Deploying renewable energy technology in sustainable buildings: a case study of the Living Wall

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Colophon

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Summary

The Netherlands is densely populated and implementing new buildings must accommodate multiple aspects of the built environment. There is also increasing pressure for buildings to reduce energy use, as currently they account for 26.6% of the EU27's final energy consumption. Energy efficiency and the application of building integrated renewable energy technologies are two ways of reducing energy demand in buildings and promoting sustainable infrastructure. NarrativA ArchitecteN's proposed Living Wall plans to bridge the gap between new sustainable buildings and functional urban integration. Designed as a multi-functional sustainable urban building and concept, the Living Wall spans two kilometers long along the A12/A27 highways south of Utrecht, the Netherlands. The purpose of the Living Wall is to shield and protect the neighborhood of Lunetten from adjacent highway noise and pollution while offering sustainable living accommodation for (ex-) students and young professionals.

This study investigates the deployment of energy conservation, renewable energy and efficient generation technology to the Living Wall. This is accomplished in three main sections. The Living Wall's energetic demands and supplies are quantified through a simple building energy model. A techno-economic analysis of the Living Wall's potential building envelope components and energy supply systems identifies economically efficient building envelopes and supply system scenarios. Energy supply scenarios are then developed within the framework of two business models and assessed in terms of their ability to deploy renewable energy technology into the market as part of the Living Wall.

The Living Wall's quantified energy demands include space heating, district hot water, and electrical power. Supply potentials estimated are for power and heat produced from building integrated photovoltaic (PV) and active solar thermal (AST) arrays. The Living Wall's energetic demands and supplies are expressed in terms of their yearly consumption/production, and daily profiles. Daily production/consumption profiles correspond to the four seasons and are used to identify peak demand/supply and calculate net building heat and electricity demand.

Results from the simple demand model indicate that the Living Wall's gross heat and power demands are 7512 MWh/year and 3114 MWh/year respectively. While at the same time, heat and power generation from AST and PV will provide 2163 MWh/year and 3159 MWh/year of renewably sourced heat and power. Unfortunately not all renewable heat and power generated may be used directly. Therefore, the net power demand is 1290 MWh/year composed primarily of evening demands, with 1829 MWh/year of excess power available for sale during the day. Net heat demand is dependent on the inclusion of hot water storage in the AST system. Net heating demands with and without hot water storage are 5908 MWh/year and 6922 MWh/year.

The techno-economic analysis investigated the economic viability of various envelope insulation and window elements paired with building supply scenarios. The analysis used the cost of conserving energy and primary energy savings as criteria for evaluating a technology's or scenario's performance. Cost of conserved energy was compared to a reference price (commercial primary energy price) to assess if the technology or scenario was economically viable or not. The five energy supply scenarios and reference scenario considered in the techno-economic potential are:

- Reference: Condensing boiler, grid purchased electricity
- Scenario 1: Reciprocating engine CHP, photovoltaic & active solar thermal arrays
- Scenario 2: Fuel cell CHP, photovoltaic & active solar thermal arrays
- Scenario 3: Air source heat pump, photovoltaic & active solar thermal arrays
- Scenario 4: Ground source heat pump, photovoltaic & active solar thermal arrays
- Scenario 5: Solid biomass boiler, photovoltaic & active solar thermal arrays

Results from the techno-economic potential identified scenario 5 as having the lowest cost of conserved energy and scenario 1 had the highest primary energy savings. Scenario 2 had the highest

absolute primary energy savings, but was not economically viable compared to the reference cost of conserved energy. When assessing the cost of conserved energy of individual technologies (i.e. not as part of a supply scenario), photovoltaic, solid biomass boiler and air source heat pump technologies outperformed the reference. Although not surpassing the reference fuel cell and reciprocating engine CHP technologies may benefit greatly from learning effects that increase efficiency and reduce costs. Cumulative effects of this could lead to their techno-economic viability in the near future.

The business model analysis investigated deploying the Living Wall's supply scenarios using both an energy service company (ESCO) and on bill financing business model. Each supply scenario was assessed in terms of its net present value under each business model. The two models were then compared qualitatively through assessing their strengths, weaknesses, opportunities, and threats. The ESCO business model outperformed the on bill financing model. From a financial point of view supply scenarios observed higher net present values in the ESCO model. Qualitatively, each model was observed to have advantaged and disadvantages, however three main points set the ESCO model ahead of the on bill financing model. First, the ESCO model does not create a split incentive as seen in the on bill financing model. Second, its financial self-incentive toward improving energy efficiency and demand reduction are beneficial to the Living Wall's residents, society and the sustainable character of the Living Wall. Third, the ESCO model can offer residents less risk and lower electricity prices.

Integrating the results from all three sections we see that through the deployment of renewable technologies the Living Wall is able to satisfy large portions of its demand in an economically viable way. However, choosing a 'clear winner' in terms of the optimal building envelope and supply technology is difficult and requires further, more detailed and focused investigation. Considerations of total energy savings, materials lifecycles and external fuel source impacts should also be taken into account when deciding on an optimal supply scenario in the context of the Living Wall as a sustainable building. Herein is a limitation of this work – the broad range of topics covered only paint a general image of deployment possibilities for the Living Wall. Nevertheless this work offers insight into the feasibility of deploying renewable generation technology from both a theoretical (techno-economic) and practical (business strategy) point of view that may be useful in the Living Wall's development process.

Table of Contents

Abbreviations

A_{NZ}^{tot}	Surface area northern zone: sum of wall window, side wall and roof areas (m^2)
A_{NZ}^{wnd}	Surface area northern zone windows (m^2)
A_{NZ}^{wall}	Surface area northern zone walls (m^2)
A_{NZ}^{fac}	Surface area of northern façade; total of window and north wall areas (m^2)
$a(n_d, d)$	Capital recovery function; n_d is reference equipment lifetime, d is real interest rate
A_{SZ}	Surface area southern zone (m^2)
A_{pv}	Photovoltaic array size (m^2)
A_{AST}	Active solar thermal array size (m^2)
ASHP	Air source heat pump
B	Benefits (NPV analysis)
AST	Active solar thermal (array)
COP	Coefficient of performance
CHP-RE	Combined heat and power reciprocating engine
CHP-FC	Combined heat and power fuel cell
c_p^{air}	Heat capacity of air
c_p^{water}	Heat capacity of water
C	Costs in NPV analysis
ΔPE_{year}	Difference in primary energy use between energy saving technology and reference in a year
$\Delta PE_{operation/year}$	Primary energy used by technology in operation (in order to save energy)
D_e^T	Total electrical demand (MWh)
D_h^T	Total heat demand (MWh)
D^{DHW}	District hot water demand (L)
D_h^{DHW}	Heat energy demand from district hot water (kWh)
DD_{NZ}	Degree days northern building zone
DD_{SZ}	Degree days southern building zone
DHW	District hot water
$D_e^{technology}$	Demanded electricity; where technology denotes demand satisfied by indicated technology.
$D_h^{technology}$	Demanded heat; where technology denotes demand satisfied by indicated technology.
f_e	Electricity primary energy conversion factor
f_h	Heat primary energy conversion factor
GSHP	Ground source heat pump
I_{solar}	Solar radiation intensity (W/m^2)
M_{year}	Yearly maintenance costs
n_{AST}	Solar thermal heat conversion efficiency

n_{pv}	Photovoltaic solar energy to electrical power conversion efficiency
η_{HE}	Heat exchanger efficiency
N	Building ventilation rate
ρ	Specific mass of air (kg/m^3)
PV	Photovoltaic (array)
P_e^P	Primary energy adjusted price of electricity €/kWh$_{PE}$
P_h^P	Primary energy adjusted price of heat €/kWh$_{PE}$
P_e^m	Market electricity price €/kWh
P_h^m	Market heat price €/kWh
PES	Primary Energy Savings
$Q_{transmission}$	Transmission heat flux
$Q_{ventilation}$	Ventilation heat flux
Q_{solar}	Solar heat flux
Q_{net}	Net heat flux
SR	Seasonal solar reduction factor
SBB	Solid Biomass Boiler
T_{ref}	Reference indoor temperature
T_d	Day average outdoor temperature
TEP	Techno-economic potential
U_{ref}^{wall}	U-value of reference wall
U_{ref}^{wnd}	U-value of reference window
U_{ins}	U-value of insulation measure added to reference wall
V_{LB}	Total volume of the living box space
WEP	Weighted energy price

1. Introduction

Intense urbanization in the post second world war era has led to suburbanization even in land scarce countries such as the Netherlands. Cities have expanded following traditional building practices and built on cheap, unused land surrounding cities. Connecting suburbs and city centers are major mobility corridors i.e. railways and highways. In the context of urban/suburban infrastructure, mobility corridors are responsible for negative social impacts, including noise and air pollution. Who wants to live beside a highway or rail line?

Architects and engineers have been challenged to design solutions for urban integration. Urban integration and multi-functional urban structures have been proposed for various purposes in literature. For example, Savvides (2004) describes the potential to plan and design urban structures using air space over, beside and under rail- and highways. In the light of sustainable development, new buildings can be designed for multiple functions within the urban fabric through internal and external building system integration – deflecting noise, producing energy, and purifying water and air.

Combining integration and sustainability, buildings can be designed to intensify urban integration and be environmentally friendly. Given residential buildings account for 26.6% of the EU27 final energy consumption, and of that 73% is devoted to heating, the potential to reduce environmental impact through reduced energy use is great (Eurostat 2007). But designing buildings sustainably is more involved than simply reducing energy use though energy efficient building envelopes, and improved generation efficiency. Chwieduk (2003) identifies three tiers of sustainable buildings; energy efficient buildings that utilize efficiency measures and efficient technologies, environmentally friendly buildings that integrate renewable energy technologies alongside efficiency measures, and sustainable buildings that utilize both efficiency measures, renewable technology and consider lifecycle impacts of the building materials (Chwieduk 2003).

Realizing sustainable buildings however must take into account socio-economic realities such as capital costs, implementation barriers and social benefits/costs. Decision makers responsible for implementing new buildings have associated energy savings in buildings with higher design, construction and energy system capital costs. However, this short-sightedness toward the bottom line overlooks potential yearly running cost reductions of up to 13% and increased building value in the market when compared to conventional building designs (Chan et al. 2009). Research such as this study can help evaluate the benefits resulting from the higher upfront costs of environmental building design, and paint a realistic picture of the benefits and drawbacks of investing in sustainable buildings.

This research investigates the energetic building design and market deployment strategy for NarrativA ArchitecteN's proposed Living Wall building. The Living Wall is designed as a two-kilometer long multi-functional sustainable building and concept. Its essence is to act as a combined noise/road air pollution barrier that shields the suburb of Lunetten from the highway, and offers affordable living accommodation for (ex-) students and young professionals in a sustainable way. The unique building design is set alongside the A12 and A27 highways to the south-east of Utrecht, The Netherlands. This research investigates the technical, economic and market potential and feasibility of renewable energy technology deployment as part of the Living Wall's sustainable nature.

1.1. Problem Definition

Given the massive energy demand of buildings in the developed world, constructing new buildings should be done in a way that is energy efficient, and utilizes renewable energy sources (Ürge-Vorsatz et al 2007). While a wealth of technical information on sustainable building technologies is available to designers, it is not utilized fully as a result of poor building architecture and design integration (Kanagaraj et al. 2011). Investigating the integration of renewable energy technologies as part of the Living Wall's energy supply mix through the construction of building technical scenarios, and the subsequent analysis of implementation barriers and business models applicable to technical scenarios, will contribute decision making knowledge toward suitable techno/economic/market options for new environmentally friendly buildings.

In designing the Living Wall many technical system configuration scenarios exist whose benefits and feasibilities remain unknown. Benefits can be relatively easily quantified through technical estimates based on system cost, performance, efficiency and life-time. Feasibility of technical options however, is dependent on the demands from system element interactions within the building. Constraints such as roof, and wall cavity space will play a role in determining which technical options can be combined together to form technical option scenarios. The economic viability of technical options and building technical scenarios must also be assessed.

Finally, how to best translate technically and economically viable Living Wall energy system scenarios to the market is unknown. Although some Living Wall building scenarios might be technically and economically viable they can face implementation barriers that hinder market deployment. To address the technical, economic and market unknowns of designing the Living Wall's renewable energy systems the following research question and sub-questions are proposed.

1.1.1. Research Questions

What renewable energy technology building scenarios are techno-economically feasible for the Living Wall and how do building scenarios perform when business models used for renewable technology deployment are applied?

The following sub questions were formulated to help structure the research and answer the main research question.

- *What energy saving and renewable energy building technologies, and technical configuration scenarios, are available, and applicable to the Living Wall?*
- *How much energy will the Living Wall demand and be able to produce for own use and/or sale?*
- *What is the most economical way deploying the Living Wall's energy system?*

1.1. Research Method and Reading Guide

The purpose of this research is threefold, centering itself on the design, choice and implementation of the Living Wall's energy systems. First, it aims to develop a Living Wall energy demand model that is used to quantify the Living Wall's heat and power demands as well as the potential heat and power supplies from building integrated renewable energy technologies. Second, it attempts to identify technical and economically viable energy technology supply scenarios. Third, it investigates the application of business models for deployment of the Living Wall's energy technology systems. The final synthesis of the three sections is a detailed picture of the Living Wall's energy supply possibilities including technically feasible technologies, quantification of demands/supplies, profile of economically efficient technology scenarios, and market implementation strategies and potential.

This research follows an embedded method where results from one section are used to guide the investigation and calculate results in the following section(s). Figure 1.1 shows how the three main sections fit together and build upon each other in terms of their main objectives and primary results. The figure shows how the main results from the Living Wall energy model are the basis for constructing the techno-economic potentials and business model analysis. Similarly the aim and result from the techno-economic potential forms a basis for choosing energy supply scenarios that are applied to business models. Thus, concepts and results discussed in detail in the early chapters are regularly referred to in later chapters as key elements in the ongoing investigation.

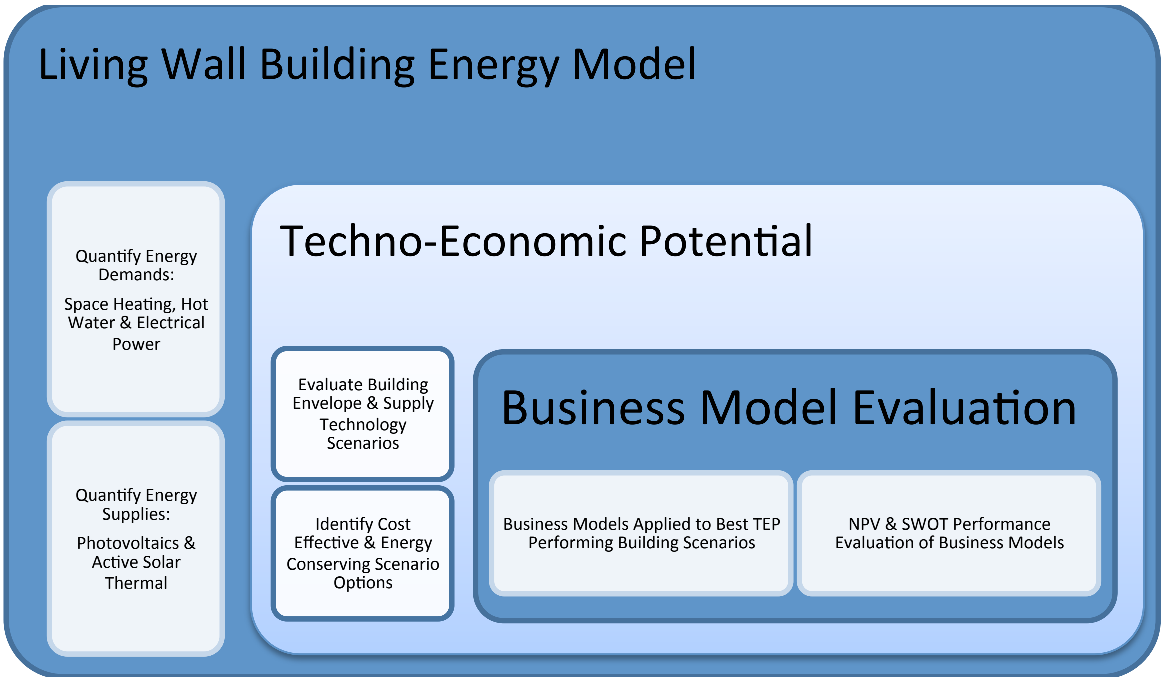

Figure 1.1: Visual representation of research's integrated structure.

This work begins in section two by discussing background on criteria for sustainable buildings, low energy building design methods, energy demand reducing components, and renewable energy technologies. Section three then explains the Living Wall energy demand model and presents the estimates of total heat and power demand and total potential supply from renewable (solar) energy technologies. This section presents the Living Wall's seasonal demand and supply profiles at hourly and per minute timescales. Using the demand and supply figures obtained in section three, section four analyzes the techno-economic potential of efficient building envelope options, supply technologies, and complete energy supply scenarios. Here the cost of conserving primary energy is compared to a reference price to evaluate economic performance. Section five then uses the best performing building envelope determined in section four, to investigate the market performance of supply technologies when deployed using two business models. Business models are investigated from the perspective of their ability to alleviate market barriers to renewable technology deployment. The last section concludes the analysis by offering a discussion on the results presented in each section, and future research possibilities.

2. Efficient & Environmental Buildings Background

This background chapter discusses categories of modern sustainable building types and goes into detail on design principles and technologies utilized in sustainable buildings. As this research is centered on a case study of the Living Wall, the information and ideas presented in this chapter are targeted for the analysis chapters that follow. The discussions form a method to the following analysis and give a context to why certain assumptions are made when modeling the Living Wall's energy demand or choosing the Living Wall's supply technologies, for example. The main thread common throughout is on investigating the reduction the Living Wall's primary energy demands through technology deployment in an economically efficient way.

2.1. Building Classifications

As described in the introduction, Chwieduk (2003) defines three types of new sustainable buildings: energy efficient, environmental, and sustainable buildings with each successive building type encompassing characteristics of the preceding. The Living Wall concept is that of an energy efficient building because it can reduce heat energy demands through insulation, high quality windows and utilization of energy monitoring and control systems. However, all new buildings in the Netherlands are required to meet strict national and EU efficiency standards (EU 2002) that are central to Chwieduk's (2003) energy efficient building concept. The Living Wall separates itself by attempting to go beyond conventional efficiency standards through architecturally efficient design that utilizes solar heating, thermal buffering, passive ventilation and increased natural light penetration.

The Living Wall is also an environmental building because if its choice to deploy renewable energy and energy saving supply technologies. A main tenant of an environmental building is the fuel used for energy production or the total primary energy footprint of the building. Architectural design measures that made the Living Wall an exceptional energy efficient building now become standard to the environmental building label because they reduce overall primary energy footprint. The Living Wall would like to deploy roof or gallery window mounted photovoltaic and/or active solar thermal arrays for the production of renewable electricity and heat. Similarly, the use of bio fuelled heating, and high efficiency heat and electricity production systems are also elements of the Living Wall's environmental building character.

Sustainable buildings are the pinnacle of new building design and optimize the flows of energy, water, and materials through the building's life. Life cycle assessment of material choice/flows, energy consumption and water use should be conducted for each decision in a sustainable building's design. In this respect the Living Wall is also a sustainable building. However this research only looks at the sustainable life cycle aspects of the Living Wall's energy use. Life cycle analysis of material and water flows are outside the scope of this work, but are considered in the Living Wall designs by NarrativA ArchitecteN.

The Sustainable character of the Living Wall's energy flows is the main focus of this research. The sections that follow discuss sustainable building design methodologies and technologies as applied to the Living Wall. Section 2.1 discusses internal and external building design integration. Internal design considerations relate strongly to the energy efficiency character of the Living Wall and considerations that can be made to enhance efficiency. External integration deals mainly with the multi-functional essence of the Living Wall, briefly discussing its function as a noise and pollution barrier. Section 2.2 then discusses the technologies investigated for deployment in the Living Wall's thermal envelope and energy supply systems.

2.2. Integrated Environmental Building Design

Integrated environmental building design follows a design process involving architects, engineers, and urban planners participating collectively at early stages in the building's development. Both Harvey (2006) and Ürge-Vorsatz (2007) point out that traditional building design follows a linear decision-making structure where each building characteristic is designed following logical sequential steps. For example, an architect designs the building's look, function and feel. Engineers and planners are then asked to design energy systems and living areas around the building within the constraints set by the architect's design concept. This method limits the energy savings potential of the building's design.

Designing a building under an integrated framework involving all parties allows better functional integration of building systems. Decisions made within one building system are designed to accommodate the needs of other systems. An example is the architectural design of the building shell being designed to promote passive heating/cooling and to accommodate renewable energy technologies. Harvey (2006) provides a "Commercial high-performance building checklist", which among other things points out integrated system design measures that lead to energy savings and renewable energy use. Wherever possible this research attempts to include design concepts listed in table 2.1.

Table 2.1: Summary checklist for the design of commercial buildings with low energy use (Harvey 2006).

Character	Measure
Orientation	• Optimize building shape for maximal benefits from solar & wind energy • Energy conservation landscaping • On site food production/ gardens • Incorporate ground source heat pumps
Envelope	• optimize thermal envelope before space conditioning systems • specify high performance windows (low U-value, spectral solar properties • specify high wall and ceiling insulation – light roof colour • internal building thermal mass – modulate temp swings • use brick cavity/pressurized curtain walls (instead of solid masonry)
Interior layout of space	• configure occupied spaces so as to maximize natural ventilation and day lighting • connect occupants to natural environment whenever possible via operable windows and day light (this should be accommodated by HVAC design) • design public areas/circulation zones as thermal buffers • encourage use of stairs through design • group similar room functions together • locate HVAC equipment to minimize HVAC loads • non window space on north side and north side thermal buffering
Lighting	• maximize use/penetration of natural light, via light shelves, fiber-optic light pipes • use light sensors alongside dimmable lights (capture and adjust to partial day lighting) • occupancy sensors • high efficiency lighting systems • lumen maintenance controls
Mechanical systems	• use variable air volume, demand controlled, displacement ventilation system • use desiccant dehumidification (latent heat exchange) for incoming air • use heat exchangers between incoming and outgoing air • use separate heating and cooling for zones with different requirements • give building occupants control over individual room environments
Heating and cooling systems	• when simultaneous heating/cooling is needed use heat pumps (integration of needs) • consider chilled ceiling radiant cooling in combination with displacement ventilation • consider exhaust-air heat pumps in addition to exhaust/supply air heat exchangers whenever heat from the cooling system condensers is not adequate to meet heating and hot water demanded • consider ground source and solar assisted heat pumps for heating when waste heat from the cooling system and recovered from the exhaust air is not adequate and consider ground source heat pumps for air conditioning in place of conventional chillers

	minimize heat distribution temperatures and maximize chilled water distribution temperatures insulate pipes and ducts for minimum leakage
Electrical systems	for large buildings consider distributing power at 480/277 instead of 208/129 volts specify energy efficient office equipment use K-rated transformers for non-linear equipment utilize direct current from PV/fuel cell for applications where DC is more appropriate
Energy load management	provide energy and control systems that collects and displays in graphical form use only control systems that allow the desired temperature to change without reprogramming
Materials	choose materials with low embodied energy specify locally manufactured materials use salvaged material when possible

2.2.1. External Integration

Integration can also be extended externally toward how the Living Wall will interact with other environment elements. Table 2.1 mentions a few external integration elements; namely roof/area gardens, and onsite renewable power generation. The concept of the Living Wall is that of a (noise) buffer between the highway and neighboring suburbs. Designing the Living Wall to act simultaneously as a noise barrier and place of living represents further meta-integration with the urban structure.

Noise barriers are a common sight along Dutch highways and throughout urban parts of Europe. Typically they are between 3 m and 5 m high directly adjacent to the highway and constructed from sound absorbing (pressure bonded softwood shavings) or reflecting (laminated plywood or Plexiglas) materials (May et al. 1980). Noise barriers have been shown to reduce traffic noise on the non-traffic side of the barrier between -5 dB and -13 dB (Watts et al. 1999) and to deflect harmful pollutant gasses such as NO_x and fine particulate matter toward the atmosphere (Ning et al. 2010). Integrating noise barriers with buildings is not new in the Netherlands, with barriers being integrated as car showrooms along the A2 west of Utrecht ("Utrecht's mile-long high-speed baffle" 2007) and photovoltaic arrays along the A9 highway close to Ouderkerk-aan-de-Amstel (Remmer et al. 2005).

2.2.2. Environmental Building Design Methodology

The design methodology adopted for a sustainable building is dependent on the building's geographical location and climate. For buildings in northern countries with cold climates several sources stress that the methodology should be grounded in an energy conservation attitude (Ürge-vorsatz et al. 2007, Bülow-Hübe et al. 2009).This means placing initial focus on reducing energy losses and utilizing energy efficient components before designing the buildings energy supply systems. After building envelope and demand related systems have been designed with energy efficiency in mind, renewable and efficient supply technologies can be chosen. Bülow-Hübe et al. (2009) describe an ascending five step design pyramid methodology as applied to low energy homes in Nordic countries.

1. Reduce heat losses (efficient building envelope)
2. Reduce electricity consumption (efficient appliances and components)
3. Utilize solar energy (orientation, passive heat/cooling)
4. Monitor and control energy use
5. Supply remaining energy via renewable sources

This methodology is included wherever possible into the framework of this research in various ways. Steps 2 and 3 are used in section 3 in the electrical demand model by choosing high efficiency appliances. Steps 1, 3 are also included in section 3 in the building's heat demand model as insulation measures, and solar energy gain (see section 3.1.3, 3.1.4). Finally steps 4 and 5 are captured in the techno-economic analysis (section 4) through utilization of renewable energy technology and assuming efficient utilization of produced energy for the building's use.

2.3. Environmental Building Characteristics

The following subsections give further background into technologies and concepts embodied in efficient and environmental buildings. First subsection provides a brief discussion on low energy building envelopes and structures. This is followed by a discussion on renewable, and energy efficient heat and power generation technologies.

2.3.1. Building Envelope and Structure

An environmental building's envelope and structure defines how the building separates its interior space from the outside environment and how it interacts with the exterior environment. Structure refers to the buildings orientation and geometry while envelope is the material construction composed of walls, doors, fenestration (windows), foundation and roof. Appropriate building envelope elements, orientation and geometry can vastly improve a building's overall energy efficiency.

Building Geometry

The chosen geometry of a building has an effect on the total surface area in relation to the useable floor space. Some geometric configurations provide equivalent amounts of floor space with reduced surface area. This is important in cold climates because heat transmission losses through the building envelope are directly proportional to the surface area of the building envelope. Therefore minimizing the ratio between building surface area and heated floor space or total building volume leads to lower heat loss in general.

Figure 2.1 compares two different geometries with the same floor space but differing surface areas. The building on the left has 20% less surface area assuming identical floor spaces. However, there are benefits to the building geometry on the right – increased light penetration, and ventilation paths are more direct, both of which can reduce electrical and cooling loads. Hence building geometry deserves careful consideration with a perspective on the building's function, and desired distribution of resource use.

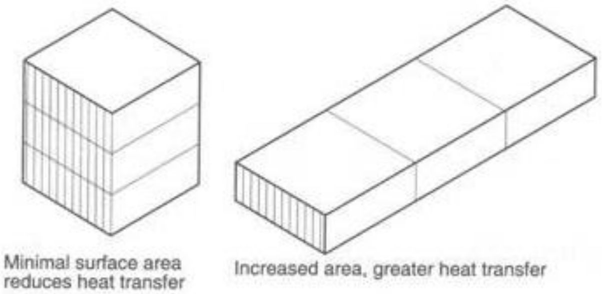

Figure 2.1: Building geometries ("Building Shape - Surface Area to Volume Ratio" 2004)

Walls & Insulation

Adequate wall, floor and roof insulation is a critical to a high-performance building envelope and there is much literature on insulation types, and strategies. In a review of modern advanced building shell components Sadineni et al (2011) identify the following physical forms insulation can take:

- Fiber blankets, bats and rolls
- Blow in loose fill
- Poured-in or concrete mix
- Rigid boards or blocks
- Foamed or spray in place
- Insulated concrete blocks
- Reflective materials

In addition to the physical form of insulation the material composition also varies quite widely. Table 2.2 gives an overview of common insulating materials along with some specific examples.

Table 2.2: Insulation material classes and various examples. Adapted from Sadineni et al (2011).

Material Class/Type		Example Insulation Materials
Inorganic	Cellular	ceramics: i.e. calcium silicate, bonded perlite
	Fibrous	wools: glass wool, rock wool
Organic	Cellular	cellulose, wood, hemp etc.
	Fibrous	cork, polyurethane (PUR), expanded polystyrene (EPS), extruded polystyrene (XPS)
Metallic		Rolled (aluminum) foil, reflective paint, metal shingles
Advanced material		Aerogels, phase change materials, vacuum insulation panel (VIP)

The thermal quality of insulation is measured according to its thermal conductivity (λ) expressed in W/mK. Thermal conductivity is a measure of how easily heat is able to pass through a material. Lower λ's are desired as they imply higher resistance to thermal transmittance and thus less inside heat is lost to the environment. Bülow-Hübe et al. (2009) state, for example, that modern low energy houses should not use insulation materials with λ's higher than 0.05 W/mK.

Related to an insulation measure's thermal conductivity is the insulation U-value for a given insulation thickness. Thermal conductivity only refers to the materials intrinsic thermal properties. The U-value (W/m^2K) on the other hand is used to express the effective thermal transmittance of heat through the given quantity of insulating material. Figure 2.2 shows the relationship between insulation thickness, material λ and the resulting U-value. Notice that as one tries to reduce the U-value further, insulation thickness quickly begins to increase.

An alternate formulation of the U-value is the R-value (m^2K/W) defined as the inverse of the U-value. Appendix B provides a conversion table of typical R-, and U- values. In this document, U-value is the preferred unit.

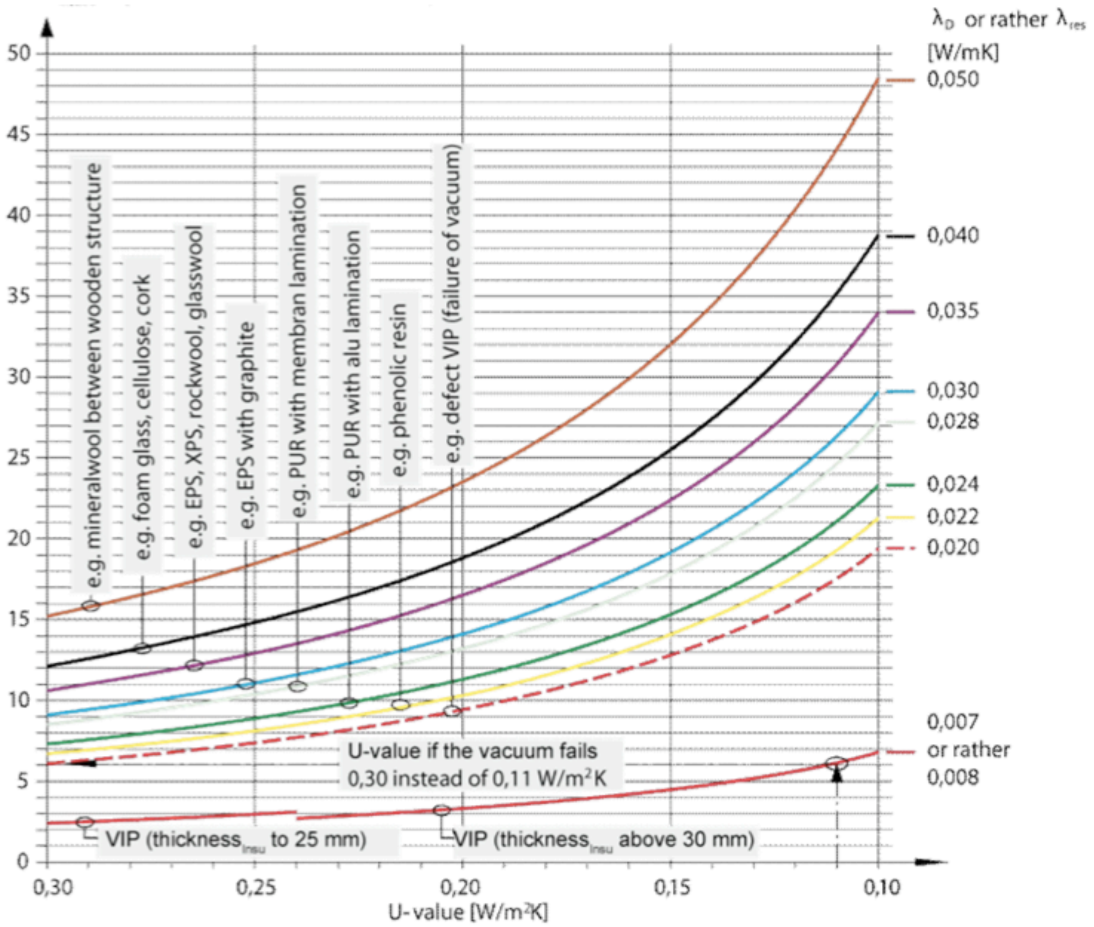

Figure 2.2: Insulation materials relationship between thickness, thermal conductivity (λ) and U-value (From Bülow-Hübe et al. 2009). Acronyms for insulation types in figure can be found in table 2.2.

