECCABS model, the RT 2005 is used as a first option for new U-values.

In order to calculate the outcomes of each insulating ESM, a reference U-value for each component of the archetype building is provided by the RT 2005 (Ministère de l'emploi, de la cohésion sociale et du logement, 2006), see Table 5.

Table 5 Reference U-values, used as new values in this thesis' simulations, for residential and non-residential buildings [W/m2] (Ministère de l'emploi, de la cohésion sociale et du logement, 2006). The left hand U-value for windows, Uw, is for residential and the right hand for non-residential sector.

Climatic Zone	***Udoor***	***Ufloor***	***Uroof***	***Uw***		***Uwall***
H1	1.5	0.27	0.2	1.8	2.1	0.36
H2	1.5	0.27	0.2	1.8	2.1	0.36
H3	1.5	0.36	0.25	2.1	2.3	0.4

The minimum thermal requirements stated above are only mandatory for new buildings. However, it is assumed that the values chosen for the ESM are applied to the whole building stock, including existing buildings. Hence it enables an estimattion of the potential energy savings when meeting the minimal requirements set by national regulation.

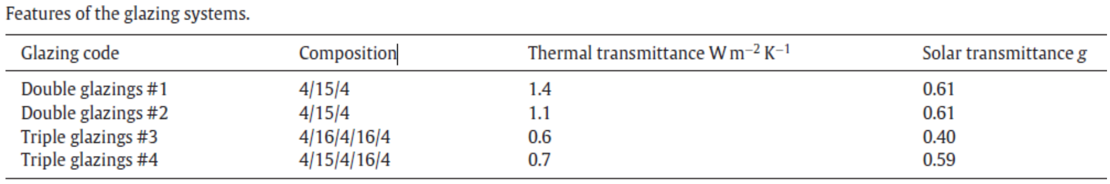
Looking at the U-value of the windows, the corresponding technologies are presented below (Verbeeck & Hens, 2004), where 5 types of insulated window technologies are being analyzed:

- Triple glazing;	Uw=2.0 W/m^{2}K
- Low e-glazing, air filled;	Uw=1.8 W/m^{2}K
- Low e-glazing, argon filled;	Uw=1.3 W/m^{2}K
- Low e-glazing, krypton filled;	Uw=1.1 W/m^{2}K
- Highly insulated glazing;	Uw=0.6 W/m^{2}K

For this thesis, air filled low e-glazing (Uw 1.8W/m^{2}K) and triple glazing (Uw 2.0W/m^{2}K) corresponds to the U-values presented in Table 4 and used in this thesis' simulations.

A window's energy performance depends on three main characteristics; glazing solar transmittance (Ts), thermal transmittance (Uw), and the frame's air leakage and installation air tightness. Other influencing parameters concern window sizes as well as the orientation of the windows on the building. Evidently, the thermal energy balance of a building is affected during the whole year, both in summer and winter. Thus, lowering the solar transmittance of the windows will reduce the solar gains and decrease the cooling demand during summer. However, the reduced solar gains may potentially lead to an increasing demand for heating during the winter period. Normally, an effective thermal insulating glazing; triple glazing, will also give a reduced solar transmittance (Gasparella, et al., 2010).

The baseline value for window solar transmittance, Ts, is set to 70% (0.70) in previous thesis (Ribas Portella, 2012). According to Gasparella et al (2010), this value may range between 0.40 and 0.61, referring to triple glazing and double glazing, respectively, see Figure 6. Looking into the RT 2012 bylaw, Chapter V Article 21, a new input value of 0.45 is chosen for this thesis (Ministère de l'Ecologie, 2010). However, this regulation also uses geographical altitudes to characterise the different building archetypes and therefore a correct implementation of its figures is hard to achieve.



Features of the glazing systems.

Glazing code	Composition	Thermal transmittance W m^{-2} K^{-1}	Solar transmittance g
Double glazings #1	4/15/4	1.4	0.61
Double glazings #2	4/15/4	1.1	0.61
Triple glazings #3	4/16/4/16/4	0.6	0.40
Triple glazings #4	4/15/4/16/4	0.7	0.59

Figure 6 Features of the glazing systems (Gasparella, et al., 2010).

When running the simulation for this specific measure, both Ts and Uw are changed in the input file as they are interrelated. For Uw, see Chapter 3.4.1.

Finally, the heat capacity of the building envelope, Cp, is not changed, referring to former sensitivity analysis in which the Cp values are shown to have low contribution to the energy output (Ribas Portella, 2012).

3.3.2 Upgrading of ventilation system

This ESM assumes that the existing ventilation systems are replaced by more efficient ones according to European Commission regulations presented below.

In previous thesis only buildings constructed after 1975 are provided with mechanical ventilation (Martinlagardette, 2009), (Ribas Portella, 2012).

The natural ventilation rate (Vcn) is unchanged, since it is a natural mechanism. The same decision is made for the sanitary ventilation (Vc) rate, since it is controlled by national regulations.

The baseline values for Specific Fan Power (SFP) and the heat losses of the fan (Pfh) set by Ribas Portella (2012) are published by the RT 2000, RT 2005 as well as the XPair website (XPair, 2012). If using the European Commission's regulation No. 327/2011; Annex IV Table 1, the fan efficiency benchmarks required are ranging between 0.32 and 0.75 (EC, 2011). These values are then implemented in the Equation 3.2 and 3.3, with the highest efficiency for the health subsector and the lowest efficiency for the rest of the building subtypes.

$$Losses = \frac{Power*(1-Effref)}{A} \qquad \text{Equation 3.2}$$

$$SFP = \frac{Pressure\ drop}{3600*Effref} \qquad \text{Equation 3.3}$$

Due to an error in former calculations where the transformation into kWs/m^3 is miscalculated, the baseline values are recalculated and changed. The area for the residential sector is now set to 110m^2. The same pressure drop is used for residential as for non-residential sector. The new figures on heat losses and SFP, both for the new baseline and for the measure when replacing the fan with a more efficient one, are shown in Table 6.

Table 6 New calculated baseline values (base) and values for ESM5 where the fan is replaced with a more efficient one. Eff = Efficiency; Pres drop = Pressure drop. * The new SFP for residential sector is calculated using an average difference of the non-residential old and new SFPs.

	Power [W]	*A [m^2]*	*Eff OLD [%]*	*Pfh base [W/m^2]*	*Eff NEW [%]*	*Pfh NEW [W/m^2]*	*Pres drop [Pa]*	*SFP OLD [kWs/m^3]*	*SFP NEW [kWs/m^3]*
R	81	110	20	0.1636	32	0.1391	475	0.9	0.594*
NR1	1374	1000	20	0.3053	32	0.2595	475	2.3750	1.4844
NR2	851	233	20	0.8116	32	0.6899	475	2.3750	1.4844
NR3	757	1489	20	0.1130	32	0.0960	475	2.3750	1.4844
NR4	4863	4167	60	0.1297	75	0.0810	475	0.7917	0.6333
NR5	297	605	20	0.1091	32	0.0927	475	2.3750	1.4844

3.3.3 Introduction of heat recovery units in households

This ESM assumes that heat recovery systems are introduced in all of the French households.

According to Juodis (2005), the heat recovery efficiency may reach about 50%, and reduce heat losses by about 17% (Juodis, 2005). Looking at Chapter V Article 23, in the bylaw of RT 2000 from 2006, the reference ventilation system is a system permitting a reduction in energy losses by 10% (RT 2000, 2006). Thus, assuming that the entire residential sector will invest in heat recovery systems, a heat recovery efficiency of 50% will be used in the simulations.

Furthermore, an introduction of heat recovery units into the residential sector would result in a decrease in the specific fan power (SFP) used, see Chapter 3.4.3. The European standard EN 13779 specifies an SFP of 750-1250J/m^3, which equals 0.75-1.25kWs/m^3. Thus, in parallel with the change of the heat recovery efficiency, the SFP is changed from 0.9kWs/m^3 to 0.75kWs/m^3 (EN 13779, u.d.).

3.3.4 Appliances efficiency

This ESM assumes that the appliances are replaced with higher standard ones. Depending on the subsector, the new values of heat gains from appliances are calculated differently according to literature.

The heat gain from appliances is said to be equal to the electricity consumption of the units. The appliances used differ a lot between the residential and the non-residential sector. First investigated will be the residential sector's potential energy savings from higher efficiency appliances. Thereafter follows the non-residential sector.

The average number of domestic appliances; including washing machines, clothes dryers, dishwashers, refrigerators, freezers, and electric ovens, sold in France during the years 2006 and 2007 where 8.65 million items (Promotion 3E, 2011). The stock of refrigerators, freezers, washing machines and dishwashers in France in 2008 was 85 174 190 items (Odyssee, 2008). Each appliance category could then be assumed to hold in average 21 million items. Adding equal shares of electric ovens and clothes dryers one ends up with a stock of domestic appliances of approximately 127 million items.

The electricity consumption of electrical appliances in domestic France were in 2008 5.5Mtoe[7] (Odyssee, 2008), which equals to 85% of the households' total electricity consumption. The rest (15%) of the electricity is used for lighting. Assuming average electricity consumption allocated over the whole domestic appliances stock, each item annually consumes;

$$\frac{231\,PJ}{127*10^6} = 1\,818\,897\,638\ \frac{J}{unit} = 1.82\frac{GJ}{unit}$$ Equation 3.4

---

[7] 5,5 Mtoe = 231 PJ

The European Commission’s Directive 66/2003 (EC, 2003) defines an energy efficiency index alpha (I_a) for refrigerators and freezers as:

$$I_{a=}\frac{AC}{SC_a} * 100 \qquad \text{Equation 3.5}$$

Where,

AC = annual energy consumption of appliance

SC_a = standard energy consumption of appliance

Equation 3.5 is assumed to be valid for all types of appliances assessed. This assumption is strengthened by the bottom up approach presented in the journal article (Anibal de Almeida, 2011) which claims that the potential electricity savings in the European residential sector, created by existing technologies on the market *and* improved user behavior, may reach 48%.

To be classified as A+ or A++, the appliance shall range as specified below:

A++ $30 > I\alpha$ Equation 3.6

A+ $42 > I\alpha \geq 30$ Equation 3.7

As an optimal technical scenario, all residences are assumed to be equipped with new appliances, all being at least A+ as it is defined above. This is then implemented as an appliance using only 42% of the energy compared to a standard one. If all households switch to new appliances, a potential energy decrease is maintained. The annual energy use scenario for each electrical unit would then be:

$$E_{consumed}^{unit} = 0.42 * 1.82 * 10^9 = 0.764 \frac{GJ}{unit} \qquad \text{Equation 3.8}$$

As in previous thesis, the heat gain from appliances is assumed to be equal to the electricity consumed by the appliances. Therefore:

$$A_c^{unit} = \frac{0.764*10^9}{3.6*10^6} [\frac{J}{\frac{J}{kWh}}] = 212 \frac{kWh}{unit} \qquad \text{Equation 3.9}$$

With 127 million items of appliances in France and about 26 million dwellings (Ribas Portella, 2012), there are approximately 4.8 items per dwelling. Thus, the heat gain per dwelling would be:

Equation 3.10

$$A_c^{dwelling} = 212 \frac{kWh}{unit} * 4.8 = 1036 \frac{kWh}{dwelling} = \frac{1035538}{8760} = 118.2 \frac{W}{dwelling}$$

Dividing by the areas defined for each of the residential subtypes gives the final baseline input figures presented in Table 7.

Table 7 New input values for heat gains from appliances in the residential sector, Ac, in [W/m²]. *Ac simple shows a reference Ac given by simply multiplying the baseline Ac with the new efficiency.

Building type	*Ac old*	*Ac new*	*Ac simple**
SFD	2.1	1.14	0.42 * 2.1 = 0.88
Private MFD	3.4	1.79	0.42 * 3.4 = 1.43
Public MFD	3.4	1.79	0.42 * 3.4 = 1.43

However, noteworthy, since only 8 650 000 appliances are sold per year, there is no such overall turnover of equipment as assumed in the scenario above. Furthermore, according to two reports published by Eurobarometer (Eurobarometer, 2008) and by Eurostat (Eurostat, 2009), respectively, only about 50% of the citizens of France are ready to choose more efficient appliances when purchasing new equipment for their homes. Additionally, ADEME presents sales figures from France in 2010, showing a percentage of A+ and A++ appliances of only 40% (ADEME, 2012). Thus, the realistic share of energy savings from replacement by more efficient domestic appliances is smaller than the one used for the optimal technical scenario above.

In the non-residential sector, policy measures regarding appliances are lacking compared to other measures in the EU, see Figure 7.

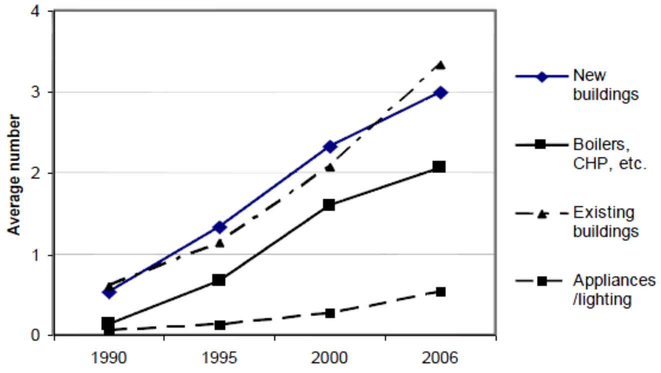


Figure 7 Average number of policy measures in EU implemented on the tertiary sector, targeted at different energy use in the period 1990-2006 (Odyssee indicators, 2006),

Ribas Portella (2012) made an estimation of the average heat gains from appliances based on a Spanish case study (Medina, 2011) and a thesis about the minimisation of consumption due to cooling in buildings (Filfli, 2006).

Regarding the offices, the same calculations as for the residential sector have been made to estimate the reductions in heat gains from appliances when limiting the devices to A+ class or higher. The energy consumption in a typical office has been extracted from (Korjenic & Bednar, 2012). Moreover, as assumed by Ribas Portella (2012):

- Working time in an office is set to 12 h per day
- An office building has 9 levels
- The office is occupied during 227 days in a year
- Number of offices buildings: 199 742
- Heated area of office building: 1000 m^2

Further, it is assumed that there are 15 work stations and 3 offices per level. Hence, one can calculate the electricity consumption of the appliances in the office sector; the resulting energy consumption figures being presented in Table 8.

Table 8 Characterisation of a typical office and calculation of energy consumption in offices (Korjenic, o.a., 2012). WSt = Working Station.

Office		***Power*** *Work time [W]*	***Power*** *Stand-by [W]*	***Total Energy*** *[kWh/building, yr]*	***No. of appliances***	***Weighted energy consumed*** *[kWh/building, yr]*
	1per					
Printer	office	103	15.4	322.5216	27	8708.0832
Battery	office	0.8	0.2	2.724	27	73.548
Radio	office	9	0	24.516	27	661.932
Lighting	office	1.5	1.5	8.172	27	220.644
Fire alarm	WSt	0.5	0.5	2.724	135	367.74
Shading	WSt	1.5	1.5	8.172	135	1103.22
Night vent.	WSt	1.5	1.5	8.172	135	1103.22
Phone	WSt	3	3	16.344	135	2206.44
Computer	WSt	56	2.3	158.8092	135	21439.242
Monitor	WSt	18.5	0.35	51.3474	135	6931.899

Thus, the total energy consumed per year by the office sector is:

$$E_{office} = total\ weighted\ energy * number\ of\ office\ building = 8.55\ TWh$$

Equation 3.11

The total number of appliances in the office sector is:

$$N_{appl} = (27 * 4 + 135 * 6)\ units/buildings * 199\ 742\ buildings = 183\ 363\ 156\ units$$

Equation 3.12

When elevating to at least A+ class, the consumption per unit is:

$$E_{consumed}^{unit} = 0.42 * \frac{E_{office}}{N_{appl}} = 19.58 \frac{kWh}{unit}$$ Equation 3.13

This gives a heat gain of:

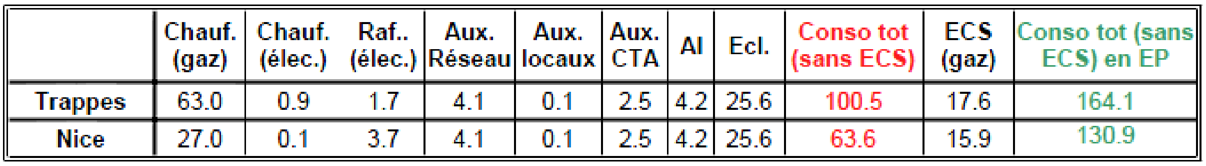
$$A_c^{office} = 2.05\ W/m^2$$

Lack of data regarding the commercial, Education and SCL buildings, requires an assumption where the possible energy savings are set to 50%. The same reduction of heat gains from appliances has been established in the Swedish case study (Mata, 2011).

For the Health buildings case, Filfi (2006) provides a study of 2 cities:

- Trappes in the Île-de-France region with oceanic inner climate
- Nice in the Côtes d’Azur region in Southern France with hot Mediterranean climate

As data are lacking, the two cities are considered as being representative for the 3 climatic zones of France: Trappes representing zone H1 and H2; and Nice the H3 zone. The values of energy consumption for appliances are provided from the best solution determined in the study, i.e. with the Best Available Technology (BAT), see Figure 8.



	Chauf. (gaz)	Chauf. (élec.)	Raf.. (élec.)	Aux. Réseau	Aux. locaux	Aux. CTA	AI	Ecl.	Conso tot (sans ECS)	ECS (gaz)	Conso tot (sans ECS) en EP
Trappes	63.0	0.9	1.7	4.1	0.1	2.5	4.2	25.6	100.5	17.6	164.1
Nice	27.0	0.1	3.7	4.1	0.1	2.5	4.2	25.6	63.6	15.9	130.9

Figure 8 Energy consumption in [kWh/m2,yr] in health buildings in the cities of Trappes and Nice, using BAT (Filfli, 2006).

The heating (Chauf (gaz)), occupants’ heat gains (AI) and lighting (Ecl.) consumption are not subtracted in this table. Thus, Equation 3.14 is applied:

$$Ac_{new\_health}[W/m^2] = \frac{[Conso\ tot - Chauf(gaz) - AI - Ecl] * 10^3}{8760h/year}$$ Equation 3.14

The resulting figures for the non-residential sector are shown in Table 9.

Table 9 New figures for heat gains from appliances, Ac, in the non-residential sector in [W/m2].

Building type	***Climatic Zone***	***Ac Ribas***	***Ac new***	***Source***
Offices		4.656	2.05	Calculated
Commercial		2.030	1.015	Assumed
Education		1.053	0.527	Assumed
Health	H1 and H2	3.377	0.879	(Filfli, 2006)
Health	H3	3.377	0.776	(Filfli, 2006)
SCL		2.45	1.225	Assumed

3.3.5 Lighting efficiency

This ESM assumes that the light bulbs are replaced with more efficient ones according to the recent RT 2012 regulation.

The values used for the installed lighting power, i.e. the heat gains from lighting, in the residential sector, are found using the calculation method Th-CE (CSTB, 2006). For the non-residential sector, the values are provided by the official text of RT 2005 (Ministère de l'emploi, de la cohésion sociale et du logement, 2006).

The values used in the simulations of this thesis are provided by the most recent regulation RT 2012, in the appendix of the calculation method Th-BCE 2012 (CSTB, 2011). This method, Chapter 9.1.3.1 '*Calcul de la puissance d'éclairage totale, Pecl_tot,l, pour Th-B'*, defines the new regulated values for the installed power to be:

- SFD and MFD: 1.4 W/m^2
- Education and Health buildings: 4 W/m^2

For the other building archetypes, the installed power depends on the parameter Eiref, which is the reference lighting given in [lux];

Equation 3.15

$$P_{inst} = 2 * \frac{E_{iref}}{100} * days\ of\ occupancy * hours\ of\ occupancy\ per\ day * \frac{1}{8760}$$

The values of Eiref are given in the Table "Tableau 75" (CSTB, 2011), see Appendix B. Eiref is calculated for each building subtype as the sum of luminance of all subcategories. For instance, for offices see Equation 3.16:

Equation 3.16

$$Eiref_{offices} = Eiref_{office} + Eiref_{meeting\ room} + Eiref_{circulation} + Eiref_{sanitary\ rooms} = 500\ lux + 500\ lux + 100\ lux + 200\ lux = 1300\ lux$$

The estimated new heat gains from lighting for each archetype building are found in Appendix C. The RT 2005 has set a maximum value for the Education sector to be 4W/m^2. However, the basline scenario was set to 3,08W/m^2. Thus, the heat gain from lighting in building subype NR3 is not being changed in this thesis' simulations.

