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Theoretical Groundwork for a Database of Building Elements for Use in Renovation to Nearly Zero-energy Buildings

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Master i energi og miljø
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Theoretical Groundwork for a Database of Building Elements for Use in Renovation to Nearly Zero-energy Buildings

Kjetil Lindberg

Norwegian University of Science and Technology

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MASTER THESIS

for

Kjetil Lindberg

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Database of building elements for use in renovation to nearly zero-emission buildings

Database av bygningselementer til bruk ved rehabilitering til nær nullutslippsbygg

Background and objective

There is increasing demand for buildings with very high energy efficiency, both in new construction and refurbishment. It is expected that 80% of the current buildings will exist in 2050, and to reach the goal of reducing energy use in the building sector, the focus on refurbishment and renovation is highly important. Equally important is the ambition longer than passive house standard that is becoming legal requirement already today. However, there are few or no specific guidelines for design and refurbishment up the nearly zero emission buildings. Therefore, a project team has to preform analyzes of building elements and solutions for each project. Consequently, this may be time demanding and not efficient. Therefore, building industry may have advantage of a good database and guidelines for relevant building elements and solutions for use in such developments, particularly in rehabilitation to the nearly zero emission buildings. With the objective set by the Norwegian government about the nearly zero emission buildings in 2020 in mind, it is highly desirable to develop a good database and guidelines as a source for available and relevant technologies to achieve this standard.

Currently at Hellnes Consult, the student participates in a research project that aims to create a database of building elements and technologies for use in renovations to the nearly zero energy buildings. The database is being built based on the format of the NS 3451 (Construction Elements). The student will specifically focus on the part related to the building heating, ventilation, and heating and cooling supply. Low energy solutions have to be considered. Due to the projects related to the nearly zero emission standard, elements related to electricity production from solar cells will be necessary. Therefore, it will be beneficial to estimate what extent of the required on-cite electricity production and what technologies are available.

The aim of the project is to develop a database that will be available to the Norwegian building industry and that will be a tool for renovation to nearly zero emission buildings.

The following tasks are to be considered:

1. Literature review on the following topic would be necessary: national requirements, energy requirement standards, building technologies relevant for refurbishment to the nearly zero energy buildings.
2. Collect data and analyze the current use of solar cell technology in the building projects in Norway, considering their role in refurbishment to the nearly zero emission buildings.

3. Develop a database for building technologies and technologies where their energy performance and cost will be included.
4. Develop a representative building model for a typical office or residential building where the relevant technologies may be tested. IDA-ICE simulation tool may be used.
5. Analyse the developed database and the simulation results together and thoroughly.
6. Prepare material for a draft article.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 20. January 2016

Olav Bolland	Natasa Nord
Department Head	Academic Supervisor

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ABSTRACT

Approximately 80 % of today's building stock will still remain in 2050. With buildings accounting for 40 % of the total energy demand, it is important to continually improve their efficiency in order to meet the goals of minimising the demand for energy from fossil fuel. Some energy efficient building concepts are already defined in Norwegian standards, and passive house buildings have become of increased popularity in recent times. The next concept in line seems to be the near-zero energy buildings, or nZEB for short. This concept has yet to receive an official definition, however some recognised companies have created suggestions for the nZEB concept ion demand from the Norwegian government. This study aims to explore what this concept craves in terms of building constructional methods and energy delivery. Due to most of the buildings of the future already being built, this study will focus on rehabilitation of current buildings. This comes with additional challenges, both legislative and other physical restrictions, which means parameters such as existing building shape needs to be considered. The report presents information on common constructional methods and how to optimise the performance of these. Further exploration of insulation methods, energy production and heat sources are performed in order to study its effect on building energy performance. Through simulation in SIMIEN and THERM, data is gathered and studied in ordered to quantify some suggested restrictions for projects aiming to rehabilitate to nZEB. These results, combined with case- and literature study, provide a basis for reflection on whether nZEB is feasible in building rehabilitation, and if so, what requirements are set for the existing building. The results gathered in this report suggest that nZEB rehabilitation is feasible if certain requirements on building shape and availability of space for both on-site electricity production and a sustainable heat source are met. The study provides groundwork for further investigation of the nZEB concept and possibly the development of a database for building elements.

Sammendrag

Omtrent 80 % av dagens bygningsmasse vil bli stående i 2050. Dagens bygninger utgjør 40 % av den totale energibruken, det er derfor viktig å hele tiden forbedre energieffektiviteten dersom vi skal møte målene for minimalisering av behov for fossile brensler. Det finnes allerede noen definisjoner for energieffektive bygningskonsepter i norske standarder, og passivhus har økt i popularitet i senere tid. Det virker som nær-null energi bygg, forkortet nZEB (fra det engelske navnet near-zero energy buildings). Dette konseptet har ingen offisiell norsk definisjon, men noen anerkjente selskaper har publisert forslag til definisjon på oppdrag av den norske stat. Denne studien ønsker å utforske hva som kreves av dette konseptet i form av bygningsmetoder og energileveranse. Siden de fleste av fremtidens bygninger allerede er bygd, vil denne studien fokusere på rehabilitering av dagens bygg. Dette skaper ekstra utfordringer, både fra regelverk og andre fysiske restriksjoner, som gjør at parametere som bygningsform må betraktes. Rapporten presenterer informasjon om vanlige byggemetoder og hvordan en kan optimalisere deres energieffektivitet. Dypere undersøkelse av isoleringsmetoder, energiproduksjon og varmekilder er utført for å studere effekten dette har på bygningens energieffektivitet. Gjennom simulering i SIMIEN og THERM, blir data samlet og analysert for å kvantifisere noen foreslåtte restriksjoner for prosjekter som ønsker å rehabilitere til nZEB. Disse resultatene, kombinert med case- og litteraturstudier, skaper et grunnlag for refleksjon om nZEB er gjennomførbart i bygningsrehabilitering, og dersom det er tilfelle, hva kreves av den eksisterende bygningen. Resultatene samlet i denne rapporten tyder på at nZEB rehabilitering er mulig dersom visse krav til både bygningsform og tilgengelig plass til elektrisitetsproduksjon og bærekraftig varmekilde møtes. Denne studien vil kunne skape et grunnlag for videre studier av nZEB konseptet og også åpner for muligheten til å utvikle en database av bygningselementer.

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List of Abbreviations and Acronyms

A/V	-	Area to volume
AAC	-	Autoclaved aerated concrete
COP	-	Coefficient of performance
DIBK	-	National office of building technology and administration
EEA	-	European Economic Area
EPBD	-	Energy performance of buildings directive
EPS	-	Expanded polystyrene
ETC	-	Evacuated tube collector
EU	-	European Union
FPC	-	Flat plate collector
LECA	-	Lightweight Expanded Clay Aggregate
nZEB	-	Nearly Zero-Energy Building
NZEB	-	Net Zero-Energy Building
PPMC	-	Pearson Product-Moment Correlation
PUR	-	Polyurethane foam
PV	-	Photovoltaic
VIP	-	Vacuum insulation panels
XPS	-	Extruded polystyrene

LIST OF APPENDICES

1 INTRODUCTION

It is estimated that approximately 80 % of today's building stock will remain standing in 2050 (Enova, 2014). Today, buildings account for 40 % of the total energy consumption in the European Union (EU, 2010). With an increasing population (Eurostat, 2015), the need for new buildings can only increase – and energy consumption with it. As the EU remains adamant reduce both its dependency on energy, and greenhouse gas emissions with it, reducing the consumption of the building sector remains an important measure to meet this objective. Legislation on building energy demand have become increasingly strict in recent years, which generates increased challenges in rehabilitation projects. This study aims to explore what is required in such rehabilitation projects in order to meet the future standards – near zero energy buildings.