Insulation costs vary according to the form of insulation (solid board, spray foam etc.) and the material choice. Sadineni et al (2011) indicate average insulation costs range from 10- 30 €/m^2. Natural fibers like cellulose, hemp, and wood fiber are in general cheaper compared with industrially produced organic compounds (polystyrene, polyurethane etc.). Mineral wools, as a result of their very widespread use, are also inexpensive in the 5-15 €/m^2 range. Advanced insulation elements however can be very costly. Vacuum insulation panels for example, cost 130-170 €/m^2 (Nanopore, 2012). Their future may be promising however when considering that they having reduced in cost by almost a factor of three in six years (based on Harvey's (2006) report stating VIP's cost 320 €/m^2 in 2006). Insulation costs used in the analysis in sections 4 and 5 can be found in appendix B.

Windows

Modern windows offer a plethora of choices including the type of glass, glazing, metalized coating, gas fill, spacer type, and framing. In general all window options are aimed at tailoring three main window performance indicators: a window's U-value (W/m^{2}K), g- value (%) and T_{vis} (%). As described in the insulation section above, the U- value is also the measure of heat transmittance through the window. A window's g-value is the measure of the total solar energy transmittance passing through the window. The last indicator, T_{vis} measures the fraction of visible light transmitted through the window. Compared to walls, windows have comparatively higher U-values, sometimes as much as 10 times higher. Heat transmission losses from higher U-values can be offset though solar heat gains from a high window g-value. While high g-values can increase solar heat gain in cold months, it can also cause high room temperatures in warm months thereby increasing cooling loads on the building.

Many competing technologies are available on the market offering a range of U-, and g-values. Some of the most discussed technologies are glazing, gas filling, thin films (low-e coatings), and alternate fillings. Window glazing is the number of window panes stacked together creating still air gaps between them. Still air reduces convection heat losses (heat loss form air moving over the glass).It is typical to find double and triple glazed windows with a variety of gas filling options. Different gasses conduct heat at different rates. Thus, by filling the air space between glazed windows with an inert gas (one that conducts heat very poorly) the windows thermal performance increases at little cost to visible light transfer (T_{vis}) or solar transmittance. An alternative to triple glazing with three glass panes is to substitute the central glass pane with a suspended transparent thermal film. This has the same effects as the extra glass pane, but with better thermal properties (suspended films have lower thermal conductivity than glass), and at lower costs (Bjorn Petter et al. 2012). Similarly, instead of filling glazed windows with gas, advanced technologies like low density solids (Aerogels) or vacuums can be introduced. Both Aerogel and vacuum fills have extremely low heat transfer properties, giving some windows tremendously low U-values. There are drawbacks however since most aerogel filled windows have reduced light transfer and solar transmittance factors. Vacuum filled window glazing's don't suffer from reduced visibility or solar heat transmittance, but have relatively higher costs (results of specialized framing and manufacturing process), and short lifetimes (difficulty holding vacuum seal) (Harvey 2006). Table 2.3 presents an overview of various window products and their U-value, g-value and T_{vis} ranges.

Table 2.3: Heat transmission and solar heat gain coefficients for various window glazing technologies (Bjorn Petter et al. 2012 and Harvey 2006).

Window Type	Characteristic	U (W/m^2K)	G (%)	T_{vis} (%)
Double glazing	Air, or krypton gas fill	2.3-2.6	70	79
Double Glazing (1 low-e coating)	Air, Argon, krypton gas fill	0.9-1.9	38-67	70-73
Triple Glazing (2 low e- coatings)	Air, argon, krypton, or xenon gas fills	0.36-1.0	32-55	50-72
Suspended film triple glazing	Argon or krypton gas fill	0.28-0.62	17-30.3	23-50
Vacuum		0.70	32	53
Aerogels	Lightweight polymer fill	0.31-1.38	7-61	7-80
Smart windows (electro chromic)	On demand variable g-value/T_{vis}	0.5-1.59	5-48	8-75

While glazing and fill options have effects that lower the U-value of a window, low-e thin film coatings vary T_{vis} and g-values. Low-e coatings are thin layers of metallic oxides deposited onto the glass that reflect incident infrared solar energy. The benefit to controlling solar heat transmittance in particular is that the amount of heat gain can be optimized for the windows orientation, and geographic location. An added benefit from low-e coatings is that the coating works both to reflect infrared radiation from entering and exiting the building through the window. Thus the window's total U-value is effectively also reduced. Another technology that has similar effects to low-e coatings is to include electro-chromic materials inside the glass. Known as smart windows, these allow the windows light transmittance and solar thermal transmittance to be changed in real time by applying a voltage across the window.

The cost of a window is very dependent on the choice of glazing, frame type, glazing spacer materials, gas filling, and low-e coating. Both Harvey (2006) and Bjorn Petter et al. (2012) indicate that the advanced window market is still immature. Window prices are therefore not always consistent across different geographic areas, and comparable window models. The costs of standard double glazed air filled windows range from 150-250 €/m^2 with the main determinant being frame and glass quality (Harvey 2006). Double and triple glazing windows with inert gas fillings cost 200-500 €/m^2. Advanced window technologies see proportionally higher costs; aerogel windows cost 400-500 €/m^2 and vacuum costing 600+ €/m^2. Adding individual elements will increase the window price; 10-20

€/m^2 per low-e coating, 10-40 €/m^2 per extra glazing, and 10-60 €/m^2 per extra inter gas fill for example (Bjorn Petter et al. 2012). Window costs used for analysis in sections 4 and 5 may be found in appendix B.

2.3.2. Energy Supply Technologies

Following the strategy of reducing energy demand and utilizing passive heating and cooling the Living Wall's final heat and electricity demands should be supplied by renewable technologies where possible. This section gives an overview of renewable or very high efficiency supply technologies for buildings.

Solid Biomass Boiler

Boiler technology is the standard heating technology deployed in the built environment today. Their operating principle is simple; fuel is combusted and the released heat is captured via a heat exchanger and transferred to a circulation fluid (usually water) that is pumped around the building to circulate heat. A solid biomass boiler uses these same fundamental principles, but instead of natural gas or oil as its fuel source it uses solid biomass (typically wood chips, pellets, or residue). Biomass boilers also differ from conventional boilers in their method of fuel delivery. Where conventional natural gas or oil boilers use a pipe, or tank to deliver the fuel, biomass boilers have a hopper and conveyer belt system that delivers fuel into the furnace. Fuel is stored either in the hopper, or a silo with a feed system into the hopper. Two consequences of this additional system is that biomass boilers assume larger footprints, and have higher capital costs. Conventional boiler costs range from 20-40 €/kW installed. Biomass boilers are comparatively more expensive, costing in the 80-120 €/kW installed range (Chau et al. 2009).

In terms of biomass boiler efficiency, it is heavily dependent on the fuel source. Running on wood pellets for example, biomass boilers achieve 88% efficiency, while this is just 66% when wood residues are used as fuel (Chau et al. 2009).

Active solar thermal heat

Active solar thermal (AST) technology is a method of collecting the sun's energy and converting it into high temperature heat for hot water or space heating applications. AST is extremely versatile and may be used in stationary (fixed) or tracking configurations. They may also be included in integrated heat systems with heat pumps, solar cells, or passive heat transfer walls. Three main types of AST exist; flat plate, evacuated tube, and compound parabolic collectors. The most applicable to buildings however are flat plate, and evacuated tube collectors.

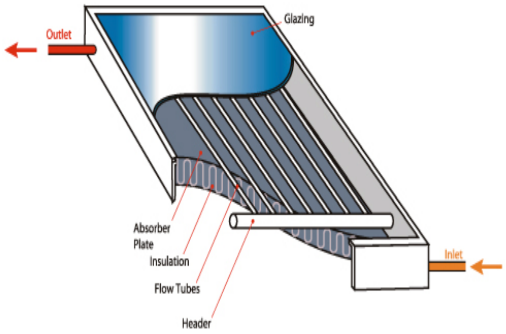

Figure 2.3: Flat plate collector ("Solar Thermal" 2012).

Flat plate collectors circulate water through tubes embedded in a black absorbing plate. The plate is covered by a glazed glass plate, and insulating material below. Figure 2.3 shows a schematic of the main parts of a flat place collector. Flat plate collectors are typically used for applications demanding temperatures up to 100°C, though some new advanced collectors can reach temperatures as high as 200°C (Kalogirou 2004).

Evacuated tube collectors use an evacuated tube with a concentrically embedded copper tube. Cold water is pumped through the copper tube down the length of the evacuated tube and returned along the space created between the evacuated tube and copper pipe. Figure 2.4

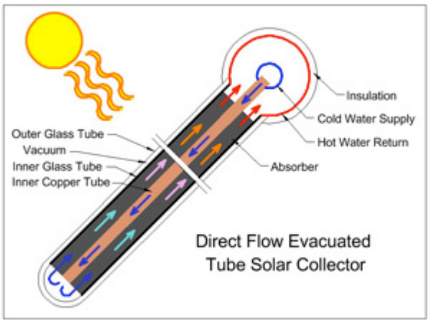

Figure 2.4: Evacuated tube collector (Holmes 2011).

shows a cross section of this process. Evacuated tube collectors have similar application temperatures as flat plate collectors. Their advantage is reduced heat loss when used in cold climates.

Collector efficiency is proportional to several collector specific factors, alongside outside air temperature, and incident solar radiation intensity. Equation 2.1 can be used to determine collector efficiency for flat panel and evacuated tube type collectors. Terms F, U, τ, and α are collector specific terms determined through empirical testing. Their value is relative to how and where the collector is installed, the collector's material composition, and the local meteorological conditions (i.e. F and U terms can decrease as the result of high convective losses from high winds). Individual coefficient values for these terms are not normally given in manufacturer data, but rather expressed as products of Fτα and FU.

$$n_{AST} = F \cdot \tau \cdot \alpha - F \cdot U \frac{T_i - T_a}{I_{Solar}} \tag{2.1}$$

Where the following are defined as,

F	Collector specific coefficient (%, empirically determined)
U	Heat exchange coefficient (W/ ºC m^2)
τ	Cover plate transmissivity (%)
α	Absoptivity of absorbing plate (%)
T_i	Inlet fluid temperature (ºC)
T_a	Ambient air temperature (ºC)
I_{Solar}	Solar radiation intensity (W/m^2)

Equation 2.1 can be better understood by assessing the two component terms. The first term, Fτα, is an efficiency measure of the total solar radiation absorbed (in manufacturer data sheets listed as optical efficiency) – i.e. what is the maximum percentage of the suns radiation the collector can absorb. The second term quantifies collector inefficiencies resulting from radiative and convective heat losses – as the collector heats up it will lose heat (manufacturer data sheets indicated as thermal loss correction). With this in mind, it becomes apparent that the choice of the most appropriate collector type based on climate is very important. In cold climates efficiencies of flat plate collectors will be reduced because convective and radiative losses resulting from cooler outside air temperatures will be greater (reflected in higher values of F and U coefficients). Table 2.4 summarizes the coefficient values suggested for various types of collectors.

Table 2.4: Summary of suggested values for Fτα and FU terms for AST array types (Harvey 2006).

Collector Type	Fτα (%)	FU (W/m^{2}K)
Flat panel: Single Glazed	90	10.0
Flat panel: Double Glazed	75	6.5
Evacuated Tube	70-80	3.3-1.3

Photovoltaic Arrays

Photo-voltaic (PV) solar cells utilize material properties of semiconductors to produce electricity from solar radiation. PV cells are offered with different doping elements, and deposition methods that affect the price and performance. Three main cell types exist; crystalline/polycrystalline, thin-film and nanocrystalline dye. The former is the traditional solar cell seen on rooftops, or at solar generation plants. Thin films are made from depositing a silicon layer on glass, while nanocrystalline dye cells are made by depositing a one molecule layer thick of ruthenium organometallic dye on a porous titanium oxide matrix. Each method yields solar cells for different applications, including traditional solar installs, and building integrated PV (BiPV). Commercial efficiency, that is, the ratio of solar energy converted to electrical energy, is between 7% and 16% (Harvey 2006) with some manufacturers claiming efficiency over 20% ("New SunPower E20 Series: the world's first 20 percent efficiency solar panel" 2012)

Costs of PV systems are still high when compared to the price of power in Europe. Crystalline PV arrays, which constitute about 90% of all produced and installed PV cells cost between 3000 Euro/kWp (IEA 2011) and 2145 €/kWp (ECN 2012). There is however prospect with the learning rates for PV's costs and electrical conversion efficiencies. Neij (2008) indicates the learning rate for PV in the Netherlands is 10%, while Europe as a whole is much higher at 20%. This indicates that for every doubling of cumulative production, a 10-20% cost reduction is observed. Thus the potential for cost reductions is still high as cumulative PV output continues to rise. Similarly there is potential to improve the conversion efficiency of crystalline PV cells. The theoretical limit of crystalline stacked junction PV cells is 40-68% depending on the number of (p-n) junctions stacked (Razykov et al. 2011). Although reaching the theoretical limit is unlikely technologies such as nanostructure PV show promise to help improve conversion efficiency in the future.

Building Integrated Photovoltaic

PV modules have the advantage of being able to be integrated in many interesting ways into a building's architecture. Examples of BiPV are roof shingles, wall siding, curtain walls, solar shading facades and windows. In some cases BiPV replace conventional wall/roof materials saving costs, while in others they are an external addition. Performance of BiPV is generally reduced when compared to conventional angled solar cell installs and is directly related to their (generally) sub optimal orientation toward the sun. Advantages of various BiPV configurations can be found in Table 2.5 below.

Table 2.5: Overview of BiPV types relative pros and cons (Harvey 2006).

BiPV Placement	Benefit	Drawback
Mounting on sloped roof	• inexpensive and simple to mount • air gap provides ventilated cooling for cell • can be oriented to optimal angle with minimal self-shading	• can be aesthetically displeasing
Integration into sloped roof	• aesthetically pleasing • displace roofing material (cost saving) • can form top layer of double skin roof or be used for water preheating (help with cooling)	• modules can heat up with lack of under ventilation • must form water tight barrier
Tilted modules on flat roof	• air gap provides ventilated cooling for cell • provides roof shading lowering roof temperatures	• requires support structure • less total roof area utilization (result of unit self-shading) • can be astatically displeasing
Modules on facades	• can be integrated in many different ways as shading façade, curtain wall, double skin façade • serve multiple building functions	• reduced energy production from cell orientation
Mounted as skylights in atria	• aesthetically pleasing • offers diversity in architecture and space	• requires optimization between electricity production, lighting and solar heating/cooling • requires air flow for cell cooling

Noise Barrier Integrated Photovoltaic

PV arrays have also been integrated as noise barriers throughout Europe. Their design varies, with several variations shown in figure 2.5. Instillation costs per Wp of this type of PV instillation depend on location, orientation, system configuration and climatic conditions. Nordmann et al. (2004) found capital costs ranged between 10 – 18 €/Wp with typical installed capacities of 30 kWp to 220 kWp.

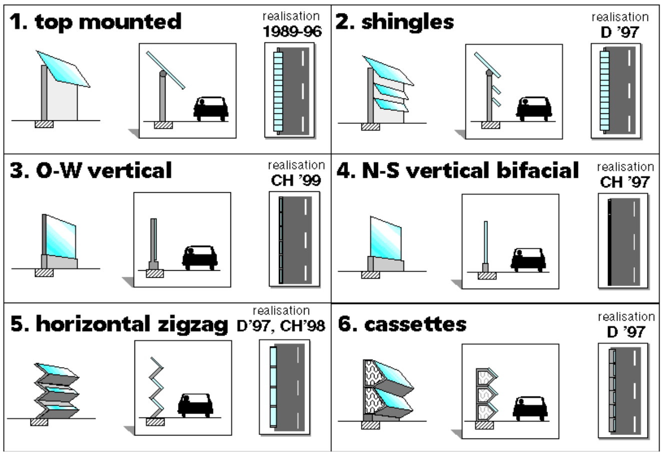

Figure 2.5: Different noise barrier PV configurations (Nordmann et al. 2004)

The Netherlands is home to one of the largest road side PV instillations, located along the A9 highway close to Ouderkerk-aan-de-Amstel (latitude 52° 22' North, longitude 4° 54' East). At this latitude, and a tilt angle of 50° the bank of 2160, 94 Wp cells generates between 600-800 kWh/kWp throughout an average Dutch climactic year (Van der Bord et al. 2001). This translates to average yearly electrical energy production between 121 MWh and 162 MWh.

Heat pumps

Heat pumps use a small amount of energy to exploit thermal properties of expansion and compression to transfer heat energy from cool to warm environments (or vice versa). Heat pumps are highly adaptable and have been deployed in a wide variety of configurations and degrees of integration in buildings (Zhai et al 2011). Heat pumps accomplish their task in two main forms, either through vapour compression or absorption. Vapour compression heat pumps are the most common in residential applications and use a gas or electrical driven compressor to drive a working fluid through a Carnot cycle. Figure 2.6 shows a schematic of the compression cycle and the main parts of a vapour compression heat pump.

Heat pumps work by drawing heat into the working fluid within the evaporator, and compressing the working fluid via the compressor. When compressed, the working fluid heats up and moves into the condenser where heat is radiated into the warm environment. In the last step, the working fluid is expanded through an expansion valve and drops in temperature. Temperatures of the working fluid are kept below ambient in the evaporator and above ambient in the condenser to induce heat transfer with the environments. Different configurations exist for the placement of the evaporator coil. Ground source heat pumps place the coil underground, while air source heat pumps use air from the environment. Similarly, condenser coilers can be placed in walls or floors to promote heat rise into the living space. Heat pumps are bi-directional, meaning they can be operated in heat delivery or cooling delivery modes.

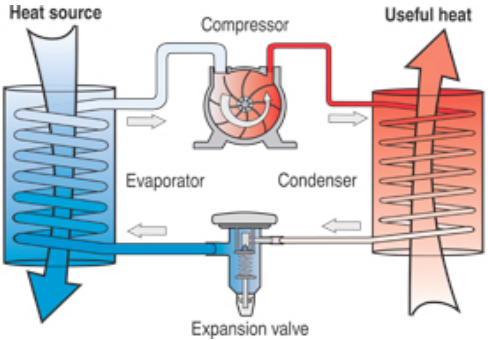

Figure 2.6 Schematic of a heat pump (IEA Heat Pump Centre, 2012)

The efficiency of a heat pump is strongly dependent on the compressor's energy source; typically electricity but also natural gas, chemical, geothermal and solar assisted are available. Heat pumps are compared according to their coefficient of performance (COP) which is the ratio of heat energy delivered to energy input. Equation 2.2 shows how the COP is calculated where T_{evap} is the evaporator temperature, T_{cond} is the condenser temperature and η is the efficiency of the compressor. The energy delivered by a heat pump can then be characterized by equation 2.3.

$$COP = \eta \frac{T_{evap}}{T_{cond} - T_{evap}} \qquad (2.2)$$

$$E_{out} = E_{in} \bullet COP \qquad (2.3)$$

As the temperature difference between the evaporator and condenser becomes larger the COP drops. For well insulated, air tight buildings, space heating demands can be met with hydronic distribution at temperatures (temperature of space heating delivery fluid) of 30-35 °C. This is excellent for heat pump performance, with COPs ranging from 3 to 8 for compressor efficiencies of 0.3 to 0.65 respectively (Harvey 2006). As hydronic distribution temperatures increase to current standards (70-90 °C) the COP drops dramatically to between 1 and 3 for equivalent heat pump systems.

Heat pumps are characterized by high investment costs and low running costs. However, since the 1970s increased applications in industry have helped lead to unit cost reductions. Still costs for heat pumps vary widely, from 400 to 2000 €/kW depending on the compressor type, condenser distribution network and evaporator type (IEA 2011).

Combined Heat and Power

Combined heat and power (CHP) generation is exactly as the name implies; both electrical power and heat are produced and delivered simultaneously. Mini-CHP is a CHP variant usually used in reference to CHP units installed in homes, or medium sized buildings. Various types of Mini-CHPs exist, with the most prominent being Stirling engines, reciprocating engines, mirco-turbines and fuel cells (Alanne et al. 2004). Throughout this document Mini-CHP systems considered are referred to as CHP.

Figures 2.7 and 2.8 show simple schematic diagrams of how turbine CHP and fuel cell CHPs operate. Turbine CHPs work by combusting fuel and using hot exhaust gasses to drive an electrical generator turbine while hot flue gasses pass through a heat exchange system to capture residual heat. Fuel Cell CHPs use fuel as a source of hydrogen atoms which are ionized as they enter the cell. The liberated electrons pass out from the fuel cell through an inverter (converting DC current to AC) and into the cathode where the hydrogen ions, electrons and oxygen react to create water. The resultant water is heated, and is collected for use in both the fuel processor, and thermal distribution system.

CHPs are capable of utilizing many fuel sources including natural gas, biomass (solid, liquid and gas) and dual firing that handle combinations of wood biomass, biogas, and natural gas (Merse et al. 2011). Currently total efficiency of reciprocating and fuel cell CHPs is 80-85%, with typical production breakdowns of 20%-50% electricity and 30%-60% heat (E&EA 2008, IEA 2011).

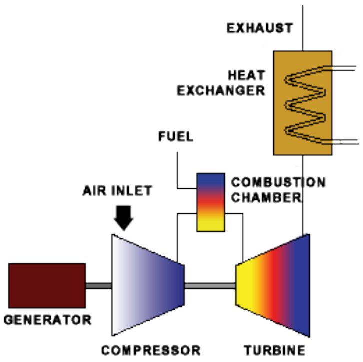

Figure 2.7: Turbine CHP schematic (Herbert 2004).

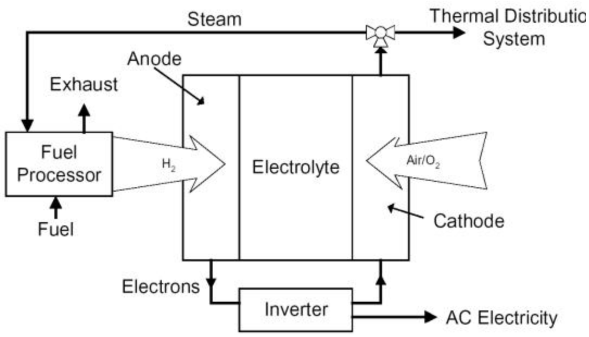

Figure 2.8: Schematic of a fuel cell CHP (ESC 2004).

Costs of CHP systems are quite dependent on the type and size of the CHP installed. Reciprocating engine CHPs have capital installed costs of 860-1650 €/kW (E&EA 2008). Fuel cell CHPs, being extremely new to the market have high capital costs in the area of 4000-5000 €/kW (IEA, 2011). Future cost reductions as the result of learning effects is promising for both CHP technologies however. Reciprocating CHPs have seen increased deployment in Europe in the last few years and are observing learning developments as a result of favorable policy (Hinnells 2008). Similarly prospects are very promising for fuel cell because of their higher electrical efficiency. Although in the early stages of market deployment, the combination of much academic research and market learning developments may well lead to rapid fuel cell technology cost reductions (Mekhilef et al. 2012).

3. Estimating Electrical and Heat Energy Supply and Demand

This section aims to answer the sub question "How much energy will the Living Wall demand and be able to produce for own use and/or sale?" This is answered through the use of a simple model developed for the purpose of quantifying the Living Wall's energy demands, and renewable energy supplies. Subsection 3.1 and its subsidiaries describe the theory and assumptions behind the model. Subsection 3.2 outlines the results from the model and assumptions. This includes the Living Wall's modeled total yearly heat and electrical demand, as well as total potential PV electrical and AST heat supplies.

3.1. Methodology

A simple model of the Living Wall's seasonal heating/electrical demands and renewable solar heat/electrical supplies was created. The model estimates hourly space heat and district hot water (DHW) demands and per minute electrical demand. Seasonal solar irradiance was used to calculate per minute electrical supply potential from a PV array and hourly thermal heat potential from a AST array. In all cases, the model is broken up into one day (24 hour snapshots) of averaged seasonal profiles to mimic variance in demand and production through the year. Estimates for yearly demand/supply are constructed by summing the product of seasonal profiles by average season length (91.25 days). The following sub sections outline the steps taken to estimate electrical, space heat and DHW demand and PV, and AST supply.

3.1.1. Reference Building

The reference building is a simulation object created to reflect the Living Wall's building design. Using total building length and minimum floor area per resident as constraints the reference building was derived as shown in figure 3.1. A summary of the living box's dimensions is presented in table 3.1 while detailed dimensions of the whole simulation reference building can be found in appendix A1. Two 'boxes' are distinguished, one, which contains the resident living space, and one that is the south facing gallery space. The living box is divided into two zones, one north and one south. This was done to more accurately reflect the influence of the gallery and parking areas adjacent to the south living wall, and ground floor on the heat transmission losses from the living space box. Figure 3.2 shows a cross section of the living box division between north and south zones.

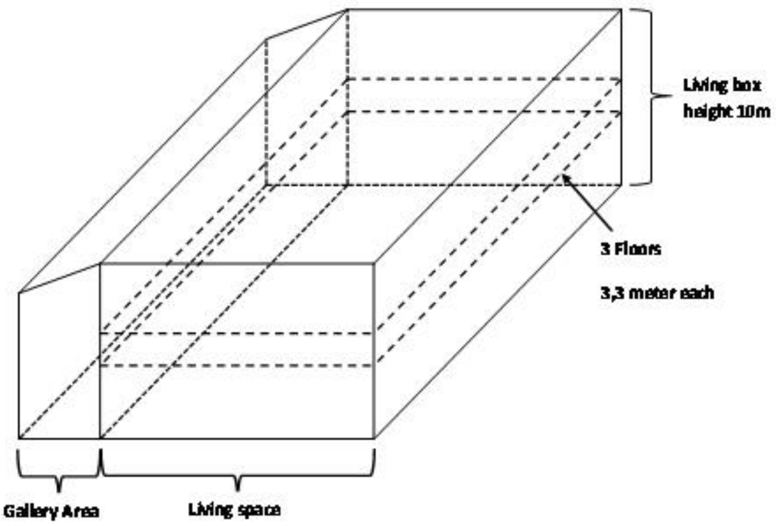

Figure 3.1: Living Wall simulation object for heat loss model.

Table 3.1: Summary of living box dimensions.

Total length	2250 m
Living box envelope height	9.9 m
Living box envelope depth	10 m
Average unit floor area	40 m^2

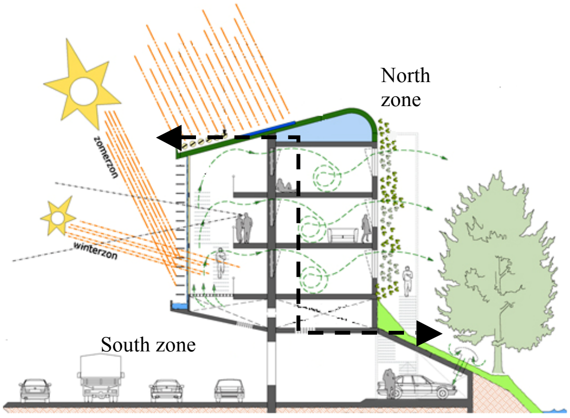

Figure 3.2: Cross section of the Living Wall design showing division of north and south insulation/window zones. Image courtesy of NarrativA ArchitecteN.

North zone

The north zone includes the north facing walls and windows, building east and west side walls, and roof. The Living Wall's thermal envelope is modeled so that it meets the minimum Dutch insulation standards outlined according to Dutch building regulations (*Bouwbesluit*). The total Living Wall envelope, composed of walls and windows, must therefore have a minimum U-value of 0.285 W/m^{2}K (R: 3.5 m^{2}K/W) ("Bouwbesluit 2012" 2012). This value is set as the Living Wall's aggregate thermal resistance, U_{total}, which is the sum of the insulating properties of all building envelope elements. Reference windows were chosen as double glazed air filled with a U-value (U_{ref}^{wnd}) of 2.6 W/m^{2}K (R: 0.38 m^{2}K/W). To then determine the reference wall U-values (U_{ref}^{wall}) in each zone, the reference window's U-values and the area they occupy must be taken into account into a weighted average equal to the Dutch standard. Equation 3.1 outlines the calculation of the reference wall U-value using the northern zone as an example. Here A_{NZ}^{wnd} is the total north zone window area, A_{NZ}^{wall} is the total north zone wall area, and A_{NZ}^{tot} is the total surface area of all parts of the northern zone.

$$U_{ref}^{wall} = \frac{U_{total} \cdot A_{NZ}^{tot} - U_{ref}^{wnd} \cdot A_{NZ}^{wnd}}{A_{NZ}^{wall}} \tag{3.1}$$

The window area in equation 3.1 was determined by assuming a window fraction (WF) of the total wall area as window space. Changing the fractional percentage of window area in the building envelope will also change the reference wall U-value, as is seen in equation 3.1. Therefore determining window area follows equation 3.2 where A_{NZ}^{fac} is the total northern façade surface area.

$$A_{NZ}^{wnd} = A_{NZ}^{fac} \cdot WF \tag{3.2}$$

Slightly lower window fractions were chosen for the northern zone compared with the southern zone, following advice for northern buildings from Bülow-Hübe et al. (2009). More south facing window area allows more direct light and thermal radiation and reduces heat transmissions losses on the cooler northern façade.

South zone

For the south zone, the effect of large air spaces adjacent to the interior floor - parking and wall - gallery needed to be accounted for. Therefore the south zone includes only the south living area wall and ground floor. As in the northern zone, an average reference U-value is determined from the total wall and ground floor space, window fraction and reference window U-value. A summary of window fractions and corresponding reference wall U-values for each building zone is presented in table 3.2. The effects of the gallery and parking areas on heat loss was then modeled using steady state heat flow (see section 3.1.3 modeling heat losses) and assumes the gallery has a full glass façade with a ceiling overhang of 7.5 m (see explanation on solar shading in section 3.1.3 and appendix A1 for gallery dimensioning).

Table 3.2. Summary of calculated reference wall U-values.

Building Zone	Window Fraction (%)	Window U^{wnd}_{ref} value (W/m^2K)	Wall U^{wall}_{ref} value (W/m^2K)
North	35	2.6	0.249
South	45	2.6	0.230

3.1.2. Simulating Electrical Demand

A residential electrical demand simulator created by Richardson et al. (2010) was used to develop four seasonal 24-hour electrical load profiles. The bottom up model calculates dwelling electrical demand based on natural light availability (time of year), number of occupants, an inventory of installed appliances per dwelling, and resident activity profiles. The model was used to simulate seasonal residential demand for single, double and four person occupancy scenarios. Each season was simulated on the yearly equinox or solstice (table 3.3). The equinox occurs twice a year and is defined by all parts of the globe having equivalent total daylight hours (about 12). The solstices are the shortest and longest days of the year. Averaging the light availability on these four days is equivalent to the yearly average light availability (12.1 hours/day).

Table 3.3: Seasonal simulation days.

Season	Simulation day of year
Spring equinox	79; March 20th
Summer solstice	172; June 21st
Fall equinox	265; September 22nd
Winter solstice	355; December 21st

Appliances

The Living Wall's appliance distributions, yearly use and consumption characteristics within the model were adjusted according to results from Van Holsteijn et al. (2008). Appliance distribution is given as the probability of finding an appliance in a household. Use is characterized by number of hours ON in a year corresponding to a given number of ON - OFF cycles. The consumption profile of a given appliance was chosen to reflect the highest, high efficiency model that has a market penetration higher than 30%. In this way, the model does not assume the highest standard appliance efficiency available on the market. Therefore, in accordance with point two from the northern design methodology (section 2.2.2) A level or higher yearly energy use figures were used. Table 3.4 outlines the appliance input parameters.