The substitution of lighting devices is just one way of decreasing the electricity use. In offices, different control systems, room orientation and occupancy sensors may contribute to electricity savings as high as 60% (B. Roisin, 2007).

In the context of the Grenelle Environment Forum, commitments from companies were defined in order to create a list of objectives regarding energy saving actions. Among the commitments signed in 2008, one refers to the phase out of incandescent light bulbs and the promotion of low consumption bulbs. Several strategies are available with existing technology. An improvement in lamp technology may reach a relative savings potential of 10-40% (Dubois & Blomsterberg, 2011).

When introducing higher efficiency lighting devices into all subsectors except Education, resulting energy and emissions saving potentials are obtained, see Figure 18. As expected, savings in lighting are most important in highly occupied sectors such as Offices and Commercial. In these subtypes the light is often left switched on even when not needed and thus the implementation of more efficient light bulbs may lead to significant energy savings.

3.3.6 Hot water production efficiency

This ESM assumes two possible ways to increase hot water and heat production efficiency; either by increasing boilers efficiencies according to (Republique Francaise, 2013), or by replacing boilers according to a current "scrapping subsidy scheme" (Ministère de l'écologie, du développement durable et de l'énergie, 2012).

In France, the energy consumption for the production and distribution of hot water accounts for 3.2% of the national energy consumption and may represent up to 25% of the energy consumption of a household (ADEME, 2006). A decrease in energy consumption for hot water can be reached by improving the systems for production and distribution.

Regarding the baseline year, the present situation for hot water production in France may be summarised as follows:

- In SFDs, the most common system is the electrical accumulation water tank accounting for 51% of the total number of dwellings (Rocheron, 2012). The rest is mostly based on gas and oil boilers (Ribas Portella, 2012) (Table 3.45).
- In MFDs, a gas heater providing heat to a semi-accumulation storage tank is mostly used; 49.8% of the MFDs (ADEME, Agence de l'Environnement et de la Maitrise de l'Energie, 2011). The rest is based on electric heaters (Ribas Portella, 2012) (Table 3.45).
- It is more difficult to quantify the technology used in non-residential buildings due to the diversity of buildings and lack of data. In the master's thesis of

Ribas Portella (2012) Table 3.46, electrical boilers and gas heaters are assumed to be used in the non-residential sector.

Different types of solutions can decrease the energy needed for production and distribution of hot water:

- Replacement of existing boilers with more efficient ones
- Replacement of existing boilers with other types of boilers, that is altering the shares of different boiler types

The use of renewable fuel sources, for example by installing solar panels, thereby changing energy source and reducing the emissions, can also be considered. However, due to lack of investments in France, the market for solar thermal energy has reached a plateau since the economic crisis in 2008 (Sia Partners, 2013). Figure 9 shows the annual heat production from solar thermal power in European countries compared to the 2020 objectives set in the National Renewable Energy Action Plan.

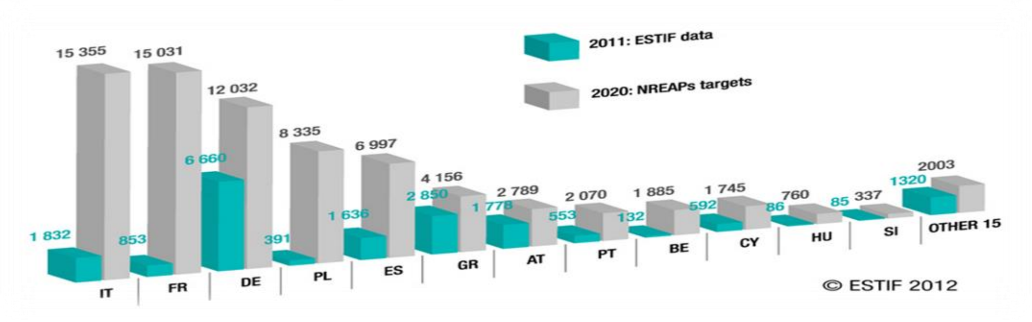


Figure 9 Annual heat production in [GWh] in EU-27, compared to the 2020 objectives (ESTIF, 2012).

With an annual production of 863GWh, France is far from its goal of 15 031GWh in 2020. Thus, no ESM regarding solar thermal energy for water production will be considered in this thesis. The measures considered in this thesis are instead an increase of boiler efficiency and the replacement of certain types of boilers.

As a first measure, a substitution of the boiler types is considered. Since July 2012, a "scrapping incentive" scheme ("*Prime à la casse des chaudières*") has been established to replace oil boilers. In the residential sector and in offices, oil boilers that are older than 15 years account for 1 million units out of the 18 million boilers in France (5.56% of the total). The government now allows a subsidy bonus for those replacing their old oil boilers (Ministère de l'écologie, du développement durable et de l'énergie, 2012):

- A 150€ reward when changing to a boiler with higher performance
- A 350€ reward when replacing the boiler with a condensing boiler
- A 400€ reward when replacing the boiler with a wood boiler

The ESM with the highest reward is supposed to be established, i.e. replacing 5.56% of the oil boilers in SFDs, MFDs and offices with wood boilers.

Heat pumps could possibly replace boilers for hot water production and space heating. However, this technology is not taken into account in the thesis as it is still not very common in France: only 1% of the energy efficiency measures applied in 2011 was related to heat pumps (ADEME, 2011).

For non-residential sectors, Chapter IV Article R.224-23 of the *Code de l'Environnement* (CE) sets minimal performances for oil, gas and coal boilers with a power output between 400kW and 50MW (Republique Francaise, 2013). Compared to the baseline values, these efficiencies are higher, except for the coal boiler, see Table 10. Since the efficiency for coal boilers are higher in the baseline scenario than in the CE, no change is made in the simulation.

Table 10 Comparison of Efficiency of boilers according to the CE and Baseline scenario. * Since the efficiency for coal boilers are higher in the baseline scenario than in the CE, no change is made in the simulation.

	CE	***Baseline***
Oil	0.89	0.85
Gas	0.90	0.76
Wood	-	0.70
Direct	-	0.98
District	-	0.82
Coal/lignite	0.86*	0.91
Others	-	0.60

For the domestic boilers (between 4kW and 400kW), the efficiency is ensured by the supplier according to regulations requirements (Ministère de l'écologie, du développement durable et de l'énergie, 2010). As a result, no control by the authorities is mandatory and therefore no change in efficiency is made for the residential sector.

Thus, as a second measure, the boiler efficiency is modified, assuming that all the oil and gas boilers reach the required efficiency set by the CE.

3.3.7 Rescheduling of hydro pumps

This ESM assumes that the working schedule of hydro pumps is regulated according to the Swedish Energy Agency.

In this thesis, hydro pumps are being defined as all circulator pumps used for hydronic heating of buildings. As baseline value in simulations performed in previous master's thesis, the specific electric power demand for the operation of hydro pumps, HyP, is set to $0.36W/m^2$, referring to (Mata, 2011).

According to the Swedish Energy Agency, the hydro pump energy consumption may be reduced by 30% only by regulating the pumps' working schedule, thereby avoiding unnecessary work during summer (SEA, 2009). If only considering a regulation of the pumps' working schedule and a maximum efficiency gain thereof, the new electricity use would be:

$$EfHyP^1 = 0.70 * \ 0.36W/m^2 = 0.252W/m^2 \qquad \text{Equation 3.17}$$

3.3.8 Package of measures

Specific measures can be related to one another, thus grouping them in certain packages is relevant. For instance, the wall insulation and the windows insulation measures can be gathered since a customer is not likely to renovate only one of them at once but would take the opportunity to insulate the whole façade including the windows. One could also find out the potential when the whole envelope is retrofitted. The reduction of electrical power measures can also be grouped (appliances, hydro-pumps and lighting) assuming that a customer driven to reduce its consumption would do this for all devices.

In this thesis, 5 different combinations of measures are being assessed, see Table 11.

Table 11 Groups of ESMs and related parameters. “All” refers to parameters presented in Table 4.

ESM No.	***Group***	***Description***	***Input parameters affected***
11	ESMs 1 to 10	All ESMs aggregated	All except boiler efficiency
12	ESMs 1 to 4	Retrofitting entire building envelope	Ufloor, Uroof, Uwall, Uw, Ts
13	ESMs 3 and 4	Retrofitting façade	Uwall, Uw, Ts
14	All except 9	Decrease in net energy only	All except boiler replacement and efficiency
15	ESMs 7, 8 and 10	Decrease in electricity	HyP, Ac, Lc

3.3.9 About possible decrease in indoor air temperature

One important ESM for Swedish households defined in the AGS report (2011), is to reduce the minimum acceptable indoor air temperature, Tmin, to 20°C (AGS, 2011). However, the baseline data of Ribas Portella (2012) presented in Table 12 shows already low residential indoor air temperatures. Looking into the other subsectors, the potential of lowering the minimum indoor air temperature below 20°C seems quite small; only Offices being above this value. However, the activities performed in this subsector are usually sedentary work and thus need a bit higher indoor air temperature.

Table 12 Baseline parameters for indoor air temperatures (Ribas Portella, 2012).

Sector	***Category***	***Tmin [°C]***
Residential	SFD and both MFD	19.0
Non-residential	Offices	21.0
	Commercial	19.0
	Education	19.0
	Health	20.0
	SCL	18.5

Another aspect of the indoor climate in France is the comparably low indoor air temperatures in the residential sectors. Here, one often leaves several rooms unheated due to low insulation rates and high heating costs. One way to handle this issue would be to discuss “comfort measures”, where a potential increase of the Tmin in the residential sector could be implemented. However, this is outside the scope of this thesis and will not be further investigated.

Nevertheless, it may still be a possibility to decrease the indoor air temperature in some of the non-residential subsectors, but this would require a more detailed analysis using a working schedule that calculates the indoor air temperatures during the hours of the day. With such a schedule, one could set the minimum acceptable indoor air temperature depending on daytime and thereby optimize the heating running time.

Summarising, this thesis will not consider a decrease in indoor air temperature as a potential energy saving measure, since this would affect the indoor climate comfort in a negative way. The following text is about the possibility of changing the Tmin in the non-residential sector in further investigations on the subject.

The indoor air temperature is below 21°C in 50% of the French dwellings (CSTB, 2006b), This also holds for the interpretation that the indoor air temperature exceeds 21°C in 50% of the dwellings. Moreover, around 5% of the dwellings have temperatures exceeding 24.8°C. Thus, one could assume that the baseline indoor air temperature in the residential sector could be set higher than the 19°C set by Ribas Portella (2012).

For the non-residential sector the new input values may be lowered in three of the cases. According to the Swedish working environment regulations, sedentary work needs a minimum indoor air temperature of 20°C, while active work needs temperatures around 14-15°C (AFS, 2009). In the French regulation system, no specific values on indoor air temperature are defined. Though, in the French working norm, the indoor air temperature is set to 20-24°C in winter and 23-26°C in summer (NFX_35-1211, 1987). These values are the same in the Canadian Commission on Health and Working Environment, which also presents the table on minimum indoor air temperature depending on activities performed found in Appendix E (Commissions de la Santé et de la Sécurité du Travail, CSST). Many of these temperatures are below the temperatures set by Ribas Portella (2012). Thus, the minimum indoor air temperature in non-residential buildings may be considered to be lowered as follows:

- 20°C instead of 21°C for the Offices
- 17°C instead of 19°C for the Commercial buildings, assuming there is a higher level of activity
- 18°C which is an average value for gyms (16°C) and cinemas and others (18°C), instead of 18.5°C for the SCL subtype

The non-residential subsystems Education and Health's input data remain the same (20°C). The residential buildings' minimum temperature (19°C) may be changed in correlation to the new baseline value.

The maximum temperature, Tmax, will remain the same for both residential and non-residential sector, since this thesis does not consider cooling. Important to notice is that an increase in Tmax for residential buildings would decrease the electricity demand for cooling, since it enables the natural ventilation tint, Tv, to act without any use of electricity.

The Tv won't change since the occupants are assumed to act for the opening of windows at the same temperature as before. Furthermore, the RT 2012 does not enforce the usage of a mechanical ventilation system, but encourages the flexible ventilation created by the occupants when opening the windows (RT2012, 2011).

3.4 Economic assessment

Below follows the cost figures that are used in the cost-efficiency calculations of each measure. Important to note is that the full costs are used as “specific cost” to reflect the investments needed for each measure and its equipment. This means that the cost for the whole measure is taken into account; not only the marginal cost.

The following costs exclude the value added tax (VAT). For more specific information, please see stated reference source.

ESM 1: ANAH (2011) presents the following values for retrofitting a building envelope. Retrofitting the roof costs 15-20€/m^2 for non-livable lofts and 60€/m^2 for habitable lofts. 40€/m^2 are chosen as cost for retrofitting the roof.

ESM 2: The floor costs 15-35€/m^2 to insulate; 25€/m^2 is chosen as average cost.

ESM 3: Interior insulation of the façade costs 25-50€/m^2, while an exterior retrofitting of the façade costs 50-80€/m^2 (ANAH, 2011). However, the regional directorate of Ile-de-France, “*Direction régionale et interdépartementale de l’Equipement et de l’Aménagement d’Ile-de-France*”, presents retrofitting costs that are higher ; costs for retrofitting a building envelope ranges between 70 and 400€/m^2, taxes excluded. Therefore, as average value for insulation of façades, 100€/m^2 is chosen (driea, 2011).

ESM 4: Replacement of windows costs are calculated using prices presented in ANAH (2011), see Appendix G. The average cost for windows replacement is then 420€/m^2 of window area.

ESM 5: Looking into numerous of different retailers’ websites gives an approximate investment cost of 240€ per unit. This value is then divided by the area of an SFD (110m^2) to get a cost per heated floor area and thus be applicable for both dwellings and non-residential buildings in the ECCABS model.

ESM 6: A heat recovery device costs between 1000 and 2500€ depending on the power of the device (Powrmatic, 2012). An average value of 1750€ is used in this thesis.

ESM 7 and 8: The cost for replacing the appliances and lighting, respectively, is estimated by looking at the residential sector’s assumed consumption rates, i.e. how often ones substitutes a device. Thus, when applying these figures onto the tertiary sector, one can expect some discrepancies in the cost-efficiency results. For appliances, an average cost of 500€ per device is assumed and divided by the heated floor area of the average SFD, since a unique cost per device applied to each dwelling would not be accurate. This gives 5.92€/m^2. The cost is set the same for MFDs as for SFDs, although MFDs may use collective equipment devices, for example washing machines and boilers, and might therefore have lower specific costs, though this is not considered in this thesis. For lighting devices different retailers’ websites are being consulted, from which it is assumed that the households are using one 100W device per 12 square meters and that a light bulb costs approximately 7€ (Lacentrale, 2009).

ESM 9: The cost for replacing a boiler depends on the boiler type. According to the journal article (F. Suerkemper, 2011), a condensing boiler costs about 1955€, while other types of boilers may cost almost ten times more. According to (ANAH, 2011) a boiler costs between 2200 and 7100€, corresponding to a 18 and 99 kW boiler respectively. A wood boiler is therefore assumed to cost 4000€ and then the subsidy of 400€ is subtracted before the cost is divided by the heated floor area, providing the cost per square meter instead of a unitary.

ESM 10: The cost for regulating the circulators working schedule is set to zero (0).

All additional maintenance costs are considered to be zero for measures that are not adding any new equipment to the building, i.e. all measures except the installation of heat recovery units into the residential sector, which is adding new equipment in need of maintenance. The maintenance cost for heat recovery units is 4% of the investment cost which gives 70€/yr (EU, 2006).

As already mentioned, all costs given above are without taxes and therefore a value added tax (VAT) of 19.6% is added to all figures (USCIB, 2013). The European Commission's Regulation No. 244/2012 defines the taxes to be included in the assessment as follows:

"[...], the relevant prices to be taken into account are the prices paid by the customer including all applicable taxes including VAT and charges. Ideally also the subsidies available for different variants/packages/measures are to be included into the calculation, [...]" (EC No.244/2012, 2012).

The costs for implementing each of the measures assessed are being summarised in Table 13. When aggregating the measures into packages, each measure's annual cost is summed up with respect to the lifetime of the package, see Appendix N.

Table 43 Annual cost per energy saving measure: specific cost [€/m^2] for insulation; unit cost [€/unit] for installation/replacement of equipment per dwelling; additional maintenance cost [€/yr]; and expected lifetime of investment [yr]. NB. Excluding 19.6% VAT. * Includes the grant of 400€.

ESM	***Specific cost per heated floor area*** *[€/m^2 of Atemp]*	***Specific cost per application*** *[€/m^2 Surface]*	***Unit cost*** *[€/unit, dwelling]*	***Extra maintenance cost*** *[€/yr]*	***Lifetime of investment*** *[years]*
1	0	25	0	0	40
2	0	40	0	0	40
3	0	100	0	0	40
4	0	420	0	0	30
5	2.18	0	0	0	15
6	0	0	1750	70	20
7	5	0	0	0	2
8	0.58	0	0	0	1
9	32.73 *	0	0	0	20
10	0	0	0	0	20

All lifetime figures used in the simulations, except for appliances and lighting, are taken from (EU, 2006) and equal to the lifetime of each investment, which is equal to the lifetime of the measure. For the appliances and lighting measures, expected lifetime of the device is assumed from searching for different warranties for the products. However, a warranty of two years for an appliance do not reflect the actual lifetime of the item and one could therefore consider prolonging this value in future work.

The discount rate used in the calculation of the annuities is 4% and reflects the societal perspective. In the sensitivity analysis, rates of 10%, 40% and 80% are assessed as well and thus an assessment with a more private perspective is conducted (Mata, et al., Submitted for publication).

The interest rate used is 3% (Mata, et al., Submitted for publication).

The time period assessed is 1 year, since no future energy prices are estimated.

3.5 Energy prices

To be able to compare the cost-effectiveness of the different ESMs assessed, the energy price for each energy carrier is assessed. The prices obviously vary during the course of the year or of a day. However an average national price is considered.

The energy prices paid by the end users are provided by two sources:

- (Eurostat, 2012)
- (Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)

The resulting figures are shown in Table 14. The prices are an average national price in Euros per kWh and are applicable for the first semester of 2012.

Table 14 Energy prices per energy carrier for France in 2012 in [€/kWh]. NB. The Energy price for other fuel sources, EPa, is a calculated average value of the other prices in the table.

Description	*Price*	*Source*
Consumer energy price of Electricity	0.0986	(Eurostat, 2012b)
Consumer energy price of Oil	0.0863	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
Consumer energy price of Gas	0.0530	(Eurostat, 2012)
Consumer energy price of biomass & waste	0.0353	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
Consumer energy price of coal	0.0652	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
Consumer energy price of district heating	0.0748	(Ministry of Ecology, Sustainable Development, Transports and Housing, 2012)
Consumer energy price of other fuels	0.0688	Calculated average value

The energy prices are assumed to be the same for residential and services sectors.

The French power demand is highly sensitive to outdoor temperature changes due to the high share of electricity in domestic heating (EC, 2012). This creates especially high drawbacks when energy saving measures lead to increased heating demands. This issue will be further treated in the discussion chapter of this thesis.

4 Results

In the following chapter, the results from the simulation processes are presented. The presentation is divided into the ESM subchapters used above. Also, estimated potentials found in literature are presented and compared to this thesis' results. A majority of the estimated energy savings given in literature refers to the delivered energy. Furthermore the cost analsysis focus on direct costs from a consumer perspective and therefore also refers to the delivered energy savings potential.

All results figures are found in Appendix I.

One of the major sources used when comparing the output data with the estimated potentials in literature, has been the European database on energy saving potentials (European Commission Directorate, 2009). This database uses three possible scenarios to estimate the energy saving potentials and will be referred to in some of the following subchapters. The three scenarios are

- Low-policy intensity scenario (LPI): rather low diffusion of BAT but goes further than the business as usual scenario; diffusion is motivated by increased market prices
- High-policiy intensity scenario (HPI): the diffusion of BAT is at its maximum
- Technical scenario: technical limits are achieved thanks to investments allocated to BAT. In practice, this maximum limit cannot be reached but it is useful to consider the scenario to evaluate the potential energy gap.