1.1 Background for Study

In May 2010, the Energy performance of buildings directive recast (EPBD recast) (EU, 2010) was presented by the EU, and came into force in July the same year. The directive demanded that all new buildings should be nearly zero energy buildings (nZEB) by 31 December 2020, however all new buildings occupied and owned by public authorities should meet these requirements by the end of 2018. While this directive purely address new construction, its principles and intent could be implemented when performing building refurbishment.

In order to meet these requirements, the member states had to adopt and publish the laws, regulations and administrative provisions necessary to comply with the articles in this directive by 9 July 2012. While Norway is not a member of the EU, this directive could be relevant to the European Economic Area (EEA) and will therefore be implemented into Norwegian law (Killingland et al., 2013). By 15 June 2012, the Norwegian government released two statements regarding climate (Miljøverndepartementet, 2012) and buildings (Kommunal- og regiondepartementet, 2012), which established that all new buildings in Norway is required to meet passive house standards by 2015 and nZEB standards by 2020.

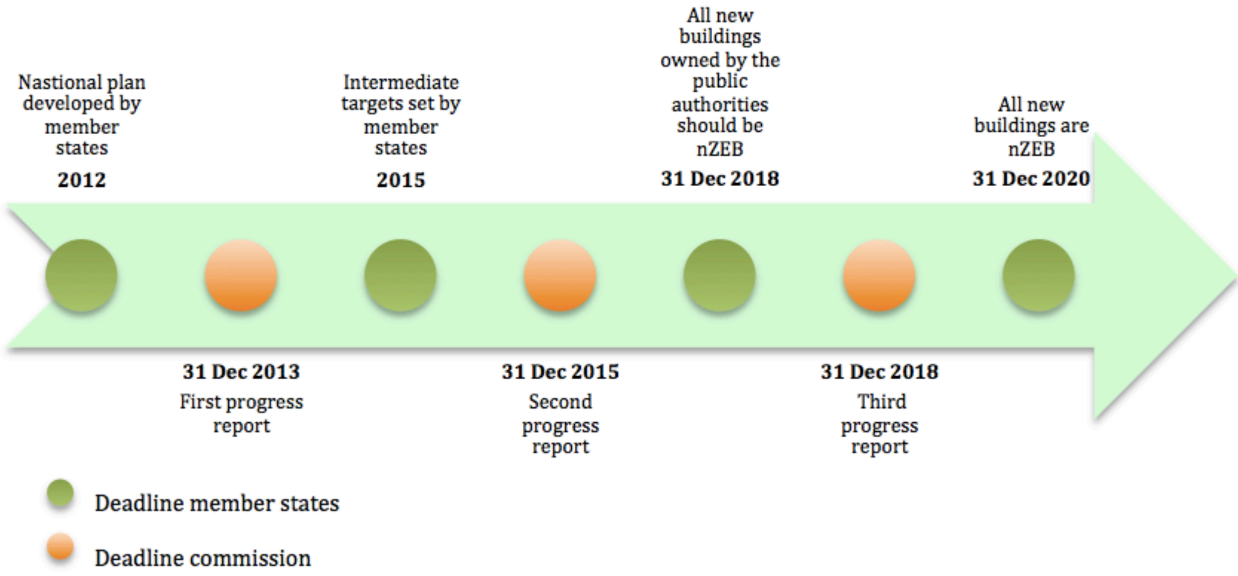


Figure 1.1: Progression plan towards nZEB in Europe (Killingland et al., 2013)

1.2 Implementation of EPBD Requirements in Norway

After adopting the directive in 2010, the Norwegian government obliged to follow the 31 articles listed in the EPBD – articles that promote the improvement of the energy performance of buildings. The directive presents requirements as regards to the establishment of a framework for a methodology for calculating a buildings energy performance, application of minimum requirements for energy performance of new buildings, as well as existing buildings subject to major renovation, plans to increase the number of nZEB, energy certification of buildings, and regular inspection of heating and air-conditioning systems. However, these requirements remain superficial in their formulations, as for the member states to define these according to their situation and climate.

From Article 3 (EU, 2010): "Member States shall apply a methodology for calculating the energy performance of buildings in accordance with the common general framework set in Annex I. This methodology shall be adopted at national or regional level."

Article 3 (cited above) order member states to develop a methodology for calculating energy performance in accordance with the framework given in the first annex of the directive. This annex describes a variety of factors and categories that any such methodology should contain. Already in 2010, a methodology was presented by *Norsk Standard*, which is an independent organisation, and the Norwegian member of both the European and the international organisations for standardisation. The developed methodology was published as: *Norwegian national standard for calculation of energy performance of buildings – NS 3031.* The national standard is used to evaluate energy performance and to show compliance with Norwegian building regulations (TEK).

From Article 9 (EU, 2010): "The national plans shall include (…) intermediate targets for improving the energy performance of new buildings, by 2015"

In June 2012 the Norwegian government released a statement (Kommunal- og regiondepartementet, 2012), which announced that by the end of 2015, all new buildings must comply with a new energy standard. This standard is adapted from the German passive house definition developed by the *Passivhaus Institut.* The standard was divided into two different documents – *NS 3700* for residential buildings and *NS 3701* for commercial buildings. The Norwegian definition of the passive house is adapted to the local climate and establishes certain requirements in regards to the building's energy performance.

From Article 9 (EU, 2010): "Member States shall ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings"

Despite the requirement set by the EPBD, as of November 2011, less than half of EU's member states had a definition of nZEB – including Norway, which has yet to present an official definition. However, the EPBD provide a generic framework for the development of such a definition:

> *"nearly zero-energy building means a building that has a very high energy performance (...). The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"*

While there is no official standard or definition describing the concept of nZEB, Rambøll were asked by the *National Office of Building Technology and Administration* (DIBK) to develop a suggestion for a national definition of nZEB – resulting in a 69-page report in 2013 (Killingland et al.).

2 BUILDING ENERGY USE AND REGULATIONS

2.1 Norwegian Building Regulations (TEK)

> *"Regulations regarding technical requirements for buildings draw the border for the minimum of attributes a building must have in order to be raised legally in Norway." (DIBK, 2010)*

Any building constructed on Norwegian soil must meet the requirements set by TEK, which aims to secure that any measures are adequately planned, projected, and executed with regards to good visual quality, universal design and so that the measure meets technical requirements for security, environment and energy (DIBK, 2010).

This report will only consider the chapter regarding building energy. TEK07 (2007) is the first version to present upper limits for total net energy demands. Previous versions would have requirements for building fabric heat transfer coefficients (U-values). The limit for building heating energy demand, should then be calculated as the combination of transmission heat loss (from U-values), loss due to air infiltration, and stated reference temperature. TEK07 and TEK10 contain upper limits for both U-values, and total net energy demand for major building categories.

Table 2.1: Energy demand limits for relevant building categories

Building Category	**Total Net Energy Demand [kWh/m2 heated GIA* per year]**		
	TEK07	TEK10	TEK10 (2016)
Apartment building	120	115	95
Kindergarten	150	140	135
Office Building	165	150	115
School Building	135	120	110

*Gross Internal Area

Table 2.2: Upper limits for building fabric U-values

Building Fabric	**Upper Limit for U-value [W/m² K]**	
	TEK99-03	TEK07 & 10
Outer Walls	0.22	0.18
Glass/Windows/Doors (incl. frame)	1.6	1.2
Roofs	0.15	0.13
Floors Above Unheated Spaces	0.3	-
Floors Adjoined to Ground	0.15	0.15

1.1.1 Soon-to-come Building Regulations

Despite the government's announcement that all new buildings will comply with the standard set for passive houses by the end of 2015, the new regulation have been pushed back from TEK15 to TEK17, meaning that the regulation will not come into force before 2017. This regulation will be developed in collaboration with the Norwegian building sector in order to deliver a regulation that will contribute to the reduction of building costs, and be simpler to understand (DIBK, 2015). Based on the previous announcements by the Norwegian government, it is expected that this regulation will be based on the standard for passive houses (NS 3700 & NS3701).