Table 3.4: List of appliances assumed present in each dwelling unit.

Appliance Category	Appliance	Probability Dwelling Has Unit (%)	Normalized Cycles/year*	ON power demand (kWh/y)	Stand-By demand (kWh/y)	Cycle demand (kWh/cycle)
Cooling	Refrigerator + freezer (2 door)	49	2243	359	0	0.0587
	Refrigerator + freezer (1 door)	18.4	1834	202	0	0.033
	Refrigerator	32.6	1834	157.5	0	0.0258
Consumer Electronics	Clock	90	-	-	17.5	-
	CD Player	90	250	4	17	0.015
	Hi-Fi	20	109	11	78	0.1
	Iron	0.9	70	12	0	0.5
	Vacuum	99	50	86	0	0.575
	Personal Computer	98	1405	198	36.8	0.7035
	Printer	66.5	200	3	34.2	0.0011
	Television (1/2)	97.7/30	1247/112	155/14	7.5/8.6	0.1509
	VCR/DVD Player	89	110	4	17.3	0.0408
	TV Receiver Box	0.936	1819	38	69.4	0.0326
Cooking	Induction Cooker	1	330	462	25.3	1.4
	Microwave/ Microwave oven**	86	51	39	17.4	0.39
	Kettle/Coffee maker	98	41	71	8.7	0.0863
	Small Cooking appliances	1	15	155	17.5	0.05
Wet	Dishwasher	59	280	267	12.4	0.954
	Tumble Dryer	62	140	246	9	1.76
	Washing Machine	100	506	200	9	0.91
Heating	Electric Space Heater	15	1000	2000	0	8.00

***Cycles per year are normalized to a cycle length of 60 minutes as a way of comparing the yearly use of appliances with different cycle lengths. **Power demand is average of microwave, and microwave oven/grill.**

Resident Occupancy and Activity

It was not feasible to calibrate the occupant activity profiles used within the model to the Dutch society in this research. The original model bases probable occupant activity on the UK 2000 Time Use Survey, which compiled the activities of thousands people in the UK through 1 day diaries at a 10 minute resolution (Richardson et al, 2010). However, the occupancy and activity module calibration factor may be changed so that yearly average electrical demand per unit is comparable to the Dutch national average. In the Netherlands, the average electrical demand per household is approx. 3300 kWh/year (IEA 2009, CBS 2012) for an average household size of 2.2 persons. Therefore the activity calibration factor was scaled according to the double occupancy scenario (following section), resulting in calibration factor value of 0.71.

Building Occupancy Profile

The building occupancy profile was assumed according to the breakdown given in table 3.5. In total the building was modeled to house 1500 people divided up into 1050 residential units. To calculate the building's average electrical demand per residential unit a weighted average of the simulated averages in table 3.5 was used. Each occupancy scenario simulation ran 500 times in an effort to average single trial demand variance.

Table 3.5. Residential unit's occupancy breakdown.

Occupancy Characteristic	Percentage of total building occupants (%)	Simulated average unit electrical demand (kWh/year)
Single Occupancy	50%	2700
Double Occupancy	30%	3350
3-4 Occupants	20%	3914

3.1.3. Modeling Heat Demand

Energetic heat demand is the sum of space heating and district hot water (DHW) demands. While the latter can be relatively straight forward to quantify given limited inputs, the former is extremely dependent on several factors. First, occupants' desired room temperatures are highly subjective to behavioral factors (i.e. putting on a sweater compared to turning up the thermostat) and one's perceived warmth. Second, the impact of small details in actual building construction can skew space heating demand estimates. Examples are levels of outdoor air infiltration, thermal bridging, and natural heat buffers within the building (Harvey 2006). For energetic heat demand a simple estimation method was chosen to avoid complex modeling of heat flows.

Degree days

Variation in the temperature difference between indoor and outdoor temperatures over the year is represented through the use of heating and cooling degree-days. A degree-day measures the variance from a reference temperature (usually 18 °C) and quantifies the total time and temperature difference between the outside and the reference (Blok, 2007). To determine the number of degree-days for a given location equation 3.3 is used where T_{ref} is the reference indoor temperature, and T_d is the daily average outdoor temperature.

$$DD = \sum_{1}^{365} \max(T_{ref} - T_d) \tag{3.3}$$

In modeling the heating demands of the Living wall, the indoor temperature is assumed to be 19°C. However, it is common practice in homes to lower the thermostat when no one is home, and at night. Therefore, the following T_{ref} temperatures were used according to the hour of the day.

Table 3.6: Daily indoor reference temperatures.

Hour of day (h)	Temperature T_{ref} (°C)
24-6	15
7-11	19
12-16	15
17-23	19

Similarly, the outdoor temperature has an effect on the yearly number of degree days. The goal in this work was to come up with 24-hour seasonal profiles and therefore a crude model of daily heating and cooling was constructed using the 20 year average high and low temperatures for each season. Temperatures were assumed to rise and fall linearly through the day and night. The heating period during the day was scaled according to the number of sunlight hours.

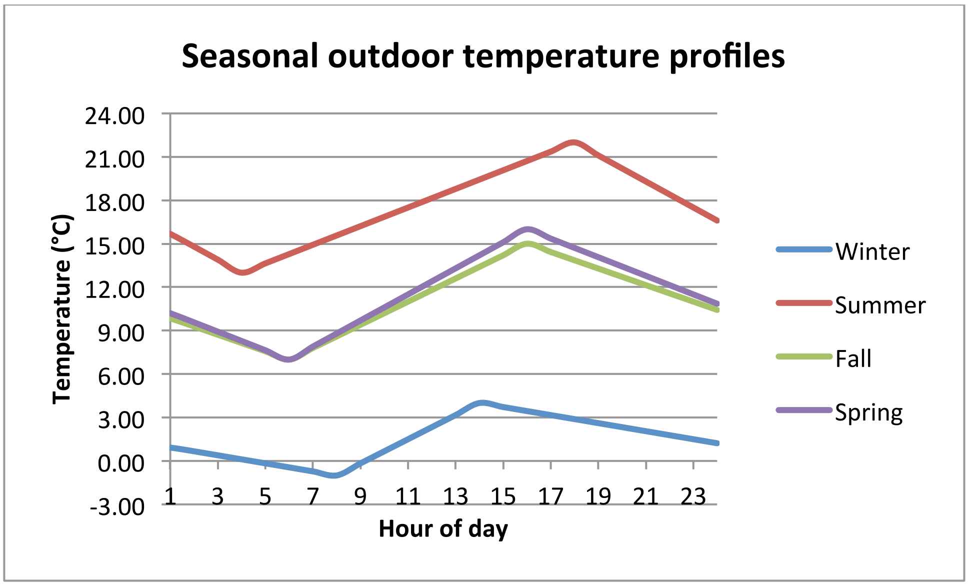

Figure 3.3: Graphical representation of the assumed daily average temperatures used for calculating total degree days.

The total degree days used in the heat transmission and ventilation sections of the model are then presented in table 3.7. Total degree days for the north zone are the actual degree days observed by the exterior of the whole building. Degree days for the south zone are the effective degree days observed by the walls and floor adjacent to the gallery and arise from the method of gallery heat modeling (see following section).

Table 3.7: Degree days used in modeling heat loss from north and south zones.

Building zone	Degree days in model
North zone (DD_{NZ})	2549.3
South zone (DD_{SZ})	2336.5

The total degree days (north zone) calculated as a result of the temperature profile model should correspond to observed degree days measurements for Utrecht. Eurostat indicates that Utrecht has had on average 2591 heating degree days per year over the last 10 years (Eurostat 2012). This is a small discrepancy with the calculated northern zone degree days and is the result of assumptions on daily average high and low temperatures, as well as the length of heating and cooling periods throughout the day. Given the crude hourly temperature model, the variation between observed and calculated degree days (1.6% difference) is considered very minimal and not able to significantly affect the results.

Gallery Area Heat Modeling

The gallery area (south zone) presents a difficult area to model heat losses because as the area is assumed not to be heated. Thus it will gain and lose heat transiently from the windows, and southern living box wall throughout the day, causing the temperature to fluctuate. To keep the model simple, the gallery space heat losses were modeled as steady state heat flow. This means two boxes are considered (living and gallery) where the heat is assumed to be instantaneously lost from the living box through the gallery to the environment. The gallery temperature can then be calculated in relation to the outside and living box temperatures. Since the living box temperature is essentially constant, the gallery temperature fluctuates according to the outside temperature. Using this, the temperature of the gallery box was calculated for the range of outdoor temperatures considered in the average seasonal temperature variability. A separate degree day profile specific for the south zone building areas was then used to model the heat buffering effect of the gallery area as seen in table 3.7.

Space Heating

Space heat demand is the sum of the buildings heat transmission and ventilation losses and solar thermal heat gains. The net heat demand of the building is calculated according to equation 3.4 where $Q_{transmission}$, $Q_{ventilation}$, and Q_{solar} are heat fluxes from transmission, ventilation and solar radiation.

$$Q_{net} = Q_{transmission} + Q_{ventilation} - Q_{solar} \tag{3.4}$$

Heat Transmission Losses

Heat transmission loss is heat lost to the environment directly through the building envelope materials. This was calculated according to equation 3.5 below (north zone example).

$$Q_{transmission} = U_{ref} \cdot A_{NZ} \cdot DD_{NZ} \cdot 24 \cdot 3600 \tag{3.5}$$

Ventilation Heat Losses

Heat losses through ventilation are dependent on air exchanged via ventilation in terms of air exchanged per hour. In the Netherlands the *Bouwbesluit* sets the standard for minimum ventilation in buildings as 0.9 changes per hour ("Bouwbesluit 2012" 2012). However NarrativA ArchitecteN prefers higher standards for air exchange to promote higher quality living environments. The ventilation rate was therefore doubled and modeled at 1.8 air changes per hour. The ventilation model also assumes a passive cross flow heat exchanger system with an exchange efficiency of 50% (Harvey, 2006). Equation 3.6 shows how ventilation heat losses were calculated where c_p^{air} is the heat capacity of air (kJ/kg·K), η_{HE} the inlet/exhaust heat exchanger efficiency (%), N the number of air changes per hour (h^{-1}), V_{LB} the total volume of the living box (m^3), and ρ the specific mass of air (kg/m^3).

$$Q_{ventilation} = c_p^{air} \cdot \eta_{HE} \cdot N \cdot V_{LB} \cdot \rho \cdot DD_{NZ} \cdot 24 \cdot 3600 \tag{3.6}$$

Solar Thermal Heat Gains

In equation 3.4 the term Q_{solar} comprises heat radiation from the sun that passes through the gallery and south living area windows heating the inside living area. The extent of this effect is modulated by the suns orientation throughout the year, and the building's geometry including overhangs, and solar facades (Harvey 2006). In this model it is assumed there is no solar façade on the gallery windows. Instead the gallery roof acts as a large overhang providing much shade. The extent of the shading effect on internal south facing windows was modeled according to the IEA's solar heating and cooling program task 20 (Elmroth et al. 1999). Table 3.8 shows the effective solar radiation per season that is incident on the south facing living area windows assuming an overhang length of 75% (7.5 m) of south wall height (height from bottom first resident unit level to joint between south wall and overhang).

Table 3.8: Effect of overhang on seasonal radiation hitting south windows.

Season	Total solar radiation incident as fraction of total (%)
Winter	78
Spring	55
Summer	47.5
Fall	50

Additionally direct and indirect radiation passing into the living box through the gallery will have passed through two sets of windows. Therefore the g-value of each window is assumed to be 0.7, further reducing the heat radiation effects of the solar gains. Finally the equation 3.7 shows how Q_{solar}

is calculated, where $g_{gallery}$ and $g_{southwindows}$ are the g-values of the gallery and south windows (%), SR is the seasonal solar reduction factor (%), and I_{Solar} is the incident solar radiation intensity (W/m^2) .

$$Q_{solar} = g_{gallery} \cdot g_{southwindows} \cdot SR \cdot A_{SZ}^{wnd} \cdot I_{Solar} \tag{3.7}$$

District Hot Water

Energy demand from hot water use is based on two main factors; the difference between mains water temperature, and the water volume demanded. Mains inlet and distribution temperatures were estimated at an average of 10 ºC and 55 ºC year round based on input parameters used by Widen et al. (2009) in modeling DHW use in Sweden. Equation 3.8 was used to determine energy demanded from hot water demand where c_p^{water} is the heat capacity of water, T_{dist} and T_{mains} are the distribution and mains water temperatures (ºC), and D_{DHW} is the volume of how water demanded (L).

$$D_h^{DHW} = \frac{c_p^{water} \cdot (T_{dist} - T_{mains}) \cdot D_{DHW}}{3600} \tag{3.8}$$

Water volume demanded is more difficult to validate since monitoring of DHW use is not widely reported in literature (Widen et al. 2009). A reliable estimate, and that used in this study, is the DHW load profile produced by Knight et al. (2007) for the International Energy Agencies' annex 42/3 program. Hourly hot water demand was modeled after the European average of 130L/day for 100m^2 floor space (approx. 2.5 occupants). Average daily use per occupant is then 52L/day and total demand is scaled according to the resident occupancy breakdown (see above). Figure 3.4 shows graphically the average residential unit's DHW demand profile.

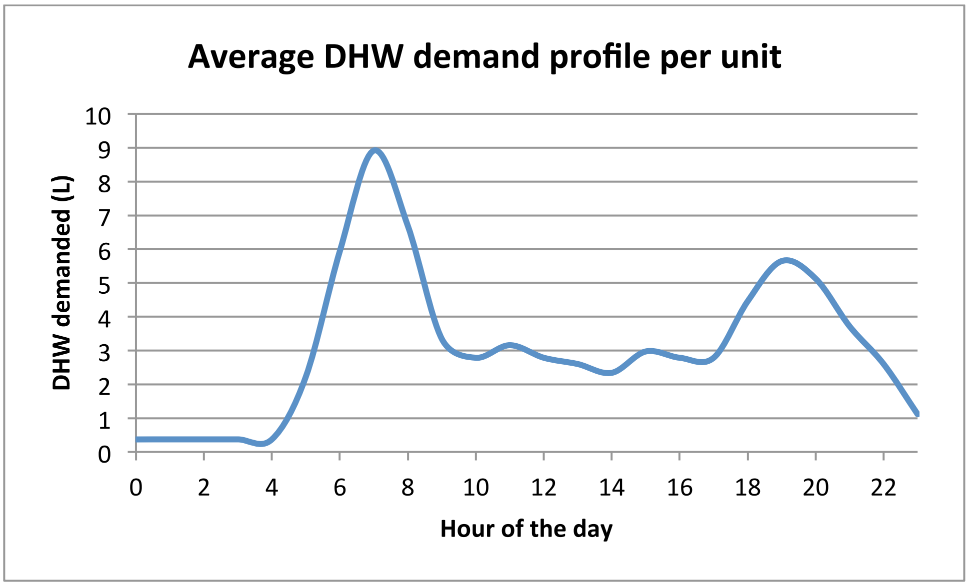

Figure 3.4: Average DHW demand profile used to determine hourly DHW demands. Adapted from IEA's annex 42 DHW profile (Knight et al. 2007).

3.1.4. Solar Energy Availability and Supply

Energy availability from the sun was estimated using the PV module in Richardson et al.'s (2011) integrated electrical/PV demand/supply simulator. The model predicts solar irradiance profiles at a one minute time intervals using the product of a sky clearness index and a maximum irradiance profile (location, and season dependent). To construct seasonal daily averages the program was used to construct theoretical maximum solar irradiance per season. The seasonal maximum irradiance profiles were then modulated by multiple day simulations of sky clearness indices. Through this, an average available solar irradiance per minute (I_{Solar}) profile was constructed for each season as displayed in table 3.9. Again, by comparison the yearly solar insolation average for the last 20 years according to the NASA Surface Meteorology and Solar Energy dataset is 3.02 kWh/m^2 (Stackhouse 2012). As the simulations were only run 90 trials per season, the difference between the simulated and recorded measurements from NASA can be accounted for through variance. The profiles were used to determine the energy supply production from PV, and AST.

Table 3.9: Simulated seasonal and yearly solar insolation values.

Season	Energy availability (kWh/m^2)
Spring	3.12
Summer	5.63
Fall	3.10
Winter	1.99
Simulated yearly average	3.46

Active Solar Thermal heat production

Using the average hourly seasonal solar irradiance profiles, seasonal thermal energy production from AST (D_h^{AST}) can be calculated using equation 3.9 from Harvey (2006) where A_{AST} is the AST array area. The exact value of the AST collector efficiency (η_{AST}) was calculated according to equation 2.1 using values for an evacuated tube collector found in table 2.4. AST array angle was set to 41º corresponding to optimal full year array angle for a fixed collector at latitude 50º (Landau 2012).

$$D_h^{AST} = I_{solar} \cdot A_{AST} \cdot n_{AST} \cdot n_{HE} \tag{3.9}$$

Photovoltaic electricity production

Similar to AST production, energy supply from PV (D_e^{PV}) was calculated as the product of incident solar radiation, array size (A_{pv}) and array efficiency (n_{pv}) – shown in equation 3.10. The array efficiency was set at 14% corresponding with solar PV panels available from Viessmann.nl. PV array angle was also set to 41º.

$$D_e^{PV} = I_{solar} \cdot A_{pv} \cdot n_{pv} \tag{3.10}$$

3.2. Results: Demand and Supply

The following sections present the results of simulating the Living Wall's seasonal power demand, modeled heat demand, and estimated heat and power supply potentials from AST and PV arrays.

3.2.1. Power Supply and Demand

Aggregate power demand for the Living Wall was estimated to be 3114 MWh per year with an average unit consuming approximately 2966 kWh. The simulated peak power demand was 1240 kW and occurred daily between 18h and 20h. Since the model is correlated to the average Dutch residential consumption, the results of overall resident average consumption are as expected. With the building having 50% single occupancy it is expected that the buildings average per unit consumption would be less than the national average which is calculated based on 2.2 an average of occupants per residence.

Figure 3.5 shows the seasonal power demand profile for all four seasons and shows the daily demand profile is highest in winter and lowest in summer. This makes sense since it correlates to both the time of year when lighting demands are maximum (winter) and minimum (summer) and times when one would expect more evening activity indoors (winter) rather than outdoors (summer).

The spring and fall daily demand profiles vary little from the winter and summer profiles respectively. This was not expected and is likely the result of the time of year activity profiling and/or the interpretation of solar light availability in the lighting demand modules. Unfortunately a more concrete explanation of this discrepancy could not be found. However, the symmetry of the spring and fall results suggests that taking their average gives a more accurate picture of the seasonal demand (see the dashed line in figure 3.5).

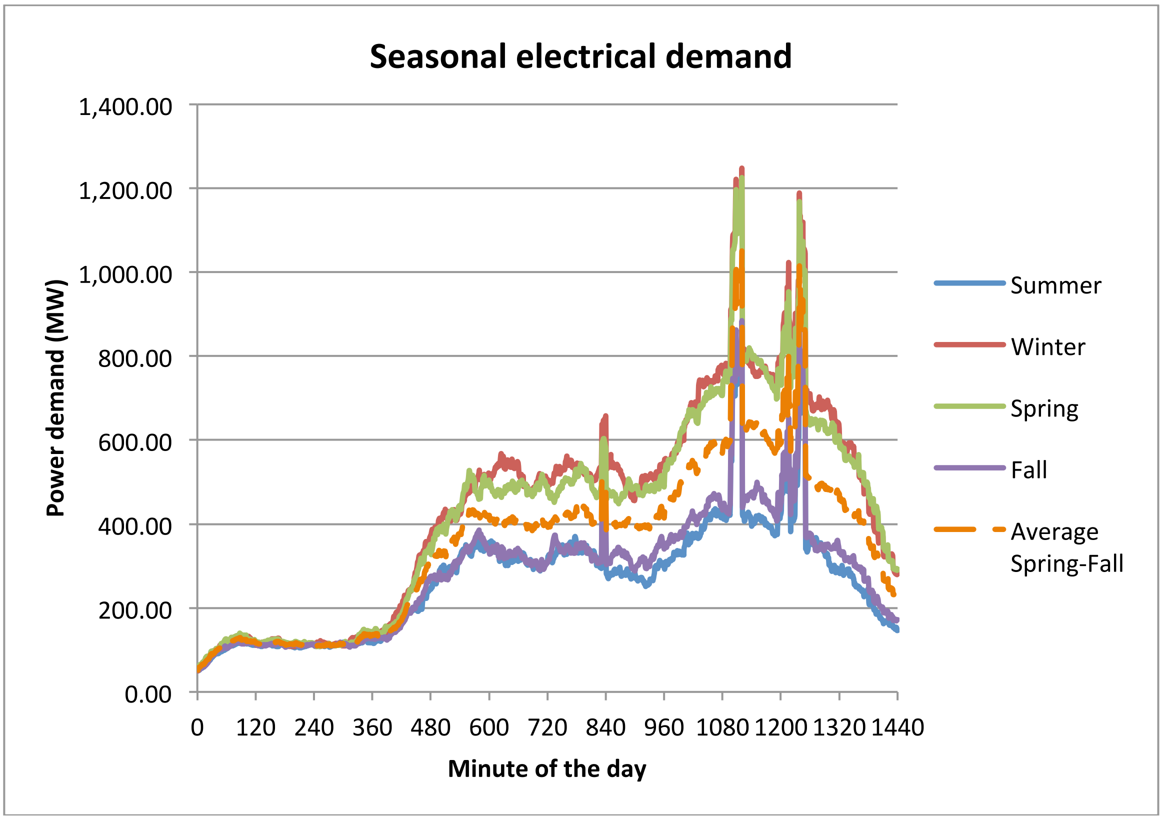

Figure 3.5: Living Wall Seasonal electrical demand for seasonal minimum, maximum and equinoxes.

Supply from PV

Total yearly power supply from PV was estimated at 3159 MWh/year for the base array size of 15 000 m^2. The seasonal per minute PV production profiles can be seen in figure 3.6. The graph shows that 90% of the energy is produced between the hours of 9 am and 4 pm corresponding with relatively low power demand periods.

Summer is observed to have the largest supply potential and winter the lowest. This is expected since daylight hours are significantly reduced and the sun's rays hit the PV array at less optimal angles during the winter season.

There appear to be small differences between spring, and fall energy production which is expected since the number of total daylight hours in these seasonal is approximately equal. Interesting to note is that peak power supply in spring and fall is only moderately reduced compared to summer. This is because the majority of hours when the average angle of incidence of the sun's rays hits the PV array at optimal angles occurs during the spring and fall seasons. Higher peak and total production in the summer season is the result of more intense incident solar radiation (despite hitting the array at sub-optimal angles) and longer daylight hours – reflected in the base width of the season's power production profile.

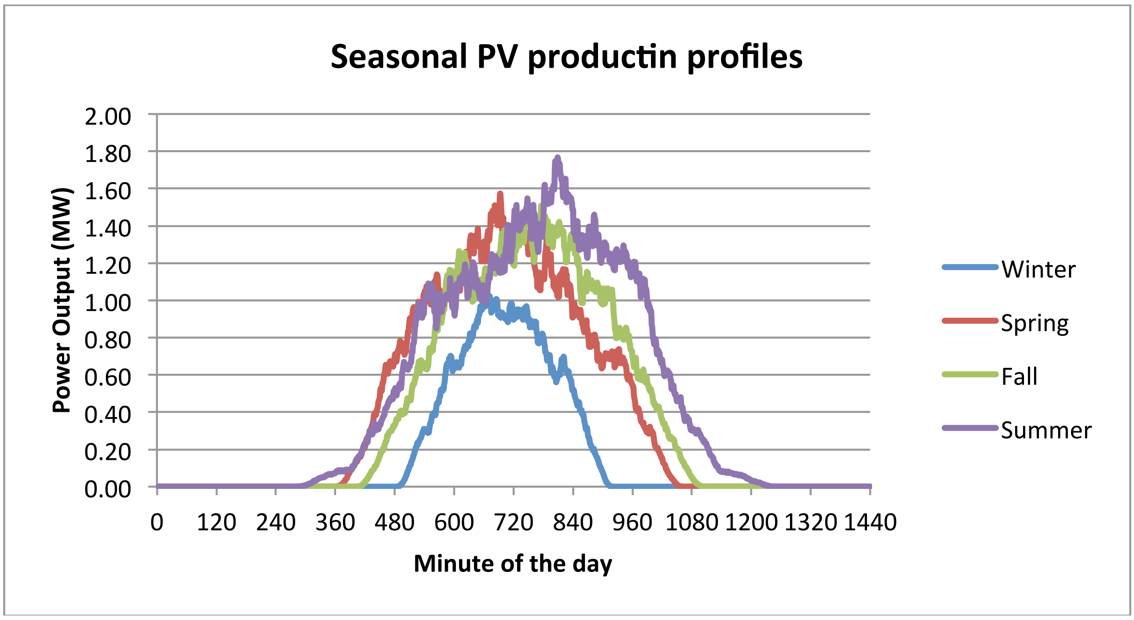

Figure 3.6: Seasonal power generated from a PV array of 15 000 m^2 at efficiency of 14% and incline of 41^o.

Net electrical demand

Superimposing the electrical demand and PV electrical supply simulations resulted in a net power demand of 1290 MWh/year with a demand profile as presented in figure 3.7. Here any point below the x-axis represents time when there is excess electrical power. Over the year a total of 1824 kWh in excess power is produced. It can be seen that winter is the only season where excess power is limited. Spring, fall and summer seasons all produce substantial quantities of excess power. Similarly, it is apparent that most electricity demanded during peak hours (16h-23h) must come from other sources (i.e. electrical grid).

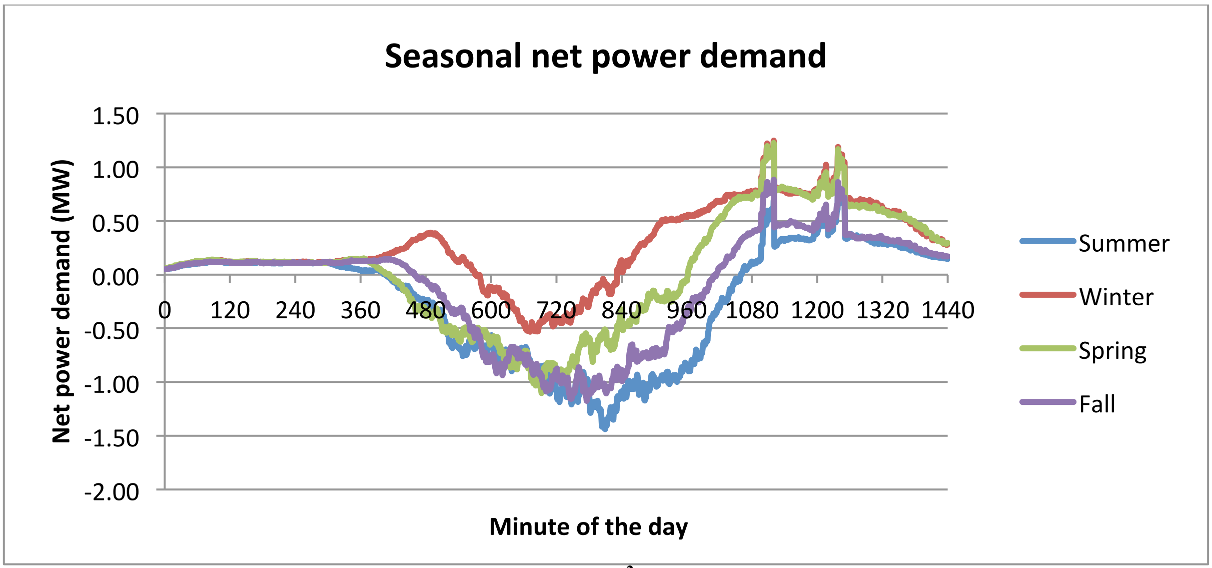

Figure 3.7: Net Power demand with a PV array size 15 000 m^2

Varying PV Array Size

Supply from PV was investigated for a range of array sizes 5000 m^2 to 25 000 m^2 at intervals of 5000 m^2. Figure 3.8 shows the potential PV electrical production, building self-electrical supply, corresponding PV solar power fraction (percentage of building's total electrical power demand supplied by the PV array), and the surplus power produced that is available for sale. Increasing array sizes obviously produce more electrical power. However, the solar fraction increases very marginally beyond 15 000m^2. This occurs because most power is generated between 9 am and 4 pm (see figure 3.6) when the building's power demands are relatively low compared to peak demands. Therefore, the benefits of increasing the array size beyond 15 000 m^2 are primarily external (selling excess power).

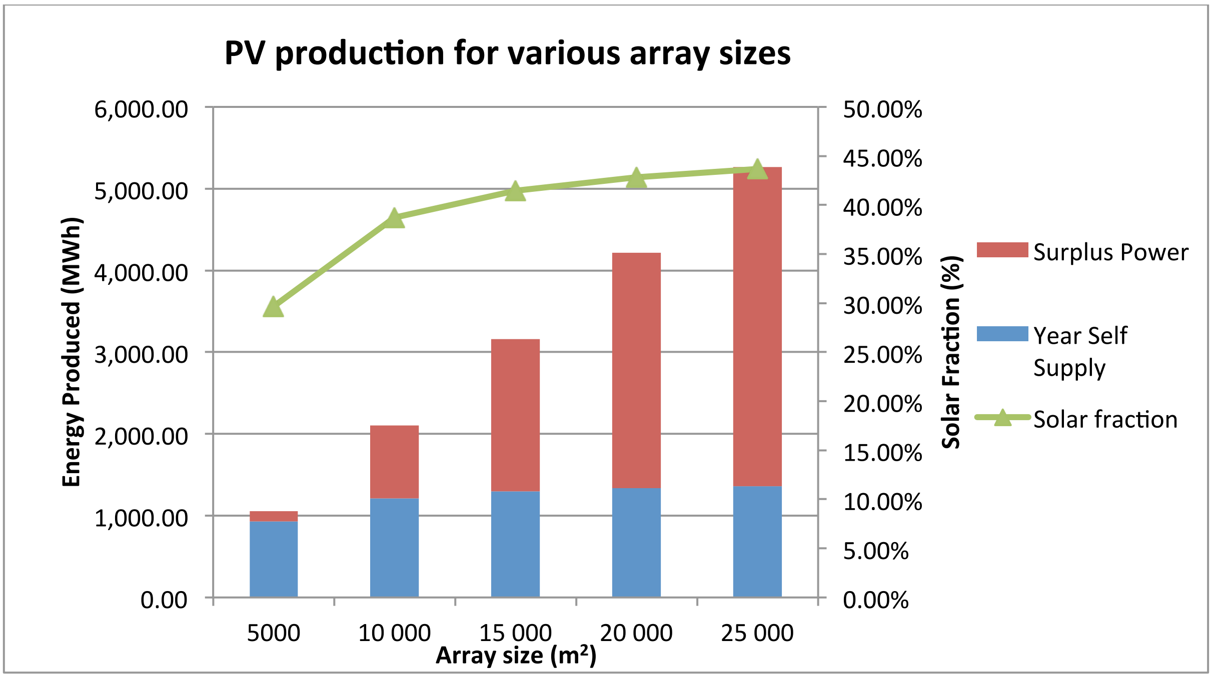

Figure 3.8: Breakdown of the Living Wall's solar fraction, self and surplus power supplies at various array sizes.

3.2.2. Heat Supply and Demand

Yearly heating demand from space heating and DHW was modeled to be 7512 MWh. Two daily peak heating demands are observed to occur between 7h-9h (morning, 2510 kW) and 19h-21h (evening, 2000 kW) with the winter peak being the highest seasonal peak. Peak demands are the result of transient DHW demands, while seasonal heat losses occurring from transmission and ventilation constitute the base demands. This spread in base heat demand between seasons can be seen in figure 3.9. The heat demand breakdown between DHW, transmission and ventilation losses is shown in figure 3.10.