4.1 Retrofitting building envelope by insulation

The first three of the measures assessed are the retrofitting of the building envelope components; floor (ground), roof and façades (walls). The results are presented in Figures 10-12 below.

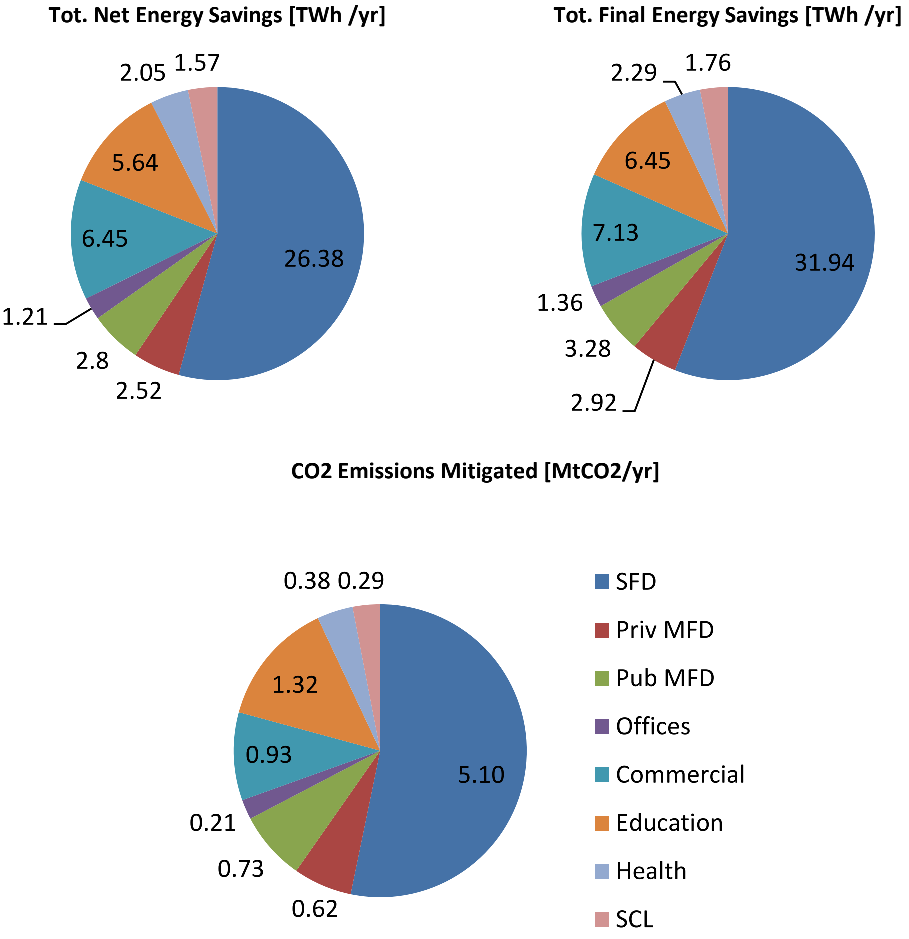


Figure 10 Potential savings by retrofitting the floor.

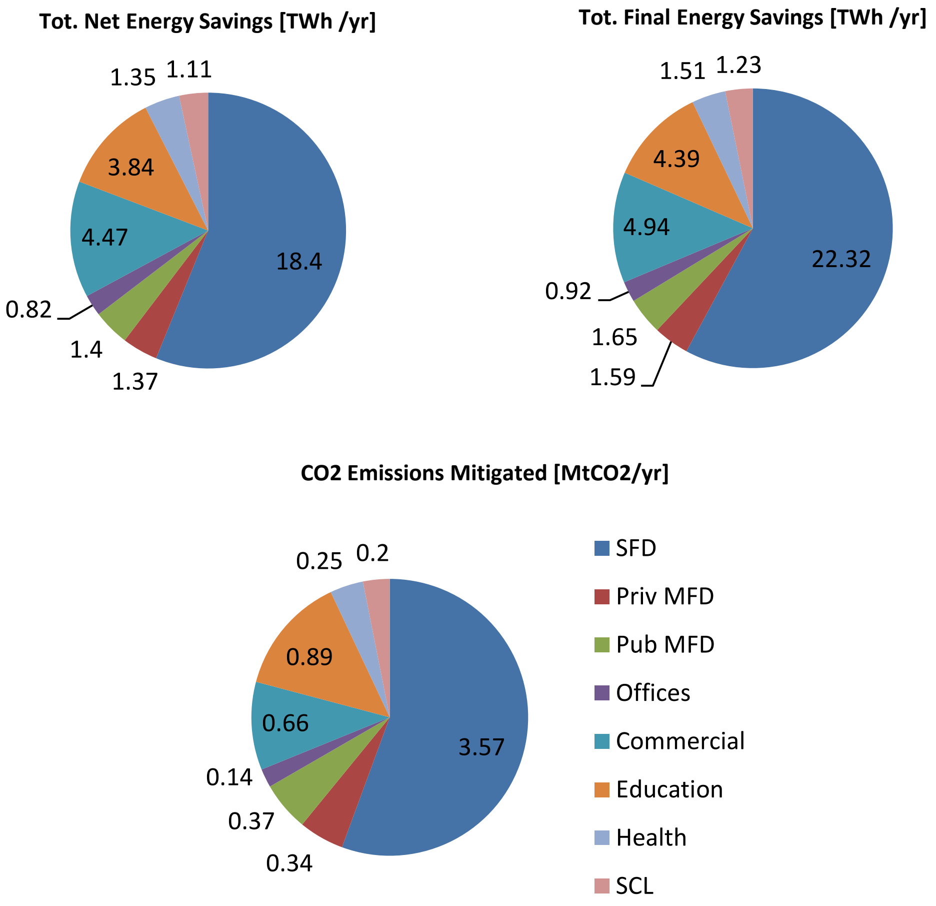


Figure 11 Potential savings by retrofitting the roof.

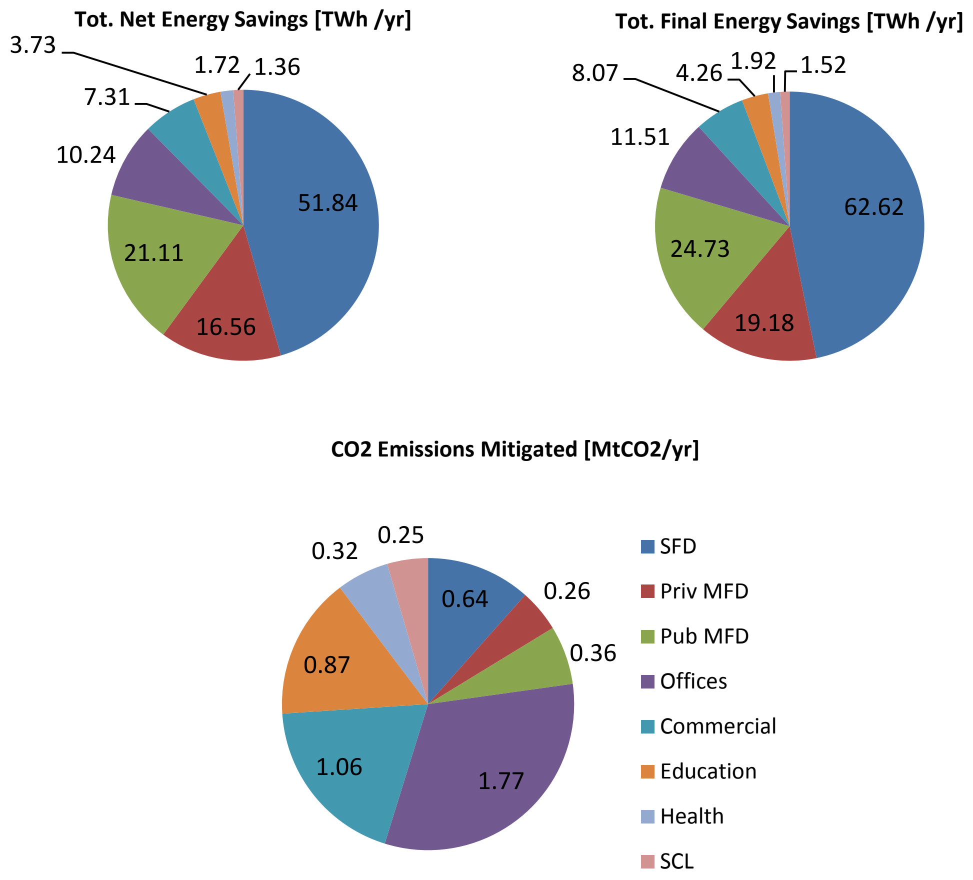


Figure 12 Potential savings by retrofitting the walls.

Table 15 presents potential energy savings from different types of insulation measures according to an ADEME study (Acchiardi, 2012). The table also includes the difference between this thesis' results and the ADEME figures.

Table 5 Comparison of this thesis' results with estimations from ADEME.

Type of components	***Potential energy savings ADEME*** *[TWh/yr]*	***Potential energy savings THESIS*** *[TWh/yr]*	***Difference*** *[%]*
Roof (residential)	56	25.56	54.3
Walls (residential)	148	106.53	28
Windows (residential)	33	17.04	48
Total savings residential	356	247.89	30
Total savings non-residential	76-167	80.51	6 (lower value)

As for the insulation of the ground, the Association for Sustainable Energy, ASDER, showed that the potential for energy savings from insulation of the floor ranges between 5 and 10% (ASDER, Maison des Energies, 2009). The final energy savings in the residential sector given by this thesis' simulations are 38.14TWh/yr which represents 8.38% of the total final savings.

Even though the non-residential total savings from insulating measures correlate with the estimation made by ADEME, the other insulation measures show significant differences. As said before, the variations in results probably arise from the difference in assumptions established in the ADEME study and in this thesis, respectively. In the ADEME study, no further explanations were given besides naming the measures and their energy savings potential. However, similarities can be noticed: insulation of walls has the greatest potential, followed by the insulation of roof and windows.

In contrast to the study performed by Veerbeck et al., this thesis' results are showing higher savings potentials for both wall and floor insulation than for roof. This may be based on differences in the existing building stock of the two countries, as well as varying shares of energy sources used for space heating compared. Looking into the former master's thesis by Ribas Portella (2012), the mean U-value of the building envelope has a normalized sensitivity coefficient of 0.7 and can be seen as one of the most sensitive parameters. The reason for such a high value on the energy savings from wall insulation, compared to for example roof insulation, may come from this sensitiveness in the model. However, the insulation of walls in today's France is lagging compared to for example Sweden. The situation of the insulation in French residential buildings has been established by ANAH (2008) and shows that insulation of walls is not as implemented as for other envelope components, see Table 16 (Anah, 2008).

Table 6 Situation of the insulation in French residential buildings (Anah, 2008).

	Roof	*Floor*	*Windows*	*Walls*
Satisfying	40%	41%	31%	36%
To be improved	24%	13%	23%	16%
Partial	22%	13%	23%	19%
Non existing	14%	33%	23%	27%

4.2 Replacement of windows

Figure 13 shows the resulting savings from replacing the windows.

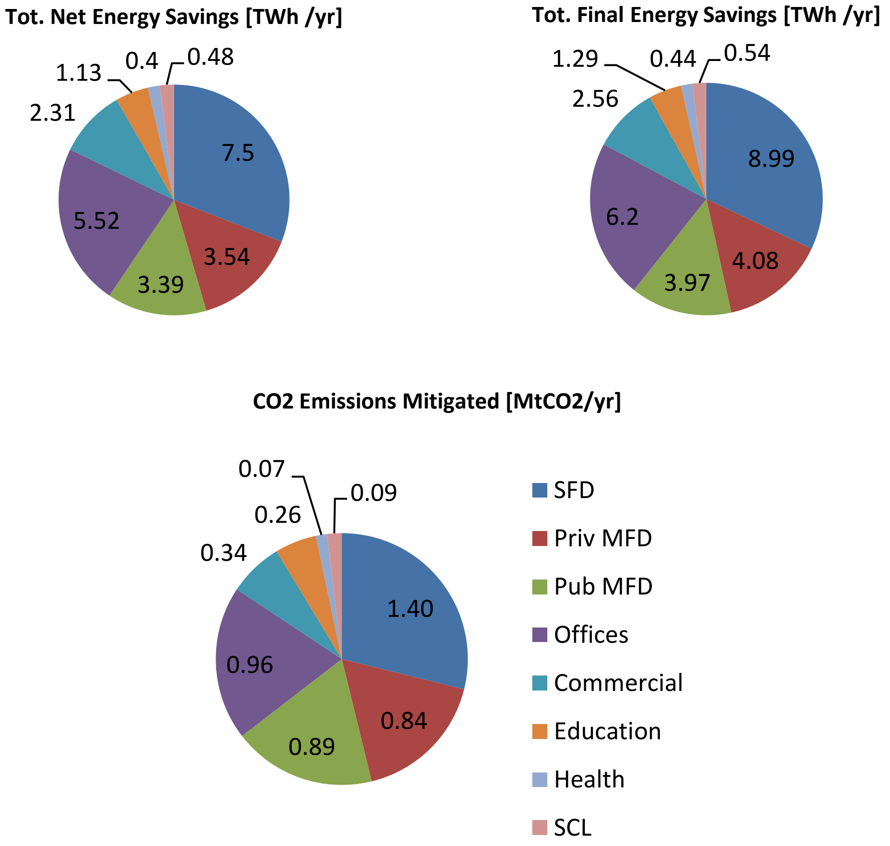


Figure 13 Potential savings by replacing the windows with lower solar transmittance and U-value.

A study made by *Glass for Europe*, a European manufacturer of glass, determined the potential benefits of the introduction of low emissivity glass in European countries (Glass for Europe, 2009). The study reveals that if low-E double glazing with a U-value of 1.1W/m^2, is implemented in existing and new buildings in France, the estimated energy savings would amount to 92 184TJ/yr with a corresponding CO_2 reduction of 9.56MtCO_2. Compared with this thesis' potential saving figures (101 196TJ/yr and 4.86MtCO_2/yr), a difference of 9.8% and 49.15%, respectively, is achieved.

Despite the difficulty to assess the assumptions made in the study, the major difference in emissions savings from windows replacement probably derives from the lower U-value used in the reference source which gives a higher potential of CO_2 mitigation and energy savings.

The ADEME study also assessed possible savings of 33TWh/yr, or 118 800TJ/yr, which makes a 14% difference with the value obtained in this work (Acchiardi, 2012).

4.3 Upgrading of ventilation system

Figure 14 shows the resulting savings from upgrading the specific fan power and the heat losses of the fan.

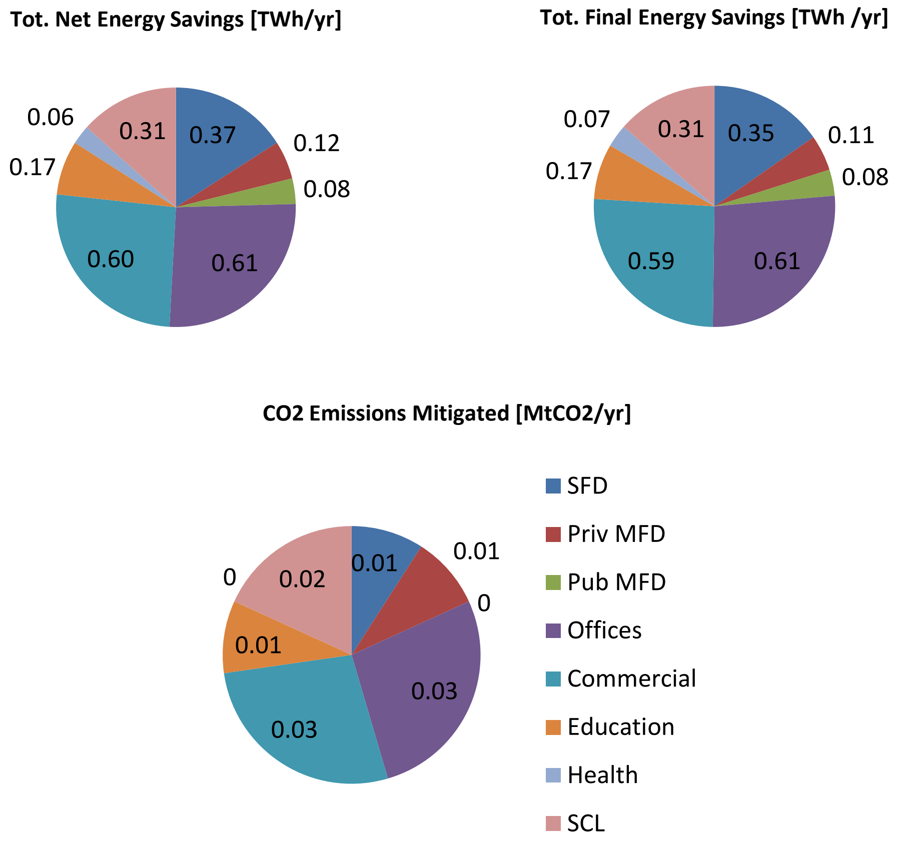


Figure 14 Potential savings by increasing the efficiency of the fan.

As can be seen in Figure 14, there is a significant net and final energy savings potential in the offices and commercial subsectors. Amongst other, this refers to these subtypes' high occupation rates during the day and the consequential requirements of air renewal. There are also high occupation rates in the health subsector, but here one already executes more stringent air quality requirements and therefore no greater savings can be found.

The non-residential sector's final energy savings potential; 1.75TWh/yr, seems to be accurate, comparing it with the estimated potential of the EU energy saving potential database (ESP); 2.0TWh in year 2015 (Enerdata et al., u.d.). However, it is difficult to compare these figures, since there is no detail of the assumptions made in the calculations of the ESP database.

4.4 Introduction of heat recovery units in households

An introduction of heat recovery units in the residential sector would lead to substantial energy savings, see Appendix I.

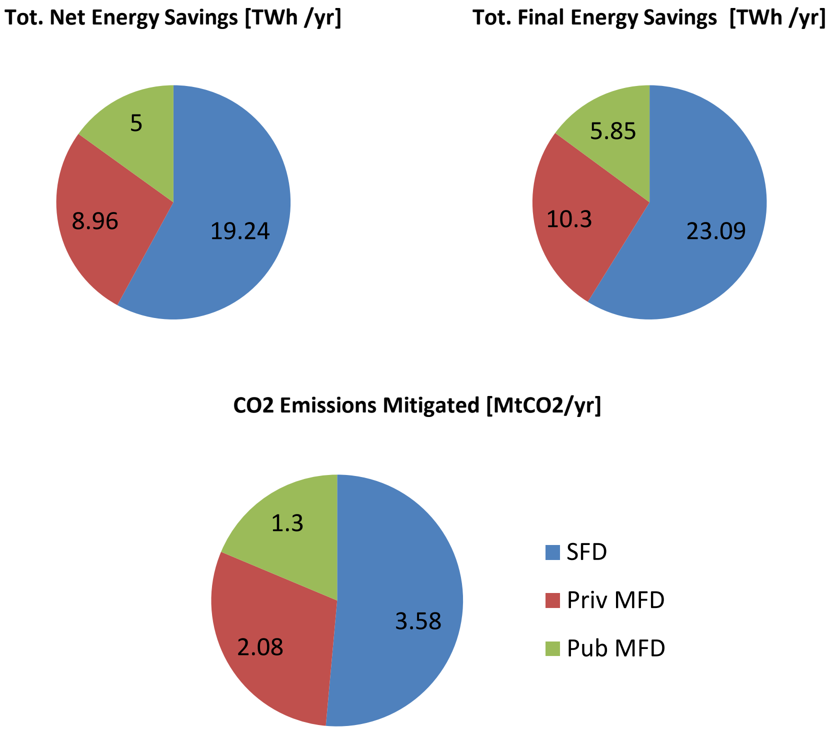
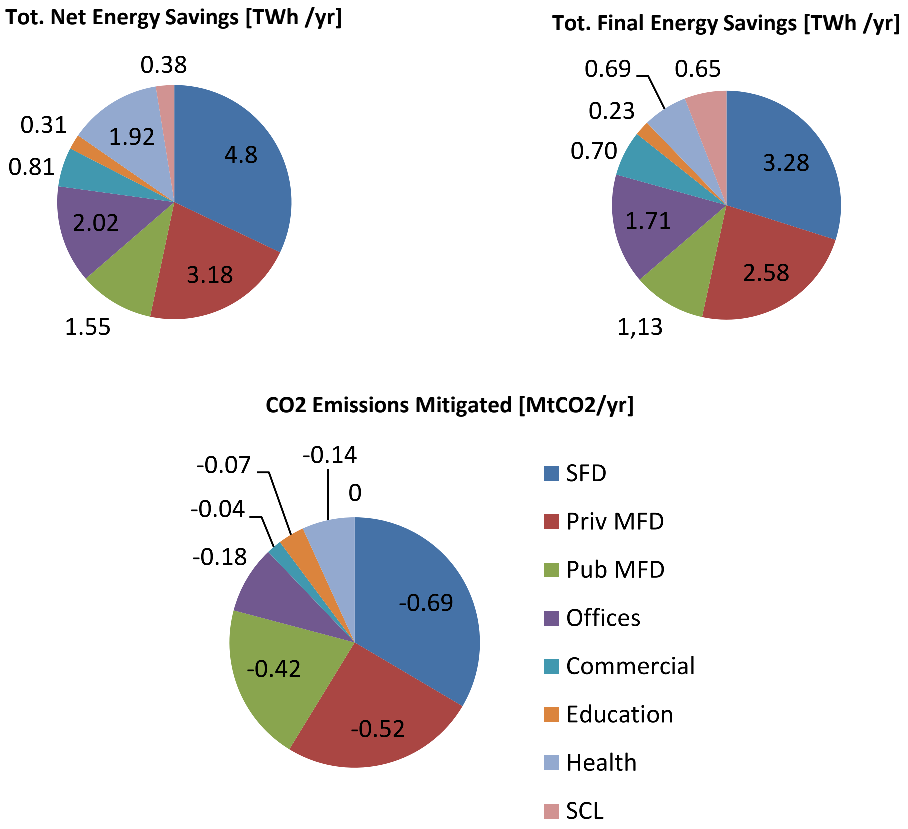


Figure 15 Potential savings by introduction of heat recovery units with an efficiency of 50% in the residential sector.