2.2 Influencing Factors on Building Energy Demand

When analysing the energy demand of a building, it is important to consider the different factors that contribute to the total energy demand of the building. These factors can be separated into two main categories: technical and physical factors, and human influenced factors. These categories can be divided into further six categories as shown in Figure 2.1. The ratio of energy demand between the categories will vary in every building, but no category will ever be completely absent.

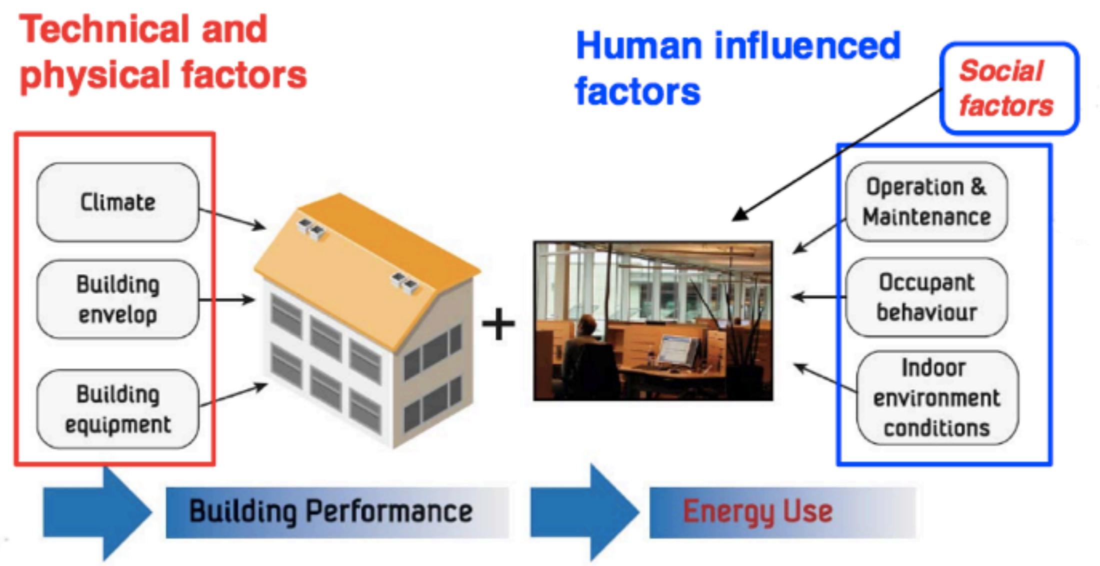


Figure 2.1: Influencing factors on building energy demand (Nord, 2015)

The *climate* has a major impact on the buildings heating- or cooling demand. In cold climates, such as Norway, the building heating demand will be significantly higher than an identical building placed in for example southern California. The effect from climate is either reduced or enlarged by the building *envelope*, as the building fabric's properties determine the heat loss from the internal space. These two factors are heavily linked and are important data to analyse, which is why this report focuses on data studies within these factors. The last category to make up the group of technical and physical factor is the *building equipment*. For example, a building with a modern efficient ventilation system will consequently demand less energy than a similar building with out-dated ventilation systems. The other category, human influenced factors, also have considerable contribution to the total building energy demand. *Operation and maintenance* explains how the building systems behave during operation, and how well maintained the systems are. For example, if the ventilation system is left on full power at all times, the building suffers from poor operation, as the ventilation system requires energy at times where it is unnecessary. Maintenance is also very important as to make sure that all equipment runs as efficient as possible. Even though they may have no access to the building's operational systems, the *occupants' behaviour* can have a significant impact on the building's energy demand. Leaving computers or lights on overnight may cause a considerable rise in energy use, especially if a large portion of occupants employs this type of wasteful behaviour. Closely related to occupant behaviour are the indoor environment conditions, as the occupants often are in control of this. Factors such as indoor temperatures and lighting levels are often adjustable by the user, and can cause large increases in energy demand if not considered carefully.

This report will touch upon all of these factors either during the data analysis or in a case study. However, due to availability and relevance to building regulations, the building fabric and climate will be subject for data analysis.

Building Fabric Design

In a cold climate like Norway, the building fabric design is especially important as it can drastically reduce the required energy for space heating. With this being a large factor in the building's total energy use, Norwegian legislation has criteria for building fabric performance. As a consequence, the U-value of the building elements become extremely relevant for further analysis and will more than likely by a key criteria in future building legislation. Therefore, investigating the connection between fabric U-values and energy demand could help estimations of future requirements for building construction.

Climatic Variations

Norway may not be considered a large country, but it is definitely long, spanning over 13 latitudes and with a vast coastline. Due to its shape and location, the Norwegian climate can vary considerably across different areas of the country. These variations could have significant impacts on the energy use of buildings, and needs to be taken into consideration when setting limits for energy demand. This study will concentrate on Oslo, as this is set as the base case in theoretical groundwork done by SINTEF (2012). The legislation would have to be regulated in order to accommodate the vast differences in climate across Norway. As can be seen in Figure 2.2, Norway has a number of climatic zones with varying temperature profiles – suggesting building location is a considerable factor in the total energy demand.

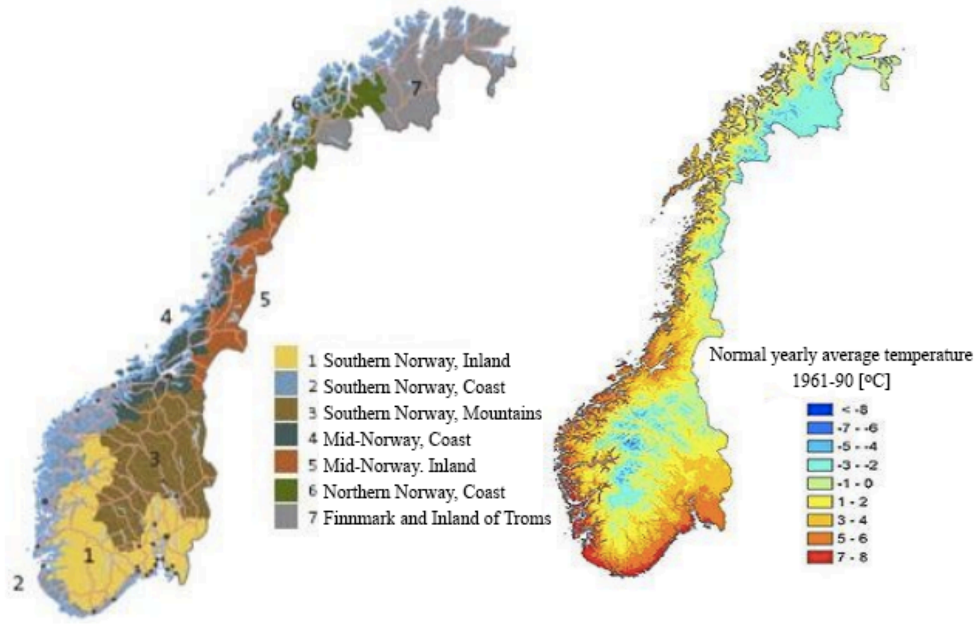


Figure 2.2: Norwegian climatic zones and their yearly average temperature (Enova, 2010)

2.3 Nearly Zero-Energy Buildings

The concept of a nearly zero-energy building is derived from the concept of a net zero-energy building (NZEB), which is typically grid connected with a very high energy performance. A net zero-energy building will balance the primary energy use so that the building's primary energy exported to the energy network is equal to the primary energy delivered to the building. This balance can be shown as a simple equation of weighted parameters (Sartori et al., 2012; Kurnitski et al., 2011).

$$E = \sum_{i} (E_{del,i} - E_{exp,i}) f_i = 0 \qquad (2.1)$$

The balance equation (2.1) presents net delivered energy as delivered energy ($E_{del,i}$) minus exported energy ($E_{exp,i}$) accounted separately for each energy carrier (i). Primary energy (E) is then calculated with the primary energy factors (f_i). Weighting factors will be addressed in chapter 2.3.2. In order to meet the criteria for a NZEB, the building would therefore be required have energy production on the property.