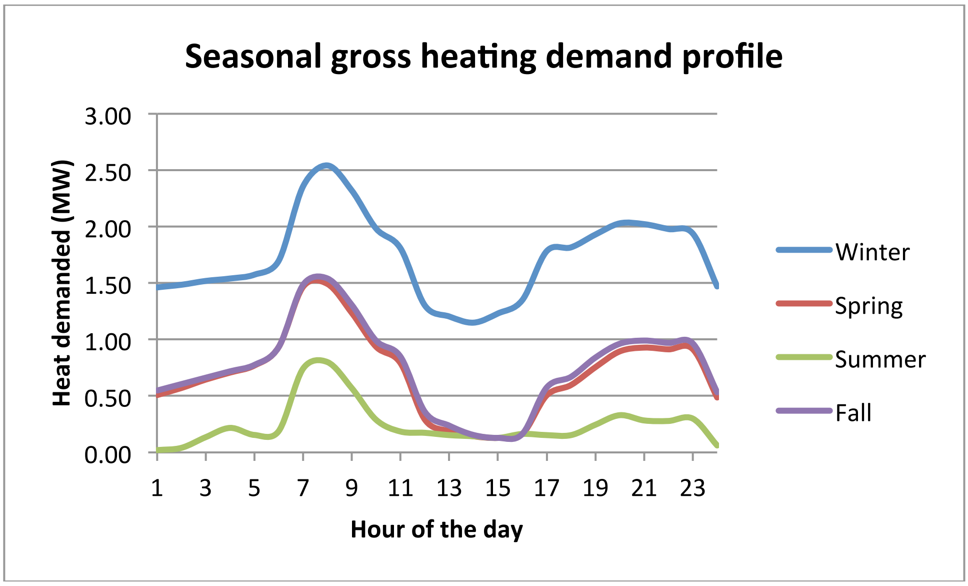

Figure 3.9: Seasonal 24 hour profiles of the Living Wall's total heat demand.

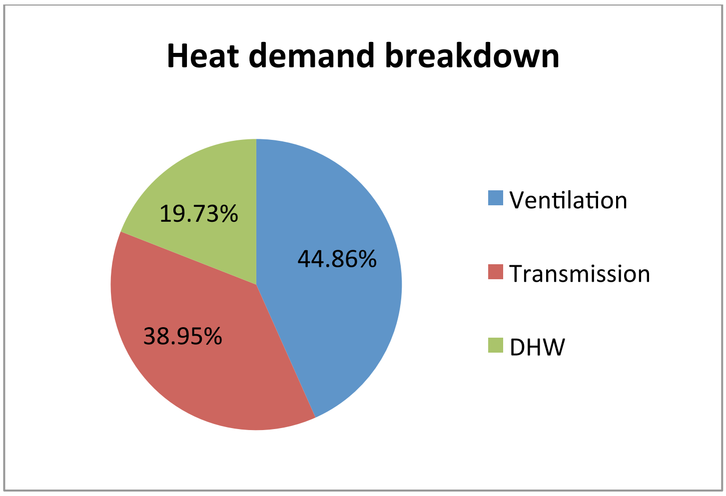

Figure 3.10: Breakdown of heating demands between ventilation, transmission and DHW.

Varying Reference Envelope U-value

The sensitivity of the reference heat demand was assessed by varying the reference envelope total U-value. Results from varying the envelope U-value from 0.285 to 0.182 (see appendix C for equivalent R values) can be observed in table 3.10. The table shows that there are marginal heat loss reductions when the U-value is increased. For a U-value decrease of 36%, only a 5% reduction in space heat losses is realized. Equation 3.5 indicates that transmission losses should follow linearly with U-value change. The discrepancy occurs as the result of heat transmission and ventilation losses being nearly equivalent. Because of this the impact of increasing the total wall U-value sees less total heat loss reductions than expected.

Table 3.10: Yearly space heating (transmission and ventilation) and total heating demand at varying reference envelope total U-values.

Envelope U-value (W/m^2K)	Space Heat Demand (kWh)	Total Heat Demand (kWh)
0.285	6029	7511
0.250	5917	7399
0.222	5830	7312
0.200	5761	7243
0.182	5704	7186

Supply from AST

To get an idea of the seasonal daily heat production, figure 3.11 shows AST heat production per season during the course of the day. Similar to PV, most energy is produced between the hours of 9h and 16h corresponding to average maximum solar intensities. Peak power is 2.68 MW in summer reducing to 1.51 MW during the winter seasons for an array size of 6000 m^2. Total yearly production from AST is 2163 MWh. The negative values observed are the result of net heat loss to the environment when the AST array is not collecting enough energy from solar radiation.

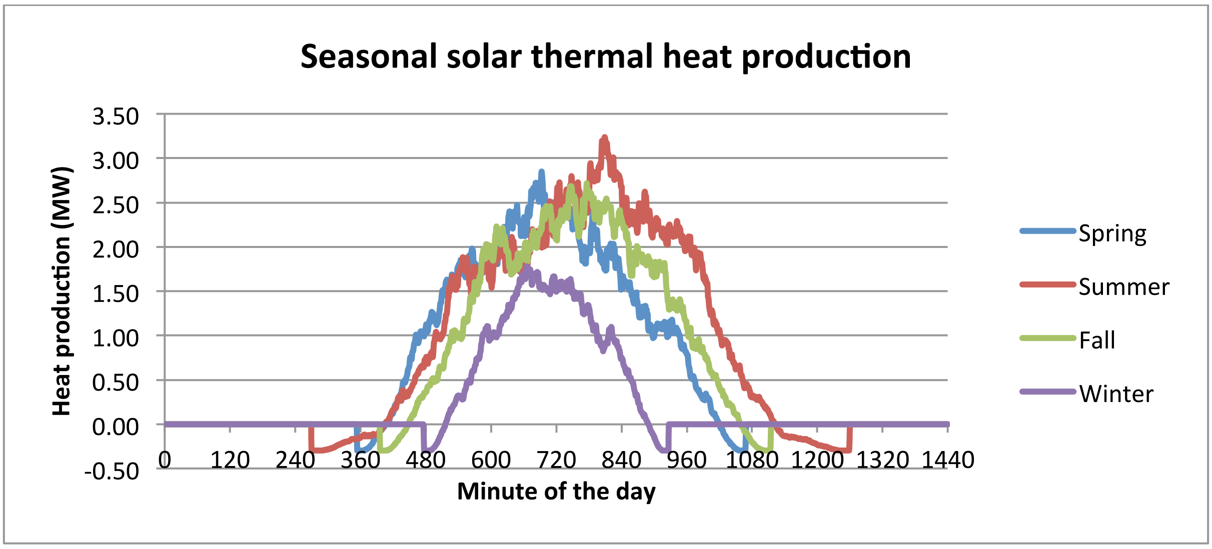

Figure 3.11: Heat production from AST array of 6000 m^2, efficiency 55% and inclined at 41 ^{o}.

Net heat demand

The seasonal daily net heating demand profiles are presented in figure 3.12. Net heat demand is 5908 MWh/year or 6922 MWh/year depending on the inclusion of hot water storage from AST (see discussion in the following section). Peak demands are unchanged compared with the gross heating demand profile. This occurs as a result of the peak demand periods predominantly falling outside daylight hours (or the time when AST is generating heat). The contribution from AST supply is nevertheless substantial, and with the exception of the winter season there is oversupply (negative regions). Considering the potential of hot water storage (see following subsection) creates the possibility for demand shifting of AST generated heat from mid-day into evening and morning demand periods. Total yearly net heating demands are presented in the following section in table 3.11.

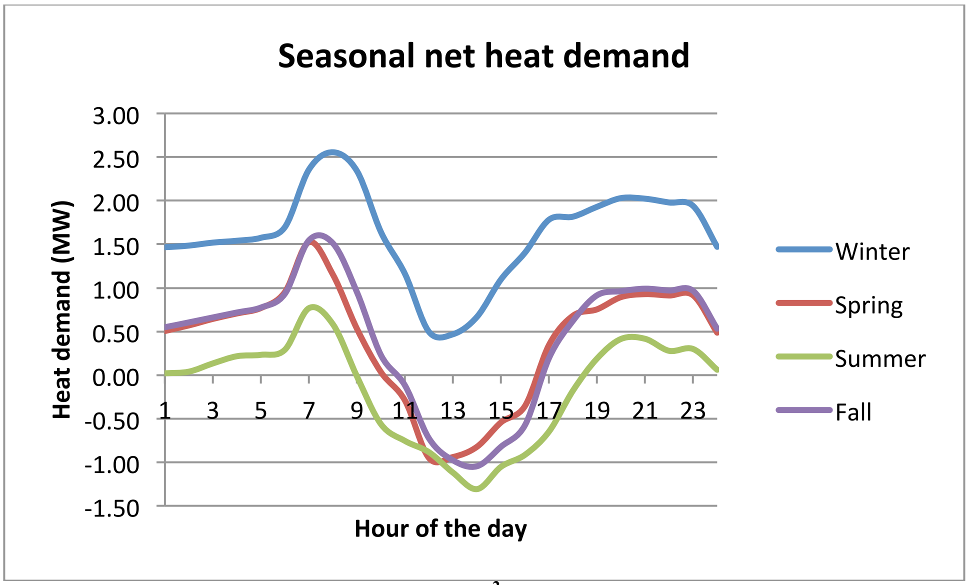

Figure 3.12: Net heating demand with AST array of 5000 m^2 not including demand shifting of hot water storage.

Varying AST array size

Similar to supply from PV, the supply potentials from AST were investigated for a range of array sizes spanning from 1500 m^2 to 7500 m^2 at intervals of 1500 m^2. Figure 3.13 shows the effect of varying array sizes on total heat produced, amount of heat available for self-supply with and without storage, and the corresponding solar fractions without and without storage. Considering the no heat storage option, marginal returns to the solar heat fraction are observed as array size increases. This is however not observed when hot water storage (efficiency 80%) is considered. The solar heat fraction is able to increase according to array size as excess heat produced is available for use later when demand is higher, and no solar energy is available. As mentioned in the previous subsection, hot water storage utilization is important in shifting supply to periods of high demand. When looking at figure 3.13, it is clear that large quantities of generated heat are lost if no storage is considered. Putting this in terms of the total yearly demands (table 3.11) the reduction potential of storage becomes more concrete - overall building heating demands are significantly reduced.

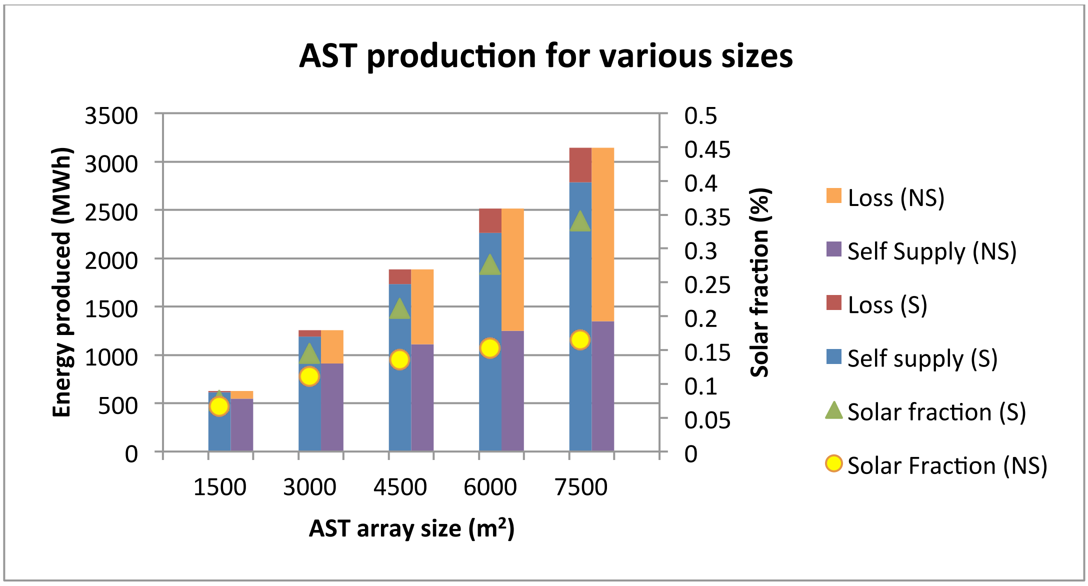

Figure 3.13: Effect of changing the AST array size, with storage (S) and without (NS) hot water storage capacity.

Table 3.11: Total yearly net heating demand for various array sizes and storage and non-storage options.

AST Array Size (m^2)	Yearly net demand (MWh): Without hot water storage	Yearly net demand (MWh): With hot water storage
1500	7623.7	7557.7
3000	7261.0	6982.2
4500	7061.6	6439.4
6000	6922.9	5908.6
7500	6818.9	5384.8

Roof Size and Real PV and AST Array Area

Up to this point the figures expressed for the array size of the PV and AST arrays have been the net collector area. This is the area of the array that is physically collecting energy from the sun. The real array area also includes parts of the array that do not collect energy (framing structures, etc.) and the total footprint area on the Living Wall's roof. Appendix A2 discusses in detail how the real array foot print areas were calculated for both the AST and PV arrays.

For the base array collector sizes, of 6000 m^2 (AST) and 15 000 m^2 (PV) the real array foot print areas are 8561 m^2 and 16 121 m^2 respectively. This is important because as a practical consideration the real array footprint cannot exceed the Living Wall's total available roof space. Table 9.1 in appendix A1 indicates the Living Wall's total roof area is 35 175 m^2. Only installing both the largest PV and AST array sizes investigated is too large for the available roof area (table 3.12)

Table 3.12: Real PV and AST array area footprints.

PV Collector Area (m^2)	PV Projected Roof Area (m^2)	AST Collector Area (m^2)	AST Projected Roof Area (m^2)	Total Projected Area (m^2)
5000	5,373.7	1500	2146.6	7520.3
10 000	10 747.5	3000	4293.2	15 040.6
15 000	16 121.2	4500	6439.8	22 560.9
20 000	21 494.9	6000	8586.3	30 081.3
25 000	26 868.7	7500	10 732.9	37 601.6

4. Constructing Scenarios and Techno-Economic Potential

Many technologies can be applied to the Living Wall in order to reduce energy demand, and to produce energy more efficiently. However, only some technologies are technically and economically feasible for market application. This section investigates the techno-economic potential (TEP) of supply technology combinations chosen for the Living Walls energy supply scenarios. Section 4.1 begins with an explanation of the main indicators used to quantify TEP of the Living Wall's energy supply scenarios. Section 4.2 describes the insulation, window, and supply technologies investigated and how they are packaged into complete Living Wall building energy supply scenarios. Finally section 4.3 presents the results from the TEP analysis including the most economically efficient supply technology scenario, and insulation and window combination.

4.1. Methodology: Techno-Economic Evaluation

To evaluate the techno-economic potential of energy efficiency and renewable supply technologies two indicators were chosen. First, the costs incurred in conserving energy otherwise referred to as the cost of conserved energy. Second, the total primary energy conserved. Individual components and scenario packages alike were compared against each other according to how much primary energy they save and the competitiveness of their cost of conserved energy. Calculating these values is discussed in the following sections along with a description of costs, and energy supply assumptions.

4.1.1. Cost of Conserved Energy

The cost of conserved energy (CCE) indicator, defined in equation 4.1, is a measure of the cost of saving additional energy when compared against a reference. In this case CCE is used to calculate the cost (€/kWh) of measures that save primary fossil energy compared to the reference. Since the CCE is calculated in €/kWh it can be compared to the primary energy adjusted cost of market electrical power and natural gas. If a measure has a CCE lower than the associated primary energy adjusted price of energy then it can be said to be economically efficient (Petersen et al. 2012).

$$CCE = \frac{a(n_d, d) \cdot \Delta I_{option} + \Delta M_{year}}{\Delta PE_{year} - \Delta PE_{operation/year}} \qquad \textbf{(4.1)}$$

Where the following are defined as:

$a(n_d, d)$	Capital recovery function, defined as: $a(n_d, d) = \frac{d}{1-(1+d)^{-n_d}}$
n_d	Technology lifetime (years)
d	Interest rate (%)
I_{option}	Additional investment costs compared to reference (€)
ΔM_{year}	Additional maintenance and fuel costs per year (€)
ΔPE_{year}	Annual conserved primary energy (MWh)
$\Delta PE_{operation/year}$	Primary energy used in operation (MWh)

Costs within CCE

Investment costs used in the CCE calculation are not upfront investment costs. Instead they are the additional costs observed when installing a given technical option as opposed to the reference. Therefore I_{option} is defined in equation 4.2, where I_{equip} is the investment cost of a supply, or efficiency technology, and I_{ref} is the investment cost of the corresponding reference technology. The exception to this is insulation where I_{option} is already the cost of additional insulation added to the reference wall insulation.

$$I_{option} = I_{equip} - I_{ref} \qquad \textbf{(4.2)}$$

Weighted price of energy

As mentioned above, the CCE can be compared to the commercial primary energy price as a way of determining if a given technology is a worthwhile economic investment. However since in this work CCE is expressed in terms of €/kWh saved, where saved energy is in units of primary energy, the commercial energy price to which the CCE is compared must also be expressed in primary energy terms. Therefore the energy price is scaled according to the appropriate primary energy conversion factor, equation 4.3.

$$P_e^P = \frac{P_e^m}{f_e}, P_h^P = \frac{P_h^m}{f_h} \tag{4.3}$$

Where P_e^P and P_h^P are primary energy adjusted prices, and P_e^m and P_h^m are market prices and f_e and f_h are primary energy conversion factors for electricity and heat.

Furthermore, scenarios are comprised of technologies producing both heat and electricity. Thus, a price of energy that combines costs of heat and electricity according to how much energy is demanded is needed. Such a price is called the combined weighted average cost of primary energy (WEP) and is calculated according to equation 4.4 where D_h^T and D_e^T are total building demands of electricity and heat. Within the TEP analysis the weighted average cost of primary energy is otherwise referred to as the reference CCE.

$$\text{WEP} = \frac{P_e^P D_e^T + P_h^P D_h^T}{D_e^T + D_h^T} \tag{4.4}$$

4.1.2. Primary Energy Savings

In this research primary energy savings (ΔPE_{year} in equation 4.1, PES throughout) is defined as how much less conventional fossil based energy is consumed when a given technology is implemented. PES was defined in this way so that the energy savings benefits of renewable technologies are taken into account from the perspective of the Living Wall. This definition treats electricity production in the same way as the IEA’s partial substitution method. Renewable heat however is considered differently than in both the IEA’s physical energy and partial substitution methods. A discussion on the rationale and methodological differences is included below for each of the affected technologies.

Primary energy savings is a way of directly comparing the benefits between energy conservation technologies and energy supply technologies. Each is energy saving; one through reducing demand, the other through more efficient supply. The general form for calculating PES is shown in equation 4.5. In all cases PES is always yearly primary energy savings. Here D is the demand satisfied and f_{ref} and $f_{measure}$ are the appropriate conversion factors for the reference’s and energy savings measure’s (technology) conversion of primary to secondary energy. Table 4.1 also outlines the primary conversion factors used throughout for heat and electricity respectively. Translating equation 4.5 into practice is complex for some technologies. The following sub sections outline examples of how PES was calculated for each energy conserving measure.

$$PES = D \cdot \left(\frac{1}{f_{ref}} - \frac{1}{f_{measure}} \right) \tag{4.5}$$

Table 4.1: Primary energy conversion factors for heat and electricity.

Secondary energy carrier	Primary to secondary conversion factor*
Electricity, f_e	0.35
Heat, f_h	0.9

***For every 1 unit of primary energy x units secondary energy.**

Energy Supply and Equipment Sizing

In calculating the PES and CCE for the supply technologies listed below, the amount of energy each scenario's supply technology supplied to the building was calculated according to the demands outlined in section 3.2.1 and 3.2.2. Two general assumptions for equipment size and yearly energy supply were that equipment size is scaled to peak heating demand and heat produced equaled heat demanded. In each scenario AST heat is preferred, meaning that supply from each scenario's alternate heat supply technology is scaled to the net heating demands outlined in section 3.2.2. The nomenclature used to denote this is D_h for net heat demand satisfied and $D_h^{technology}$ (where technology indicates the technology satisfying a portion of the total demand) for any demand satisfied that is not a net total demand. For example, the Living Wall's total heat demand (D_h^T), is the sum of D_h^{AST} and D_h where D_h , the net heat demand, may be satisfied by any technology (CHP, heat pump, SBB etc.)

Photovoltaic and Solar Thermal Arrays

Following the definition of PES as abated conventional fossil energy the PES from PV is defined in equation 4.6 where D_e^{PV} is the total energy produced by the PV array. This equation expresses the amount of fossil energy in the reference generation scenario required to produce the same amount of electricity produced from the PV array. This method is consistent with the IEA's partial substitution method of calculating primary energy.

$$PES = \frac{D_e^{PV}}{f_e} \tag{4.6}$$

The PES from AST is calculated according to equation 4.7 where D_h^{AST} is the heat demand satisfied by AST heat production. Similar to PV, this equation (4.7) is an expression of the conserved fossil energy that the AST system satisfies.

$$PES = \frac{D_h^{AST}}{f_h} \tag{4.7}$$

Calculating PES in this way conflicts with the IEA's physical energy method that states that thermal heat from AST is a primary source (IEA 2005). The problem with using the IEA's definition of primary energy in the context of applying energy saving benefits to the Living Wall is that it views energy in absolute terms instead of from the perspective of benefits of deploying technology to a given situation. From the perspective of the Living Wall energy from AST and PV is offsetting conventional (fossil) primary energy demand that would be consumed by the Living Wall if the Living Wall had not chosen to deploy renewable supply technology.

For example, using the physical energy method for the PES calculation of the AST array's PES results in negative PES (indicating that the technology costs the Living Wall primary energy). The negative PES occurs because heat generated in the array is considered primary energy, and heat delivered to residents (after passing through a heat exchanger into the heat distribution network ~ 50% efficiency) is secondary heat. The result is a PES formulation that penalizes the low efficiency of useable heat delivery from AST compared to high efficacy of gas fired boiler heat in the reference. In a global sense this is accurate because the Living Wall must consume primary energy to heat itself. However from the perspective of the Living Wall using the IEA's physical energy method does not reflect the relative energy savings benefits from AST heat production that the Living Wall observes.

Solid Biomass Boiler

According to the IEA's statistics manual SBB fuel (wood pellets) is considered a primary energy source (IEA 2005). However by the same reasoning as given in the previous section SBB heat is considered to be offsetting conventional fossil energy demand. Thus in calculating the PES for the SBB equation 4.8 is used.

$$PES = \frac{D_h}{f_h} \tag{4.8}$$

Combined Generation (CHP)

CHP generates heat and electricity simultaneously from primary energy. To determine the PES, the relative supplies of heat and electricity generated must be determined. First, the primary energy equivalent of the total heat and electricity generated by the CHP is determined. Second the primary energy equivalent of the CHPs fuel consumption (natural gas) and energy losses must be subtracted from the total primary energy saved. Equation 4.9 shows the basic setup where PES is expressed in terms of net heat demanded (D_h) and CHP electricity production (D_e^{CHP}).

$$PES = \left(\frac{D_e^{CHP}}{f_e} + \frac{D_h}{f_h} \right) - \frac{D_h}{n_h} \tag{4.9}$$

The relationship between heat and electricity produced by the CHP is given in terms of the CHP's production efficiencies listed in table 4.2. The relationship between produced heat and electricity is shown below in equation 4.10 where n_t, n_e and n_h are system total, electrical production and heat production efficiencies respectively.

$$D_e^{CHP} = \left(\frac{n_t - n_h}{n_h} \right) D_h^{CHP} \tag{4.10}$$

Table 4.2: production efficiencies used in TEP model for CHPs.

	CHP-RE	CHP-FC
n_t	0.85	0.8
n_e	0.4	0.5
n_h	0.45	0.3

Using this relation, the PES can be expressed as a function of heat supplied by the CHP. The resulting equation (4.11) gives the PES expressed according to the heat supply.

$$PES = D_h \cdot \left(\frac{n_t - n_h}{n_h f_e} + \frac{1}{f_h} \right) - \frac{D_h}{n_h} \tag{4.11}$$

Heat Pumps

Determining the PES for a heat pump is straightforward and follows directly from equation 4.5. Heat pumps express their primary energy conversion rate in terms of their COP, which is used in equation 4.12 to express their PES. A summary of the COPs used is presented in table 4.3.

$$PE_{savings} = \frac{D_h}{f_h} - \frac{D_h}{COP} \tag{4.12}$$

Table 4.3: Heat Pump COPs used in TEP analysis.

HP Type	COP
GSHP	4
ASHP	2.5

Insulation and Windows

PES from insulation and windows is the difference between energy losses with the reference U-value and the U-value including the insulation or window element. Equation 4.13 gives an example of the PES calculation for insulation measures, where U_{ref} and U_{ins} are the respective U-values for the reference wall and reference wall plus additional insulation.

$$PES = \frac{24 \cdot (U_{ref} - U_{ins})}{f_h} \cdot (DD_{NZ} \cdot A_{NZ} + DD_{SZ} \cdot A_{SZ}) \tag{4.13}$$

4.2. Supply Technology Scenarios

Five energy supply scenarios were investigated for the supply of the Living Wall's energy demands. Scenarios include combinations of PV, AST, CHP, ground source heat pump (GSHP), air source heat pump (ASHP) and SBB technologies. The scenarios were compared to a reference energy supply scenario comprised of a conventional natural gas fired boiler and grid purchased electricity. Each scenario contains two solar supply and one supplementary supply technology that supplies either heat or heat and power. The following subsections explain the reference supply scenario assumptions, the five energy supply scenarios, and different building envelope combinations.

4.2.1. Reference Supply Scenario

The Living Wall's reference supply scenario assumes all heat is supplied via a natural gas condensing boiler (efficiency 90%) and all electricity is grid purchased. Grid purchased electricity is assumed to have a fixed fuel to user efficiency average of 35% over the lifetime of the building (Harmsen & Graus, 2012). The electrical fuel to user conversion efficiency is based on the current electrical production mix in the Netherlands and excludes renewable sources (wind, solar and hydro). This figure can however change over time with changing fuel mixes in power plants, and the source of electrical production i.e. proportionately more electricity produced from CHP and mini-CHP.

4.2.2. Living Wall Supply Scenarios

The five energy supply scenarios investigate the potential of supplying the Living Wall's heat and power demands from a variety of sources. Each scenario's central design is with PV and AST as the "main'' supply technology, while different types of CHP, heat pump, and SBB technologies supplement to remaining net demands. Table 4.4 outlines the heat and power supply technologies and fuel source for the reference and five supply scenario packages. Each scenario assumes the Living Wall has a connection to the Dutch power grid, and natural gas supply network.

Table 4.4: Summary of main supply technology scenarios.

Scenario	Heating Supply		Power Supply	
	Technology	**Fuel**	**Technology**	**Fuel**
Reference	Condensing Boiler	Natural Gas	Electrical Grid	Ave. Dutch mix
Scenario 1	Solar Thermal Array (Evac. Tube)	-	Photovoltaic Array	-
	Reciprocating Engine CHP (CHP-RE	Natural Gas	Reciprocating Engine CHP (CHP-RE)	Natural Gas
Scenario 2	Solar Thermal Array (Evac Tube)	-	Photovoltaic Array	-
	Fuel Cell CHP (CHP-FC)	Natural Gas	Fuel Cell CHP (CHP-FC)	Natural Gas
Scenario 3	Solar Thermal Array	-	Photovoltaic Array	-
	Air Source Heat Pump	Grid Electricity		
Scenario 4	Solar Thermal Array (Evac Tube)	-	Photovoltaic Array	-
	Ground Source Heat Pump	Natural Gas		
Scenario 5	Solar Thermal Array (Evac Tube)	-	Photovoltaic Array	-
	Solid Biomass Boiler	Solid Biomass (wood pellets)		

4.2.3. Building Envelope Technologies

In addition to supply technologies, insulation and window measures were considered as separate scenario options that could be combined with the five supply scenarios. Different insulation and window types were explored as combinations of north-south insulation, and north-south windows. This was done for two reasons; first, additional insulation measures that decrease the Living Wall's aggregate envelope U-value might not be cost effective. Given the high Dutch standard for insulation in new buildings it is not clear if there is enough energetic savings to justify the extra costs of better windows or more insulation. Second, the gallery and parking area in the south zone might have strong impacts on the economic performance of extra insulation measures. Compared to the north building zone the south zone has fewer effective degree days and therefore has reduced potential for energy savings from additional insulation measures. In total the TEP of 56 north-south insulation pairs and 20 north-south window pairs was investigated.

Frequently used insulation types were chosen out of inorganic fibers, organic fibers, and organic cellular insulation types. As discussed in section 2.3.1 insulation takes on many physical forms. To standardize the insulation TEP analysis all thermal properties and costs represent the 'compressed board' form of insulation. Table 4.5 gives an overview of the specific insulation types investigated within each category. Similarly, window types are arranged according to their type of glazing and/or gas filling. As mentioned in the reference building section 3.1.1 the reference windows are double glazed air filled. Successively more insulating windows have inert gas fillings, or extra glazing layers. While a huge assortment of window glazing and air filling options are available, only four core windows were investigated. The investigated windows types are also listed in table 4.5. The table only lists the type of insulation or window used in creating the north-south pairs. In practice, the north-south window and insulation pairs are constructed from the total combinations of all different insulation types and all window types applied to north and south building zones.

Table 4.5: Window and insulation types used in north-south insulation and window pairs.

Window Type	Characteristics: Glazing/Air Fill	Insulation Category	Insulation Name
Double Glazed (Reference)	2 glass panes Air filled	Inorganic Fibers	Rockwool
Double Glazing	2 glass panes Argon gas Low E coating		Glass Wool
Triple Glazing	3 glass panes Krypton gas fill Centre pane -Low E coating	Organic Cellular	Cellulose
Aerogel	2 glass panes Aerogel synthetic insulator filled		Flax Hemp Fiber
Vacuum Glazing	2 glass panes Vacuum fill (10^{-4} bar)		Wood fiber
		Organic Fibers	Expanded polystyrene board
			Polyurethane board

When the 56 north-south insulation and 20 north-south window pairs are combined into whole building insulation and window pairs, a total of 1120 possible north-south window and insulation combinations arise. Each combination was considered as a possible building envelope configuration for the Living Wall. Possible envelope configurations were then combined with the five energy supply scenarios to calculate the CCE and PES of the Living Wall's composite energy supply scenarios: all the technically feasible building envelopes and supply technology configurations.

4.3. Results: Techno-Economic Potential

The following four sections present the results of the TEP. Results are presented first for whole building scenarios that include all window/insulation combinations with the five supply scenarios. This is followed by discussions on the TEP of individual components of the supply scenarios including supply technologies, windows, and wall insulation.

4.3.1. Whole Building Energy Supply Scenario Combinations

Figure 4.1 presents the results of calculating the CCE and PES for all building envelope combinations and supply technology scenarios. Each point in the plot represents one of the 1120 building envelope combinations paired with each of the building energy supply technology scenarios. The reference building envelope is also plotted (indicated as S1-5 ref. envelope in the legend) to give a perspective of the impact the different envelope combinations have on the overall CCE and PES performance. The primary supply technology for each scenario is also indicated in the graph's legend. The weighted price of primary energy (Reference CCE line in figure) is used as the benchmark for evaluating a scenario's economic performance.

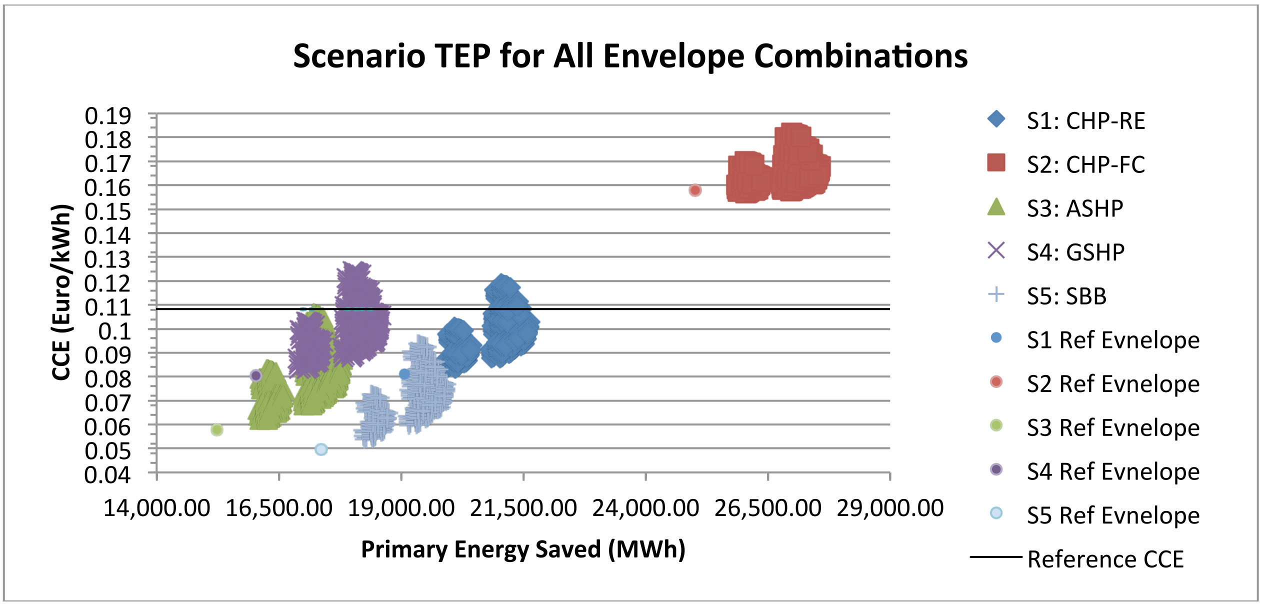

Figure 4.1: Summary of CCE and PES of all scenario combinations.