According to a report in the REHVA Journal, in a scenario introducing heat recovery in the residential sector, there is a potential CO_2 emissions reduction of 6Mt/yr (Händel, 2011). The simulations' resulting figures for this thesis show a potential decrease of 6.96MtCO_2/yr in France. The assumed efficiency of the heat recovery device in the simulations is set to 50% and the introduction of heat recovery units is applied to the whole residential sector. However, the efficiency used in the REHVA report is unknown.

4.5 Appliances efficiency

The results from upgrading the appliances energy efficiency and thereby reducing the heat gains from them, Ac, are presented in Figure 16.


Tot. Net Energy Savings [TWh /yr]

Tot. Final Energy Savings [TWh /yr]

CO2 Emissions Mitigated [MtCO2/yr]

Figure 16 Potential savings by introduction of higher efficiency appliances. NB. Negative figure means increased emissions.

The residential sector is dominating the energy savings potential of this measure. The SFDs host the major part of the appliances while in the MFDs some appliances, e.g. washing machines, are shared between occupants.

The negative figures of the emissions are due to the fact that no cooling is considered in the simulations. During winter, however, the decrease in heat gains from the appliances only leads to increases in heating and no decreases in cooling demand. If considering cooling one may obtain positive emissions savings during summer, since cooling demand will decrease with more efficient appliances.

The results of this thesis show a potential reduction in net electricity demand in the residential sector of 25%. In an IEA report “a major end-use metering project in four European countries” showed an average savings potential in each of the 400 households assessed, to be more than 1000kWh/yr when substituting existing equipment with the most energy-efficient available on the market (IEA, 2003). These results correspond to a reduction in total electricity consumption between 20 to 35% depending on the country and thus match this thesis results.

Regarding the total final energy saved in the residential sector, 6.99TWh/yr is potentially saved when elevating all appliances to at least A+ standard according to the calculations. In the HPI scenario of the ESP database, a greater share of A++

appliances is achieved in 2030, which increases the potential energy savings to 7.9TWh/yr. These potentials correlate with the thesis' simulation results.

Regarding the non-residential sector, the total final electricity savings potential reaches 7.82TWh/yr, running the ECCABS model. The potential estimated by the ESP database shows an LPI scenario in 2015 of 4.8TWh of electricity saved, including computers and monitors; copying and printing; servers; commercial refrigeration and freezing; central air conditioning; and other motor appliances. As mentioned before, the quite high discrepancy probably depends on the different ways of assessing the measure.

4.6 Lighting efficiency

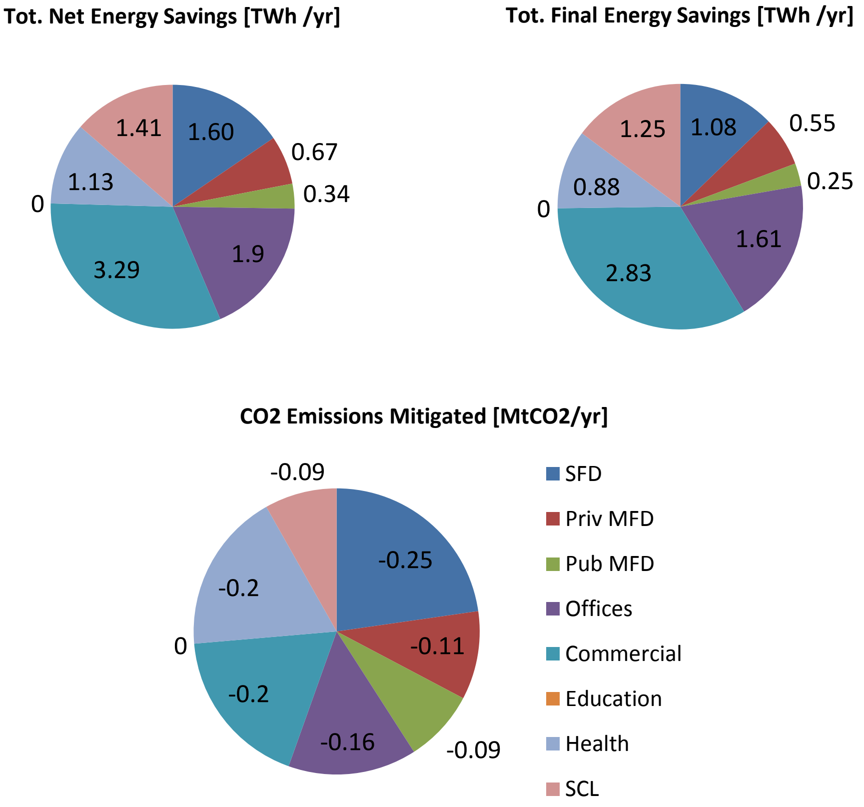


Figure 17 Potential savings by introduction of more efficient lighting. NB. Negative figure means increased emissions or energy use.

When meeting the minimal requirements set by the RT 2012 calculation method, the residential sector is able to save up to 1.88TWh/yr of final energy. A report on estimated energy saving potential ordered by the European Commission showed that the French residential sector could save 1.96TWh/yr of energy according to a scenario assuming the cost-effective penetration of Compact Fluorescent Lamps (CFLs) in each French household (Bertoldi & Atanasiu, 2007).

The ESP database reports of energy savings potentials in 2015 that goes in line with this thesis' results, depending on its three scenarios: LPI=0.5TWh/yr; HPI=1.1TWh/yr; and Technical=1.5TWh/yr. The value provided in this thesis is thus close to the technical scenario prediction for the year 2015. As said before, this scenario is unlikely to be reached and thus a longer time period would be needed to save this amount of energy. The ESP database also showed that potentials of 1TWh/yr and 2.2TWh/yr are achievable in the LPI and HPI scenarios in the year 2020. The LPI assumed a strong penetration of the CFL (50% of the lighting points) but a slow introduction of LED technology, while the HPI scenario assumed a stronger penetration of both CFL (80% of lighting points) and LED and set the rest to be incandescent lamp. The technical scenario is made of CFL and LED essentially.

Hence, the RT 2012 requirements would initially be met through a HPI scenario around the year 2020. However, this is only a technical improvement scenario and does not include any consumer behavioural change. Therefore, it may be assumed that the requirements could be reached sooner if social drivers were taken into account.

Regarding the non-residential sector, only offices lighting is available in the ESP database. It is the only data accessible since building offices are one of the most energy intensive consumers among the sectors assessed in this project, due to its high use of electricity. In Europe, the consumption of offices reaches 306kWh/m^2,yr (Dubois & Blomsterberg, 2011), whereas in France the offices' consumption is 268kWh/m^2,yr (ADEME, 2011). The thesis' simulations result in a final electricity savings potential in offices of 3.21TWh/yr when meeting the RT 2012 requirements. The ESP database figures on electricity savings potential in office lighting in 2015 amount to 3TWh/yr in all three scenarios. Hence, similar to the appliances case, it could take longer time in the residential sector than in the tertiary sector to reach the potential savings.

4.7 Hot water production efficiency

Boiler efficiency

Figure 18 shows the results from changing the efficiency of oil and gas boilers in the non-residential sector.

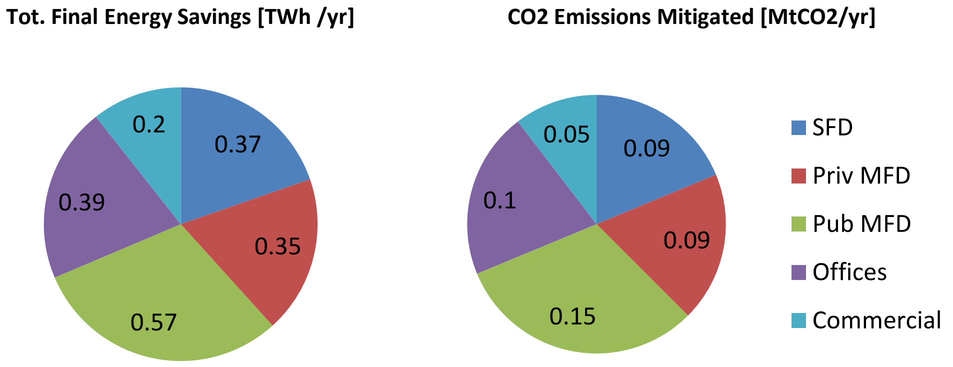


Figure 18 Potential savings by introduction of boilers with higher efficiency.

Boiler share

When substituting 5.6% of the oil boilers with new wood boilers, one may mitigate some of the CO_2 emissions, while the final energy use would increase, see Figure 19.

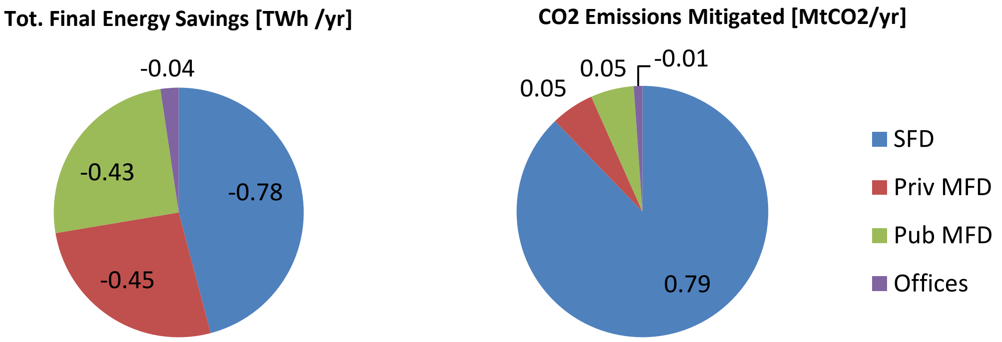


Figure 19 Potential savings by changing the share of different types of boilers. NB. Negative figure means increased energy use.

From increasing the efficiencies of the tertiary boilers, the thesis shows an energy savings potential of approximately 1% (1.88 out of 192.07TWh/yr). When the oil boilers are substituted with wood boilers, the energy use is increasing due to a lower efficiency of the wood boilers compared to the oil boilers, while the emissions are decreased. Thus, this measure only matters for emissions saving purposes.

The measure is currently ongoing in France and no estimation of its potential savings has been made so far. However, the ESP database estimates a potential energy saving from water heating in the residential sector of France to be 1.7TWh/yr in 2015 for a LPI scenario; 2.3TWh/yr for HPI; and 4.6TWh/yr as technical potential. Interesting enough is that a change from oil boilers to wood boilers, as the French "*prime à la casse de chaudières*" subsidies now are rewarding, would increase the energy use of the consumers, but lower the CO_2 emissions from the households' water heating (0.89 MtCO2/yr).

4.8 Upgrading of hydro pumps

The upgrading of hydro pumps, or circulators, refers to a regulation of the working schedule that creates 30% higher efficiency of the unit.

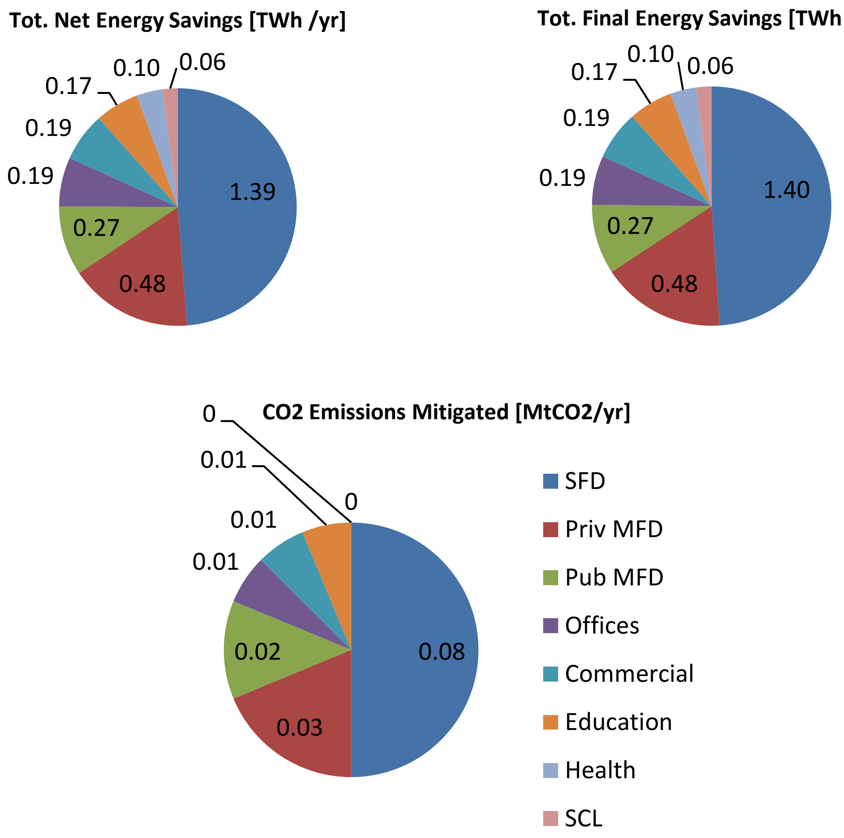


Figure 20 Potential energy savings by increasing the efficiency of the hydro pumps.

According to the results from the ECCABS model simulations, a regulation of the working schedules of the circulators would give a total reduction of $0.16MtCO_2$/yr. An EU project report providing information needed for EU energy labels, estimates the potential CO_2 mitigation from increasing the efficiency of hydro pumps in the EU residential sector as well as introducing labels, promotions and minimum efficiency standards, to reach between 5.6 and $12.8MtCO_2$ in 2020 (EU SAVE II Project, 2001). The French CO_2 emissions' share compared to the EU-27's share is about 11% which equals $0.62\text{-}1.42MtCO_2$. If following the ECCABS simulations, savings of $0.16MtCO_2$/yr in France would result in $1.12MtCO_2$ saved in 2020. This figure fits into the range estimated in the different scenarios of the EU report and lies in the upper part due to the optimistic assumptions made when running the simulations.

4.9 Packages of measures

All measures aggregated

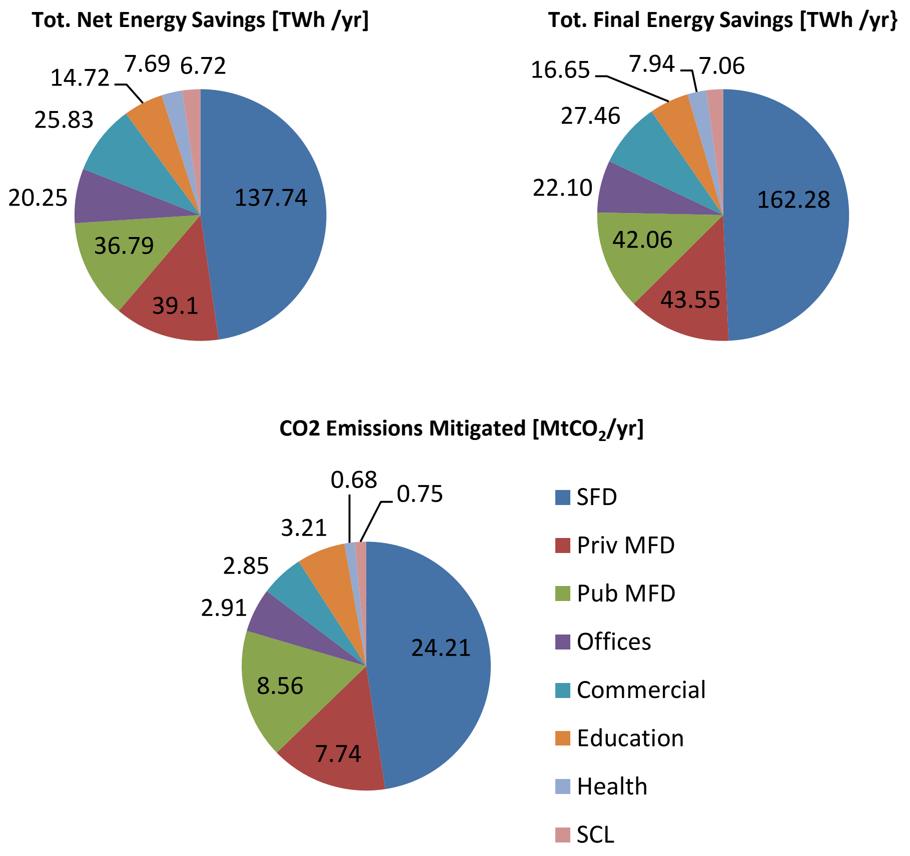


Figure 21 Potential savings by combining all the measures assessed in the thesis, except boiler efficiency.

Regarding the total final energy use after having implemented all measures, the new consumption would reach 316.57TWh/yr (647.17-330.6TWh/yr). Allocating this energy consumption over each building subsectors' total area gives an annual final energy use of 130kWh/m^2. The Grenelle objective states the new primary energy consumption limit for the existent building sector to be 150kWh/m^2,yr instead of today's 240kWh/m^2,yr (French Government, 2011). This implies a 38% reduction in primary energy use. Though one is not able to determine the corresponding primary energy reduction in this thesis, the results show a similar magnitude; 54% in final energy use (from 239.12 to 130kWh/m^2,yr).

A study about energy savings through the introduction of "French energy efficiency certificates", also known as White Certificates, evaluates the potential savings as shown in Table 17.

Table 7 Energy savings potential in residential and tertiary sectors (ADEME, 2011).

	Final energy consumption *(TWh/yr)*	***Energy savings potential*** *(TWh/yr)*
Residential (ADEME)	440	356
Residential (THESIS)	455.1	247.89
Tertiary (ADEME)	220	77
Tertiary (THESIS)	192.07	80.55

The study assumes the application of the BAT on the whole building stock. The savings in the non-residential sector are very close to the estimated potential with only 3TWh of difference in the results. However the residential savings obtained in this thesis are rather low compared to the estimated potential of the ADEME source. Several reasons may explain this difference of 100TWh:

- The segmentation used for the estimation may differ by the number of dwellings.
- The type of measures applied may differ.
- The assumed number of appliances in the dwellings may differ.
- The assumption made in the ADEME study was that BAT is applied on the whole building stock, which results in a higher energy savings potential than for this thesis simulation results, which have excluded some parts of the building stock (e.g. restaurants and hotels).

Regarding the CO_2 emissions mitigation, ADEME established scenarios for GHG emissions reduction in 2030 and 2050 (ADEME, 2012), see Table 18.