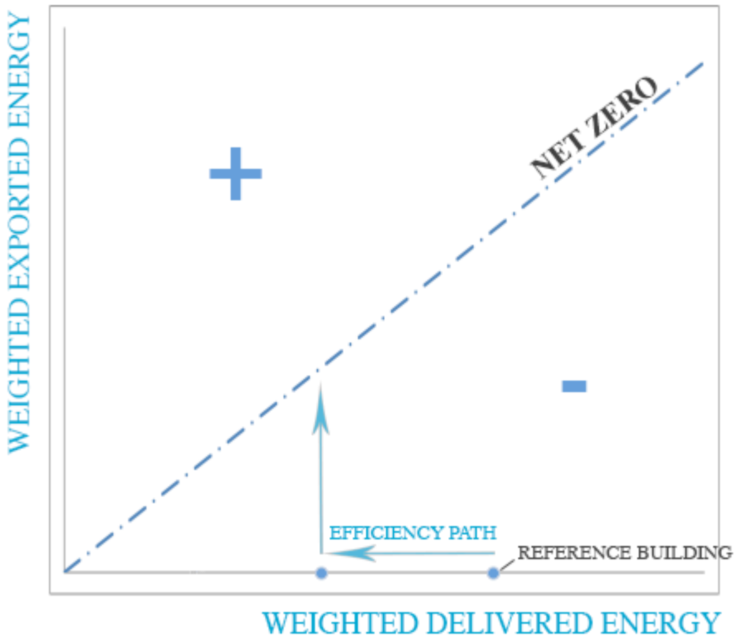


Figure 2.3: Visual representation of the NZEB concept

Figure 2.3 shows a visual representation of this balance – with the building's total weighted energy use along the horizontal axis and the weighted generated energy along the vertical axis. The area in the lower right represents buildings with a larger demand than production (net primary energy > 0 kWh), and buildings located in the upper left would have a more energy production than demand (net primary energy < 0 kWh). The reference building plotted in the figure represents a typical building by today's standards, with no on-site energy generation and a relatively high weighted energy use. In order to move a building towards NZEB, it would be beneficial to first move along the *efficiency path*. The efficiency path represents measures taken in order to improve the energy efficiency of a building, and thereby lower its weighted energy demand. By doing so, the building would require less energy production in order to satisfy the balance presented in eq. 2.1, represented in the figure as the dotted line.

The nearly net zero-energy building would be in the lower right region of Figure 2.3, however as the name suggests, it would have to be near the net zero line. Contrary to the net zero-energy building, the nZEB should not be required to satisfy eq. 2.1, but rather eq. 2.2 below.

$$\boldsymbol{E} = \sum_{i} (\boldsymbol{E}_{del,i} - \boldsymbol{E}_{exp,i})\boldsymbol{f}_i > \mathbf{0} \qquad \textbf{(2.2)}$$

However, satisfying 2.2 is not the defining factor of nZEB, rather a license to operate with a negative net energy production. This would suggest that on-site energy production is not a definite requirement – however nZEB is classified as a *very high energy performance* building (EU, 2010) which in any case requires significant energy saving measures. In general terms, nZEB would require either:

$$\boldsymbol{E}_{del} \ll \boldsymbol{E}_{del,ref} \textbf{ and } \boldsymbol{E}_{exp} = \mathbf{0} \qquad \textbf{(2.3)}$$

or

$$\boldsymbol{E}_{del} \leq \boldsymbol{E}_{del,ref} \textbf{ and } \boldsymbol{E}_{exp} > \mathbf{0} \qquad \textbf{(2.4)}$$

where

E_{del} is the total weighted delivered energy to the nZEB

$E_{del,ref}$ is the total weighted delivered energy to the reference building

E_{exp} is the total weighted exported energy from the nZEB

Since no exact definition have been given by the EPBD, the specific values for the net primary energy demand has been left for the member states to customise according to their climate and legislation.

2.3.1 System Boundary and the Balance Concepts

As visualised with Figure 2.3, eq. 2.1 can be solved in a multitude of ways. In order to appropriately calculate the net primary energy demand, a suitable system boundary must therefore be established. The boundary is used to compare energy flows in and out of the system. The system boundary of a building includes (Sartori et al., 2012):

- *Physical boundary*: encompasses the building (or a group of buildings) and determines whether energy production is 'on-site' or 'off-site'.
- *Balance boundary*: determines the kinds of energy uses are included in the balance (i.e. heating, cooling, ventilation).

The EPBD (EU, 2010) does not establish a set balance boundary, but does set some minimum requirements in its second article (*Definitions*):

> *"energy performance of a building means the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting"*

This definition of energy performance helps to understand the first sentence of the EPBD definition of nZEB – *"nearly zero-energy building means a building that has a very high energy performance(...)"*. The definitions does not explicitly state whether electronic appliances should be included in the balance boundary, however all other major energy flows are obligatory to be included.

There are different methods for calculating the balance of a building, such as the one shown in the previous chapter (eq. 2.2). This type of balancing is called an *import/export balance* and requires an estimation of self-consumption if used in the design phase. Since few building codes require calculations for estimated self-consumption during the design phase, estimations of delivered and exported amounts remain largely unavailable. In most cases, data on end users temporal consumption patterns (i.e. electrical appliances, hot water, lighting) are absent and only values for load and generation can be obtained. Therefore a *load/generation balance* is used instead:

$$\boldsymbol{E} = \sum_{\boldsymbol{i}} (\boldsymbol{E}_{\boldsymbol{load},\boldsymbol{i}} - \boldsymbol{E}_{\boldsymbol{gen},\boldsymbol{i}}) \boldsymbol{f}_{\boldsymbol{i}} \qquad \textbf{(2.5)}$$

In such a balance, the overlook of the interactions between generation systems and loads is equivalent to assume that, per each carrier, the load is entirely satisfied by delivered energy and generated energy is entirely fed into the energy networks (Sartori et al., 2012).