When compared against the reference CCE the majority of scenario 1, 3, 4 and 5 building envelope combinations were below the reference CCE, indicating they are economically viable. Three points are apparent from looking at Figure 4.1:

- Most of scenario 1, 3, 4, and 5 options are technically and economically feasible.
- The choice of supply technology has a strong impact on the PES.
- Building envelope combinations always save more PES than the reference envelope, but seldom is their CCE better.

Zooming in on scenario 1 (figure 4.2), the spread between CCE and PES of all building envelope combinations can be seen clearly. This result is typical of all scenarios. The most economic (i.e. those envelope combinations) options are those with the lowest CCE. However, some building envelope combinations have higher PES and marginally higher CCE's and it is not clear which is actually performing better. To compare these, the quotient of CCE divided by PES is used as an indicator. The expression $\partial CCE / \partial PES$ is used to evaluate options against each other with the lowest value being the best. In figure 4.2 the lowest $\partial CCE / \partial PES$ was used as the slope of a line (equivalent best options line) for a visual comparison. The line represents the CCE to PES ratio needed to be comparable with the best option.

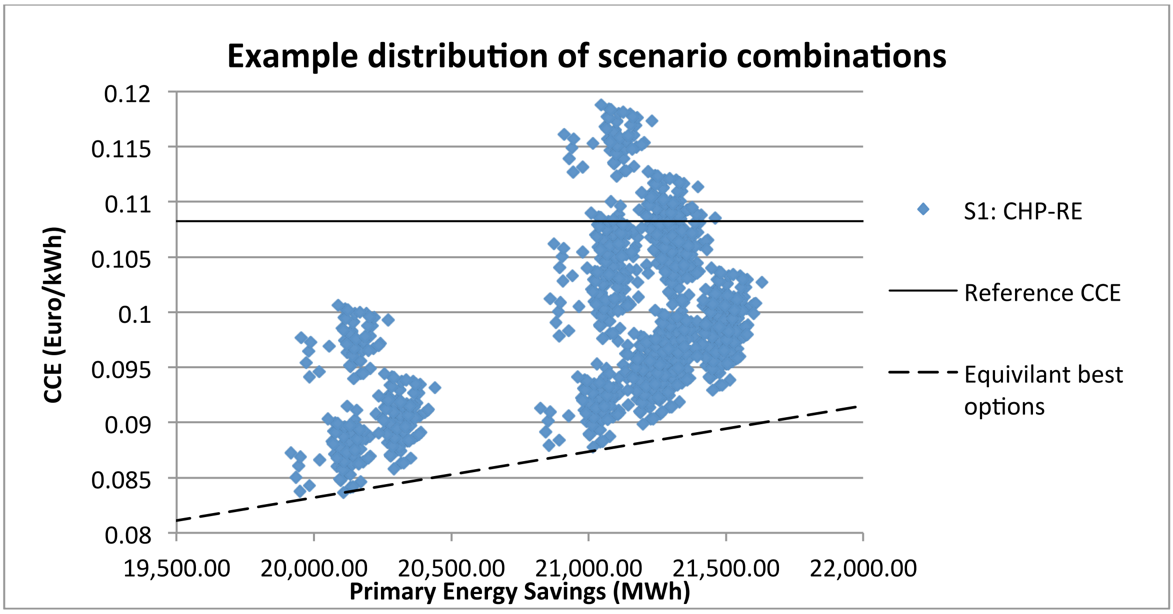

Figure 4.2: Example of all scenario 1 combinations' CCE plotted against their PES.

When $\partial CCE/\partial PES$ is calculated for every evenlope combination for each scanrio the top three building envlope options per scenario can be identified as those with the lowest CCE to PES ratio. The best three envelope combinations for each scenario are presented in figure 4.3. Again a line of comparison has been drawn using $\partial CCE/\partial PES$ as the slope of the best performing SBB envelope combination.

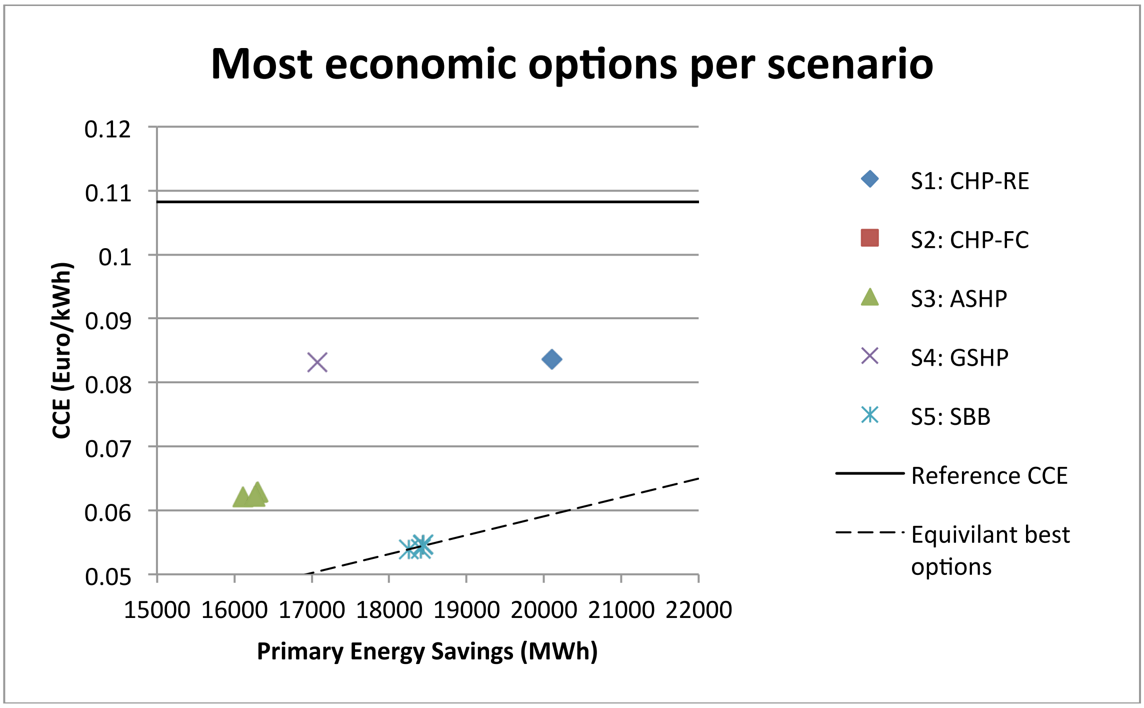

Figure 4.3: Comparison of 'Best' scenario combinations.

The best three building envelope combinations with lowest $\partial CCE/\partial PES$ value are presented in table 4.6 with their respective CCE. These options also had the lowest absolute CCE's of all the building envelope options. The table also identifies the north-south window and insulation componentes that compose the building envelope in each case. Scenrio 2 has been excluded because no option is economically efficient.

Table 4.6: Overview of lowest CCE building envelope combinations per scenario.

CCE (€/kWh)				Insulation		Window	
Scenario				**Building Zone**			
1	**3**	**4**	**5**	**North**	**South**	**North**	**South**
0.0830	0.0617	0.0820	0.0537	Cellulose	Reference	D. Glazed	Reference
0.0834	0.0624	0.0825	0.0544	Cellulose	Rockwool	D. Glazed	Reference
0.0834	0.0625	0.0825	0.0544	Rockwool	Cellulose	D. Glazed	Reference
0.0828	0.0618	0.0819	0.0538	Cellulose	Cellulose	D. Glazed	Reference

The top three building envelope combinations per scenario that were both economically viable and saved the most primary energy are listed in table 4.7. Here the composition of the north-south insulation and window envelope components is very different when compared to the best performing CCE options.

Table 4.7: Economically efficient evnelope combinations that save the most primary energy.

PES (MWh)				Insulation Type		Window Type	
Scenario				**Building Zone**			
1	**3**	**4**	**5**	**North**	**South**	**North**	**South**
21631	17793	-	19933	PUR	PUR	Triple Glazed	Triple Glazed
21609	17771	-	19911	PUR	PUR	Aerogel	Triple Glazed
21603	17765		19905	PUR	Rockwool	Triple Glazed	Triple Glazed
-	-	18508	-	Rockwool	Rockwool	Aerogel	Triple Glazed
-	-	18515	-	PUR	Rockwool	Aerogel	Aerogel
-	-	18510	-	PUR	Cellulose	Triple Glazed	Aerogel

The following subsections discuss the results for building envelope components and supply technologies in more detail.

4.3.2. Supply Technologies

Figure 4.4 shows the CCE and PES for supply technologies as individual components as applied to the Living Wall. Three supply technologies (ASHP, SBB, and PV) performed better than the reference CCE while AST, CHP-RE and GSHP technologies fell just above the reference CCE. However, given how close AST, CHP-RE and GSHP are to the reference CCE it is likely that any change in fuel prices, capital costs, or equipment efficiency is enough to shift their results below the reference CCE. This is especially true for technologies that are in relatively early stages of their learning curve. Early and mid-stages in the learning process indicate that as market deployment progresses the technology will observe improvements in efficiency, and reductions in costs. CHP-RE for example is in the mid-stages of its learning process and can expect cost reductions potentially making it economically viable compared to the reference CCE.

The CHP-FC was the only technology that was far above the reference CCE. This was expected to some extent because CHP-FC technology is still young; it has relatively higher expected capital and maintenance costs, and became available for commercial deployment in 2011-2012. As CHP-FCs are young they are also early in their learning curve. However, several sources (Hinnells 2008, Mekhilef et al. 2012) speak promisingly about CHP-FCs stating that their higher electrical efficiency could lead them to become a dominant CHP type in the building sector. Therefore it is also possible that in the near future cost reductions make CHP-FC competitive with the reference CCE.

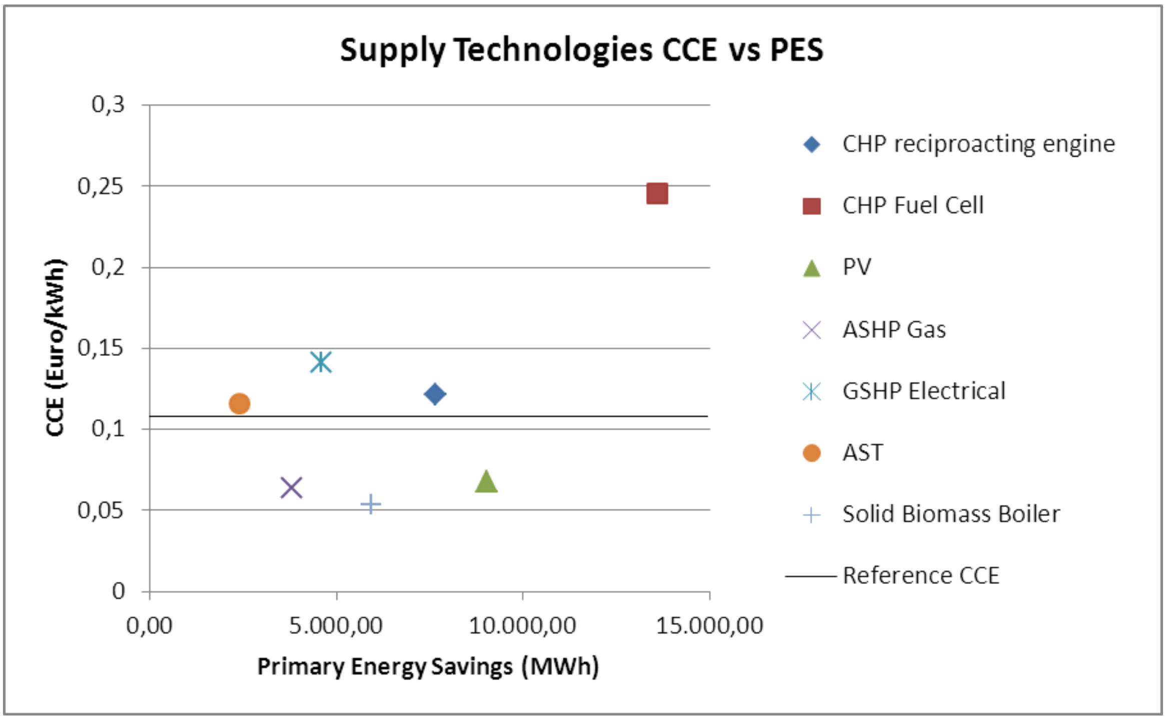

Figure 4.4: CCE and PES of indivdual supply technologies outside of scenarios.

CCE Sensitivity to Capital Costs

The relative percent change in CCE resulting from captital cost changes of -20%, -10%, +10% and +20% can be seen in figure 4.5. Technology sensitivity to captial costs is fairly linear for PV, GSHP, and AST – that is for proportinoal changes in capital costs nearly equivilant changes in the CCE are observed (strong coupling). For the SBB, CHP-FC, CHP-RE, and ASHP technologies, the change in CCE is less than the proprtional change in capital cost. This means the benefits from capital cost reductions in these technologies are not as realized in the CCE (weak coupling). In other words, the stronger the coupling between the CCE and capital cost, the more promising the outlook is for prospective technologies with expected learning curve related cost reductions (AST, PV etc.). Figure 4.6 shows the effect of a -10% capital cost change on supply technologie's CCE in relation to the reference CCE. Similar plots for -20%, +10% and +20% can be found in Appendix D1.

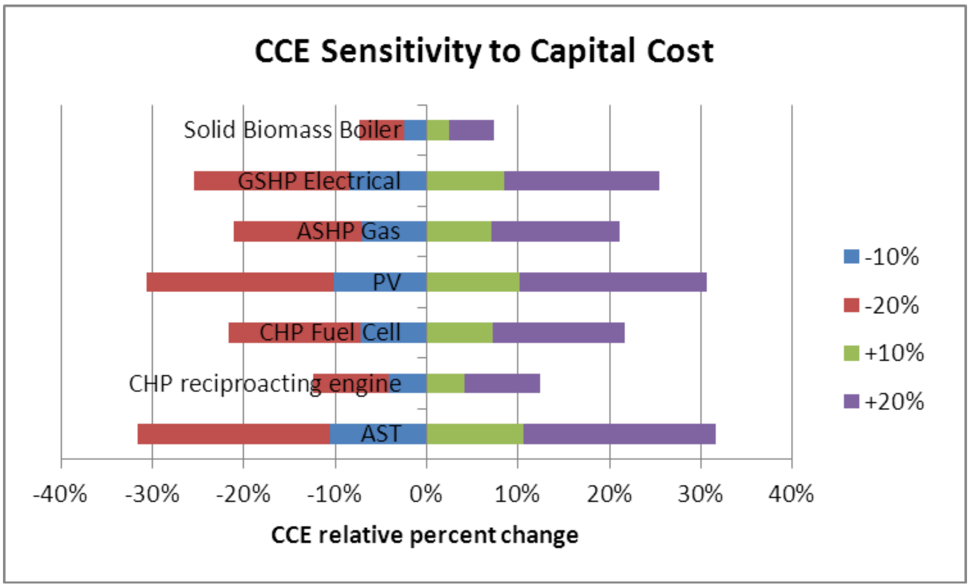

Figure 4.5: CCE sensitivity to capital cost change.

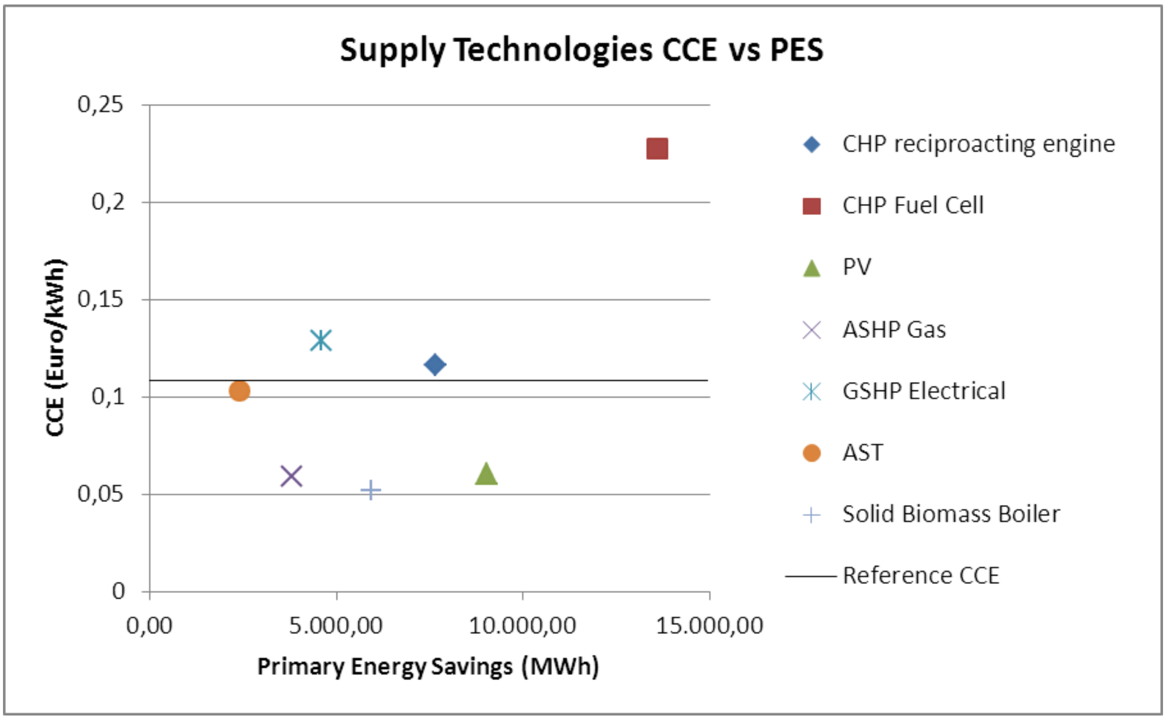

Figure 4.6: CCE and PES of indivdual supply technologies when considering a -10% capital cost change.

CCE Sensitivity to Fuel Price Increase

The economic performance of most supply technologies is negatively coupled with the fuel price (i.e. for large increases in fuel price there are proprotinally smaller increases in CCE) Figure 4.7 shows supply technologie's percent change in CCE for fuel price increases of 25% and 75%. These increases reflect fuel price increases that are possible over the lifetime of the equipment (~20 years). Figure 4.8 show the relationship between supply technologies CCE's and the reference CCE in the most extreme fuel price change scenario (a similar figure for the 25% scenario may be found in appendix D2). Here the impacts of fuel price changes are clearly seen. In the 25% increase scenario, AST and CHP-RE become economically viable, while at 75% increase all three of AST, CHP-RE and GSHP are evonomically viable. SBB on the other hand shows a strong positive coupling to fuel price change. As fuel price incrases its CCE also increases moving it closer to the reference CCE.

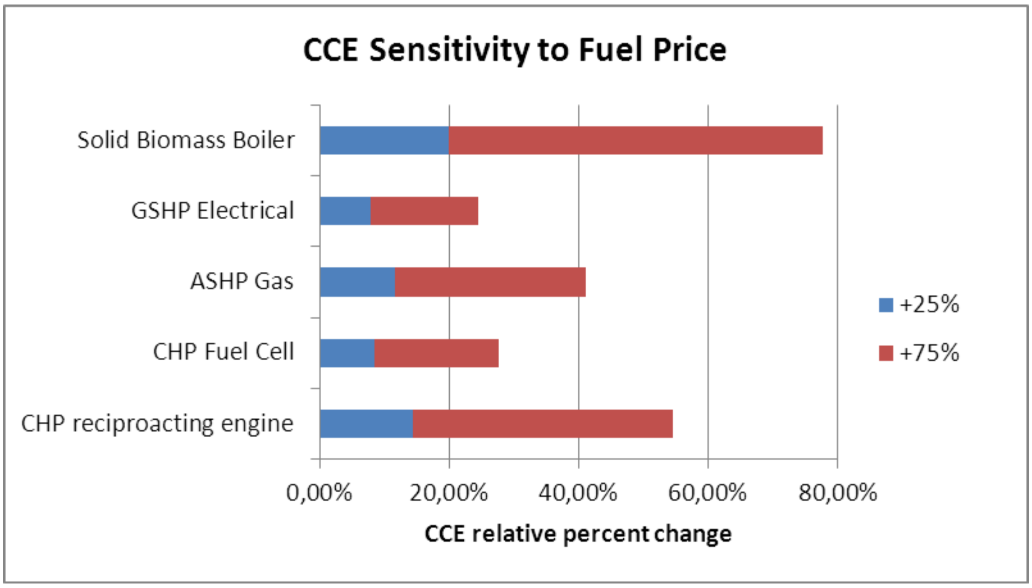

Figure 4.7: CCE sensitivity to fuel price varation.

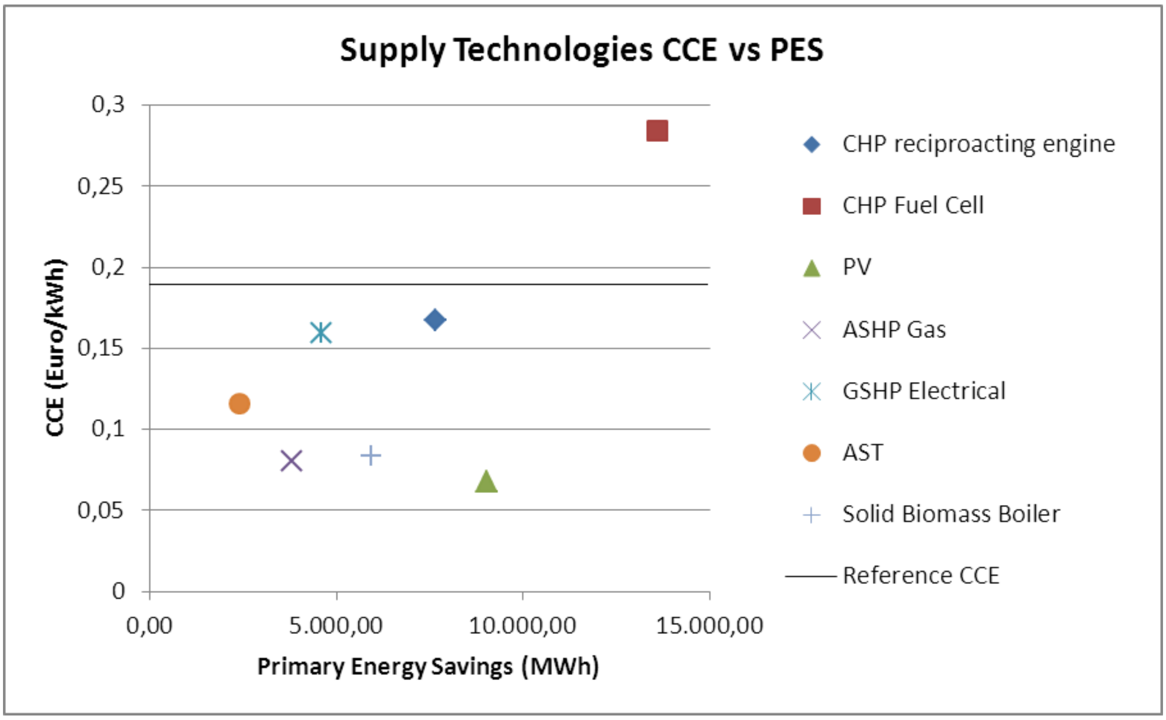

Figure 4.8 Supply technology CCE performance with a 75% fuel price increase.

4.3.3. Windows

When calculating the CCE of north-south window combinations it was observed that no combinations were economically viable. This however makes sense since the main benefits from high quality (low U, high solar fraction) windows are not maximized in the building's design. Northern windows will make excellent use of low U-values minimizing transmission losses, but have little function for high solar fractions aimed at increasing solar heat gains. Similarly, windows facing into the gallery gain little from extra low U values, and receive proportionally little direct solar radiation after accounting for losses from the gallery windows, and solar shading. Although the window combinations are not economically viable, figure 4.9 still shows that argon filled double glazed, krypton filled triple glazed and aerogel windows all save more primary energy than the reference windows at comparable CCEs. The plot shows the CCE and PES for all possible north-south window combinations with south windows indicated through the marker's colour, and north windows indicated using different marker shapes.

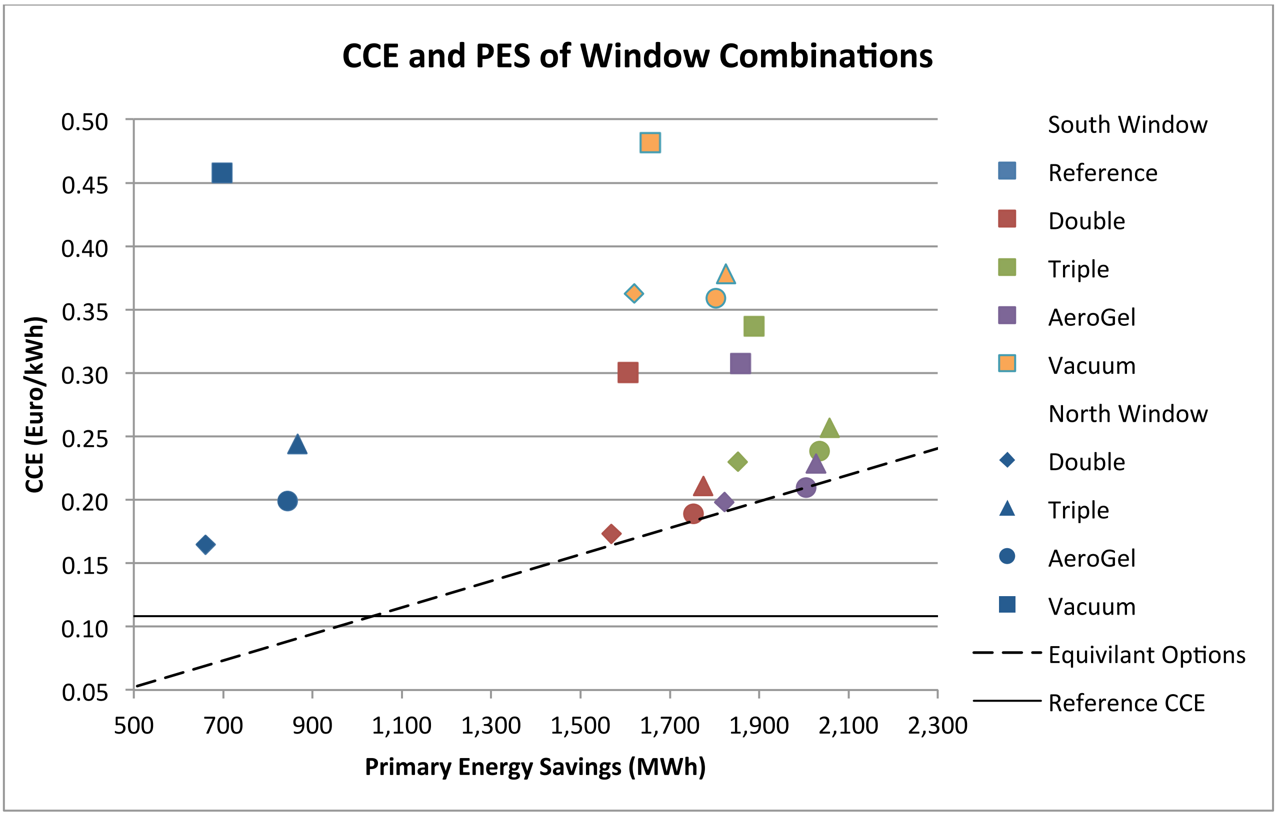

Figure 4.9: Performance of all north-south window combinations.

4.3.4. Wall Insulation

Of the dual insulation combinations plotted only six north-south insulation combinations passed the Reference CCE. Figure 4.10 shows the results of all north-south insulation combinations again using colour to denote the south insulation type and marker shape to indicate north insulation type. The six economically viable insulation combinations are summarized in table 4.8.

As insulation thickness was increased fewer options were viable. The effect of the gallery has a similar effect as seen with windows on the energy savings along south interior wall. Heat transmission losses from the south zone are into the gallery, since the gallery will on average be warmer than the outside air temperature the potential for savings for insulation along the south zone is lessened. Thus as insulation thickness increases, the CCE will also increase because of marginal gains in energy savings. Table 4.8 also indicates which of the best performing north-south insulation combinations are viable at 20 cm and 30 cm insulation thickness (also see appendix D3).

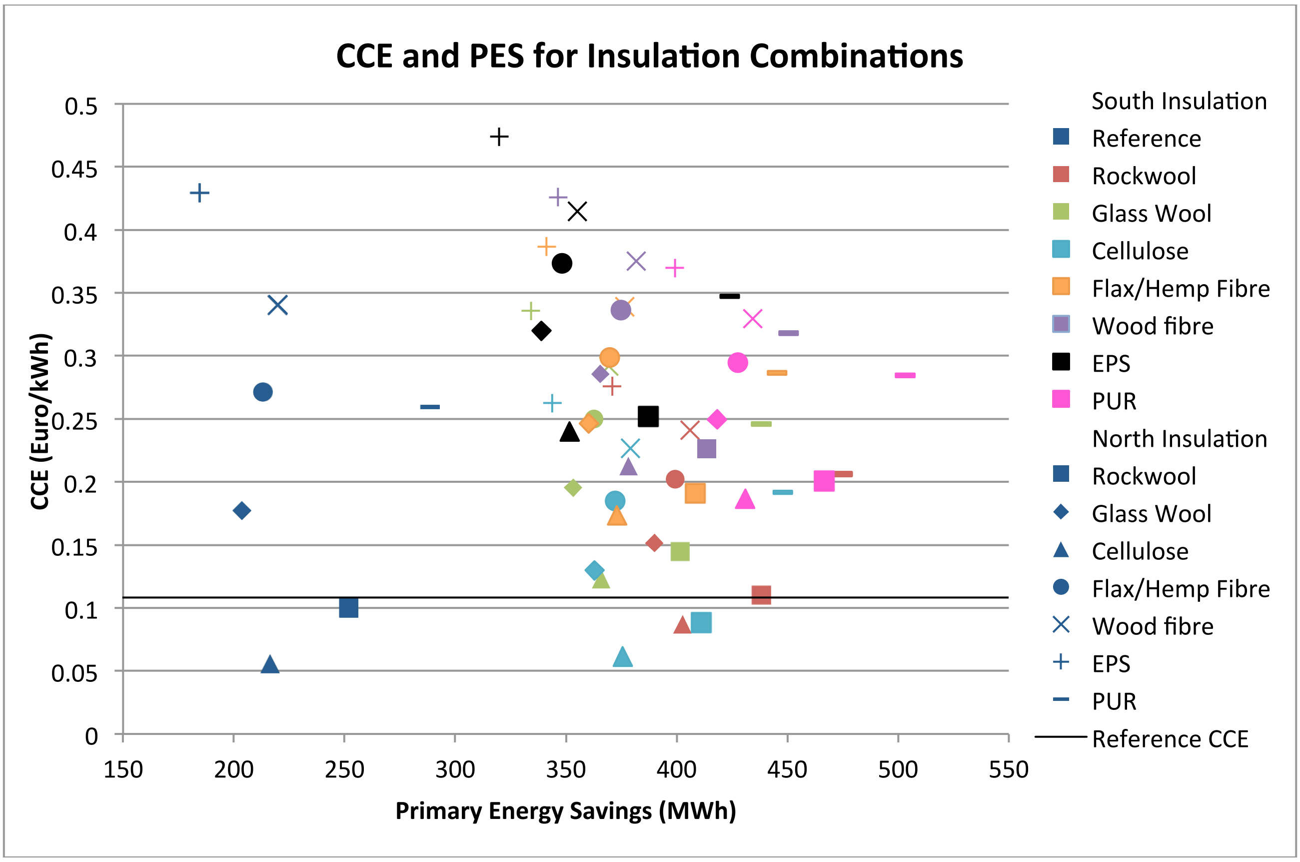

Figure 4.10: CCE and PES of north-south insulation options at 10 cm thickness.