Table 8 GHG emissions scenarios for 2030 and 2050 (ADEME, 2012)

$MtCO_{2eq}$	***1990***	***2030***	***2050***	***% reduction 1990/2030***	***% reduction 1990/2050***
Residential	66	26	9	-59.1%	-86.36%
Tertiary	30	13	2	-56.7%	-93.33%

Though the above values are in $MtCO_{2eq,}$ the potential annual CO_2 emissions mitigation given in the thesis equals 56% of the baseline and is close to the ADEME level of 2030.

As an overview, approximately 75% of the energy and emissions savings obtained in this thesis occur in the residential sector. To start with, this reflects the residential sector's significant share of heated area which is around three times bigger than the tertiary sector. Moreover, the old dwellings constructed before 1975, i.e. dwellings with low thermal performances, make 61% of the total residential stock and this might explain the great energy savings potential in this sector. In the non-residential sector, offices, commercial and education subsectors together make approximately 20% of the total energy savings and avoided emissions. Health and SCL subsectors show a smaller potential, which correlates to the health subsector's already stringent energy requirements and the SCL subsector's irregular occupancy rates. Table 19 illustrates these potentials by showing the savings per m^2 and building type.

Table 19 Savings per m^2 and building type when applying ESM 10.

Sector	***Building subtype***	***Tot. Net Energy Savings*** *[kWh /m^2,yr]*	***Tot. Final Energy Savings*** *[kWh /m^2,yr]*	***CO$_2$ Emissions Mitigated*** *[kgCO$_2$/m^2,yr]*
Residential	SFD	93,55	110,21	16,44
	Priv MFD	76,36	85,05	15,12
	Pub MFD	129,03	147,51	30,02
Non-residential	Offices	101,38	110,64	14,57
	Commercial	127,43	135,47	14,06
	Education	80,74	91,32	17,61
	Health	72,19	74,54	6,38
	SCL	100,27	105,34	11,19

The CO$_2$ mitigation and energy saving potentials are mainly created by insulation measures, see Figure 22 and 23. This reflects the fact that the energy demand in France is largely dominated by space heating, which reaches 63% of the total net energy demand in the baseline scenario.

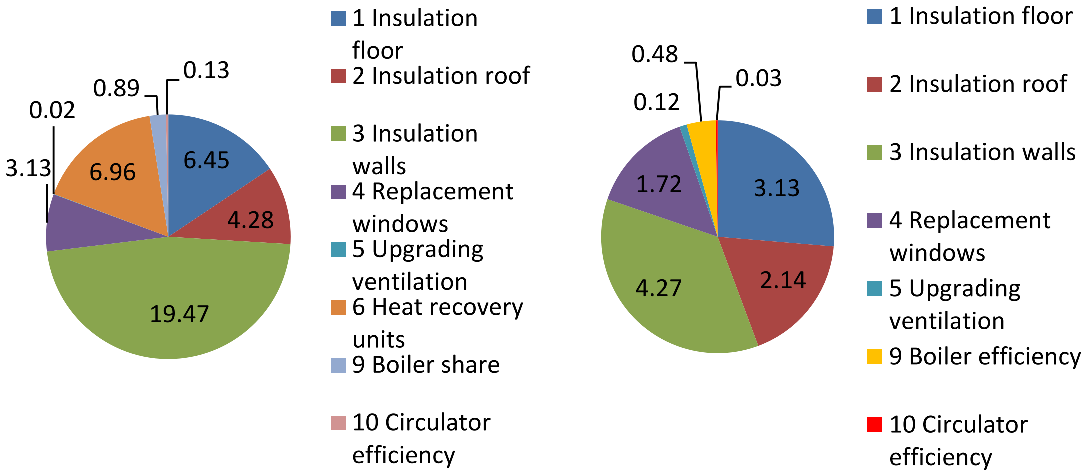


Figure 22 Total CO_2 emissions mitigated per measure in residential (left) and tertiary (right) sector.

Apart from insulation, heat recovery introduction and windows replacement also show high potentials, as they both influence the space heating demand. As seen in the introduction chapter, heating is provided not only by electricity but also by gas and oil. Consequently, measures reducing space heating demand also decrease the CO_2 emissions significantly. ESM5 (ventilation upgrading) and ESM10 (circulators efficiency), mainly affect the electricity demand and thus have less impact on the total emissions savings. However, the measures for appliances (ESM 7) and lighting (ESM8) are increasing the CO_2 emissions. This probably depends on the increased need for space heating during winter when the heat gains of the devices are decreased. However, since the ECCABS model does not account for cooling, the saved cooling demand during summer is not considered in these figures.

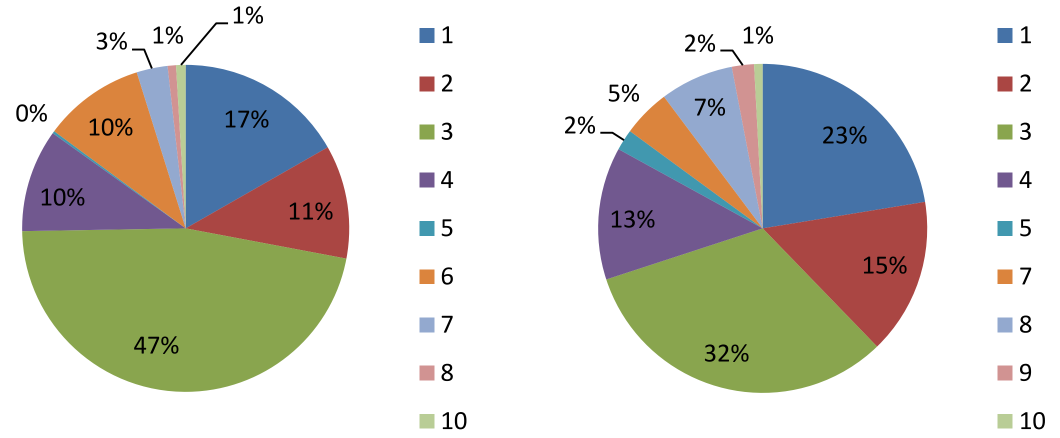


Figure 23 Share of total saved final energy in residential sector (left) and tertiary sector (right), per measure. NB. The colours are not referring to the same measure in the two pie charts. ESM9 (boiler replacement) is not included in the residential part; ESM6 (heat recovery units) is not included in the non-residential part. ESM9 for the tertiary sector refers to boiler efficiency increase.

The heat recovery plays a big role in the residential sector's potential to avoid CO_2 emissions; 30% of the mitigated emissions rely on this measure. The potential savings from replacing the boilers look the same for both residential and tertiary sector; 4%, and refers to the different allocation of energy sources in the two sectors.

Retrofitting entire building envelope

Figure 24 shows the results from aggregating measures 1-4; floor, roof, walls and windows. For these simulations, the U-value for the doors is set to 1.5, see Table 4 Chapter 3.4.1.

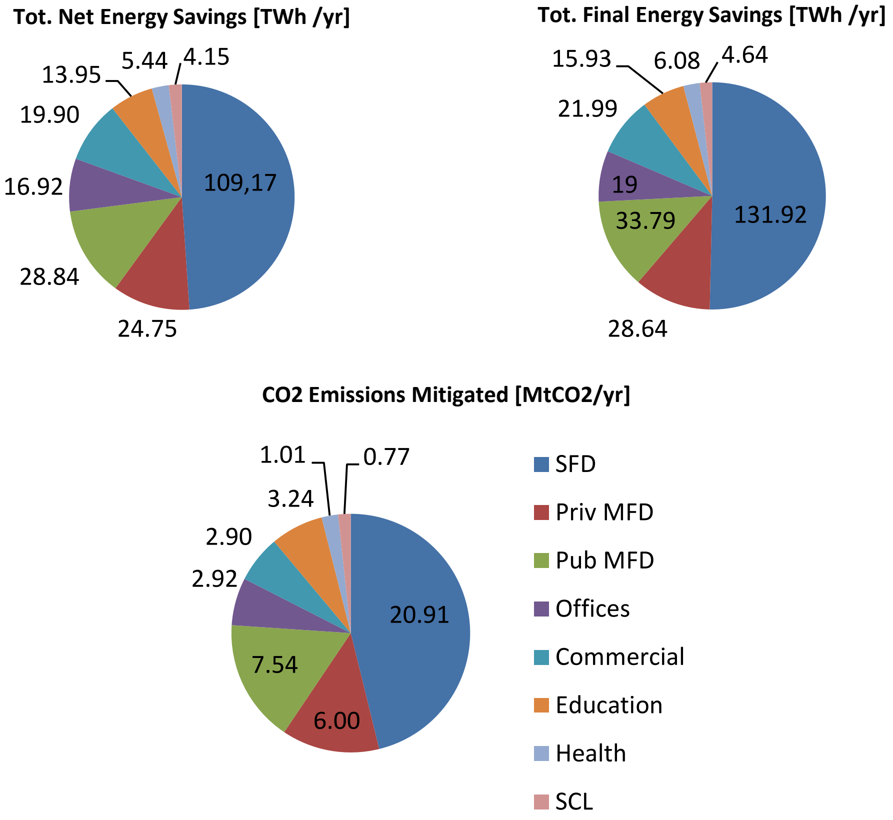


Figure 24 Potential savings by retrofitting the entire building envelope.

The probability of retrofitting the entire building envelope at once may be seen as quite small in most of the building sector, due to the high costs. Rather one can assume that the insulation measures will be applied one at a time during a longer time period. However, what can be seen from the simulations is that almost 190TWh/yr can be saved in the residential sector and 65TWh/yr in the non-residential sector. This reflects the ratio of the two sectors' areas, where the residential sector's heated floor space is about three times bigger than the tertiary sector's. The ADEME study referred to above shows the same relation between the two sectors (a factor of 2-4), though these figures are higher since it also includes heating and ventilation measures (Acchiardi, 2012).

Retrofitting façade air tightness

This measure includes insulation of the walls as well as a replacement of the windows.

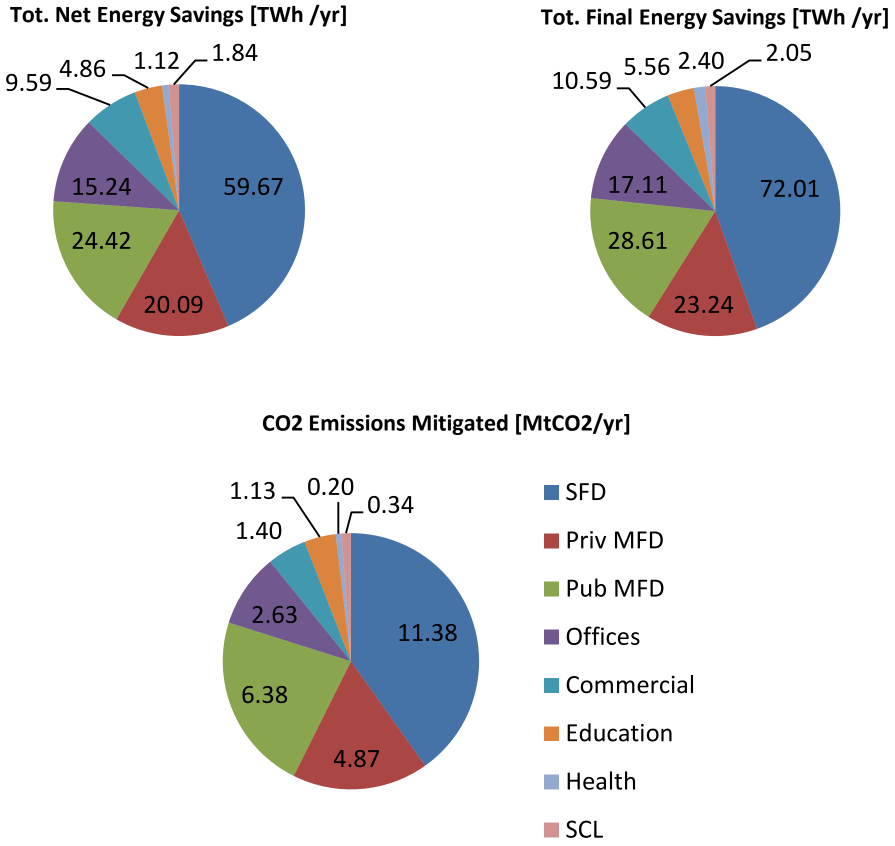


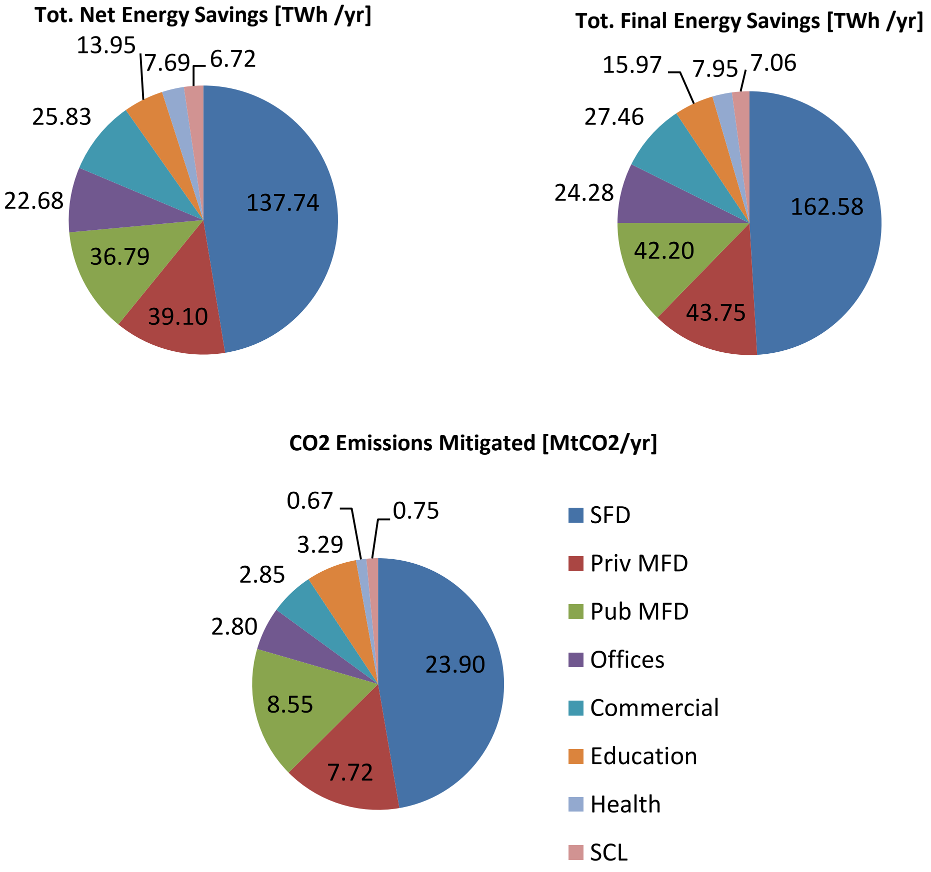
Figure 25 Potential savings by insulating the walls and replacing the windows.

If only looking on the façade, by replacing the windows and insulating the walls one could achieve approximately 120TWh/yr of energy savings in the residential sector and almost 40TWh/yr saved in the tertiary sector. These figures also reflect the area ratio between the two sectors (a factor of 3).

Further, a combination of wall insulation and windows replacement facilitates the work if organized to take place at the same time and may reduce both economical and time consuming disturbances.

Decrease in net energy

To see the potential decrease in net energy only, all measures except the boiler replacement are aggregated.


Tot. Net Energy Savings [TWh /yr]

Tot. Final Energy Savings [TWh /yr]

CO2 Emissions Mitigated [MtCO2/yr]

Figure 26 Potential savings by aggregating all measures except boilers replacement.

The overall decrease in net energy use (290.5TWh/yr) is the same obtained as when aggregating all measures, whereas the delivered energy is decreased with about one additional terawatt hour. Thus, the boilers accounts for a small decrease in delivered energy, which probably refers to the lower efficiency of the wood boilers compared to the oil boilers replaced.

Decrease in electricity use

This measure focuses on the potential electricity savings and thus assesses appliances, lighting and hydro pumps efficiency.

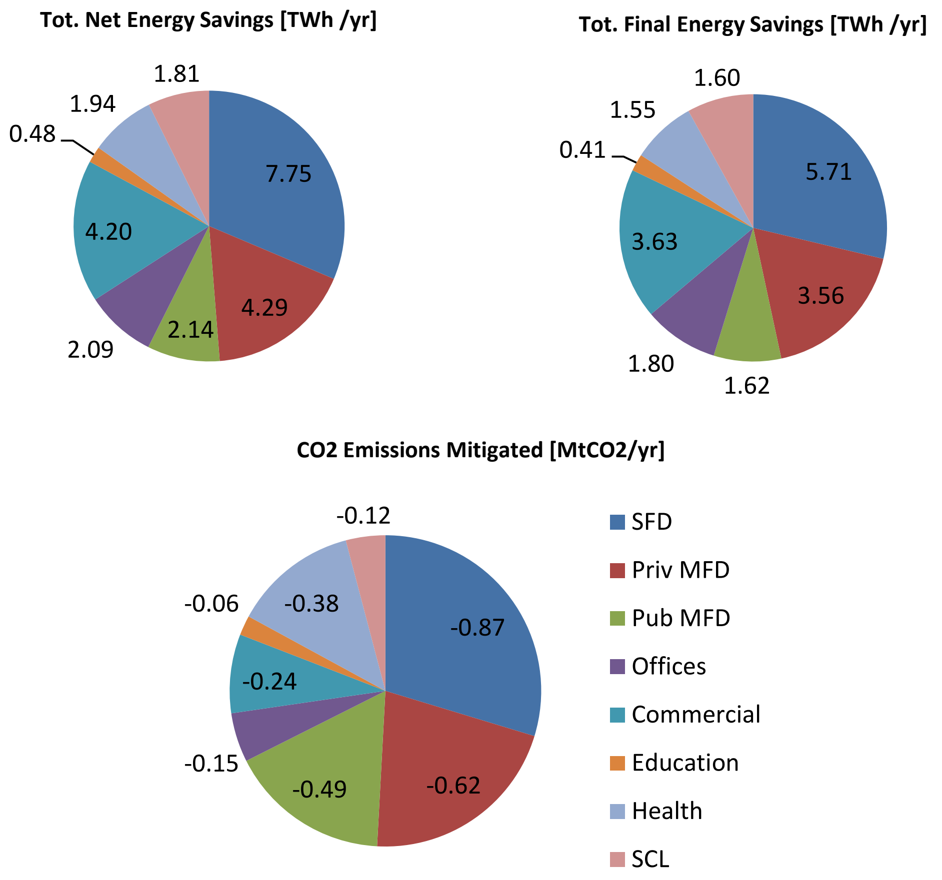


Figure 27 Potential savings by increasing the efficiency of appliances, lighting and hydro pumps. NB. No lighting measure is considered for the education subsector.

The ECCABS simulation results show that about 20TWh/yr of final energy can be saved through electricity saving measures, i.e. 10.99TWh/yr in the residential sector and 8.99TWh/yr in the non-residential sector. The highest savings are found in the single-family dwellings, the private multi-family dwellings, the offices and the commercial subtypes where lighting and appliances are highly represented as stated previously. For the case of France, these measures would however increase the CO$_2$ emissions.

The ESP database's LPI scenario estimates a 1.1TWh/yr energy saving in the residential sector (including refrigerators; freezers; dishwashers; washing machines; and dryers) and 3.8TWh/yr in the tertiary sector (including office lighting; computers and monitors; copying and printing; and commercial refrigeration and freezing). The HPI scenario estimates 1.9TWh/yr for residential and 4.9TWh/yr for tertiary, while the technical potential gives 5.2TWh/yr for residential and 5.0TWh/yr for tertiary sector, respectively.

4.10 Summary of energy and emissions results

Table 20 shows a summary of the results, where this thesis' results are set in relation to previous studies of the estimated technical potentials for energy savings in the French building stock. Depending on the data provided, some of the figures are representing the whole building sector assessed; several of them only the subsectors. Also note that some of the figures refer to CO_2 emissions and some to energy savings. As already mentioned, discrepancies between this thesis' results and the reference sources' estimated figures may to a big extent depend on differences in assumptions made in the surveys.

Table 20 Summary of technical potential savings in this thesis compared to literature's estimated figures.