The time span for calculating energy balance is almost implicitly a calendar year, however a balance can be calculated based on monthly values of generation and load, where only the residuals are accumulated in order to display the annual totals. This approach may be considered a monthly load/generation balance or a special case of import/export balance where a 'virtual monthly self-consumption' is assumed (see Figure 2.4). This balance is calculated by eq. 2.8, substituting eqs. 2.6 and 2.7:

$$\boldsymbol{E}_{\boldsymbol{gen},\boldsymbol{m},\boldsymbol{i}} = \sum_{\boldsymbol{m}} \mathbf{max}\,[\mathbf{0}, \boldsymbol{E}_{\boldsymbol{gen},\boldsymbol{m},\boldsymbol{i}} - \boldsymbol{E}_{\boldsymbol{load},\boldsymbol{m},\boldsymbol{i}}] \qquad \textbf{(2.6)}$$

$$\boldsymbol{E}_{\boldsymbol{load},\boldsymbol{m},\boldsymbol{i}} = \sum_{\boldsymbol{m}} \mathbf{max}\big[\mathbf{0}, \boldsymbol{E}_{\boldsymbol{load},\mathbf{m},\boldsymbol{i}} - \boldsymbol{E}_{\boldsymbol{gen},\boldsymbol{m},\boldsymbol{i}}\big] \qquad \textbf{(2.7)}$$

$$E = \sum_{i} (E_{load,m,i} - E_{gen,m,i}) f_i \qquad (2.8)$$

where *m* stands for the month

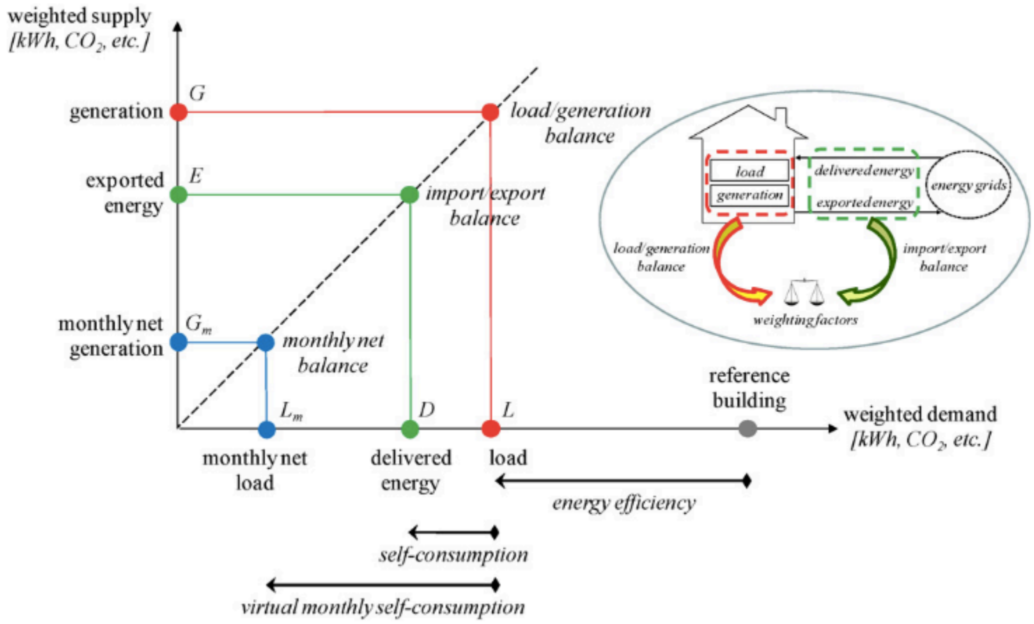


Figure 2.4: Graphical representation of the three types of balance (Sartori et al., 2012)

The three balance concepts are coherent with each other – meaning that when applied to the same case, they will give the same net balance. As demonstrated in Figure 2.4, the three points lie on a straight line in a 45^{o} angle, however not necessarily passing through the origin, as this implies a net zero balance.

Self-consumption from energy from on-site renewables is treated differently between the balances, and can be seen as either an energy efficiency measure or a supply measure. In the load/generation balance, it is considered a part of the generation, increasing the weighted supply and would move the point up parallel to the y-axis of Figure 2.4. An import/export balance instead considers the renewable energy production an energy efficiency measure, thereby reducing the weighted demand and moving the point downward the x-axis instead.

2.3.2 Weighting Factors

Weighting factors play an important role in the energy balance concepts and are used to compare energy carriers. Different sources of delivered energy have varied losses in the energy chain (i.e. conversion, transmission), and therefore should be weighted differently. These factors help creating a comparable value for each energy carrier and aim to encourage the use of renewable sources by increasing the non-renewables' impact on the energy balance. There are several metrics used as weighting factors, but the four primary are: primary energy, CO_2, site energy and energy cost. Despite the EBPD (EU, 2010) stating that primary energy factors are to be used when determining whether a building is nZEB, Norway prefer the use of CO_2 emissions as a weighting factor. The difference being that primary energy factors give a number related to system efficiency, while CO_2 gives an indication of the carbon emissions from that specific energy carrier.

2.3.3 Suggestion for a Norwegian Definition

This report will consider the suggestion presented by Rambøll, in their 2013 report (Killingland et al.), in addition to a later proposal by Futurebuilt (Andresen et al., 2016) as the Norwegian definition of a near zero-energy building. The latter document is largely derived off the first, however it provides concrete energy goals for a selected few building categories. While this is not an official definition, the first report was produced on demand of the government and thoroughly investigates the framework of nZEB in Norwegian conditions.

Temperature, solar radiation and wind are among the factors that greatly affect a building's energy demand and potential for on-site generation. Norway's climate varies greatly as the country spans more than 13 latitudes (Killingland et al., 2013). In order to realise nZEB in a cost-effective manner, the requirements should also be adjusted according to local climate, as has been done in the standards for passive houses (NS 3700/3701).

nZEBs will more than likely interact greatly with nearby energy networks, but should aspire towards low impact on regulation needs in the system. Flexible energy production, storage and smart grids will be essential in realising nZEB on a large scale. Measures to increase production for local- or self-consumption could be incentivised in order to reduce traffic onto the grid.

The EPBD stress the importance of production from local renewable sources as well as production on-site. In order to properly categorise these sources, the following system boundaries and hierarchy is proposed:

Table 2.3: System boundaries and hierarchy for renewable energy production on- or off-site

Level	Energy Production Options	Examples
0	Reduce demand through low-energy technologies	Insulation, daylight optimisation, highly effective HVAC systems, thermal mass
Energy production on-site		
1	Renewable energy production on the building's footprint	PV-panels, solar thermal energy, small-scale wind turbines
2	Renewable energy available on-site	PV-panels or solar thermal energy placed on the ground or on supports, small-scale hydro turbines, free standing wind turbines
Energy production off-site		
3	Renewable energy gathered off-site, but converted on-site	Biomass, pellets etc. converted to electricity and/or heat
4	Purchasing of off-site renewable energy directly used for appliances or heating	Renewable energy from energy companies, i.e. energy with certificate of origin

System boundary for local energy production will differentiate between electricity and thermal energy production. Local electricity production comprises level 1-3, meaning that the production/conversion should happen on-site, but could be based on renewable fuels imported across the physical boundary of the system. Local thermal energy should in addition encompass district heating.

As an indicator of energy performance, weighted net delivered energy will be used, meaning an import/export balance will be the main calculation method, which allows exported electricity to be taken into consideration. However, the report recommends that only thermal energy towards self-consumption is to be regarded, meaning thermal energy production is only considered an energy efficiency measure as per import/export balance methodology.

The building fabric of nZEB should underpin the intention of a high energy performance building, and fabric elements equal to those of a low-energy building, or alternatively passive houses as described in NS3700/3701, should be the minimum requirements. This will create a natural evolution from the intermediate goal set by the Norwegian government, to be presented in TEK17, which is based on the same standards.

The balance boundary should include all energy consumption tied to the operation of the building, including electrical appliances. In nZEB, embodied energy could make up a considerable portion of the total energy use throughout its lifetime. Embodied energy is the total energy used to produce and transport the material used in the building. This energy is currently not considered in energy calculations, but the report proposes that this is gradually incorporated into the energy requirements starting 2020.