Table 4.8: Summary of economically viable insulation combinations between north and south zones at thicknesses of 10, 20, and 30 cm.

Insulation Combination		Economically viable?		
Building Zone		**Insulation thickness**		
North	**South**	**10 cm**	**20 cm**	**30 cm**
Rockwool	Reference	Yes	-	-
Cellulose	Reference	Yes	Yes	Yes
Rockwool	Rockwool	Yes	-	-
Cellulose	Rockwool	Yes	-	-
Rockwool	Cellulose	Yes	-	-
Cellulose	Cellulose	Yes	Yes	Yes

5. Business Case Development

The goal of this chapter is to evaluate the economic potential of deploying the energy supply scenarios investigated in chapter 4 using two different business models for each supply scenario. However, deploying renewable technology in buildings has encountered various barriers to deployment. Section 5.1 discusses background on renewable energy technology deployment barriers and how they apply to the Living Wall. This is followed (section 5.2) by a discussion on types of business models that can be used to relieve barriers. Two business models are then applied to the Living Wall for investigation (section 5.3). Finally, section 5.4, assesses the feasibility of the Living Wall business models though quantitative net present value (NPV) and energy savings analysis, and qualitatively through strengths, weaknesses, opportunities, and threat (SWOT) analysis.

5.1. Renewable Technology Deployment Barriers

Implementing renewable heat and electricity generation technologies as part of the Living Wall's concept is central to the Living Wall's main quality as a sustainable building. However introducing renewable technologies into the built environment encounters challenges and difficulties that prevent projects from being realized. Key implementation barriers for energy efficiency and renewable energy supply in buildings are reviewed in detail in the IEA's REBIZ document (Wurtenberger et al. 2011). Implementation barriers are anything that creates difficulty for market diffusion of renewable technologies. Four categories of implementation barriers are defined; Market/Social, Information failures, Regulatory Processes, and Financial. When considering the Living Wall only some implementation barriers are relevant. In this case barriers that are applicable to owner occupied and tenant occupied buildings are considered. Table 5.1 below summarizes barriers applicable to the Living Wall and is followed by a short description of each barrier and how it applies to the Living Wall.

Table 5.1: Summary of applicable barriers. Adapted from Wurtenberger et al. (2011).

Market/Social	Information failures	Regulatory Processes	Financial
• Supply Price Distortion • Split incentives	• Lack of information on financing options • Lack of interest by energy companies • Lack of knowledge by installers	• Building Permit process	• Low return on investment • High Upfront costs • Difficult access to capital • Higher technology risks

Supply price distortion

Supply price distortion refers to the cheap reference price of energy from conventional sources that do not include external supply impacts (i.e. resource depletion, pollution etc.). This affects the Living Wall in that it makes comparing renewable sourced supply to conventional supply costs unfair. Thus some scenarios might be very sustainable but are not economically viable because of price distortions.

Split incentives

A split incentive is when the investor/developer and the beneficiary differ. An example of this is when a tenant pays utility bills, but the building owner has invested in an energy efficiency technology.

Lack of information on financing options

Information on financing refers to limited actor knowledge in dealing with both upfront costs and financing schemes for running costs and cash flows. Business models differ in their treatment of energy supply management, and tenant/owner cost sharing. The Living Wall has potentially high up-front costs (see investment cost barrier) that could be reduced or financed more effectively though the use of financing options such as on bill financing, applicable tax reduction, and subsidies.

Lack of interest by energy companies

Energy retailers have an obvious disinterest in supporting a client's initiative to reduce energy use. Recently however energy suppliers are adopting alternative business models that secure energy supply to a customer while implementing renewable generation technologies. Examples are utilities supporting homeowners with loans for small scale PV and wind instillations. Firms however must use alternate means to finance renewable energy projects without direct help of public energy utilities.

Lack of knowledge by installers

Renewable generation systems and energy savings technology performance is highly dependent on proper installation and setup. In addition, renewable systems in buildings often involve the integration of several systems designed to work in combination (i.e. solar thermal heat combined with CHP or heat pump heat as part of the same district heating system). In comparison to installing conventional energy systems there are fewer certified installers for renewable technologies. Furthermore, projects such as the Living Wall present systems engineering and integration challenges that may have not been attempted at large scales (Zhai et al. 2011). Utilizing PV, AST, and CHP or heat pump technologies, the Living Wall can achieve higher building energy performance if systems are properly integrated, calibrated and installed.

Building permit process

Wurternbuger et al. (2011) indicate building process and permit application procedures are often lengthy for some renewable systems, specifically when drilling is involved (geothermal energy/ground source heat pump). The proposed Living Wall site is situated on land that borders the A12 and A27 highways and is controlled by the Rijkswaterstaat and the municipality of Utrecht. While not the focus of this report, acquiring permission to build in this area could be time consuming.

Low return on investment

Various sources indicate renewable technologies are not competitive with conventional supply and therefore cannot give adequate returns on the capital investment (IEA 2011, Yang 2010). Time preference also plays a role since some renewable investments have high returns over longer periods (i.e. insulation in building shell) thereby observing long payback periods that make them unattractive.

High Upfront costs

High upfront costs reflect the higher investment costs needed to install renewable supply technologies (i.e. PV, AST) and build high quality building shells. Closely linked to low return on investment, high costs are relative to the acceptable risk, and discount rate the developer chooses to apply to the project. In the case of the Living Wall's energy systems the upfront costs are indeed much higher than the reference case. Table 5.2 shows the total investment costs per scenario in comparison to the reference scenario.

Table 5.2 Investment costs for building shell, energy systems, and complete scenario.

Scenario	Complete System Upfront Cost (M€)	Insulation/Windows Costs (M€)	Energy Supply System Components (M€)
Reference	3.4	3.3*	0.1
1	12.3	4.1	8.2
2	24.0	4.1	19.9
3	13.0	4.1	8.9
4	10.8	4.1	6.7
5	10.2	4.1	6.1

*** reference window costs and cost of minimum insulation needed to meet Bouwbesluit standards.**

Difficult access to capital

As renewable and energy efficiency technologies have higher upfront investment costs suitable access to capital is required. Difficulty accessing capital is influenced by other barriers like perceived higher risk of technology, and lack of technical knowledge. This barrier is specifically related to home owners, and small business owners. While not directly applicable to the Living Wall's case, this barrier gives insight into financing schemes that could be applied for owner occupied units. In the Netherlands several energy suppliers offer technology leasing options relieving capital requirements of private owners.

Higher technology risks

Real or perceived risk is often associated with renewable technologies in the form of higher discount rates, or higher required investment returns. PV, AST, CHP and heat pumps are all established technologies and carry minimal risk of failure. An exception with CHP and heat pumps is the risk fuel price fluctuations. In general the energy systems considered for the Living Wall should be considered low risk since they minimize fuel price variation, and on average provide a steady flow of electricity and heat.

5.2. Business models for targeting barriers

In addressing barriers that hinder the deployment of the Living Wall's energy systems this section discusses possible business models that are applicable to the Living Wall. Here, a business model is the strategy applied in a business' revenue streams, key activities, resources, and financial structures. Whether a business model should be undertaken is referred to as the business case and is the logic and rationale for initiating an activity (Wurtenberger et al, 2011). Two types of models are distinguished; product service systems and models based on new revenue/financing schemes.

5.2.1. Product Service Systems (ESCOs)

Product service systems combine the delivery of an energy product (electricity, heat, energy performance) alongside the service of energy systems. Product service systems take the form of energy service companies (ESCOs). ESCOs are a third party company that leases with building owners, utilities, technical suppliers, etc to supply energy, energy efficiency improvements or a combination of both. Their primary function is to oversee the functionality of energy supply systems, or energy savings measures in a building. Three ESCO types can be defined:

- Energy supply contracting (ESC)
    - Supplies energy at a fixed rate over the contract period.
- Energy performance contracting (EPC)
    - Guarantees building energy efficiency performance improvements.
- Integrated energy contracting (IEC)
    - Supply energy at fixed rate, and implement energy efficiency guarantees.

Several advantages arise in utilizing ESCOs in buildings compared with 'in house' building energy supply management. ESCOs are specialized, consolidate energy supply issues and concentrate only on the energy systems of the building. This saves building management time and money hiring technical/repair personnel, negotiating with utilities, acquiring new/replacement technology and acquiring financial incentives. Furthermore, ESCOs primary revenue stream relies on the performance of energy systems within the building. There is thus an incentive for ESCOs to perform admirably in their duty to reduce energy consumption, and/or supply energy at an agreed rate. Compare this to 'in house' where building management is committed to many tasks all at once.

For new buildings, it seems appropriate to implement either an ESC or IEC ESCO. While EPC ESCOs can be applied to new builds, it doesn't make much sense since this would imply using traditional energy supply systems and hiring an ESCO to guarantee the building is energy efficient. Making the building energy efficient is indeed a good first idea, and the use of an IEC will accomplish this at the same time as implementing high performance (primary energy saving) energy supply. Utilizing an IEC should therefore be considered as part of TWL's business model because it:

- Guarantees building energy efficiency performance
- If implemented during construction, guarantees proper instillation of energy systems
- Assures efficient use of generated energy through comprehensive energy use monitoring
- Outsources and consolidates commercial and technical risks (purchasing, maintenance etc.)
- Assures functional performance and price guarantees
- Consolidates financing and subsidies

5.2.2. Revenue Models

Business models also exist that incorporate new revenue or financial schemes in their methodology. Of these the most applicable to the Living Wall are; Utilizing a feed in remuneration scheme, on-bill financing, and leasing of renewable technology.

SDE+ Feed in tariff

Feed in remuneration schemes are familiar in Northern Europe and offer a fixed rate incentive per unit of renewable energy sold correlated to the difference between renewable energy and grey energy generation costs. In the Netherlands the Stimulering Duurzame Energieproductie (SDE+) subsidy is a feed in tariff available for industrial producers of renewable heat and electricity and reimburses companies and non-profit organizations for investment in renewable energy production infrastructure. A per kWh subsidy is paid based on the difference between the cost of conventional energy and renewable energy over set investment periods of 5, 12, and 15 years (Agentschap NL 2012). The subsidy applies to PV installations greater than 15 kW, solar thermal arrays larger than 100 m^2, and biogas fuelled heat pump, CHP and boiler systems. The subsidy's per kWh feed in rates range between 0.013 €/kWh and 0.093 €/kWh for PV production and 0.021 €/kWh and 0.081 €/kWh for renewable heat production. The amount awarded increased according to the phase of the year. For example, phase 1 pays 0.013 €/kWh (PV) and had an application period from March 13th to May 1st 2012. The SDE+ limits the potential payback according to the product of load hours (maximum load hours PV 1000h and AST 700h) and maximum power output.

On Bill Financing

On-bill financing provides relief from high upfront costs and access to capital by allowing the purchaser to payback the initial costs via their energy bill (Wurtenburger et al 2011). This scheme is usually set up through a public utility with a 'roll back' energy program where energy produced is counted against energy consumed (i.e. paid the same price as consumed energy). In this way the purchaser is able to repay the loan cost through the energy saved by the system. Although usually offered through a public utility, an ESCO could also fill the role of the Utility.

In the Netherlands Green Choice's Zonleen and ENECO's Zon&Zeker programs are two examples of residential on bill financing options for PV. Residential purchasers are offered a three year fixed energy price when the utility installs PV, and connects purchasers with a special reduced interest rate loan offered through Green Loans ABN AMRO.

A similar option to on bill financing is leasing of renewable technology. Leasing of equipment is fairly straightforward, involving the lease of equipment under a lease to own architecture. Leasing can be provided in combination or through an ESCO or utility provider and usually applies for large projects.

Rijkspremie Zonnepanelen Subsidy

Although not a novel financing scheme, the Zonnepanelen subsidy is a rebate on purchased PV modules for resident homeowners. The subsidy guarantees homeowners a reimbursement of 15% of the investment cost up to a maximum of 650 €. Installs must range between 0.601 and 3.5 kWp and while larger arrays are accepted their subsidy contribution is lessened. The subsidy applies to purchased and leased panels provided the homeowner loans the PV array under a lease to own purchasing structure. No subsidy is awarded however if the panels are purchased or leased through a third party (Agentschap NL 2012).

5.3. Applied Business Models (Business Case Scenarios)

Using the above ideas two business models have been developed as strategies to deploy the supply scenarios in section 4.2.2 to the Living Wall. The models are tailored to the Living Wall's attributes and to maximize the use of state financial incentives available for renewable technologies.

5.3.1. The Living Wall Energy Service Corporation

The Living Wall ESCO model involves the establishment (or contracting) of an integrated energy contracting company that acts as an intermediate suppler for the Living Wall's energy demands. Here the Living Wall ESCO manages energy produced by the Living Wall's energy systems and is responsible for all costs associated with energy production equipment (investments, maintenance, etc.). This includes sale of electricity/heat to residents, sale of excess electricity to market/major energy supplier, and purchasing of electricity and natural gas. This model allows for both owner occupied and tenant occupied units. Below is a summary of the model's revenue streams, key activities and financial structure.

Revenue streams

- Sale of surplus power to grid
- Sale of power and heat to residents
- Acquisition of feed in tariff for renewable power and heat (SDE+ subsidy)

Key Activities

- Ensure efficient self - use of energy (minimizing purchased energy or maximising balance between purchased and sold power)
- Ensure building energy efficiency and system performance
- Monitoring of occupant/building use and generation
- Responsible for rate procurement/negotiation of power purchase/sale
- Future outlook for further building energy savings/value maximization from generation equipment

Financial Structure

This model follows an energy supply contracting pricing methodology with a (potential) profit sharing scheme for residents. Residents are offered a fixed rate energy price in €/kWh that is ideally less than the market rate. The Living Wall ESCO acts here in a similar fashion to a utility by purchasing/generating heat and electricity and selling it to the resident at the fixed rate. The difference between the market energy rate and the total supply cost is the total value added by the building, and is shared between residents and the Living Wall. In this way there is an incentive to residents to live in the Living Wall, and for the building to operate as an independent ESCO.

A simple breakdown of the total unit energy cost can be seen in figure 5.1. In this example, subsidies and feed in tariffs would be included through reducing the total supply cost and therefore contributing to the resident savings.

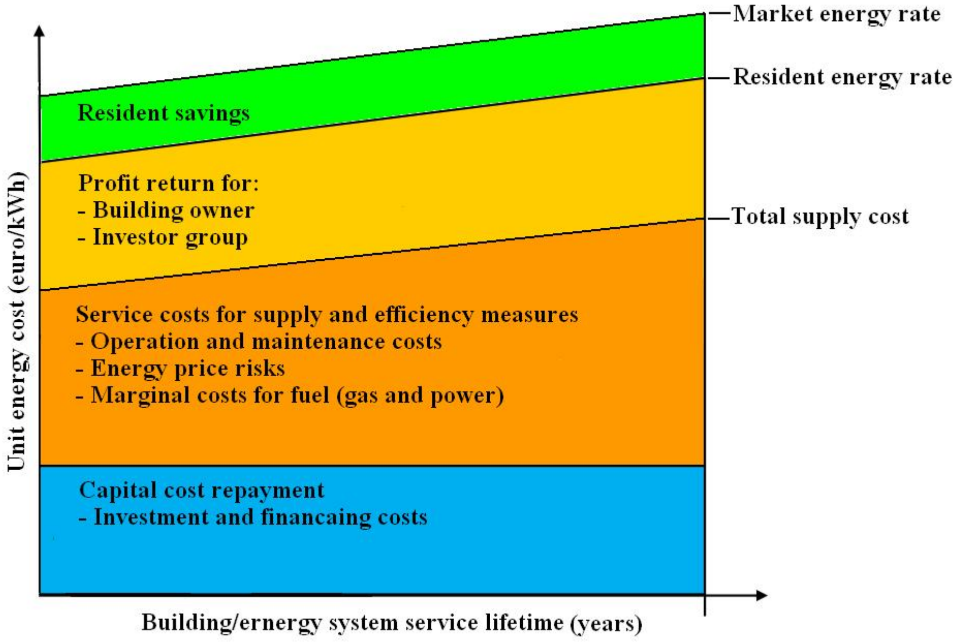

Figure 5.1: ESCO model unit energy cost breakdown.

5.3.2. The Living Wall Resident/Building Association

The Living Wall resident association model is a variation on the above Living Wall ESCO model that separates power and heat generation and use between the resident and a Living Wall building association. Residents would buy and sell their own electrical power, while purchasing heat from the Living Wall at a flat rate. This requires residents purchase or loan allocated segments of the Living Wall's PV array as part of an on bill financing model in order to make use of the Rijkspremie Zonnepanelen subsidy. As one of the foundations of the Living Wall is to provide affordable accommodation a leasing/loan structure facilitated through rent payments is preferable (equivalent of on bill financing). The aim of this model is to maximize the use of the Rijkspremie Zonnepanelen subsidy and higher feed-back electrical rates available to residential homeowners.

Revenue Streams

- Building Association
    - SDE+ feed in tariff for AST heat supply
    - Resident purchased heat at fixed rate
    - Resident fees for PV loan and service of PV system
- Resident
    - Residents benefit from meter 'roll back' on electricity produced up to 5000 kWh – after paid 0.092 €/kWh

Key Activities (Building Association)

- Ensure efficient self- use of energy (minimizing purchased energy)
- Monitoring of occupant/building use and generation
- Purchase of gas or electricity for heat supply
- Facilitate loan or brokering of capital funds for resident PV purchase
- Oversee operations and maintenance of building energy systems including PV array

Financial Structure

The financial structure of this model is broken into two parts corresponding to heat and power supply. Heat supply is structured in essentially the same way as in the previous ESCO model. Residents are offered a fixed €/kWh rate for heat consumption that is at, or below the market rate. The building association assumes supply risks, operation, maintenance and gas/electricity costs summing to a total supply cost.

The financial structure of the resident PV array segments is broken into three sub segments: capital costs, operation and maintenance costs and running costs. Capital costs and operation and maintenance costs are closely associated with the Building Association for two primary reasons; first, the Building Association facilitates the loan for resident's PV array purchase and second, it carries out installation and maintenance on the PV array on behalf of the resident.

To finance the PV array residents are offered the option to either purchase the array outright, or lease the unit with the help of the Building Association. Figure 5.2 shows a schematic representation of how the financing is arranged with the Building Association, financial institution and resident. Residents do not deal with the loan payment directly since it is included in the rental price. The building association procures (on the resident's behalf), and pays the principle and interest on the resident's PV array loan using the fraction of the rent payment allocated for the PV array loan.

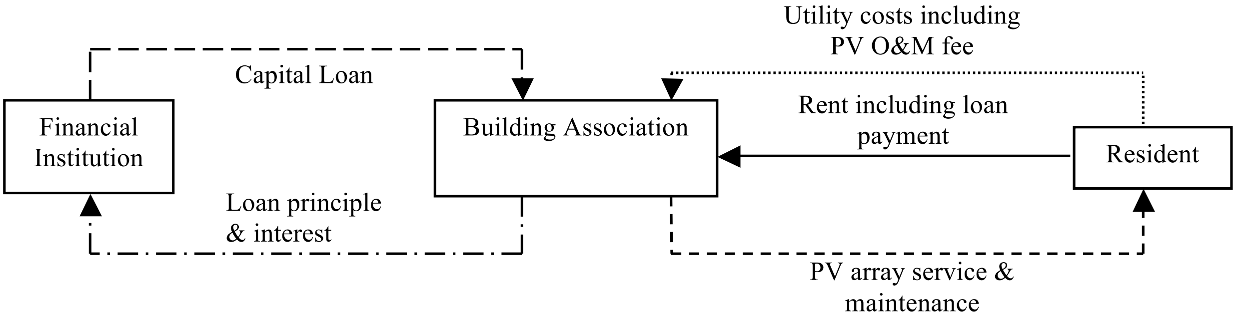

Figure 5.2: Schematic diagram of capital costs and O&M payment structure.

Running costs include the buying and selling of power and are entirely separate from the financial streams connected with the building association. Residents benefit from a meter 'roll back' system (offered through various Dutch utility companies, ENECO and Green Choice for example) where power supplied to the grid by their PV array segment is deducted from the power they consume.

5.4. Business Model Evaluation

The two business models are evaluated to give an idea of their performance against each other, and how the different supply scenarios perform using the two models.

5.4.1. Method of Analysis

The two models described above are evaluated using an NPV and SWOT analysis. The NPV provides a quantitative comparison of value for each model applied to the most techno-economically viable options found in chapter 3. SWOT analysis on the other hand addresses qualitative aspects of the model itself. A short description of methods follows.

Net present value method

Calculating the NPV represents the present worth of all future and present cash flows. Positive NPVs are preferable because they indicate the project currently has a positive value. When comparing NPVs higher values are preferable since this indicates a project has more potential value than the alternative. Equation 8.1 outlines how NPV is calculated (Blok 2007), where $I_{scenario}$ is the total investment costs of a Living Wall energy supply scenario, B is the benefits or positive cash flows, C is the costs or negative cash flows and L is the project lifetime.

$$NPV = -I + \sum_{i=1}^{L} \frac{B - C}{a(L,d)} \qquad \textbf{(5.1)}$$

Since the Living Wall project involves large investment costs, the NPV cash flows assume a capital loan repayment structure. The loan structure assumes the current prime interest rate of 5.10% (De Nederlandse Krediet Maatschappij, 2012) and an initial capital down payment of 15% of the total loan value. The core assumptions used in the economic scenario for the NPV analysis are summarized in table 5.3.

Table 5.3: NPV economic scenario assumptions.

NPV Parameter	Value
Lifetime	20 years
Interest rate	15 %/year
Project loan down-payment	15%
SDE+ Subsidy phase	3; application period 18 June to 3 September 2012
Industrial power sale price (night)	0.03 €/kWh
Industrial power sale price (day)	0.05 €/kWh

According to energy system manufacturer's data the energy supply systems have lifetimes of 20 years on average. This is shorter than the building's lifetime, and therefore the lifetime for NPV analysis is set to reflect the energy system life. Inflation is not taken into consideration over the project lifetime. This means all costs and revenue streams are real values, presented in 2012 euros.

The choice of interest rate is arbitrary, and reflects the expected return on the energy system investment at a given level of risk. For higher risk, private companies seek higher returns on investment. However, with higher expected returns, projects that might otherwise be profitable could observe negative NPVs. Social projects typically use interest rates of 4-6%, while private projects look for higher rates of return, anywhere between 15%-50% according to the perceived risk. The base economic analysis uses an interest rate of 15% indicating potential investors can expect to make 15% on their initial investment each year. This kind of project and interest rate is attractive for investors with large amounts of capital that are looking for lower risk, and more secure returns.

In the scenarios using CHP to provide heat and power, some of the power produced exceeds the buildings demands and is therefore sold back to the grid. Industrial rates for day and night sale to grid were obtained from NUON and listed in table 5.3 (Nuon 2012).

Reference Supply Case

The NPV of the reference energy supply scenario was calculated according to the business models above to provide a baseline for comparison. Two reference cases are considered, one with a centralized district heating system/boiler, and one with individual condensing boiler units in each residential unit. In each the fuel source is natural gas. The main difference here is boiler investment costs, and purchased energy costs. With the centralized heating system natural gas is purchased collectively by the ESCO/building association at the business/industrial rate. In the resident individual boiler case however, residents purchase their own natural gas at the residential rate (see table 5.4). In both cases electricity is purchased from the grid according to the same structures described in the ESCO and residential business models.

Costs and financial structures

A primary difference between the business models investigated is the treatment of the buying and selling of electrical power. Electricity and energy tax rates per kWh differ for residential and business/industrial users depending on total yearly demand. Table 5.4 gives an overview of the prices used.

Table 5.4: Summary of energy tariffs and taxes.

Connection Type	Buying (€/kWh)			Selling (€/kWh)
	Base Price	Energy Tax	Total**	Total
Business/Industrial*	0.072	0.011	0.083	0.05/0.03***
Residential	0.091	0.136	0.227	0.092

***Applies to business using between 50-10 000 MWh per year (Nuon 2012). ** Exclusive VAT. ***Prices vary for day/night**

As described in the Living Wall resident business model outline, residential electricity use is not included in the NPV calculation. This is for two reasons; first resident users receive 'roll back' which is equivalent to buying and selling power at the same rate. Second, in cases where resident users are paid for excess power sold to the grid this value is not realized by the building and/or investors.

In the ESCO model however, the base case is treated as buying power at the industrial rate, and sold to resident units at the residential tariff. This leads to a 0.0144 € margin that could be applied toward the building or resident (as savings). In the NPV calculations, it is allocated toward Living Wall project value.

Similarly, gas prices are different for residential and business/industrial users. Gas rates used in the NPV analysis can be found below in table 5.5. Only in the reference scenario with district heating is there a difference between the applied residential price of heating energy and industrial gas prices.

Table 5.5: Rates for residential and industrial gas (Nuon 2012).

Price Breakdown	Business/Industrial	Residential
Base Price	0.3630	0.4584
Energy Tax	0.0400*, 0.0127**	0.1984
Area Surcharge	0.0074	0.0072
Total	0.4104, 0.3831	0.6640

***Applies for use between 170 000 – 1 000 000 m^3/year. ** Use between 1 000 000 and 10 000 000 m^3/year**

Use of Subsidies in NPV

Financial incentives are included in the analysis as either reductions in the initial investment (Zonnepanelen Subsidy) or as benefits from sold energy (SDE+). With 1500 resident units, and a modeled array size of 15 000 m^2 the zonnepanelen subsidy equates to approximately 556 €/residential unit reduction in investment costs. This remuneration is only included in the Resident ESCO model.

SDE+ feed in tariff is included in both the resident association and the ESCO models. For the Living Wall resident model only the feed in rate for AST is applied. While in the Living wall ESCO rates from AST and PV are included. The rates are calculated based on successful application of phase 3 tariff band. At phase 3 the SDE+ subsidy translates to 0.061 €/kWh, 0.053 €/kWh and 0.0065 €/kWh in net feed in tariff benefits for AST, PV and SBB respectively. Since the SDE+ has five phases, NPV sensitivity to changes in the applied SDE+ rate was also investigated. Table 5.6 below shows the feed in remunerations rates for AST and PV for all 5 application phases. Note that SDE+ also applies to self-consumed energy. This means it is applied to thermal energy in the same way as if the energy were being sold.

Table 5.6 SDE+ feed in tariff rates 2012 (Agentschap NL 2012).

SDE+ Application Phase	AST Feed in tariff (€/kWh)	PV Feed in tariff (€/kWh)	Solid Biomass boiler (€/kWh)
Phase 1	0.021	0.013	0.0065
Phase 2	0.041	0.033	0.0065
Phase 3	0.061	0.053	0.0065
Phase 4	0.081	0.073	0.0065
Phase 5	0.081	0.093	0.0065

Energie Investeringsaftrek (EIA) Tax Incentive

The EIA is a before tax incentive that allows a qualifying amount of renewable technology investments to be deducted from the before tax income of a company or corporation. The EIA tax break is included in NPV calculations for applicable equipment in both business models. EIA scheme allocates 41.5% of qualifying investments for deductions from taxable profit. Therefore for corporate tax rate of 25.5% approximately 10.5% of the initial investment is deducted from the after tax profits (Agentschap.nl). Since the EIA applies to entrepreneurs only, the Living Wall resident model only includes the AST system under the EIA scheme. For the Living Wall ESCO model, both PV and AST systems are included.

Applying the EIA to an investment is straight forward if the investment is paid in full in the first year. In this case the following equation (5.2) indicates the value of the subsidy where $I_{qualify}$ is the qualifying investment (€), EIA_{Rate} is the EIA allocation amount (%) and T_{Corp} is the corporate tax rate (%).

$$\text{EIA Amount} = I_{qualify} \cdot EIA_{Rate} \cdot T_{Corp} \qquad \textbf{(5.2)}$$

However when the investment is purchased using a loan, the EIA value must be amortized according to the loan payments. To do this, the net present EIA amount is deducted from the total loan principle thereby reducing all future loan expenses. Equation 5.3 shows how to calculate the current year EIA NPV.

$$\text{Current year EIA NPV} = \frac{I_{qualify} EIA_{Rate} T_{Corp}}{(1 + d_{loan})} \qquad \textbf{(5.3)}$$

5.4.2. NPV Results

Results from the NPV analysis showed that of the scenarios investigated in section 4, the SBB had the highest NPV under both ESCO and resident business models. Figure 5.3 and table 5.7 display the NPV's of the supply scenarios as evaluated under each of the two business models. The reference scenarios are indicated as 'Reference CH' for the building central heating variant and 'Reference RB' for the individual resident boiler option. The NPV of the reference scenarios is used as the benchmark within each business model for comparing the NPV performance of other supply scenarios. The dashed lines correspond to the minimum NPV needed to outperform the best performing reference scenario. If a scenario's NPV is higher than the dashed line it has a higher NPV and is therefore a better option financially. In the ESCO model, the ASHP and SBB have higher NPV's than the reference. Under the resident association model the CHP-RE, GSHP, and SBB perform better than the central heating reference.

A scenario with a positive NPV that is below the reference line (i.e. CHP-RE, or GSHP in the ESCO model) means it is still a profitable scenario, but is not preferred financially because the return on investment in these scenarios will be less than scenarios with higher NPV's (references). This points out a weakness in NPV analysis – namely that it makes a decision on the better option without considering other benefits. For example, in the ESCO model, we saw the CHP-RE and GSHP scenarios should not be chosen because they do not perform better than the reference scenario's NPV. This says nothing about the sensitivity of each scenario to future fuel price changes/shocks, or the reduced total energy demand of the Living Wall resulting from choosing either of these scenarios. Also, recalling results from section 4.3.1 the range of envelope options using the SBB saved less primary energy than, for example, the range of envelope options using CHP-RE. This is not reflected in the NPV results here and qualitative consideration must be taken when considering the 'best' supply scenario. Thus NPV performance alone should not be the sole indicator for choosing the Living Wall's supply scenario.

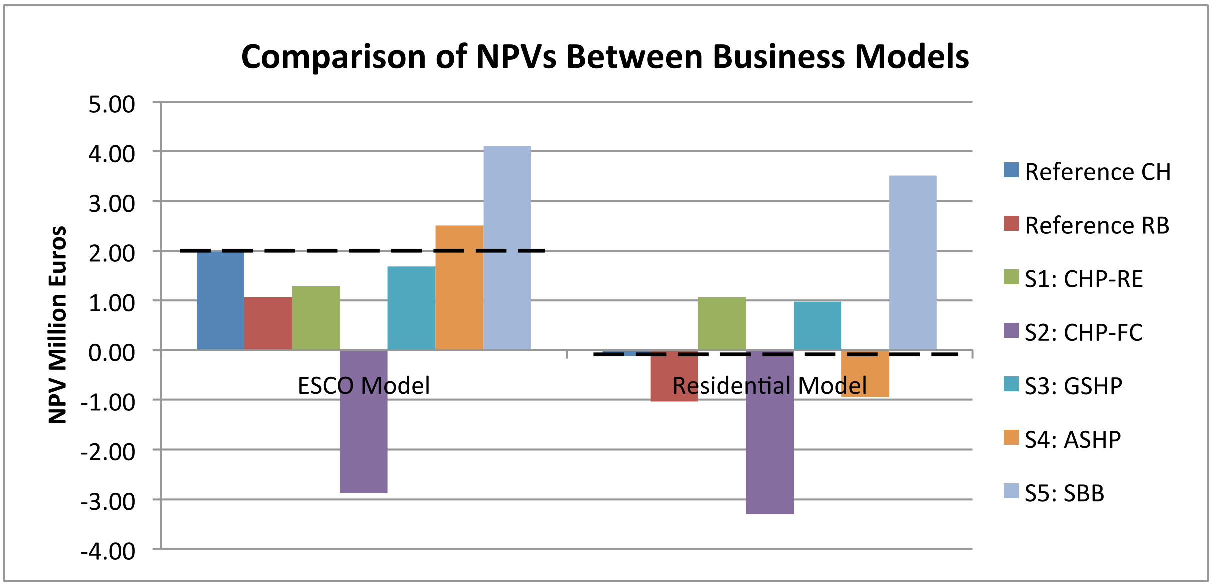

Figure 5.3 Comparison of NPVs for technical scenarios under different business models.

Table 5.7 Summary of scenario NPVs.