Measures	*This thesis' savings*	*Literature savings*	*Source*
1 Floor	8.38 % energy savings	5 to 10% energy savings	(ASDER, Maison des Energies, 2009)
2 Roof	25.56 TWh/yr	56 TWh/yr	(Acchiardi, 2012)
3 Walls	106.53 TWh/yr	148 TWh/yr	(Acchiardi, 2012)
4 Windows	101 196 TJ/yr	92 184 TJ/yr	(Glass for Europe, 2009)
5Ventilation	1.75-2.96 TWh	2.0 TWh in 2015	(European Commission Directorate, 2009)
6Heat recovery	6.96 $MtCO_2$/yr	6 $MtCO_2$/yr	(Händel, 2011)
7 Appliances Residential	25% of energy savings	20 to 35% energy savings	(IEA, 2003)
	6.99 TWh/yr	6 TWh/yr in 2030	(European Commission Directorate, 2009)
7Appliances Tertiary	7.82 TWh/yr	4.8 TWh/yr in 2015	(European Commission Directorate, 2009)
8 Lighting Residential	1.88 TWh/yr	1.96 TWh/yr	(Bertoldi & Atanasiu, 2007)
		1 TWh/yr and 2.2 TWh/yr in 2020 (LPI/HPI)	(European Commission Directorate, 2009)
8 Lighting Tertiary (offices)	3.21 TWh/yr	3 TWh/yr in 2015	(European Commission Directorate, 2009)
9 Boiler replacement Residential	1.88 TWh/yr	1.7 TWh/yr and 2.3 TWh/yr in 2015 (LPI/HPI)	(European Commission Directorate, 2009)
10 Hydro Pumps	0.16 $MtCO_2$/yr; 1.12 $MtCO_2$ in 2020	0.62 – 1.42 $MtCO_2$ in 2020	(European Commission Directorate, 2009)

Figure 28 shows each of the ESMs and its specific contribution in decreasing the French energy consumption and CO_2 emissions.

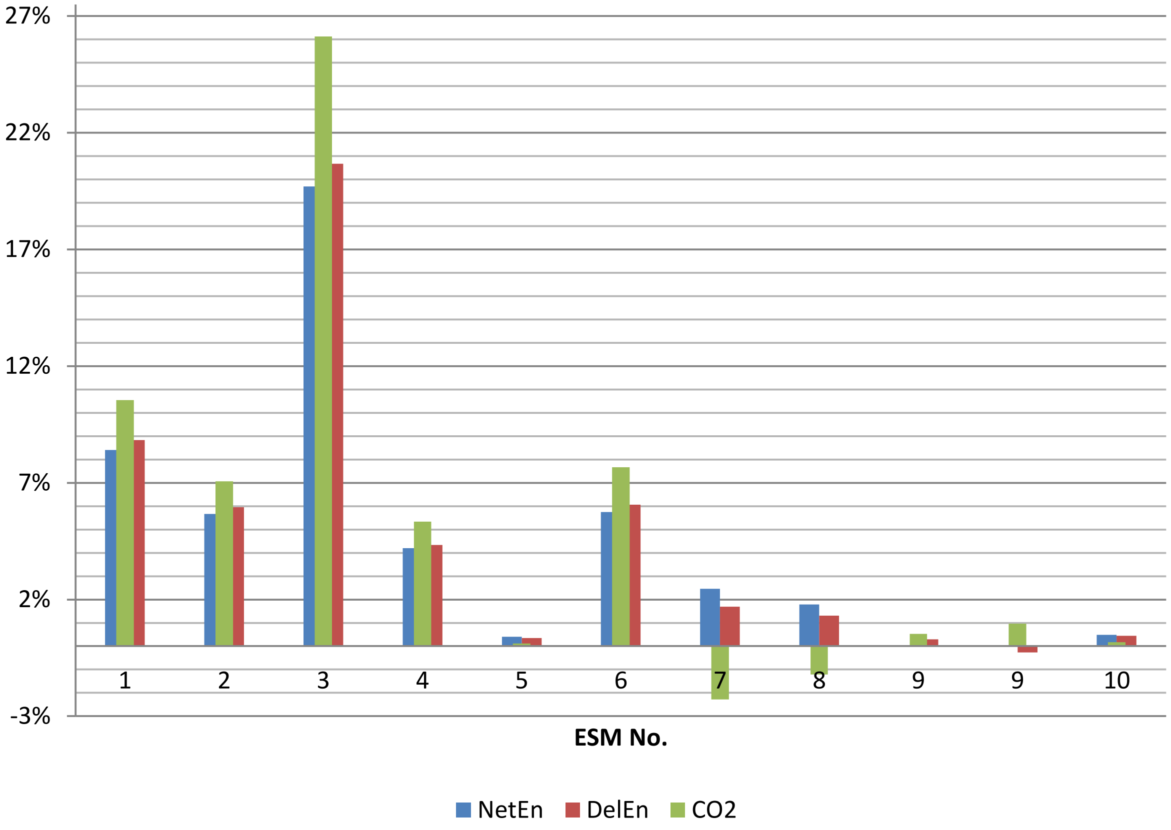


Figure 28 Total saved net energy; total saved delivered (final) energy; and total mitigated CO_2 emissions, in percentage of baseline consumption per ESM applied to all building subtypes.

Looking at the emissions reduction, insulation measures and the introduction of heat recovery units into the residential sector (ESMs No.1-4 and 6) are the most favourable ones with a possible final energy reduction from 4% to 20% of the baseline. Hence, as said in the introduction chapter, space heating demand is the end use that should be in focus from an emissions mitigations perspective.

Individually applied in the residential sector, the measures make it possible to save between 0.37TWh (ESM9) and 106.53TWh (ESM3) of final energy annually.

Residential sector

An aggregation of all measures shows that it is possible to reduce the annual final energy consumption of the French residential stock by 247.89TWh, i.e. 54% of the baseline scenario’s total delivered energy demand, see Table 21.

Table 21 Final energy savings in the residential sector per measure assessed and arranged with the highest energy savings potential on top.

ESM No.	***Description***	***Individually*** *[TWh/yr]*	***Aggregated***
3	Retrofitting walls	106.53	
1	Retrofitting floor	38.14	
2	Retrofitting roof	25.56	
4	Replacing windows	23.15	
6	Introduction of heat recovery units (residential)	22.86	
7	Appliances efficiency	6.99	
10	Hydro pumps efficiency	2.15	
8	Lighting efficiency	1.88	
5	Upgrading ventilation system	0.54	
9	Replacing boilers (share)	-1.66	
Total		226.14	247.89

Figure 29 shows the final energy saved in the residential sector by fuel category for each one of the different measures. The insulation of the walls gives the highest energy savings potential; 106.53TWh, which are made in the space heating demand and therefore also decreases the use of gas and oil.

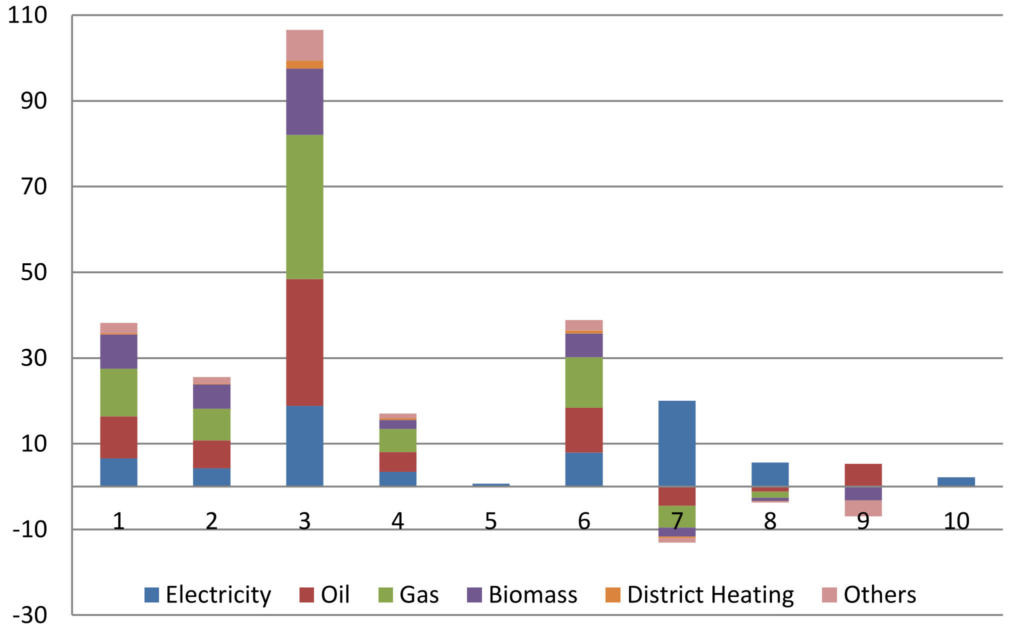


Figure 29 Final, or delivered, energy saved in the residential sector in [TWh/yr], presented in fuel shares affected by the different measures 1-10.

The insulation measures (ESMs No.1-3) and the replacement of windows (ESM4), which exclusively influence the space heating demand, have a balanced mix of fuel savings which concords with the shares used as input figures for SFDs and MFDs. As seen in Figure 3, these results concord with the current renovation situation in France's residential sector.

The introduction of heat recovery units in the residential sector (ESM6) results in a high potential of decreasing energy demand, while upgrading the ventilation system (ESM5) and regulating the hydro pumps' working schedule (ESM10) only result in marginal electricity savings.

For lighting and appliances power reduction measures (ESM7 and ESM8) the increase in space heating demand (negative part with oil, gas and wood) is probably due to a decrease in the heat released by those devices. The reduced heat gains of the devices leads to a greater heating demand, but is compensated by the electrical savings (20TWh for appliances). As it can be seen in the figure, the heat demand is therefore met with mostly oil and gas furnaces, leading to increasing CO_2 emissions.

The replacement of boilers (ESM9) clearly shows an increase in wood demand, as well as a decreased oil demand. Due to the lower efficiency of the wood boilers compared to the oil boilers, this measure results in an overall negative energy savings potential. However, the CO_2 emission will decrease and therefore this might be a potential measure when looking into the climate change aspect.

Tertiary sector

Aggregating all measures except the efficiency increase of the boilers shows a possibility of reducing the annual final energy consumption of the French non-residential sector by 82.71TWh. This equals to about 40% of the baseline scenario's total delivered energy demand, see Table 22. Overall, the allocation of the energy savings is similar to the residential sector.

Table 22 Final energy savings in the non-residential sector per each measure assessed and arranged with the highest savings potential in top. ESM6 is not applied to this sector. * The ESM9 with boiler efficiency is not applied into the aggregated figures and therefore is not included in the total.

ESM No.	***Description***	***Individually*** *[TWh/yr]*	***Aggregated***
3	Retrofitting the walls	27.28	
1	Retrofitting the floor	18.99	
2	Retrofitting the roof	12.99	
4	Windows replacement	11.03	
8	Lighting efficiency	6.12	
7	Appliances efficiency	3.98	
9	Replacing boilers (efficiency)	1.88*	
5	Increasing the efficiency of the fans	1.75	
10	Upgrading hydro pumps	0.71	
9	Replacing boilers (share)	-0.04	
Total		82.81	82.71

Figure 30 shows the final energy savings by fuel category when applying the measures in the non-residential sector. Similar to the residential sector, the insulation of walls remains the measure with the highest energy savings potential; 27.32TWh, all of it deriving from saved space heating.

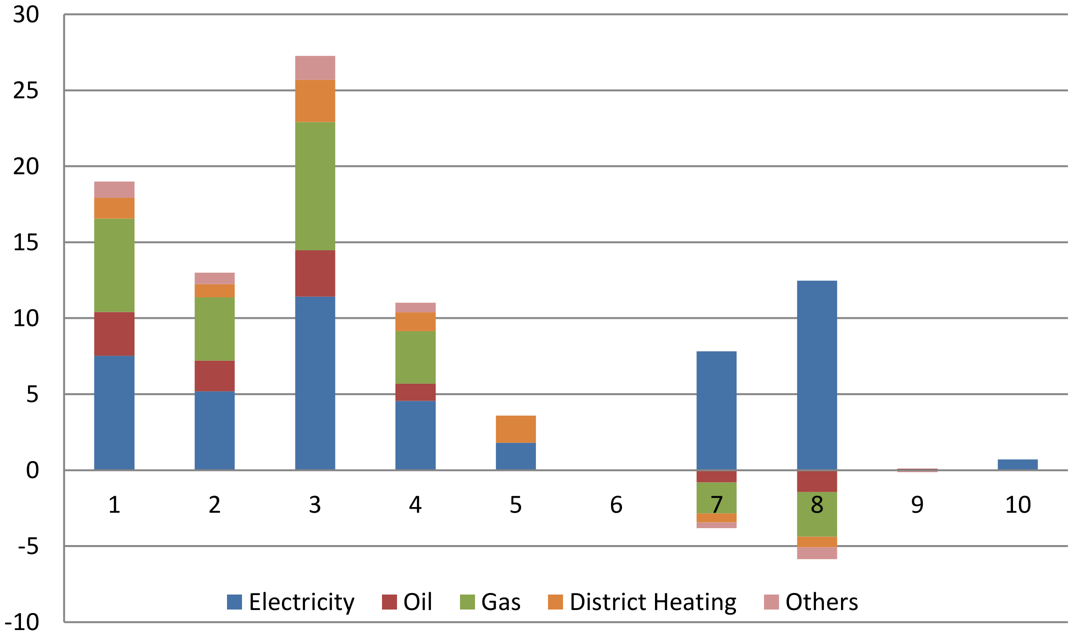


Figure 30 Final, or delivered, energy saved in the non-residential sector in [TWh/yr], presented in fuel shares affected by the different measures 1-10.

The insulation measures (ESM No.1-3) and the replacement of windows (ESM4), exclusively influence the space heating demand. The different mix of fuel savings compared to the residential sector derives from the diverse fuel shares allocated for each sector's boiler types. Hence, most of the savings are made in electricity and gas, which are the main fuels for electrical boilers and gas heaters used in the tertiary sector.

Similarly to the residential sector, the upgrading of the ventilation systems (ESM5) and the upgrading of hydro pumps (ESM10) result in low savings in electricity.

The same observation is done for lighting and appliances power reduction measures (ESM7 and ESM8), where the increase in space heating demand (negative part for oil, gas and district heating) probably reflects a decrease of heat released by those devices. However, the bigger electrical savings are compensating for the increased heating demand and lead to a reduction of the final energy use. Looking at the CO_2 mitigation potential, the increased heating demand eventually results in higher emissions and therefore the introduction of more efficient lighting and appliances should be further investigated before introduced as ESMs in France.

The energy savings potential from replacing oil boilers with wood boilers are negligible. However, similar to the residential sector, the CO_2 emissions may be decreased and therefore this measure should be considered from a climate change perspective.

4.11 Cost-efficiency per measure and per group of measures

Tables 23-26 present the maximum technical and the cost-effective potentials, respectively, for each measure and group of measures assessed. In Appendix K, the results are presented per building type. The maximum technical potential is the amount by which it is possible to reduce energy demand or CO_2 emissions by implementing already demonstrated technologies and practices without the specific reference costs. The cost-effective potential is the techno-economic, or profitable, potential to reduce energy demand or CO_2 emissions (Mata, 2011). The weighted average coefficient makes it possible to assess the effect on average French building. Data for each building type are found in the simulation results.

Table 23 Maximum technical potential for each measure assessed. Weighted average equivalent annual cost (WAvgEAC); weighted average cost per energy saved (WAvgS); weighted average unit cost per energy saving (WAvgCE); and weighted average abatement cost (WAvgAC).

ESM No.	***WAvgEAC*** *[€/yr]*	***WAvgS*** *[€/yr]*	***WAvgCE*** $[€/kWh_{saved},yr]$	***WAvgAC*** $[€/tCO_{2,mitigated},yr]$
1	110.6	244.2	0	-6.7
2	177	164.6	0.091	912.9
3	990.1	572.2	0.182	1 784.2
4	817.2	123.5	1.101	9 562.3
5	43.5	14.9	4.939	3 153.9
6	329.9	168.1	0.121	835.3
7	588.1	105.3	1.644	4 371
8	134.6	73.9	0.873	2 326.4
9	446.7	5.9	9.539	2 985.1
10	0	18	-0.096	-1 671
Average	363.8	149.1	1.84	2 425.3

Table 249 Cost-effective potential for each measure. Cost-effective total saved delivered energy (Cef TotSDelE); cost-effective total saved emissions (Cef TotEmS); cost-effective weighted average unit cost per energy saving (Cef WAvgCE); cost-effective weighted average abatement cost (Cef WAvgAC). NB. The minus (-) shows that when the savings are zero or below, there is no cost.

ESM No.	***Cef TotSDelE*** *[TWh/yr]*	***Cef TotEmS*** *[MtCO$_2$/yr]*	***Cef WAvgCE*** *[€/kWh, yr]*	***Cef WAvgAC*** *[€/tCO$_2$,yr]*
1	49.94	8.53	-0.041	-352.8
2	25.91	4.41	-0.035	-306.5
3	64.75	11.87	-0.011	-126.1
4	-0.94	-0.15	0	0
5	1.84	0.12	-0.006	-62.9
6	0.15	0.03	0	-0.4
7	0	-2.23	-	0
8	6.78	-1.12	-0.062	-133
9	-1.69	0	0	-
10	3.03	0.2	-0.096	-1 671
Total	149.76	21.65	Avg. -0.014	Avg. -209.8

Table 25 Maximum technical potential for each group of measures assessed.

ESM No.	***WAvgEAC*** *[€/yr]*	***WAvgS*** *[€/yr]*	***WAvgCE*** *[€/kWh$_{saved}$,yr]*	***WAvgAC*** *[€/tCO$_{2,mitigated}$,yr]*
11	4 796.1	1 519.6	0.252	3 949.5
12	2 229.6	1 120	0.267	2 464.3
13	1 942.1	693.3	0.324	2 960.3
14	4 182.7	1 517.5	0.213	3 373.1
15	922.8	186.4	0.213	3 842.3

Table 26 Cost-effective potential for each group of measures assessed.

ESM No.	***Cef TotSDelE*** *[TWh/yr]*	***Cef TotEmS*** *[$MtCO_2/yr$]*	***Cef WAvgCE*** *[€/kWh, yr]*	***Cef WAvgAC*** *[€/tCO_2,yr]*
11	0	-0.08	0	0
12	106.18	18.73	-0.013	-137.5
13	22.94	5.13	-0.007	-63.2
14	3.01	0.1	-0.005	-23.9
15	-0.03	-3.29	0	0

From aggregating all measures (ESM11), the result shows that an annual investment of €59 billion[8] would potentially save 329TWh/yr, representing 50% of the baseline final energy consumption in the French building sector, as well as $51MtCO_2$ (56%) annually. The aggregated ESMs are significantly less expensive to implement than if retrofitting a building in many steps. Thus it seems more profitable to implement the measures during a major retrofitting of a building.

The annual investment related to the residential sector is €48 billion which would save about 54% of the baseline final energy consumption. In the book by Charlot Valdieu et al. (2011), an estimation of the investment needed to reach the 38% energy reduction goal (compared to the baseline year 2008) of the *Plan Grenelle* have been made. The *Plan Grenelle* aims at renovating 400 000 dwellings per year till 2020 representing an investment of €12 billion/yr. An addition to this value is the investment needed for the rest of the dwellings; €15 billion/yr, that gives a total investment of €27 billion/yr till 2020 (Charlot-Valdieu & Outrequin, 2011). Thus, the calculated investment of this thesis is similar to the estimated figures of Charlot-Valdieu et al. assuming that the baseline scenario of 2005 is the same as the year 2008.

Nevertheless, if only considering the implementation of cost-effective ESMs, the potential final energy savings would reach 149.76TWh/yr, i.e. 23.14% of the baseline, which means that the reduction of energy consumption would be only halfway through the objective of the *Plan Grenelle*. Applying only profitable measures would cost in average $-1.4€_{cents}/kWh_{mitigated}$ and $-209€/tCO_{2mitigated}$ while applying the measures (individually) to reach the maximum technical potential would cost on average $1.84€/kWh_{mitigated}$ and $2425.3€/tCO_{2mitigated}$. Hence, there is a trade-off between cost efficiency and achieving the maximum energy savings.

Evaluated individually, the results reflect the cost-effective possibilities for an average French building. The most profitable ESM is the regulation of the hydro pumps' working schedule (ESM10) as the related investment costs were assumed to be zero. The lighting measure is also profitable as the investment cost of bulbs are low (0.69€/m^2). The insulation measures are cost-effective except for the windows

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[8] One billion on short scale equals 10^9.

replacement which has a high investment cost per square meter (502.22€/m^2 due to expensive low-E glazing and high labour costs). The wall insulation measure which has the highest energy potential is yet less cost-efficient than the other insulation measures.