A superordinate definition is proposed for nZEB:

> *"Nearly zero-energy buildings in Norwegian conditions should have 70 % lower energy demand than TEK10 (current regulation level). Energy use is calculated as net delivered energy to the building. Energy deliverables are weighted in accordance with their impact on climate or ratio of renewables." (Killingland et al., 2013)*

This definition implies that a nZEB is located in the area between the net zero line as presented in Figure 2.3, and a parallel line with the same gradient shifted along the x-axis to cross at 30 % of TEK10 levels – presented as the sky blue area in Figure 2.5.

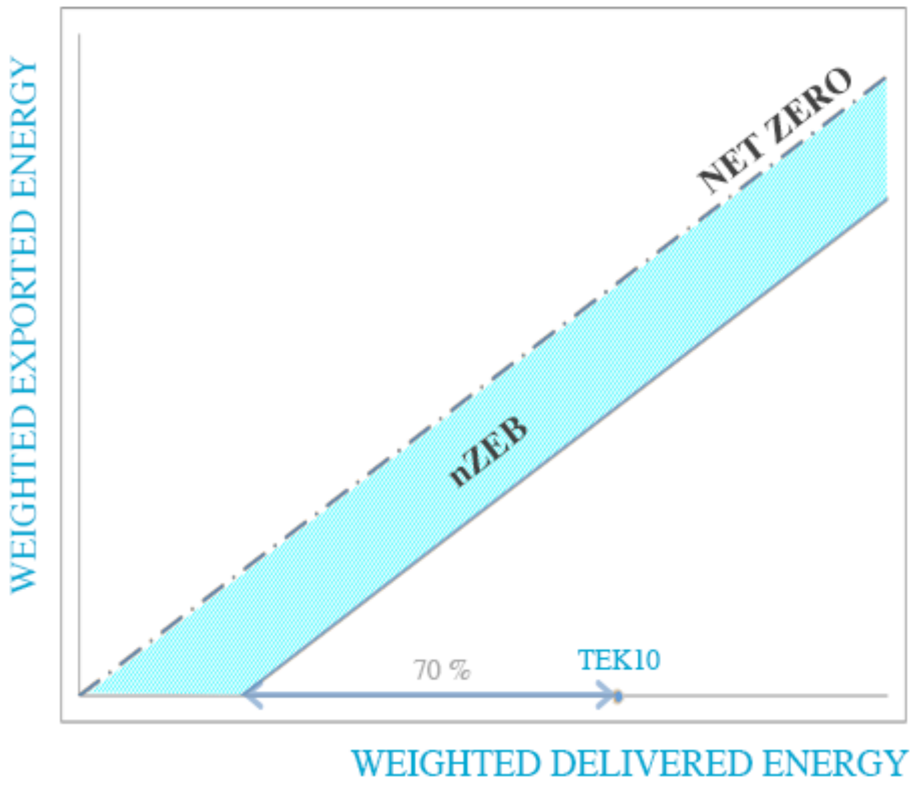


Figure 2.5: Graphical representation of the superordinate nZEB definition

In addition to this superordinate definition, Futurebuilt has suggested energy demand limits for some building categories (Andresen et al., 2016), and is presented in Table 2.4 below. The values are compared to the energy levels that applied when the Rambøll report was produced in 2013 – values that since have been altered.

Table 2.4: nZEB energy requirements as suggested by Futurebuilt

Building Category	Weighted delivered energy [kWh/m²]	Reduction compared to TEK10 [%]
Apartment building	40	65.2 %
Kindergarten	35	75.0 %
School	35	70.8 %
Office building	40	73.3 %

This report also provides energy factors for grid electricity, district heating and bio heating, as presented in Table 2.5. These factors will allow buildings to properly estimate their weighted energy demand, when determining whether demand is sufficiently low.

Table 2.5: Energy factors for heating

Energy carrier	Energy factor
Electricity	1.0
District heating	0.43
Bio	0.37

Considering the strict weighted delivered energy values as provided in Table 2.4, these factors will have considerable impact on a building's ability to achieve nZEB status, and can drastically reduce the amount of required on-site energy production.

3 METHOD

While the initial aim was to begin the assembly of a database of building elements, due to lack of available collective information on nZEB rehabilitation the study evolved into a theoretical groundwork. This will provide the basis for further studies and possibly the assembly of such a database. The study began with a comprehensive literature study of the three main subjects: building energy, façade construction and energy sources. Once sufficient information was gathered on these subjects they were further explored in manners appropriate for each subject. Building energy demands were explored through SIMIEN simulations and case studies of energy efficient building projects. The data from the SIMIEN simulations were then analysed for trends and correlations in order to determine what factors should be considered of high importance when planning a nZEB rehabilitation project.

Façade construction is an important subject due to the poor quality of older buildings' building envelopes. This study investigates constructional methods and the approaches for adding additional insulation on common wall types. Additionally, simulations in THERM are done to study the effect on heat flow and temperature distribution in building elements from different insulation methods.

Energy sources remain a significant factor due to the likely requirement of on-site energy production in nZEB projects. Sustainable heating sources and their advantages are presented and the data from SIMIEN simulations are used to show their impact on building heating demand. Additionally, solar-based production in the shape of PV and thermal collectors are presented as valuable options for further energy demand reduction.

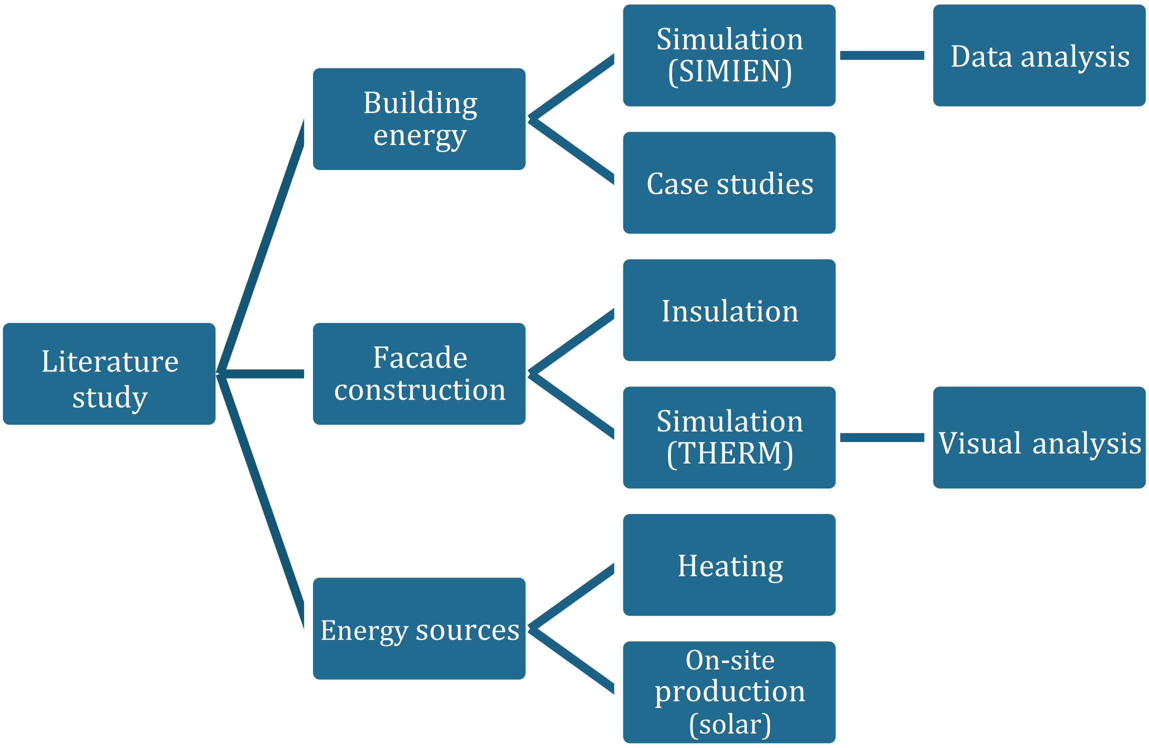


Figure 3.1: Method breakdown

3.1 SIMIEN

SIMIEN is a Norwegian simulation tool for calculation of energy use and consideration of the internal climate of buildings. It is used to evaluate buildings in accordance with building regulations, energy grading, calculate yearly- or seasonal energy demand, validation of indoor climate criteria, and dimensioning of heating, ventilation and cooling.