Scenario	ESCO Model (M€)	Resident Model (M€)
Reference Central Heat (CH)	1.98	-0.12
Reference Resident Boilers (RB)	1.07	-1.03
S1: CHP-RE	1.28	1.07
S2: CHP-FC	-2.88	-3.30
S3: GSHP	1.69	0.97
S4: ASHP	2.51	-0.94
S5: SBB	4.10	3.51

Comparing NPV results between the two business models indicates a strong case for the ESCO model. NPV's of all scenarios were reduced significantly in the residential model scenario indicating that the ESCO model can expect higher returns on investment. However, this overlooks the fact that monetary benefits of self energy production from PV in the resident association model are allocated to individual residents though lower (effective) electrical rates. The ESCO model also generates revenue from residents on the margin between the industrial purchased power price and the residential sale price. This margin doesn't exist in the resident association model because residents themselves buy and sell electricity directly from/to the grid. Therefore the NPV analysis above may only be used to compare scenario performance within each business model and another method is needed to fairly compare a scenario's NPV performance across the two business models. This is investigated in more detail in the section below on comparing benefits for residents.

Sensitivity of NPV to SDE+ phase

The sensitivity of a scenario's NPV to the SDE+ phase asks how much the NPV will change given an earlier or later SDE+ phase is granted compared to the default SDE+ phase three assumed. Sensitivity to the SDE+ subsidy introduces extra risk in the supply system choice. Should the SDE+ subsidy be abruptly cancelled, especially early in the project's lifetime, it will have strong impacts on yearly revenue. Figure 5.4 shows the relative percent change in each scenario's NPV for changes in the SDE+ phase.

The CHP-RE and GSHP scenarios have the highest sensitivity to changes in the SDE+ subsidy. This is interesting because both of these scenarios had lower NPV's than the central heat reference scenario. Increasing the SDE+ phase from three to four and the GSHP has a higher NPV than the reference CH. Similarly with the CHP-RE, at SDE+ phase five it has a comparable NPV to the reference (see also appendix E1).

In the alternative case where SDE+ is stopped, or an earlier phase (one or two) is awarded, all but the SBB scenario are affected. At lower SDE+ phases scenario's below the reference's NPV become less attractive financially. Below SDE+ phase two, the ASHP scenario no longer has a higher NPV than the reference case. The SBB scenario is the exception and showed higher NPV than the reference even with no SDE+ subsidy awarded. Thus here we can conclude that acquisition of the appropriate SDE+ phase is critical to its economic performance for all supply scenarios except the SBB.

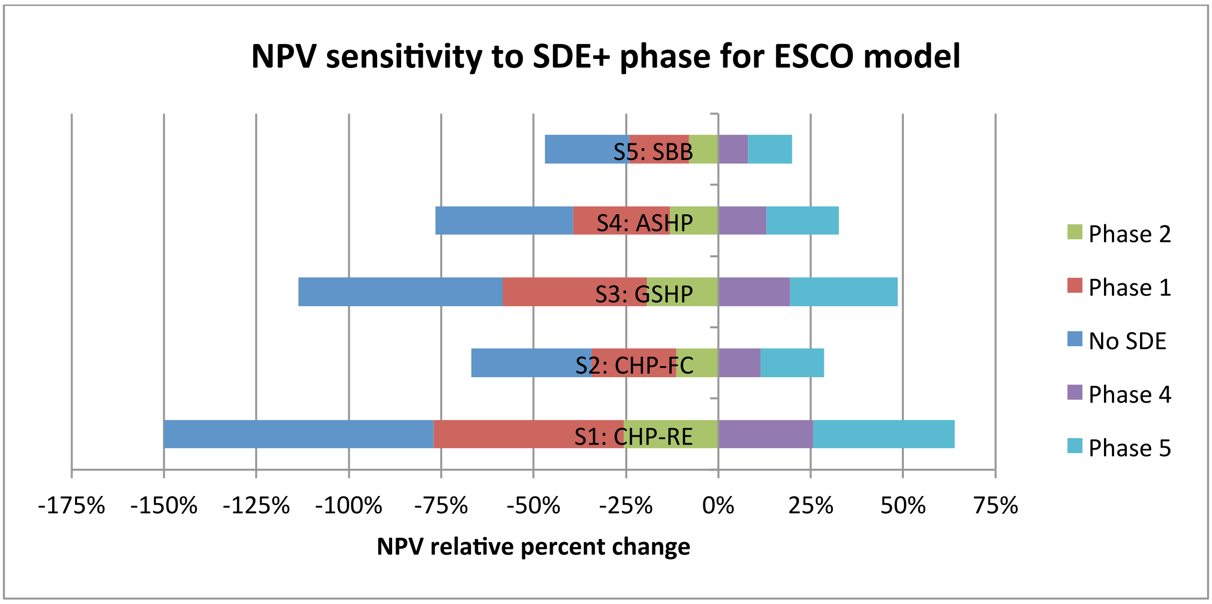

Figure 5.4. Sensitivity of NPV to SDE+ subsidy phase.

Sensitivity of NPV to interest rate

Sensitivity of scenario's NPV to changing the interest rate under the ESCO model was relatively uniform. The NPV of all scenarios was reduced equally with an interest rate doubling. When interest rate was reduced by half, the increase in NPV was more varied. Figure 5.5 shows the percent change in a scenarios' ESCO model NPV for interest rates for 7.5% and 30%. Since the change in the reference scenario's NPV is similar to the changes observed in other scenarios, the relative NPV performance of scenarios compared to the reference remains the same at different interest rates. Similar observations apply for figure 5.6 where the relative percent changes of scenarios' NPV under the resident association model are shown. The only exception was the large change in the ASHP's NPV in the 30% interest rate case.

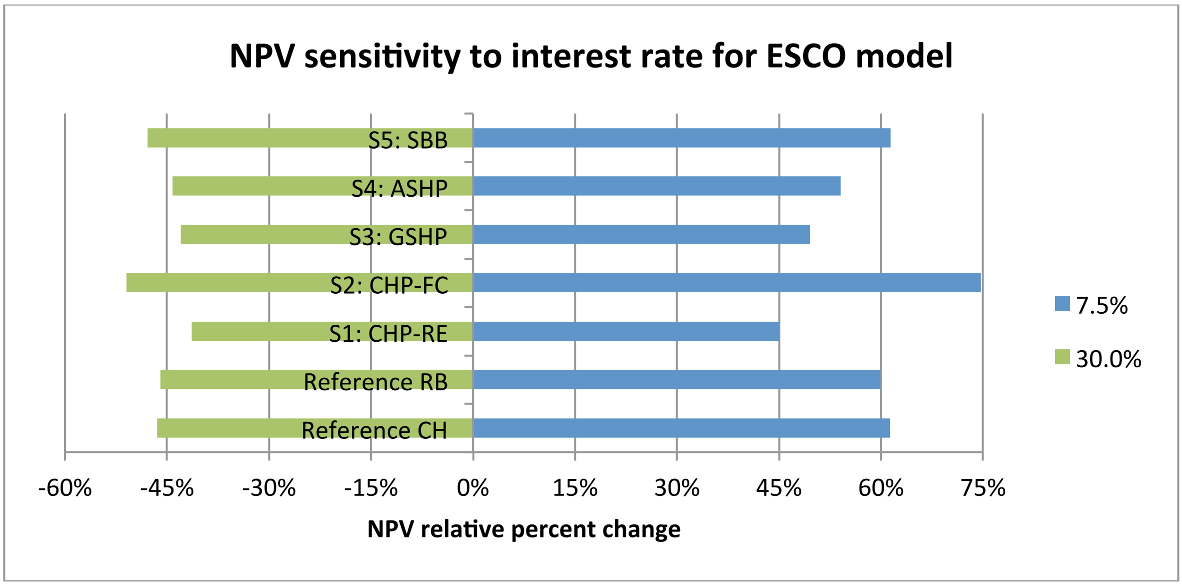

Figure 5.5 Sensitivity of ESCO model to interest rate

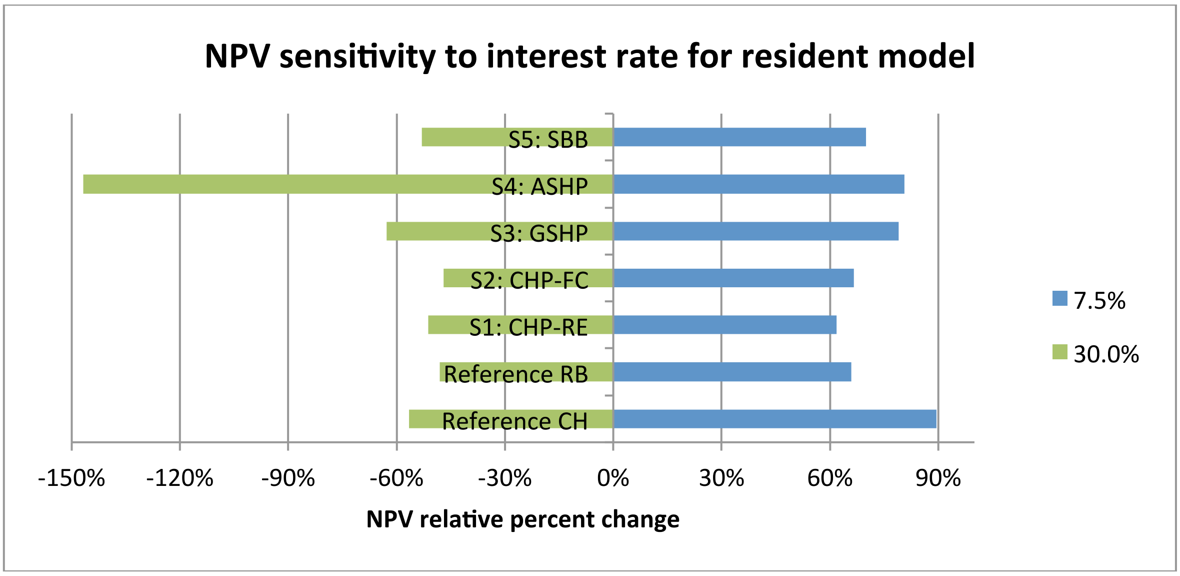

Figure 5.6 NPV sensitivity to interested rate in residential model.

Comparing benefits for residents (Sensitivity of ESCO model to resident electricity prices)

As mentioned above, the base NPV analysis does not account for the difference in energy price as seen from the resident's perspective. In order to directly compare supply scenarios between the two business models the price residents pay for electrical power is used as a common reference. Electricity is chosen because heat is treated equally in both ECSO and resident models and therefore the NPV's of each model will change by the same rate.

In the resident association model the resident's price per kWh electricity used is primarily dependent on the loan costs from the resident's allocated segment of the PV array. This is because the total demand per resident is approximately equal to the average total PV production per resident. Therefore resident 'electrical' costs under the resident model are almost solely composed of loan repayment (also includes small electrical unbalance and maintenance costs). Based on an average resident's PV array purchase/install cost of €3500 loaned at 5.5% over periods of 6, 8, 10 years, the effective €/kWh rates observed by each resident are 0.231 €/kWh, 0.183 €/kWh, and 0.154 €/kWh respectively. When compared to the resident's €/kWh electrical price in the ESCO model (0.227 €/kWh) the electrical prices in the resident association model are relatively lower.

To directly compare supply scenarios' performance in the ESCO and resident association models, the electricity price charged to residents in the ESCO model was set equal to prices in the resident association model. The base resident electrical rate in the ESCO model (0.227 €/kWh) was changed to match resident's effective electrical price under the resident association model corresponding to PV loan terms of 8 and 10 years. Figure 5.7 shows the effect on supply scenario's NPV in the ESCO model at resident electrical prices of 0.183 €/kWh (8 year loan term) and 0.154 €/kWh (10 year loan term). In this figure the NPV's of supply scenarios under the resident model should be used as the benchmark for comparing the performance of the same supply technology under the ESCO model at the different resident electrical prices.

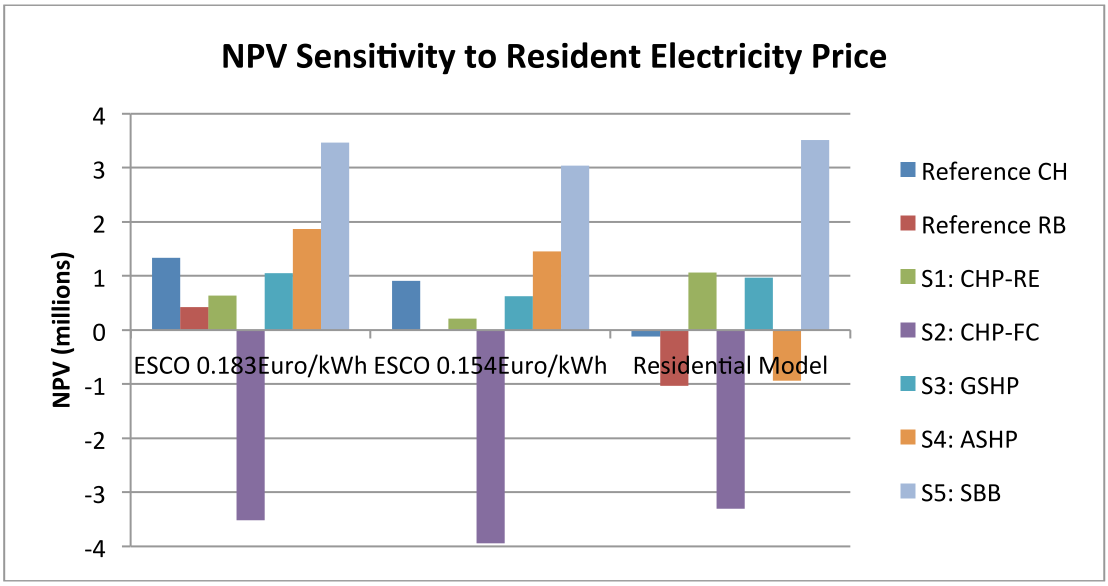

Figure 5.7: NPVs of ESCO model when resident electrical sale price is reduced.

The sensitivity of the ESCO model to changing resident electrical prices is significant. Table 5.8 indicates whether an ESCO model scenario's NPV was higher (+), lower (-) or equivalent (E) to the resident association scenario's NPV at the two different resident electricity prices. When resident electricity price is set to 0.183 €/kWh the ESCO model, outperforms the resident association model because we see few NPV's below the resident association (i.e. mostly + in table 5.8). However, the opposite is true when the resident electrical price is set to 0.154 €/kWh – most ESCO model NPVs are lower than the resident association's NPVs.

Table 5.8: Comparison of ESCO model scenario's relative performance to resident association model.

Supply Scenario	Scenario's performance in ESCO model compared to resident association model	
Resident Electricity Price	**0.183 €/kWh**	**0.154 €/kWh**
Reference Central Heat (CH)	+	+
Reference Resident Boiler (RB)	+	+
S1: CHP-RE	-	-
S2: CHP-FC	E	-
S3: GSHP	+	-
S4: ASHP	+	+
S5: SBB	E	-

Continuously lowering the resident electrical price in the ESCO model will result in little revenue generation for the ESCO with increased benefits (cost savings) to residents. The result here is that at a resident electricity price somewhere between 0.183 €/kWh and 0.154 €/kWh the two models show roughly equal NPV's for most supply scenarios. The exact resident electricity price at which the NPV of specific scenarios are equal between the two business models will however differ.

5.4.3. SWOT Analysis

The SWOT analysis shows that there are many hidden implications when considering the implementation of either of the two business models investigated here. Many pros and cons exist that must be weighed against the financial and energy savings realities of each model and scenario. The following sections discuss differences between the two business models strengths, weaknesses, opportunities and threats.

Strengths

The strengths of the Living Wall ESCO, and Living Wall resident association models can be found in table 5.9. Three major differences between the models are observed; alleviations of split incentives, upfront cost impacts, and electricity rates.

Both business models are able to stimulate the deployment of renewable energy technology in the single/multi-unit rental market. However the Living Wall ESCO model is the only model of the two that is able to fully alleviate the split incentives barrier between residents and the Living Wall owners. Under the Living Wall resident association model residents purchase a segment of the PV array, but may not live in the Living Wall long enough to fully recoup the benefits of this. Two problems arise from this. First, it increases pressure on the Living Wall association because they will bear the debt load during transition between occupants. Second, knowing they cannot recoup benefits from their investment new residents might not wish to participate. Implementing the Living Wall ESCO model in this case creates no split incentive, provides a hassle free experience from the perspective of the resident, and effectively deploys renewable energy PV technology.

Each business model has different points of strength when considering their upfront costs. The upfront costs of the Living Wall ESCO model are as indicated in table 5.2 providing no obvious incentive to application. If however the Living Wall ESCO project is implemented or backed by a reputable ESCO in the building services sector, investor confidence might overshadow the higher costs. This is in contrast to the Living Wall resident association model where the upfront costs are reduced first through the Rijkspremie Zonnepanelen subsidy, and second through the financing scheme of the PV array. The total PV array cost in this case can be effectively eliminated from prospective investor upfront costs because it is sourced through individual resident loans via a bank. This makes the upfront costs of the Living Wall resident model comparatively more attractive.

Finally, both business models offer residents reduced electrical rates (when compared to conventional homes/apartments) but observe differences in implementation, and associated risk. In the Living Wall resident association model residents pay reduced electricity rates because of the ‘roll back’ scheme from the electricity produced from their PV array segment. This introduces risk to the resident that is not observed in the ESCO model where the reduced rate offered to residents is the result of the ESCO’s ability to acquire and produce electrical power at industrial rates.

Table 5.9: Comparison of Living Wall ESCO and Living Wall resident association strengths.

Business Model	Strengths
Living Wall ESCO	*General* • Model has strong intrinsic value generation when negotiating for energy prices as a whole (i.e. buying and selling at industrial, and residential rates respectively) • Maximizes use of EIA incentive (AST and PV) • No split incentive barrier; both resident and building owner observe benefits • Integrates self-produced power and heat with self-demand. I.e. higher system integration is possible between heat and power generation technologies. • ESCOs are relatively familiar business models in northern Europe, likely making adoption and acceptance of the Living Wall project positive.

	- Excellent ability to respond to changing electrical demand profiles especially with regard to modeled versus actual demand. *For the building owner* - The building owner is able to collect additional revenue from the buying and selling of heat and electricity that is otherwise missed when residents procure their own energy needs. - Energy contracting can easily be specifically tailored to the demands of the Living Wall since all energy technology related assets are operated by the ESCO. - Technological risk is outsourced to expert, thereby minimizing technical risk to the building owner. *For the resident* - In general, lower €/kWh rates for power and heat can be observed by the resident when compared to prices in conventional dwellings. - Energy monitoring can help guide residents to saving energy and thus reducing total energy costs.
Living Wall Resident/Building Association	*General* - In general, electrical power from PV receives a higher €/kWh rate than the ESCO model. - Enables installation of renewable energy equipment in a market area (single/multi-unit rental) that would otherwise never undertake such projects. - Project value is mostly independent from continued SDE+ subsidy payments. *For the building owner* - Reduced upfront costs since the PV array is effectively financed by the residents and makes project more attractive to investors. *For the resident* - Residents observe effectively fixed electricity prices and residents occupying units past the loan payback time on the loan will have effectively 'free' power so long as the 'roll back' scheme exists. - Since building association holds part of the risk associated with the upfront cost debt, low income and poor credit individuals can be included in scheme.

Weaknesses

The weaknesses of each business model are presented in table 5.10. A common weakness is the models application of complex revenue and financing schemes. Complex revenue schemes can cause uncertainty in potential investors, or can baffle prospective residents. As mentioned a difference here is that the ESCO model has the advantage of shielding residents from its complex financial workings. The results of each models financial structure are also different in their allocation of risk. In the Living Wall ESCO, price shock risk is taken on entirely by the ESCO, while in the Living Wall resident association model residents are exposed to electrical price shocks (this is especially true if 'roll back' metering is discontinued).

A definite difference in the models' weaknesses is the barriers to implementation. The ESCO model is not immune to barriers such as high upfront costs, difficult access to capital, and lack of interest from investors. These barriers are however much less severe than the risk of non- or delayed deployment of the PV array in the Living Wall resident association model. Since the PV array in this model is financed through residents, the instillation of the PV array suffers from two difficult realities. First, residents choosing not to participate in the PV scheme would result in underdevelopment of the PV array. Second, if the building is slow to achieve full occupancy deployment of the PV array will lag behind potentially costing more in install costs, and creating logistical difficulties.

Table 5.10: Comparison of Living Wall ESCO and Living Wall resident association weaknesses.

Business Model	Weaknesses
Living Wall ESCO	*General* • ECSOs involve complex financing models and building owner, or ESCO will have to implement accounting systems for resident energy/cost balances. • High upfront costs are still present and pose a potential barrier if down payment capital is difficult to acquire. • Excess electrical power from PV fetches a lower €/kWh rate when compared to the residential model. *For the building owner* • Return on investment is highly dependent on the generation equipment installed. ESCO model does not guarantee adequate returns. *For the resident* • Resident electricity rates may be higher than in resident model.
Living Wall Resident/Building Association	*General* • PV array segments may only be installed as building occupancy fills and residents agree to participate in financing scheme. This creates two problems: o If residents choose not to participate roof space intended for PV goes underutilized. o If building occupancy is slow to fill the PV array will lag behind in installation – potentially causing logistical/technical barriers and cost increases. *For the building owner* • Model creates a variation on the split incentive barrier: building association has increased work on behalf of resident to facilitate seamless PV loan acquisition but realizes no/little gains from their work. • Building Association is exposed to risk of loan default when facilitating PV loan payments through rent collection i.e. if resident abruptly leaves. *For the resident* • Residents intending to only live a few years might not want to participate in the PV purchase scheme, or feel they will be paying for a PV array segment that a future resident will recoup benefits from → split incentive.

Opportunities

Similar opportunities between both business models listed in table 5.11 exist for resident behavioral energy demand reduction. This could be achieved in the Living Wall ESCO model by smart metering and introducing residents to monitoring their own energy consumption. The opportunity for similar behavioral demand reductions in the Living Wall resident association model on the other hand is based on resident involvement. Involving residents in the collective management of their own building's energy issues (i.e. through volunteer resident representatives) could also be a productive method to changing resident's opinions and behaviors on energy use.

The models also both have opportunities with respect to rising energy prices. The Living Wall ESCO can use rising energy prices as motivation to seek opportunities to maximizing profits, and reducing the Living Walls energy demands. This is one of its objectives as an energy service company. The opportunity with rising energy prices in the Living Wall resident association model is less obvious. Residents who perceive rising energy prices as a threat/reality can choose to pay their PV loan faster so as to recoup larger benefits in the future when prices are higher.

Table 5.11: Comparison of Living Wall ESCO and Living Wall resident association opportunities.

Business Model	Opportunities
Living Wall ESCO	*General* • On-going energy efficiency improvements and reduced total energy costs. • Further integration of system components (i.e. excess PV supply used in winter to power GSHP) could lead to higher profit margins. *For the building owner* • Rising energy prices make ESCOs and energy saving measures more attractive. • PV array size is less constrained when compared to the resident model and integration into the gallery as well as the roof could bring considerable additional income. *For the resident* • Widespread potential for smart meters tracking electrical and heat consumption – help communicate with residents on behavioural demand reduction.
Living Wall Resident/Building Association	*General* • Relationship between building association and resident created by the PV finance structure could be run with active resident involvement and extended to other collective energy savings initiatives (i.e. behavioural demand reduction). *For the building owner* • If residents are not willing to participate in purchasing PV array segment, it might create a market for the Living Wall to sell roof PV segments to home owners in the Lunetten neighbourhood – this could: ○ Allow local residents to install PV arrays larger than they otherwise could on their home ○ Provide extra income to the Living Wall. ○ Increase the Living Wall's integration with community. *For the resident* • Residents have time flexibility on financing their PV array segment → resident's choice of effective electrical rate.

Threats

The threats to the success of each model are relatively few, as seen in table 5.12. A threat both models share is their reliance on respective subsidy schemes. The Living Wall ESCO is reliant on the SDE+ subsidy, and the Living Wall resident association relies on the 'roll back' of electrical power sold to the grid. Stopping of either of these respective subsidies has definite negative impacts on each model. The Living Wall ESCO would observe much lower returns on investment while the Living Wall resident association would lose its ability to offer residents lower electricity rates, one of its primary features.

Table 5.12: Comparison of Living Wall ESCO and Living Wall resident association threats.

Business Model	Threats
Living Wall ESCO	*General* • Should the SDE+ subsidy be abruptly stopped the return on scenarios with renewable technology would drop considerably. *For the building owner* • Providing a price guarantee to residents would expose the ESCO to fuel price fluctuation risks and if fixed contracts are used the ESCO has potential to lose money before contracts can be renegotiated.
Living Wall Resident/Building Association	*General* • The implementation of this model is less clear cut when compared with the ESCO model. While energy utilities reacted positively (ENECO) it was clear an arrangement needed to be made to account for renting tenants. *For the resident* • Relies on energy companies offering ongoing electricity 'roll back' incentive. Without the 'roll back' incentive this model loses much of its value to the resident.

6. Discussion

The results presented in each of the above chapters depend heavily on the initial assumptions taken in modeling the Living Wall's energy demands in section three. Changes in the Living Wall's heat and power demand and supplies will have impacts on both the viability of supply technology in the techno-economic analysis and economic performance of business models. The linked nature of results in the preceding chapters is important to recognize when considering that the model of the Living Wall's energy demands is a simple approximation. This means that reevaluation of the Living Wall's energy demands to include more specific elements of its design and construction should be considered to ensure accurate representation of the chosen ventilation method, levels of building infiltration, transient heat flows (gallery area heat flux, and internal heat gains) and thermal bridging, for example. Commercial heat demand software may be used to verify heating demand estimates while also including the considerations previously listed.

On the other hand electrical demands are difficult to verify without empirical data. This is because resident behavior is very difficult to model and plays a strong role in determining electrical demand. This rationalizes the fact that this work utilized a method of modeling electrical demand to match average consumption and can therefore assume that over the long run the energetic and financial results will hold up. However, with more detailed empirical data opportunities may arise for higher profit generation (i.e. if an ESCO model is assumed) through intelligent management of inter- and intra-building electrical load distribution (i.e. choosing when to sell to the grid, and when to focus on building self-use).

Building Envelope Choice

In section four, the TEP analysis showed that with different supply technology packages, many window and insulation options were economically efficient according to the reference CCE. This is interesting because when evaluated individually many window and insulation measures did not perform better than the reference CCE. Yet when packaged as part of a whole building energy system they performed well, a result of the strong influence from the choice of the Living Wall's energy supply technology scenario. Knowing this, grants freedom and confidence in choosing economically efficient insulation and window technologies for the building envelope. Building envelope components may therefore be selected based on a multitude of factors not limited to energy savings and cost performance. Considerations that reflect the Living Wall's sustainable image can be taken into account such as insulation and windows material sources, and after life disposal. In short, because of the huge range of economically viable envelope components/combinations the Living Wall has the freedom and ability to also optimize non-energetic life cycle elements of its building envelope.

Considerations on energy savings and NPV analysis

In the above discussion in section 5.4.2, results from NPV analysis indicated a clear financially optimal supply scenario (not comparing between business models). On the other hand, choosing a ‘clear winner’ on financial grounds alone is contrary to the concepts of sustainable buildings introduced in section 2.1. Sustainable buildings should optimize energy, materials, and external impacts from a lifecycle perspective. As a start this means finding a balance between the financial optimal supply scenario and the supply scenario with optimal primary energy savings and minimal external/material environmental impacts.

However, finding a balance between financial, energy saving and external impacts is a challenge, mostly because it is unclear how to do so. The NPV analysis showed that the SBB scenario was financially best, but saved less primary energy compared to the CHP-RE. Digging further into lifecycle impacts of these two technologies we see their fuel sources are also a source of controversy. Are the external environmental impacts of using wood chips for fuel more devastating than natural gas? This is clearly not within the scope of this work, but the question outlines how thinking extensively about multiple aspects of the Living Wall’s supply and building envelope technologies emphasizes the difficulty of identifying a ‘clear winner’.

Future Research

There are several areas of this work that could be extended with respect to both the Living Wall and in a general context to similar types of multi-residential buildings. Future work could be carried out enhancing the detail of the techno-economic potential analysis. Such work could apply to both the Living Wall specifically and multi-residential buildings in terms of both new and retrofit projects. For example, this study did not attempt to determine the Living Wall’s economic optimum level of insulation. Considering insulation types other than fixed board insulation and by varying insulation thickness at smaller increments might give insight into the following:

- The level of insulation thickness that minimizes the CCE and maximizes PES per building zone.
- Alternate wall constructions and insulation forms could save building material costs.

Future work may also be carried out on the extensive range of window choices available. This study only considered four types of windows with the main focus on their thermal efficiency. One could investigate the economics of installing BiPV integrated windows, or ‘smart’ electro-chromic windows in the gallery for increasing power production and controlling solar gains.

Another interesting area of future work is investigating the potential of the Living Wall ESCO selling the Living Wall’s excess daytime PV production to Lunetten businesses. For ¾ of the year, the Living Wall will produce excess power during the day when resident demand is low. The Living Wall ESCO is able to sell this energy back to the grid during the day for 0.05 €/kWh, but higher rates might be possible (i.e. standard electricity business tariff from NUON is 0.072 €/kWh) if this energy is brokered to local businesses.

Finally there is much study in literature on further integration of building energy systems. Examples of these are combined PV and AST arrays and converting and storing excess electricity and heat using heat pumps (PV assisted heat pumps). Carrying out an investigation into the economic and market performance of these technologies would help their deployment and uptake as integrated with current systems in a building.

7. Conclusions

This work was a case study on the Living Wall, a proposed urban integrated building south of Utrecht, the Netherlands. More generally, this research investigated the deployment of renewable energy technology (both energy saving and generation) into the built environment. To accomplish this, a simple model of the Living Wall's energetic supplies and demands was constructed to act as a basis from which to conduct a TEP and business model analysis. The TEP assessed technologies that were economically feasible by evaluating insulation/window types, supply technologies, and supply scenarios (combinations of insulation, window and supply technologies) in terms of their cost of conserving primary energy (CCE). Finally, the business model analysis took supply scenarios and investigated the NPV and SWOT performance of a building ESCO model, and on bill financing model.

Results from the simple model of the Living Wall's energetic characteristics are summarized in table 7.1. Implications from changing the PV and AST array sizes were the main considerations when looking at the net power and heat demand figures. As PV array size changed the Living Wall's self-consumption leveled off, indicating that as PV array sizes increased the amount of surplus power also increased. The same was true for AST array sizes, except the main conclusion was that larger AST array sizes supported the use of hot water storage units.

Table 7.1: Summary of results from the Living Wall energy demand model.

Demands	Gross (MWh/year)	Net (MWh/year)
Heat	7512	5908 (storage) 6922 (no storage)
Electricity	3144	1290
Supplies	**Total (MWh/year)**	**Surplus (MWh/year)**
PV	3159	1829
AST	2163	-

The TEP analysis showed that when combined into supply scenarios and applied to the Living Wall, many insulation, window and supply technologies were economically feasible. In particular supply scenarios including CHP-RE, GSHP, SBB and ASHP technologies were all feasible within a wide range of insulation and window combinations. Only supply scenarios including a CHP-FC were not economically viable when compared to the commercial price of primary energy. The supply scenario with the lowest absolute CCE was scenario 5 (SBB) while scenario 1 (CHP-RE) had the highest primary energy savings of the economically viable options. When considering that CHP-RE is in relatively early stages of its learning curve, future technical and economic improvements may improve its CCE and PES performance. The same cannot be said however for SBB, while cost improvements may occur, potential for technical improvements is limited.

Investigating the deployment of Living Wall energy supply scenarios using an ESCO and on bill financing model showed that the ESCO model is more robust in several aspects. Financially, supply scenarios in the ESCO model had higher NPV's when compared to the same supply scenarios in the on bill financing model. At the same time, the ESCO model was able to offer residents lower than market rates on their electrical energy price. The on bill financing model on the other hand, offered the resident the ability to determine their own electrical rate through the choice of loan payback time. The ESCO model was also able to eliminate split incentives between resident and building owner that are created in the financing structure of the on bill financing model. Finally, the ESCO model is more motivated in terms of reducing energy demands, and seeking out new opportunities for energy efficiency when compared to the on bill financing model.

Identifying a clearly optimal Living Wall supply scenario is difficult. Considerations like total energy savings, materials lifecycles and fuel source impacts should be taken into account in the context of the definition of a sustainable building. Such aspects are not easily quantified or compared on a level playing field and future work on environmental/lifecycle impacts may provide clearer answers. Investors and developers of the Living Wall need to consider financial and sustainable priorities when making a choice on the energy supply configuration of the Living Wall.