From a technical potential perspective, thermal insulation has been indicated in former studies to be the most cost-efficient one (Paul Baudry, 2007). This corresponds well to the results found in this thesis.

4.11.1 Building subtypes' response to the ESMs

Below follows a short summary of the building subtypes' response to each of the measures assessed. Table 27 shows a summary of the building archetypes that would benefit from implementing each of the ESMs.

Table 27 Summary of cost-effective implementation of measures in relation to building archetypes.

ESM No.	***Subtypes positively affected***	***Cost-effective CO_2 mitigation***	***Cost-effective energy reduction***
1	R1:3 before 1975	X	
	NR1:5 before 2000	X	
2	R1:3 before 1975	X	X
	NR1:5 before 1977		X
	NR2	X	
3	R1:3 before 1975	X	
	NR1:5 before 1977		X
4	-		
5	NR2:4		X
	NR1:4	X	
6	R2:3 (Electricity)		X
7	NR1:2, NR5	X	
	R2:3, NR1, NR4:5		X
8	NR2, NR5		X
	NR1, NR4 after 2000 in H3	X	
9	-		
10	R1:3, NR1:5	X	X

Insulation of floor

Residential buildings constructed before 1975 show negative abatement costs (earnings), while buildings built after 1975 seem to be already too well refurbished to profit from this measure. Insulating the floor is not profitable for the non-residential sector and in buildings constructed after 2000 the abatement costs tend to be very high. However, in non-residential buildings built before 2000 the abatement costs are showing to be profitable, which refers to big emissions mitigation potentials.

Insulation of roof

Residential buildings constructed before 1975 profit economically from insulating the roof. Furthermore, the SFDs have the lowest unit cost per energy saving. Public MFDs and commercial buildings show the lowest abatement costs and are thus the most efficient ones when looking at emissions mitigation.

Tertiary buildings constructed before 1977 as well as buildings built during the years 1977-2000 in climate zones H2 and H3, profit from insulating the roof. The exception is SCL buildings built after 1977 in climate zone H3.

Insulation of walls

Due to their big areas, the equivalent annual cost is low for the SFDs for all insulation measures. Residential buildings constructed before 1977 show profitable abatement cost, which also holds for SFDs and private MFDs built during the years 1977-2000 in climate zone H1 and for public MFDs buildings in climate zones H2 and H3. Non-residential buildings built before 1977 profit from insulating the walls, with the exception of commercial and education buildings in climate zone H3, as well as SCL buildings in zone H2 and H3.

Replacement of windows

This measure is non-profitable for both tertiary and residential sector. Further, tertiary buildings built after 2000 in most of the climate zones show increasing emissions. Replacing the windows will also lead to increased emissions in the residential sector for buildings that have already been refurbished.

Upgrading of ventilation system

This measure is not profitable for the residential sector and the emissions savings are small. In the non-residential sector, an upgraded ventilation system shows an overall cost-efficient investment, with lowest unit costs in the education subsector. However, offices and health buildings show high and non-profitable figures. The abatement cost is profitable for all tertiary sectors except health sector, which means high emissions mitigation potentials. Offices built before 1977 in climate zone H2 are showing increased emissions connected to this measure.

Introduction of heat recovery units in households

The average unit cost for installing heat recovery units into the residential sector is 4.8-9.7€cents. However, there is a high abatement cost related to this measure and the biggest savings are found in the MFDs, while there is no cost-efficiency for SFDs. The most profitable buildings to implement this measure are the ones using electricity as energy source.

Appliances efficiency

Substituting the appliances with more efficient ones, leads to high abatement costs and an overall increase in emissions in most of the subsectors, with some exceptions; offices, commercial and SCL buildings built after 2000. In the residential sector, CO_2 emissions are only saved in buildings using electricity as energy source; in the other buildings the emissions are increasing.

The average unit cost per energy saving is lowest for MFDs, health and SCL subsectors. The offices subsector shows to be profitable both in unit cost and abatement cost.

Lighting efficiency

Overall, this measure shows good economic figures. However, more efficient lighting would increase the emissions. One can see a profitable unit cost per energy saving in the commercial and SCL subsectors, and small unit costs for the MFDs. The only tertiary subsectors showing profitable abatement costs are offices and health buildings built after 2000 in climate zone H3; and commercial buildings built after 2000 in H1. Here is also where the only emissions mitigation occurs. In residential buildings the emissions are only saved in buildings using electricity as energy source; in the other buildings the emissions are increasing.

Hot water production efficiency

This measure is not a cost-efficient way of saving energy. The only results showing a cost-efficient application of the measure are resulting in higher energy consumption. One can also see increasing emissions in the residential sector when substituting the oil boilers with wood boilers; the only buildings showing mitigated emissions are the ones using “other” energy sources than electricity. Especially offices seem to be non-profitable of this measure.

Upgrading of hydro pumps

Regulating the working schedules of the hydro pumps seems to be a profitable measure, since no investment cost is taken into account. This measure turns out to be profitable for all subsectors, as well as for the environment.

Figure 31 illustrates each of the residential building subtypes and their final energy consumption (X-axis) after having implemented a certain measure to a certain cost (Y-axis). The same illustration is made for the non-residential sector in Figure 32. These two figures show that a certain measure may lead to a very diverse distribution of results depending on what building archetype one is looking at.

The lifetime cost of each measure implemented in the residential sector ranges from -10€/(m^2,yr) to around 6€/(m^2,yr). The distribution of building archetypes for wall insulation is the most diverse when it comes to cost, but as most of the measures it also shows a trend of leading to a final energy demand between 110-150kWh/m^2.

Looking at the roof insulation measure, which is said to be the most cost-effective one according to literature, it seems to be overall less costly than the wall insulation; floor insulation going somewhere in between.

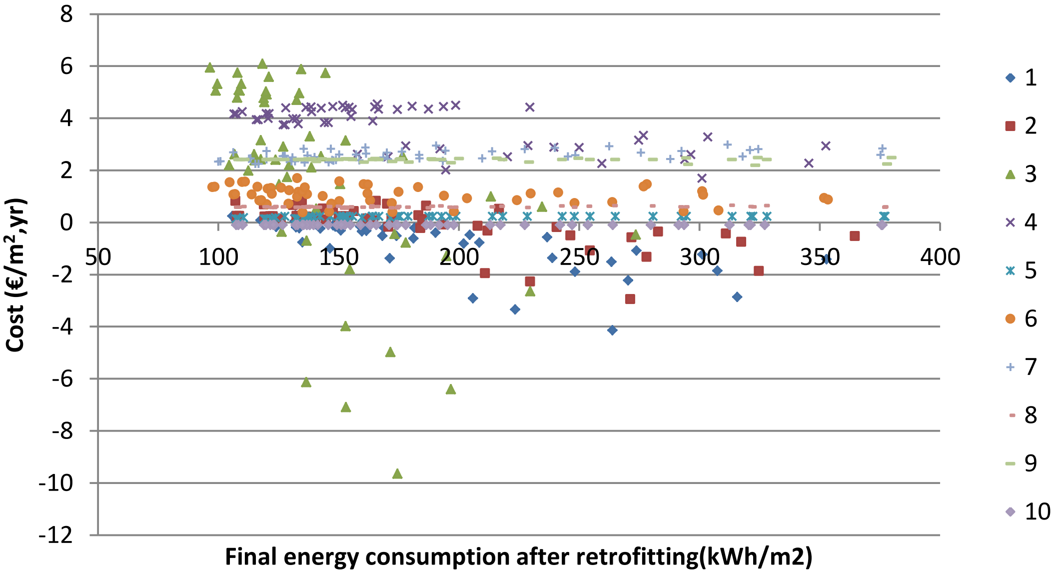

Figure 31 Distribution of residential buildings per ESM (1-10); costs and energy demand per year. Cost = Initial investment cost –Σ (net present cost of energy savings per year).

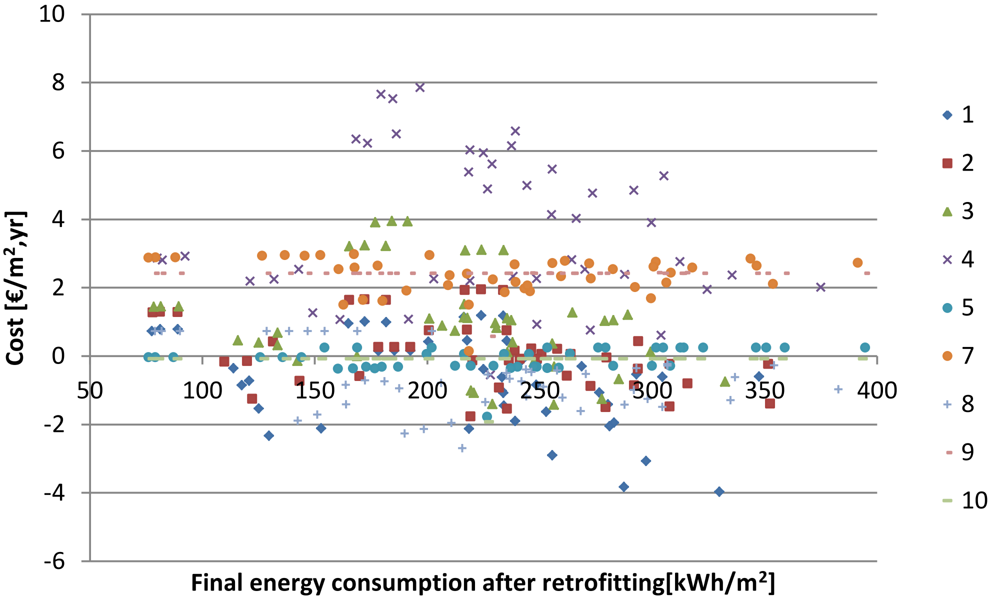

Figure 32 Distribution of non-residential buildings per measure (1-10); cost and energy savings per year. Cost = Initial investment cost –Σ (net present cost of energy savings per year).

For the tertiary sector, roof insulation and lighting efficiency measures seem to be the less expensive ones. Insulating the roof seems to generate cost savings for some of the buildings, especially those with higher energy demand. However, from these figures one can see that one needs to look into each of the building archetypes' response to the measures to be able to apply the most beneficial ones.

Figure 33 illustrates the average cost savings per final energy saved by an average building (both residential and tertiary buildings included), in relation to the measure's savings in final energy. ESM8 and ESM9 are not considered since they increase the final energy demand when looking at the whole building sector. Here, once again, one can see that the passive strategies that are focusing on energy demand reduction are showing the biggest energy savings; while the active strategies that are increasing the efficiency of the devices save more money per energy saving but do not contribute as much to the final energy savings potential.

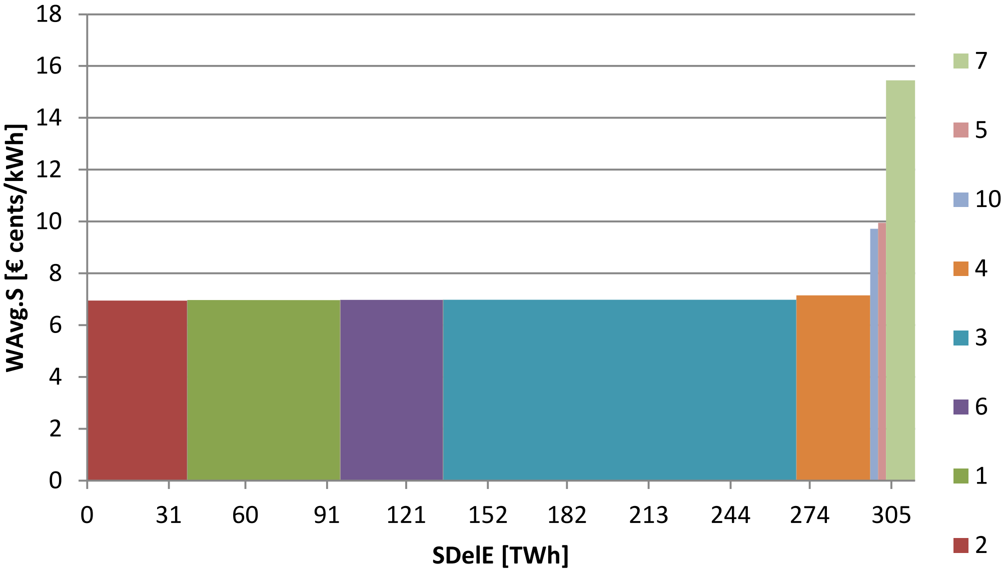

Figure 33 Cost savings per delivered energy saved and the measures' (1-10) potential energy savings, looking at the whole building sector.

To understand the cost-energy relationship from implementing the ESMs, Figure 34 illustrates the net cost needed to reach a certain energy consumption level of each average building subtype.

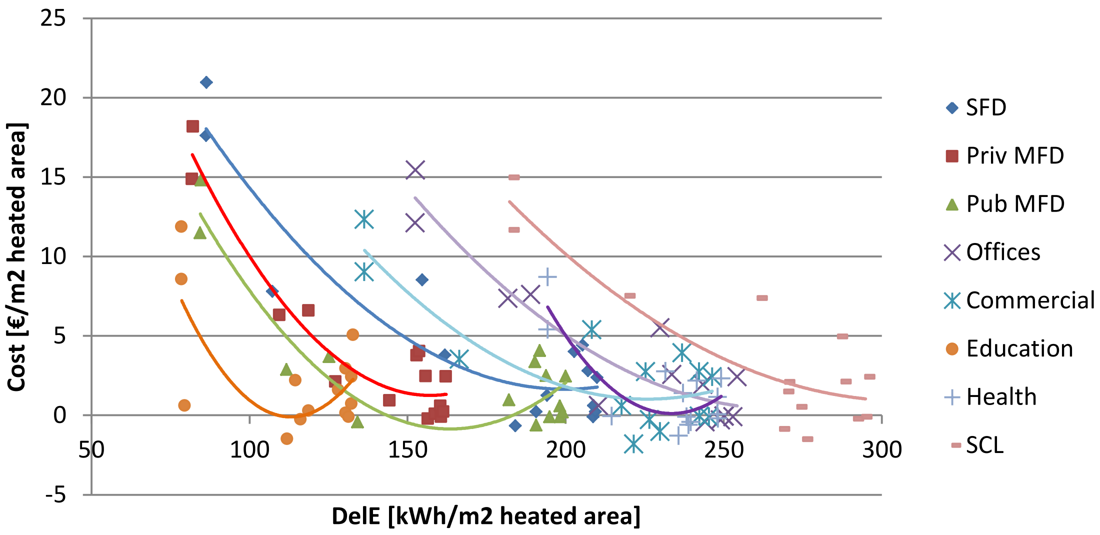

Figure 34 Net cost per implemented measure and the reference energy consumption of an average building subtype. Cost = Initial investment cost –Σ (net present cost of energy savings per year). The lines are polynomial trend lines of the second order.

From Figure 34 one can see an overall trend for six of the eight building subtypes, where the optimal energy consumption (i.e. the global minimum) is lower than the baseline consumption. The trend lines of Offices and SCL on the other hand, have their global minimum at the righter most measure point and are seemingly more difficult to retrofit in a cost-efficient way.

The residential buildings' energy demand is ranging between 80-220kWh/m^2; the tertiary sector consumes between 80-300kWh/m^2.

The most cost-efficient measure for an average SFD building is to insulate the floor (ESM1). At an annual net cost of -0.7€/m2 the building would have an annual final energy consumption of 184kWh/m2. To reach the lowest energy consumption; 86kWh/m2,yr, a net cost of 17.7€/m2,yr would be needed.

An average private MFD building would gain 0.23€/m2 per year from insulating the floor and would thus reach a final energy consumption of 157 kWh/m2,yr. The lowest energy consumption of 82 kWh/m2,yr would cost 14.9€/m2,yr to achieve.

For the public MFDs, one could save 0.63€/m2,yr by implementing ESM1, thereby reaching an annual final energy consumption of 191kWh/m2. However, one may reach an even lower energy demand by implementing ESM3, wall insulation, and still save 0.43€/m2 per year but at an energy consumption of only 134 kWh/m2,yr.

For the tertiary buildings' figures, see Table 28.

Table 28 Annual net cost and energy consumption from implementing the most cost-efficient measure to an average building subtype.

Building subtype	***Most profitable ESM***			***Lowest potential final energy consumption***	
	ESM	Cost [€/m^2]	Final energy consumption [kWh/m^2]	Cost [€/m^2]	Final energy consumption [kWh/m^2]
R1	1	-0.7	184	17.7	86
R2	1	-0.23	157	14.9	82
R3	1	-0.63	191	11.5	84
NR1	8	-0.43	244	12.1	152
NR2	1	-1.82	222	12.3	136
NR3	1	-1.5	112	11.9	79
NR4	1	-1.29	236	8.7	194
NR5	8	-1.52	275	15	182

5 Sensitivity Analysis

For some of the energy input data, finding accurate reference sources were difficult and therefore some of the sources may need to be updated in future works. The results of the simulations also depend on the choice of reference years when gathering the input data. Due to lack of data, there has been no strong consistency of reference year, i.e. the most stringent regulation to be found today is used, and this might affect the accuracy of the result. Furthermore, some of the input data are relating from other countries than France and the differences in climatic conditions between the countries may present additional sources of error.

The precision of the results in this thesis is assessed through a sensitivity analysis. The sensitivity of the energy input parameters is already being assessed in previous thesis (Ribas Portella, 2012). In this thesis the sensitivity of the cost-efficiency; see Table 23-26, of each of the measures is assessed, considering different discount rates (r) and energy prices (EP) developments. A normalised sensitivity coefficient is calculated to define the output parameters' sensitivity to a change in the input values. The normalised sensitivity coefficient shows the change in a given output parameter when the input increases or decreases with 1%, following Equation 5.1 and Equation 5.2 (Mata, et al., Submitted for publication).

$$S_{i,j} = \frac{k_j}{y_i} \times \frac{\delta y_i}{\delta k_j} = 1, \dots, n \ and \ j = 1, \dots, m \qquad \text{Equation 5.1}$$

$$\frac{\delta y_i}{\delta k_j} \approx \frac{y_{i(kj+\Delta kj)} - y_{i(kj-\Delta kj)}}{2\Delta k_j} = 1, \dots, n \ and \ j = 1, \dots, m \qquad \text{Equation 5.2}$$

with k_j the "j^th^" input; y_i the "i^th^" output; and Δk_j the increment which is here ±1%.

Table 29 shows the results from Equation 5.1.

Table 29 Normalised sensitivity coefficient calculation in relation to discount rate and energy prices set for the simulations.

Input Parameter	***Initial set value*** *k_j*	***Overall change in input*** *$2\Delta k_j$*	***Output*** *y_i*	***Normalised Sensitivity Coefficient*** *S_{ij}*
Average energy price	0.068	0.001377	WAvg.S	1
			WAvg.CE	-0.05
			WAvg.AC	-0.29
			Cef TotSDelE	0.87
			Cef TotEmS	1.32
			Cef WAvg.CE	3.53
			Cef WAvg.AC	1.13
Discount rate	0.04	0.0008	WAvg.EAC	0.4
			WAvg.CE	0.33
			WAvg.AC	0.44
			Cef TotSDelE	-0.88
			Cef TotEmS	-1.34
			Cef WAvg.CE	-3.57
			Cef WAvg.AC	-0.07

The cost-effective coefficients are the most sensitive to change in energy prices since a greater price will lead to avoided costs that are higher when more energy is saved. The coming trend of increasing fuel prices will potentially benefit emissions mitigation. WAvg.S is sensitive since it is based on the annual running costs for which the fuels costs play an important part.

The discount rate has a high effect on the cost-efficiency of the measures investigated. If considering a societal perspective where the discount rate is set to 4%, great cost-effective energy savings may be achieved. If on the other hand considering a private perspective where one looks into each individual's willingness to pay for an ESM, the potential cost-effective savings decreases drastically to account for less than 1% of the baseline scenario's energy consumption.

In Appendix L, the energy prices are being altered between -5% and +15% of the baseline energy price in accordance with historical energy price data for France. This is to show in real figures the energy price's effects on the measures' cost-efficiency.