All building fabric elements are described by dimensions and properties, creating zones of which are calculated in 15-minute intervals during simulation. This study focuses on the yearly simulation in order to calculate the building energy demand and its distribution between the energy posts. Also, these simulations also reveal the required dimensions of the heating sources and the ratio of heating demand it covers – which is used when comparing the available heat sources. The program is widely used by businesses as well as SINTEF in their theoretical groundwork.

3.2 THERM

The THERM website describe the tool as “a state-of-the-art computer program developed at Lawrence Berkeley National Laboratory (LBNL) for use by building component manufacturers, engineers, educators, students, architects, and others interested in heat transfer. Using THERM, you can model two-dimensional heat-transfer effects in building components such as windows, walls, foundations, roofs, and doors; appliances; and other products where thermal bridges are of concern. THERM's heat-transfer analysis allows you to evaluate a product’s energy efficiency and local temperature patterns, which may relate directly to problems with condensation, moisture damage, and structural integrity. THERM’s two-dimensional conduction heat-transfer analysis is based on the finite-element method, which can model the complicated geometries of building products.”

In this study THERM is used to visually analyse the difference between external- and internal insulation of facades. The temperature distribution and heat flux will reveal thermal bridging in these elements and visually present the effect of insulation and construction methods.

3.3 Data Correlation Analysis

In order to measure correlation between the data, the Pearson product-moment correlation (PPMC) is used. This is the most common measure of statistical correlation, and is a measurement of linear association between to sets of values. This is done by calculating the Pearson product-moment coefficient for the two sets of values, $\{x_1,\dots,x_n\}$ and $\{y_1,\dots,y_n\}$, and is given by:

$$\boldsymbol{r = \frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\overline{x})^2\sum_{i=1}^{n}(y_i-\overline{y})^2}}} \tag{3.3}$$

The resulting value from eq. 3.3 lies between -1 and 1, where the two extremes represent negative and positive total correlation respectively. The closer to zero the r-value gets, the greater the deviation from the line of best fit. An r-value of 0 would suggest no linear correlation, however any extremes (-1, 0 or 1) are exceptionally rare – meaning a conclusion on whether the data is linearly correlated can seldom be done without further investigation.

When deciding whether the data can be considered correlated, a hypothesis test can be done based on the r-value calculated from eq. 3.3. The test concludes on whether there is statistical significance (α). Most commonly a significance of 0.05 (5 %) is used. Statistical significance is achieved when the p-value is lower than the significance level. The p-value is the probability of finding the observed, or more extreme results, given that the null hypothesis is true. The test is based on the rejection or acceptance of the null hypothesis, which is the default position that there is no relationship between the datasets. The test is done in the following manner:

1. Calculate the Pearson r-value of the datasets
2. Find the degrees of freedom by subtracting 2 from the sample size and look up the critical r-value (r_c) from the table (Taylor & Francis, 2014)
3. If the absolute value of the r-value exceeds the tabulated critical value, the null hypothesis may be rejected (see Figure 3.2).

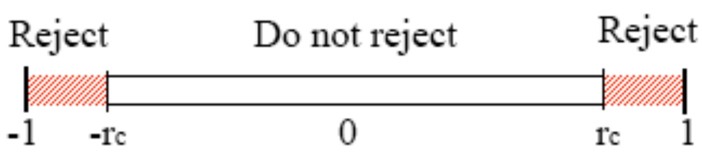


Figure 3.2: Graphical representation of a hypothesis test

4 Strategy For Choosing Energy Saving Measures in Refurbishment

When refurbishing a building with the aim of significantly reducing its energy demand, a sound strategy of prioritisation is necessary. There are vast amounts of solutions and opportunities for energy saving measures, however both financial resources and time are usually limiting. In order to achieve the goal of optimal energy efficiency within the given restrictions, the ideal measures must be identified by comprehensive investigation. However, some guidelines do exist that provide suggestions for the general impact of different categories of measures. One recognised example of such guidelines is the Kyoto pyramid shown in Figure 4.1 below. When deciding on what measures to implement, the pyramid suggest beginning at the lower levels and moving upwards. New and flashy technology is not necessarily synonymous with optimal energy efficiency measures, and so by prioritising resources in this manner, effective measures for reducing energy consumption will always be addressed. However, it is important to underline that all buildings and projects may differ in what measures will be deemed most effective, depending on the distinctiveness and the state of the building. Still, the pyramid provides a plan for progression and analysis, and presents an effective way of prioritising measures in a typical building refurbishment project.

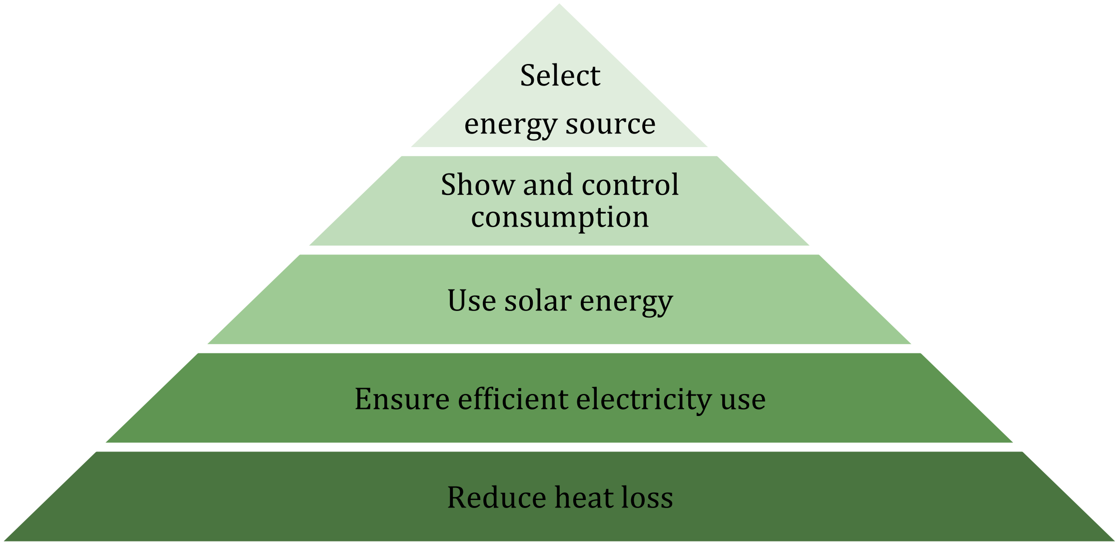


Figure 4.1: The Kyoto pyramid

As per the pyramid-structure, the first energy post to be addressed is the building heat loss. Especially in the cold northern climate, the energy demand for space- and water heating is massive compared to any other building energy requirement as exemplified by Figure 4.2, which show the energy demand distribution for typical dwellings. Due to vast difference in equipment, this distribution is less likely to be an accurate representative for commercial buildings, however THEMA Consulting Group (2013) suggest that heating for office buildings still remain the single largest energy post, with more than 50 % of the total energy demand. Given the high proportion, any reduction in heating demand would significantly affect the energy performance of the building. The obvious place to begin would be the building fabric, given the clear dominance of space heating demand (Figure 4.2). In addition to material decay, older buildings usually contain out-dated technology, and advancements in insulation technology and construction methods could allow building fabrics to achieve drastically reduced thermal conductivity values (U-values) and improved air tightness should they be replaced or refurbished.