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9. Appendix A

9.1. A1: Reference Building Specifications

Table 9.1: Summary of building dimensions used in the living wall box and gallery box simulation objects

Building Dimensioning	Living (Thermal) Box	Gallery
Size and Shape		
Length	2250 m	2250 m
Depth	10 m	7 m
Height	9.9 m	9.9 m
Floor-Floor Distance	0.3 m	-
Floor Area Per Unit	40 m^2	-
Volume Per unit	120 m^2	-
Volume	180 000 m3	155 925 m^3
Stories	3	-
Envelope Areas		
Floor to basement/environment	20 000 m^2	15 750 m^2
Roof	20 000 m^2	15 750 m^2
Side Wall	180 m^2	138.6 m^2
Windows	13 500 m^2	18 000 m^2 (gallery windows)
▪ North	5400 m^2	-
▪ South	8100 m^2	-
Walls	62 680 m^2	-
▪ North	12 600 m^2	-
▪ South	9900 m^2	-

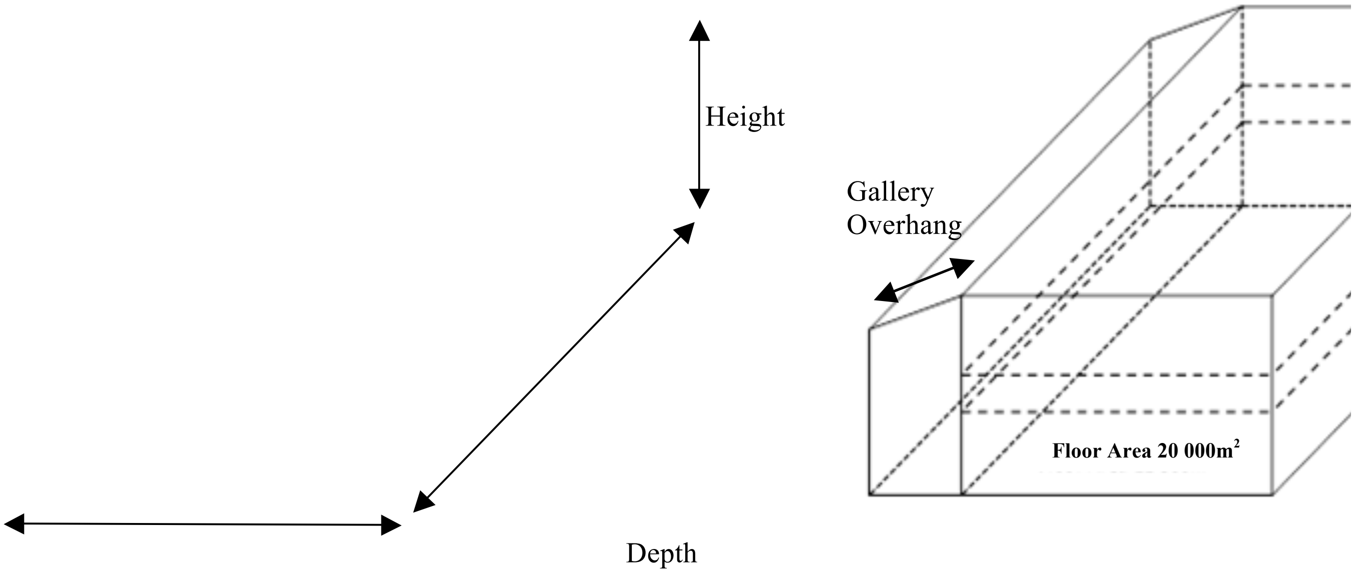

Figure 9.1: Reference simulation object dimensioning.

9.2. A2: Collector Array Areas

The array areas given for PV and AST in section 3.2.1 and 3.2.2 do not represent the total area occupied by the array systems. Numbers used in section 3.2 are collector areas (physical energy collection area). To determine the real array areas the inclined array must be projected onto the inclined roof surface and non collection array area need to be accounted for. Table 9.2 shows the relationship between panel collection area, and total area for single panels.

Table 9.2: PV and AST single panel dimensions.

Array	Collector Area (m^2)	Total Area (m^2)	Collection fraction (%)	Mean collector length - L (m)
PV	1.56	1.58	98.7	1.65
AST	3.23	4.32	74.7	2.13

All solar collecting arrays are assumed to be fixed at an incline of 41° mounted on a roof inclined at 25° with both measurements relative to the horizontal. The effective panel tilt relative to the roof is therefore 20°. Figure 9.2 shows the composition of the projected array area on the roof. The projected array area is the sum of the lengths x and y which can be found using basic trigonometry and the mean collector length. Collectors are separated by the distance y because this prevents collectors shading other collectors placed behind. Note that his is the minimum distance and site specific conditions could result in larger values between collectors (y).

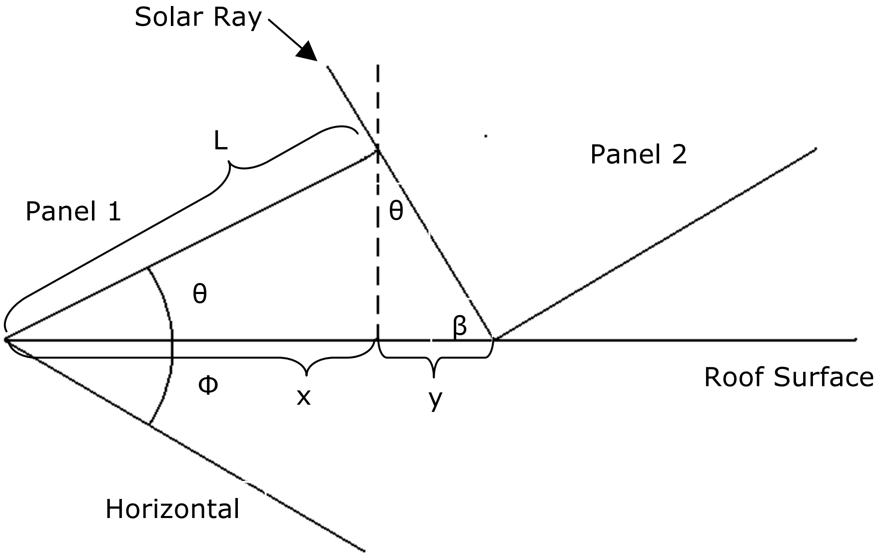

Figure 9.2 Schematic description of array projection onto roof surface. Variables: θ = 21°, Φ = 20°, β = 69°.

10. Appendix B: Input Costs Summary

Table 10.1: Summary of equipment costs

Supply Technology	Capital Costs (€)	Maintenance Costs (€/year)	Fuel Costs (€/year)	Cost of Installed Power (€/kW)
AST	1 636 486.53	32 729.73	-	756.40
CHP-RE	2 360 160.00	84 357.96	467 011.78	983.40
CHP-FC	13 615 200.00	220 644.05	700 517.67	5673.00
PV	4 021 875.00	2170.00	-	2145.00
ASHP Gas	960 000.00	19 200.00	84.062.12	400.00
GSHP Electrical	3 084 000.00	61 680.00	110 981.58	1285.00
Solid Biomass Boiler	384 000.00	15 360.00	237 711.56	160.00
Reference Boiler	96 000.00	1920.00	295 164.99	40.00

Table 10.2 Summary of insulation unit costs.

Insulation Type	Unit Cost (€/m^3)
Rockwool[1]	51.30
Glass Wool[2]	73.40
Cellulose[3]	24.50
Flax/Hemp fiber[4]	117.50
Wood fiber[5]	152.30
Expanded polystyrene board[6]	161.25
Polyurethane board[7]	152.30

1: ("Rockwool RWA45, RW3, RW4, RW5, RW6, Cavity Slabs" 2012)
2: ("Isover APR 1200" 2012)
3: ("Comparison of natural insulation materials" 2012),
4: (RGJ International, 2010)
5: ("PAVAFLEX – FLEXIBLE WOOD FIBRE INSULATION" 2009)
6: ("Gyproc thermaline basic TE 40", 2012)
7: ("Kingspan TW55" 2012)

Table 10.3: Summary of window unit costs.

Window Type	Unit Cost (€/m^2)
Reference Windows[1]	230
Double Glazing (Argon Low E)[1]	356
Triple Glazing (Suspended Film Krypton Fill)[2]	475
Aerogels[3]	425
Vacuum[1,4]	600

1: (Harvey, 2006)
2: ("SeriousWindows 1125" 2009)
3: ("Aerogel" 2012)
4: ("About SPACIA-21" 2003)

11. Appendix C: Material and Technology Data

Table 11.1: Summary of generation technologies lifetimes.

Supply Technology	Lifetime (years)
AST	20
CHP-RE	20
CHP-FC	15
PV	25
ASHP Gas	30
GSHP Electrical	30
Solid Biomass Boiler	20
Reference Boiler	20

Table 11.2: Summary of window U- and g-values.

Windows	U-Value (W/m^2K)	G-value (%)
Reference Windows	2.60	0.7
Double Glazing (Argon Low E)	0.80	0.7
Triple Glazing (Suspended Film Krypton Fill)	0.24	0.17
Aerogels	0.30	0.4
Vacuum	0.70	0.32

Table 11.3: Summary of insulation U-values for additional insulation

Insulation	U-Value* (W/m^2K)	λ (W/mK)	Typical Range $\lambda^{1, 2}$ (W/mK)	North Composite* (W/m^2K)	South Composite* (W/m^2K)
Reference	0.249	-	-	0.24917	0.2302
Rockwool	0.300	0.030	0.032-0.042	0.14	0.13
Glass Wool	0.430	0.043	0.031-0.044	0.16	0.15
Cellulose	0.390	0.039	0.038-0.040	0.15	0.14
Flax/Hemp Fiber	0.400	0.040	0.040-0.042	0.15	0.15
Wood Fiber	0.380	0.038	0.037-0.040	0.15	0.14
Expanded polystyrene board	0.500	0.050	0.030-0.38	0.17	0.16
Polyurethane board	0.230	0.023	0.022-0.028	0.12	0.12

***At reference plus 10 cm additional insulation.**

1: (TIMSA 2012)

2: (Van Leemput et al. 2008)

Table 11.4:R-value to U-value conversion chart.

R-value (m^2K/W)	U-Value (W/m^2K)
0.5	2.00
1	1.00
1.5	0.667
2	0.500
2.5	0.400
3	0.333
3.5	0.286
4	0.250
4.5	0.222
5	0.200
5.5	0.182
6	0.167
6.5	0.154
7	0.143
7.5	0.133
8	0.125

12. Appendix D

12.1. Appendix D1: Capital cost sensitivity

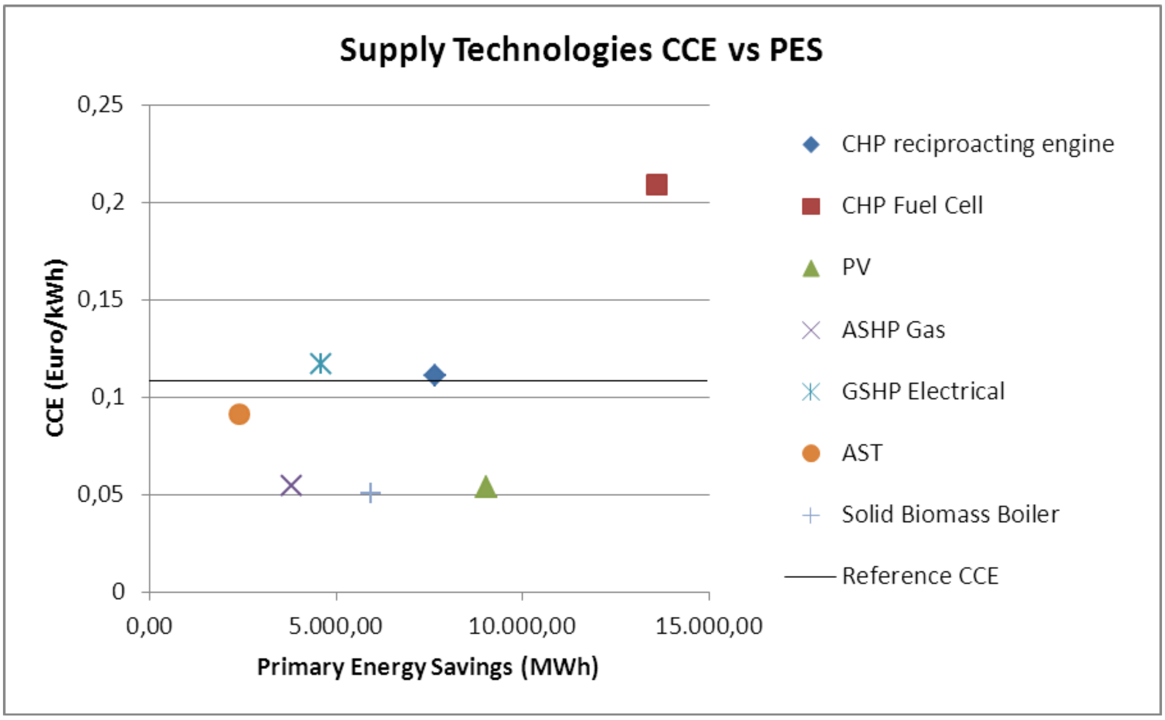

Figure 12.1 Supply technology plot with a -20% capital cost change

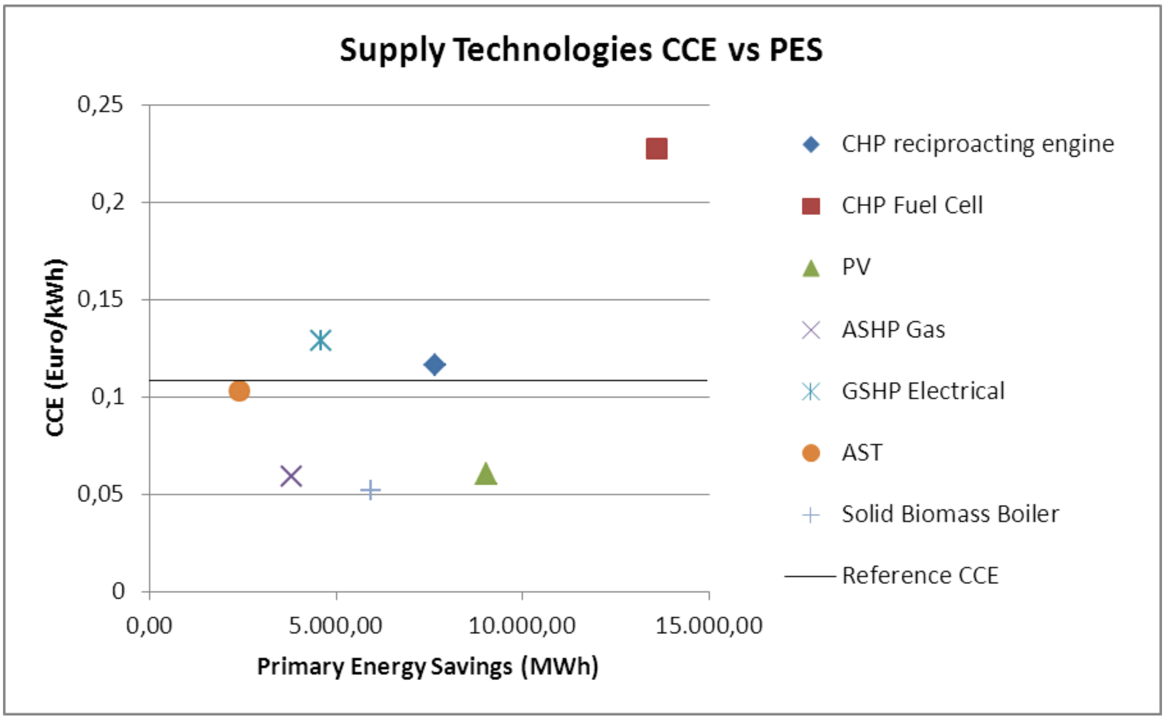

Figure 12.2 Supply technology plot with a -10% capital cost change.

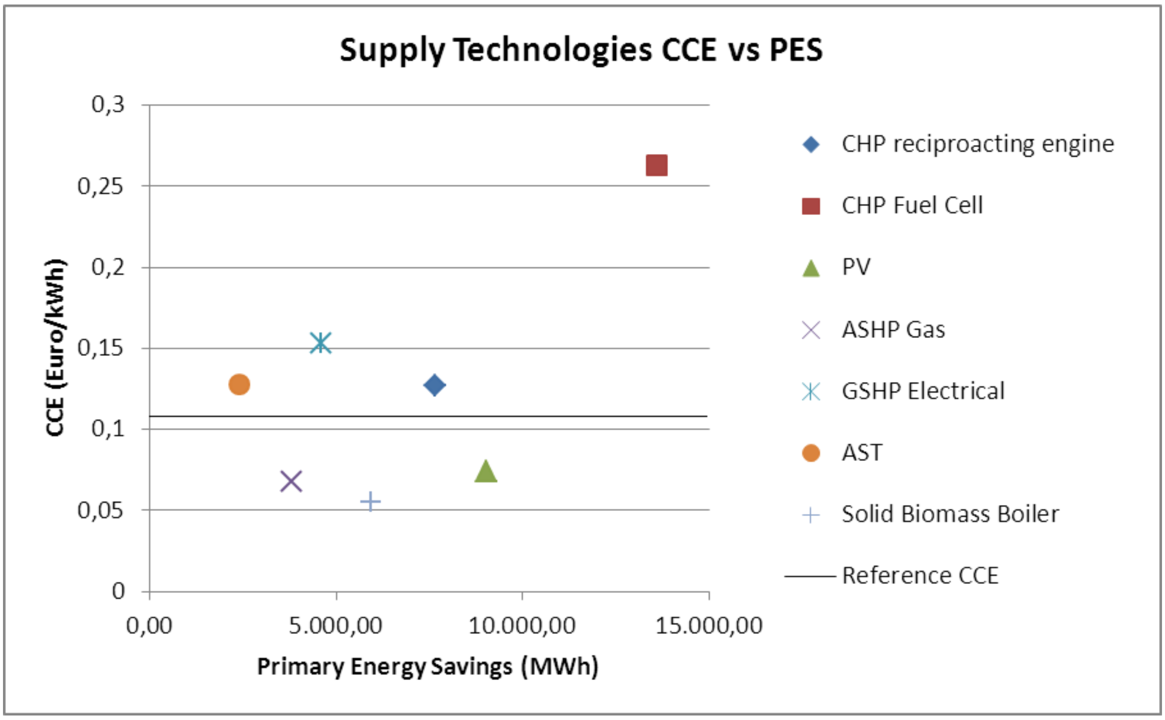

Figure 12.3 Supply technology plot with a +10% capital cost change.

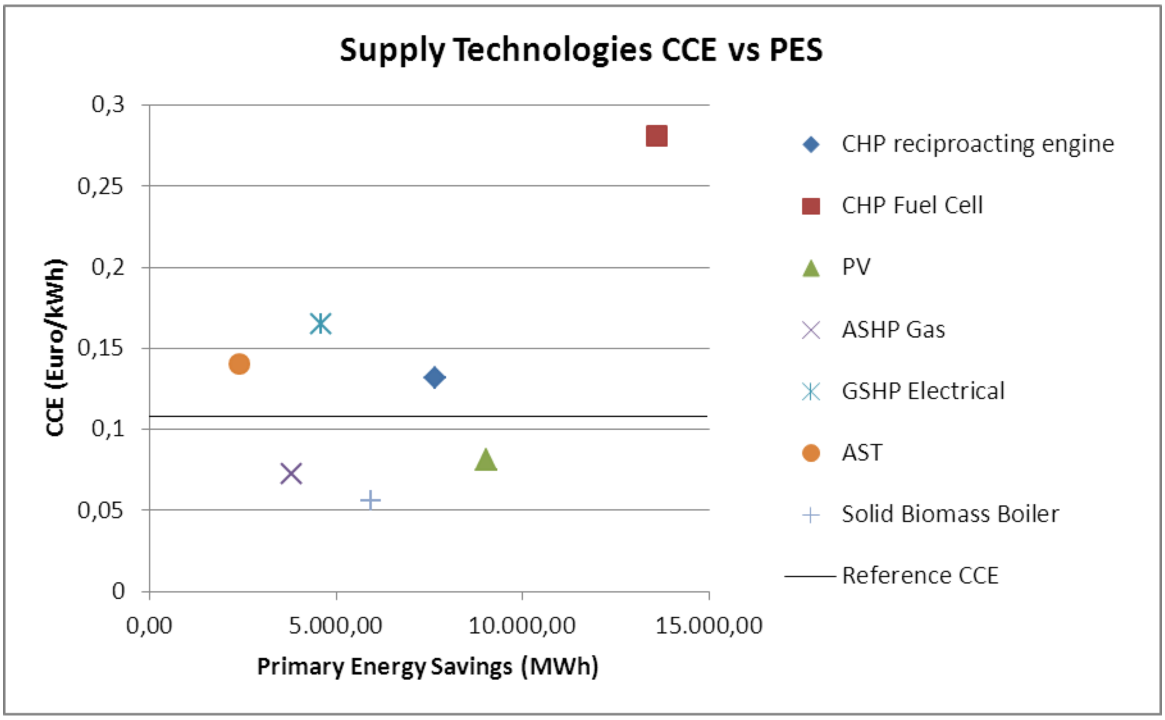

Figure 12.4 Supply technology plot for a +20% capital cost change.

12.2. Appendix D2: Fuel price sensitivity

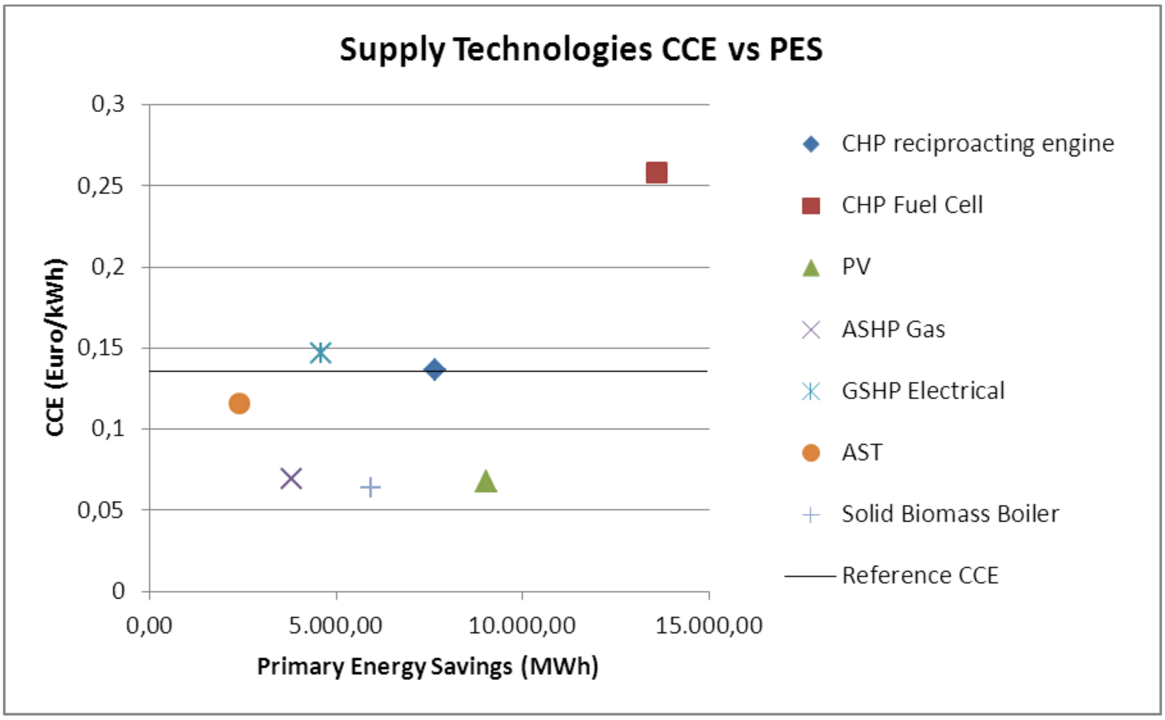

Figure 12.5 CCE plot with a 25% fuel price increase.

12.3. Appendix D3: Effect of varying insulation thickness

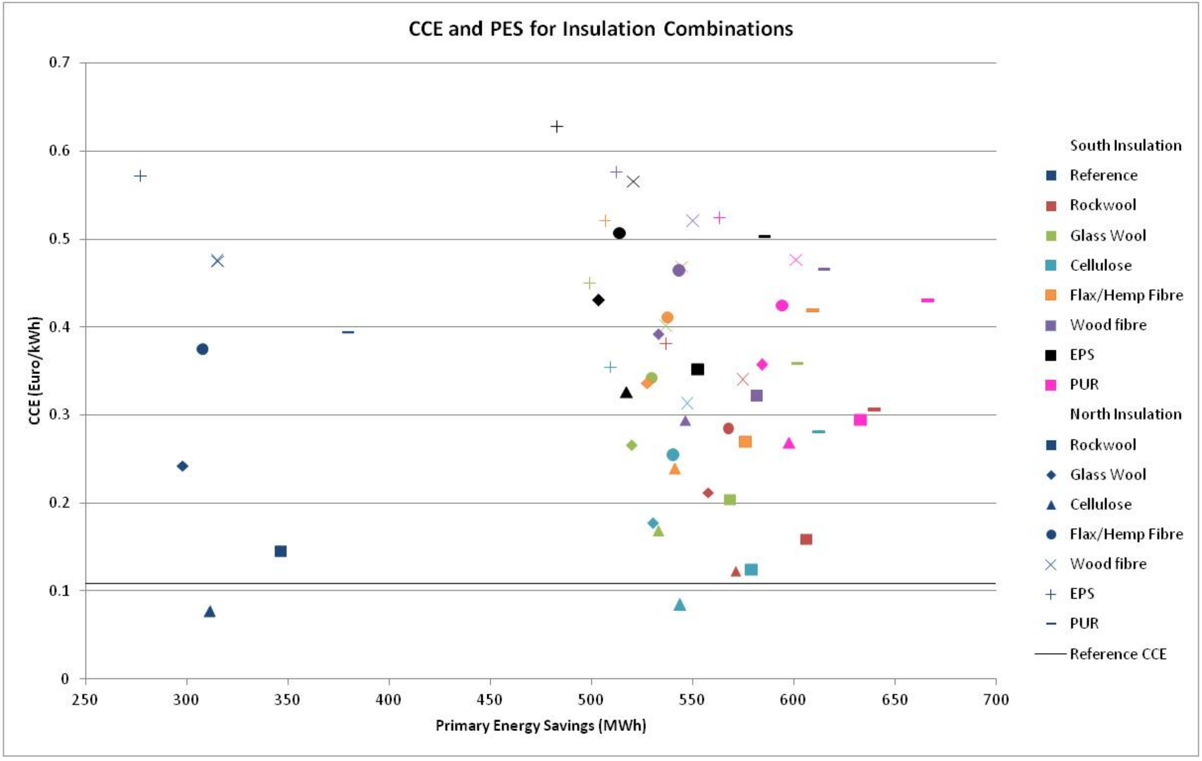

Figure 12.6 Additional insulation thickness 0.20 m.

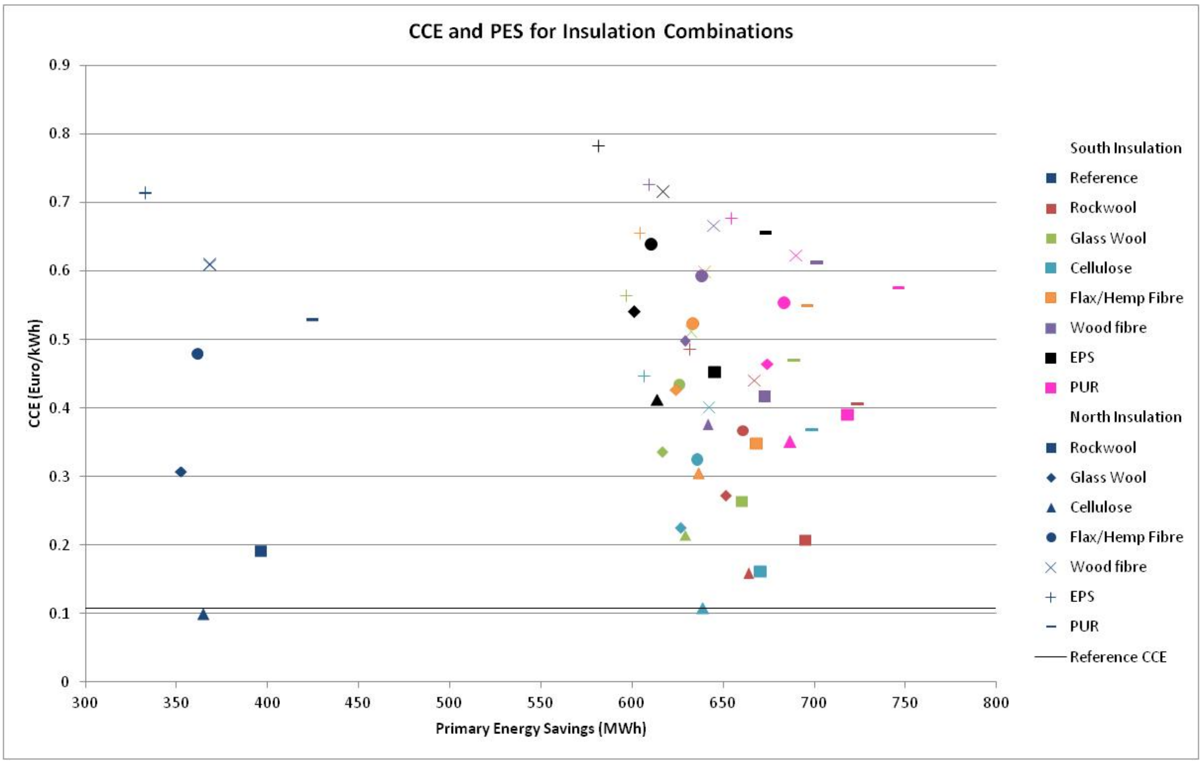

Figure 12.7 Additional insulation thickness 0.30 m.

13. Appendix E: SDE+ Sensitivity NPVs

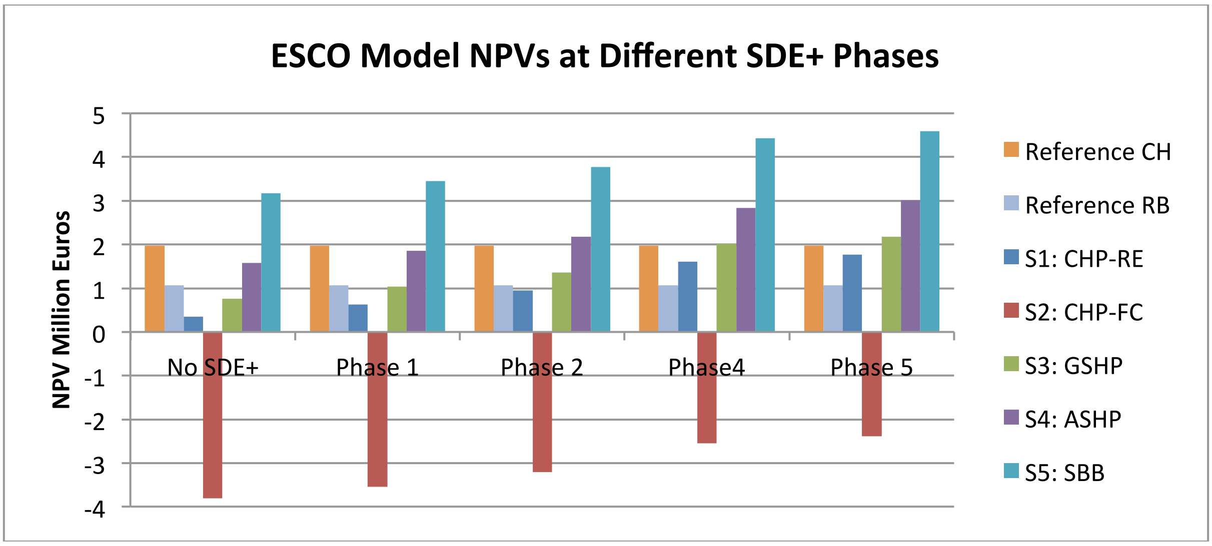

Figure 13.1: Plot of supply scenarios using ESCO model at all phases of the SDE+ subsidy.