Looking at the normalised sensitivity coefficients resulting from changes in discount rate, the values are similar to the energy prices. A further sensitivity analysis regarding the discount rate is conducted in the following chapter. Here, the discount rate is set to 4% in the baseline scenario and is then changed to discount rates with a more private perspective, i.e. 10%, 40% and 80%, respectively. These values are chosen with regards to former works performed by (Mata, et al., Submitted for publication).

5.1 Effects of the discount rate

Figure 35 illustrates the discount rate's effects on the weighted average unit cost per energy saving (WAvgCE) and per measure assessed including all building subtypes.

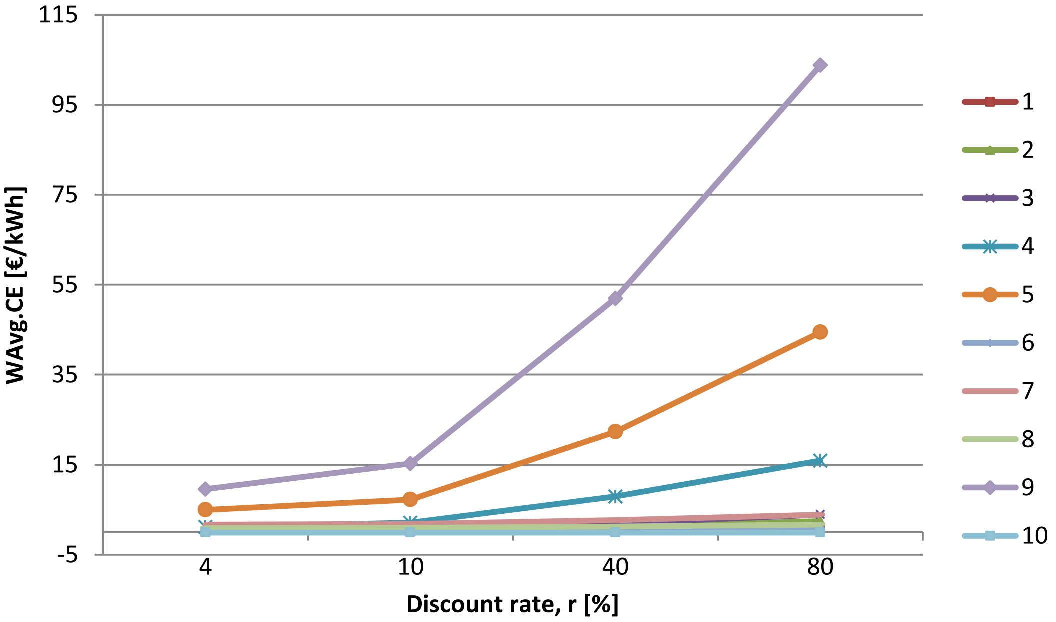

Figure 35 Annual weighted average unit cost per energy saving [€/kWh] for different discount rates and per measure.

The discount rate has a greatest impact on the unit cost for ESM9, ESM5 and ESM4; i.e. boiler replacement, upgrading of ventilation system and replacement of windows, respectively. These ESMs show a significant increase in cost at higher discount rates due to higher investment costs leading to higher payback time for the consumer.

Figure 36 shows the total annual cost-effective final energy savings potential (Cef TotSDelE*)* for each measure including all subsectors and its relation to the discount rate. Here, the discount rate affects the energy savings potential of ESM3, ESM1 and ESM2 the most; i.e. insulation of walls, floor and roof, respectively. The cost-effective potential to save energy shows a decreasing relationship to higher payback requirements. Thus, a retrofitting of the building envelope shows the greatest sensitivity since these measures make the greatest share of the total energy savings potential.

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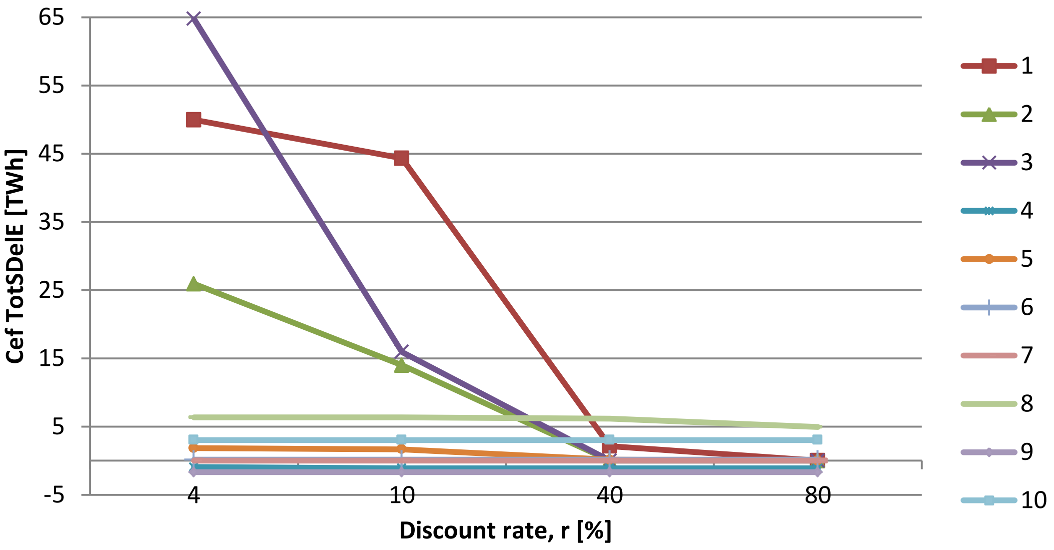

Figure 36 Annual total annual cost-effective final energy savings potential in [TWh] for different discount rates and per measure.

Further, single dwelling occupants with their own boiler have, for practical reasons, more control over their energy consumption and are thus more likely to invest in energy efficiency. This means that the discount rate is lower for single-family dwellings than for multi-family dwellings (L.G. Giraudet, n.d.). At a high discount rate, i.e. at a scenario where the customers are averse to investing in energy saving measures and require high profits, the measures only save about 5TWh annually. This equals only 0.7% of the baseline final energy consumption in France.

The resulting figures for each measure assessed from running the simulations and altering the discount rate between 4% and 80%, are presented in Appendix M.

Table 30 Results from sensitivity analysis of discount rate. Weighted average equivalent annual cost (WAvgEAC).

	WAvgEAC *[€/yr]*			
No. / %	4	10	40	80
1	110.6	223.9	875.7	1 751.3
2	177	358.2	1 401.1	2 802.1
3	990.1	2 003.9	7 838.5	15 677
4	817.2	1 499.1	5 653	11 305.5
5	43.5	63.6	194.9	387.3
6	329.9	476.8	1 423.8	2 760.8
7	588.1	639.1	905.8	1 283.5
8	134.6	142.3	181.2	232.9
9	446.7	713	2 431	4 856.3
10	0	0	0	0
Average	363.8	612	2 090.5	4 105.7

The equivalent annual cost per energy saving, see Table 30, shows a high sensitivity to an increase in the discount rate. The regulation of the hydro pumps' working schedules (ESM10) are assumed to take place at no charge and is thus unaffected by the discount rates.

The cost-efficient potential of saved delivered energy decreases with higher discount rates for the ESM1, ESM2, ESM3, ESM5 and ESM8, see Appendix M. The ESM4, replacement of windows, shows an increase of energy consumption. None of the other measures' potential energy savings seem to be affected by the discount rate. For ESM7 and ESM10 the investment costs are very small or even zero. The ESM6 only applies for the residential sector and is therefore not showing any impact on the result of the whole building stock assessed. ESM9 only affects a very small share of the boilers and therefore only has marginal effects on the result. The cost-effective amount of emissions saved shows the same relationship to the discount rate as does the potential energy savings, except for ESM8 where the small change in electricity savings is not affecting the emissions.

At a discount rate between 4 and 10%, the residential building stock may consume between 70 and 100kWh per heated area and year at an annual net cost of 20-50€/m^2, see Figure 37. For the non-residential sector, ranging between 70 and 220kWh/m^2,yr, the annual net cost is even smaller, see Figure 38. Thus one can read from the figures that the private perspective has higher requirements for short pay-back times than has the market or societal perspective.

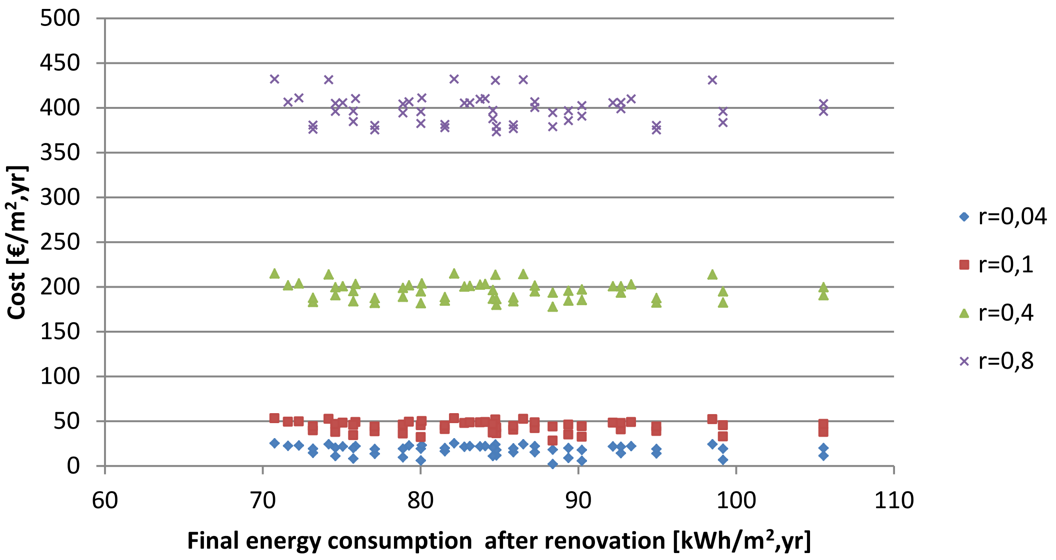

Figure 37 Distribution of residential buildings in relation to their energy consumption and the net cost for implementing all measures aggregated at different discount rates. Cost = Initial investment cost –Σ (net present cost of energy savings per year).

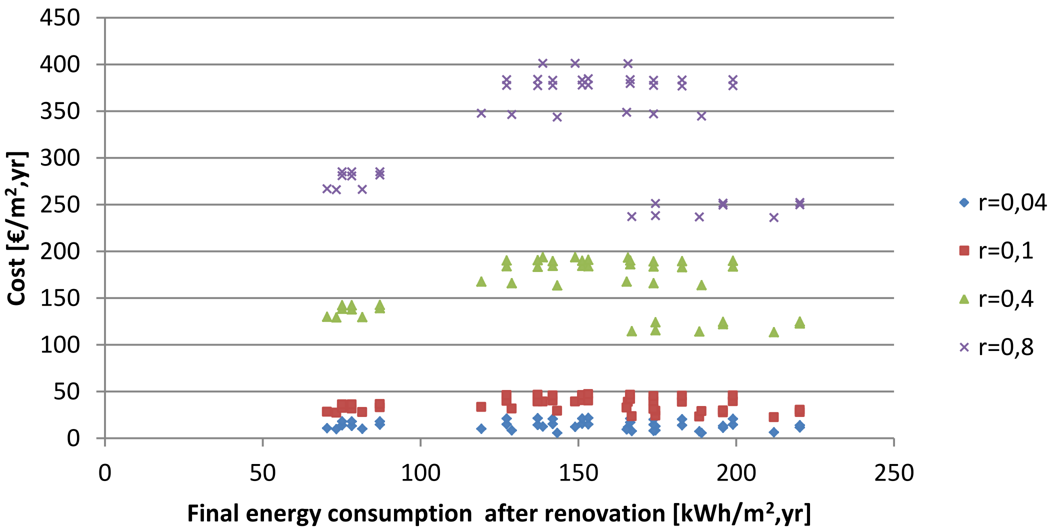

Figure 38 Distribution of tertiary buildings in relation to their energy consumption and the net cost for implementing all measures aggregated at different discount rates. Cost = Initial investment cost –Σ (net present cost of energy savings per year).

6 Discussion

This thesis gives no general advice for the whole building stock, since the characteristics of the building archetypes (construction year, climate zone, fuel shares) differ in a way that one measure could be efficient for one archetype and not for another. Rather, one has to look into both the energy savings potential and the CO_2 mitigation potential in parallell with the measures' cost-efficiency and should not base any recommendations solely on one of the three aspects.

When the savings of a measure are relatively low it is important to conduct further assessments to evaluate the actual costs for implementing such a measure on the market. Example of such assessments could be life cycle energy and life cycle cost assessments. Energy saving measures inevitably lead to material use and transportation and therefore a marginal saving in energy consumption created by a specific measure may not end up with net final savings when considering the energy used for its implementation.

The difference in assumptions between the estimated potentials found in literature and the thesis' calculation may lead to discrepancies. For example, the French government does not set specific goals for the non-residential sector but only gives incentives to implement energy saving measures. In the residential sector, the *Plan Grenelle* aims at retrofitting 400 000 dwellings per year while this thesis assumes that the entire stock introduces the ESM at once, thus leading to differences when comparing the results.Besides, overestimations may occur as most of the assumptions made in the thesis establish that the whole building stock are meeting the requirements of the thermal regulations (which is in reality applied only to new buildings), while previous studies often assume a market breakthrough of a certain type of technology (such as the CFL for the lighting measure) or a set of BAT.

Relatively high sensitivities are found in the cost-efficiency simulations regarding discount rates and energy prices. Thus, future energy prices are supposed to highly effect today's investment costs. One important aspect of the cost related simulations is that the baseline maintenance cost is set to zero since it was assumed that the ESMs would take part during a major retrofitting of the building and not during a normal replacement cycle. Thus the retrofitting of buildings only accounts for the additional maintenance cost. This might lead to cost-efficiencies that are showing too low potentials, if assuming that older equipment needs more costly maintenance than new ones. Thus, the results may lack the small savings obtained from maintenance costs when substituting devices. Though, this is not relevant for measures such as substitution of boiler types, where the new equipment type is of another category. Here, the resulting cost-efficiencies might differ in both directions depending on the maintenance variance; it may be either over or underestimated.

When it comes to the appliances and lighting, the investment costs for lighting and appliances are quite high, especially for the latter one. Former work in this field performed by Mata used an investment cost of zero, arguing that no device is exchanged before its broken, while in this thesis the appliances are assumed to be exchanged more frequently than is actually needed, i.e. even if the device is not broken. Thus, the savings potentials and the efficiencies for lighting and especially for appliances may be considered to be in the lower range.

Another issue arises from the investment costs applied on the model. Most of them are established as an average cost per heated m^2, e.g. appliances, or per unit[9], e.g. heat recovery, for each measure. This investment cost is then applied to all the building subtypes that are related to the corresponding ESM. Of course, in reality these costs differ from one subtype to another and especially between residential and non-residential sectors, leading to possible discrepancies.

The cost calculations do not explicitly include carbon pricing schemes already implemented in Europe, since the thesis focuses on the consumer's perspective. However, one can argue that the application of such schemes is implicitly included in the fuel prices and would eventually end up being paid by the consumer. Hence it is rather difficult to assess the net amount of money paid for the energy consumption by the consumer.

Moreover, behaviours can vary from one actor to another; while private customers would look for comfort or economic savings, the tertiary sector would follow another reasoning related to their specific activities. Hence, these different stakeholders are likely to have a varying willingness to invest in an ESM, regarding the future risks and the short or long term perspective. Thus, one may question if the hypothesis assuming the same low discount rate of 4% for all the measures in both sectors is adequate, assuming a societal perspective. The private consumer is likely to have a higher implicit discount rate than in the tertiary sector when considering investing in an ESM. As there is a higher demand and more consistent occupancy in the tertiary sector, uncertain returns are lower and are thus resulting in lower discount rates. The sensitivity analysis showed that the majority of the measures' profitability would have more or less the same range between 4 and 10% discount rate, while they start to differ greatly from 10 to 80%. Hence the societal perspective may not strictly apply for the whole residential sector, which usually stands for the higher discount rates, and therefore the resulting cost-effective energy savings may be overestimated for this subsector.

Further, the rebound effect has not been taken into account. This phenomenon refers to a change in customer behaviour when energy efficiency measures are being established. However, this factor is not relevant for the ECCABS simulations as it only looks into technical and economic potentials, while the rebound effect is more linked to the so called achievable potentials. The achievable potential also includes market realities and thus integrates more complex factors such as technical, economic and social limitations. For instance, one could consider the difficulty of reaching a market breakthrough for a certain technology, e.g. heat recovery units or triple glazing windows, none of them widely used in present France. Market transformation is thus a difficult parameter to estimate.

The recently introduced French energy policies presented in Chapter 1.2 will hopefully have a positive effect on the renovation rate of existing buildings in France. Maybe one should also consider investigating the possibility to incentivise a faster introduction of heat recovery units. A reward as the one used for boilers replacement may be one way to go. As already stated, the main focus when it comes to the 2°C target should be on reducing the space heating demand. This statement is strengthened by the fact that the last years increase in oil and gas prices has created incentives for

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[9] Per unit means per dwelling and thus only refers to the residential sector.

house owners to reduce their energy demand. For the society as a whole, also a reduction in electricity consumption is important since the thermal power plants are sensitive on an intermittent market such as the French power grid and thereby increases their carbon dioxide emissions during inconsistent winter seasons.

Summarising, the energy policies of France can be seen as a tool to affect and increase the achievable potential and they need to aim for both a reduction in energy demand and for increasing efficiencies. Where the profitability of an ESM is too small or non-existent, the policies should create incentives for the consumers to implement the measure. Where the measure is already profitable, the policies' task is to guide the market in a sustainable direction where new technology is invested in and sustainable life styles are rewarded.

7 Conclusion and further work

A total of 10 individual ESMs (active and passive measures) have been assessed in this work, as well as packages of these measures. Features of the ESMs have been evaluated according to the current French regulations and official national texts regarding buildings performances.

The potentials of energy and emissions savings of the ESMs were estimated through their implementation on the whole French building stock. The maximum saving potential when applying all the measures has been estimated to reach 329TWh of delivered energy, representing 50% of the baseline energy consumption in the French building sector, as well as 50MtCO_2 (56% of the baseline) per year.

Cost-effectiveness evaluation of the ESMs has been performed which results in a total cost-effective savings potential of around 150TWh and 20MtCO_2 annually. An annual investment of €59 billion would potentially enable France to reach the maximum potential; a techno-economic potential saving 149.76TWh (20% of baseline) and 21.35MtCO_2 (23% of baseline).

This thesis has verified the technical potential's accuracy of the ECCABS model and its transferability to different building stocks. The model is a relatively quick tool for investigating different energy saving measures and can be used for rough evaluations of potential energy policies. The energy, CO_2 emissions and cost-efficiency assessments should not be implemented on their own, but rather evaluated in parallel. Also, future policies should recognise the different characteristics of the building sector and consequently gradate each regulation in relation to each building subtype. For some measures, even a separation into requirements per building archetype would be profitable; i.e. taking into account construction year, climate zone and fuel sources. However, for summarising, the greatest savings potentials are found in single-family dwellings and the main energy and emissions savings are shown to be connected to insulation measures, thus a focus on energy demand is anticipated. Oversimplifying, the passive strategies account for the biggest share of the energy and emission savings potential, while the active strategies have the highest cost savings potentials. The substantial sensitivities found for the cost-efficiency of the results both when it comes to discount rates and energy prices should be noted. It is obvious that when evaluating the different measures, policies meant for private house owners should imply a discount rate from a private perspective, while a more societal policy should use a lower discount rate

Below follows some proposed further work on the subject.

- Include cooling into the calculations and thus make a higher Tmax a possible ESM.
- Implement a MATLAB code where the daily indoor temperature schedule is being presented and where different minimum temperatures for different hours of the day may be programmed. Include a potential increase of the Tmin in the residential sector as a comfort measure.
- Consider including the expected changes in climate for updating the weather files.
- Include consumer behaviour and life style changes, more than only through elaborations with the discount rate.

- Broaden the scope to include primary energy, thereby broadening the possible choice of ESMs to include also fuel market shares and local renewable fuel sources.

- This thesis only considers CO_2 emissions, not CO_2 equivalents, and production and transportation related emissions are not included in the measures. This and the emissions related to different types of insulating materials might be of interest to investigate in future work.

- Older buildings that are classified as protectable monuments need further consideration when it comes to a realistic application of the measures.

- Introduce an additional characterisation parameter of the building archetypes taking into account their geographical altitude, thereby reflecting the French thermal regulations' characterisation of the building stock.

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