The energy delivered to a building can be credited to one of two energy posts: heating or operation. While heating can be delivered in a variety of ways, operational energy demands are restricted to electricity. These demands stem from appliances and indoor environment systems (i.e. lighting, ventilation), and regardless of building use will require a considerable portion of the building's energy budget. The second level of the Kyoto pyramid suggests optimising the efficiency of this demand post. This does not yet include control systems, but rather appliances and systems that are energy efficient during operation. Next, it suggests utilising solar energy. Again this is through passive measures, such as building orientation, shading and optimised glazing. Active production (i.e. PV-panels) is not included in this post. The show and control post suggest installing efficient controls for building operating systems (i.e. HVAC, lighting), and give building inspectors access to metering systems in order to detect anomalies early. None of these three posts are studied in significant depth in this study, as its focus is on building design and energy delivery rather than operation efficiency.

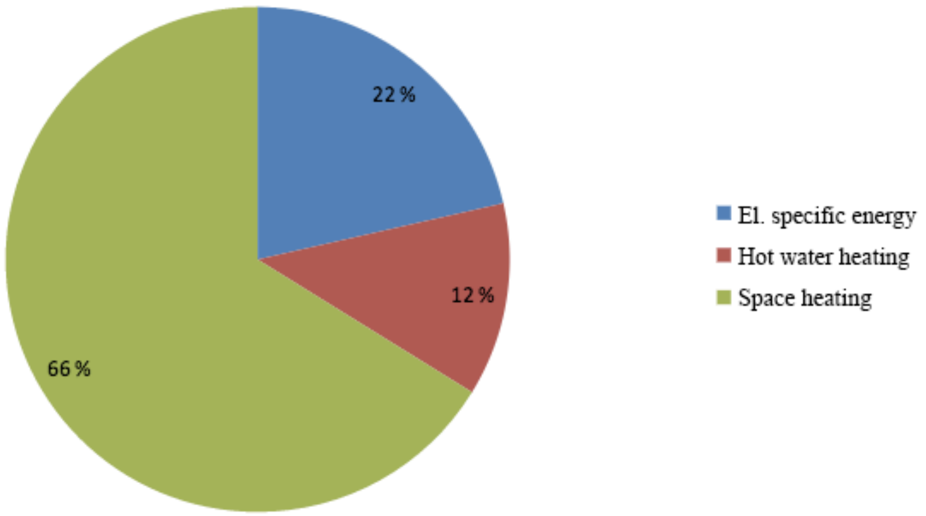


Figure 4.2: Demand distribution in a typical Norwegian household (Bergesen et al., 2012)

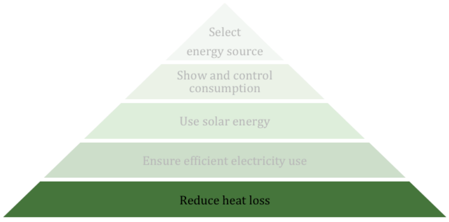
Selecting the appropriate energy source can significantly improve the performance in buildings due to the improved energy factors (Table 2.5), alternatively a high-COP heat pump may be utilised. This will allow heating demand to be further reduced in the energy balance calculations. Details on heat sources are presented in chapter 9.

4.1 Suggested Building Fabric Requirements For Rehabilitation Projects

When rehabilitating old buildings with the aim of achieving a nZEB standard, the building fabric elements become highly important – as suggested by the Kyoto pyramid (Figure 4.1). However, it is also important to consider the economical aspect of such projects, as most proprietors work within the restrictions of a budget created in order to ensure profits. The building fabric insulation are therefore important to dimension in order to properly balance the diminishing benefits with building energy efficiency and economical consciousness. There are many examples of successful rehabilitation projects that meet the standards set for passive house buildings, however these projects often crave significant investment and attention to detail. Introducing further restrictions would likely put off many developers and create substantial difficulties for all parties involved. In consultation with the company that this study is performed in collaboration with, Hjellnes Consult, the building requirements are suggested close to those of passive houses. From their experience, this is largely achievable and stricter requirements would likely turn projects financially infeasible. The suggested value ranges are presented in Table 4.1.

Table 4.1: Suggested building values for nZEB rehabilitation projects

Element	Suggested value
U-value outer wall	0.10-0.15 W/m^2 K
U-value floor	0.08-0.15 W/m^2 K
U-value roof	0.08-0.12 W/m^2 K
U-value windows	0.70-0.80 W/m^2 K
Infiltration	0.5-1.0 ach^{-1} (50 Pa)
Normalised cold bridge values	0.03-0.09 W/m K
Efficiency of ventilation heat recovery	80-85 %



5 Reducing Heat Loss in Common Facades Found in the Norwegian Building Stock

Facades are the largest areas on the building envelope and therefore have the largest potential for heat loss. Adding an additional layer of insulation improves the thermal performance of a façade by increasing its thermal resistance. There are mainly three ways of adding additional insulation to an existing wall: internal insulation, external insulation and cavity insulation. Internal- and external insulation is done in similar manners – by an additional layer of insulating material on either of the internal or external surface of the façade. Cavity insulation is done in one of two ways; either by tearing down the cladding and filling gaps with insulating material, or by spraying the insulation material through drilled holes in the façade. Deciding on which solution to implement is dependant on several factors such as existing constructional materials, if the building facades are listed for conservation, available space, and constructional methods. Cavity insulation is usually a complimentary measure and is often combined with (at least) one of the other two solutions. Each method has several advantages and disadvantages, both when compared to each other and in general. Therefore every building façade intended for additional insulation should be properly examined, allowing for every consequence to be mapped before deciding on method.

Table 5.1: Advantages and disadvantages of external- and internal insulation

Insulation method	Advantages	Disadvantages
External insulation	• Theoretically no limit to the amount of insulation that can be added (if space is available). • The entire façade is insulated in a continuous layer. This results in the blockage of existing thermal bridges from internal walls and floors. • Less risk of condensation and moisture, due to the inner surface of the façade's temperature remaining unchanged. • Corrosion of existing reinforcement may be prevented. • All internal floor area is retained.	• Possible restrictions due to densely built up area or legislative restrictions. • Changes the architectural expression of the external façade. And could therefore be restricted if listed for conservation. • May require moving of windows and doors to avoid too deep placement in the façade.
Internal insulation	• Preserves the façade. • Can be implemented in densely built up areas. • Possible to insulate specific rooms.	• Internal floor area is reduced. • Existing thermal bridges remain, increasing heat loss, corrosion of reinforcements, and risk of condensation. • Could have practical complexities, due to electrical- and heating systems, and immovable interior.

Table 5.1 present the pros and cons of the two most relevant insulation methods, and clearly shows why external insulation is preferred whenever possible. External insulation does not only improve thermal performance by blocking off existing thermal bridges, but preserves internal floor area which comes with significant economical advantages. With astronomical building prices, especially in urban areas, retaining as much floor area as possible is crucial. The main differences between the two methods are also illustrated in Figure 5.1 – thermal bridging and temperature distribution through the façade elements.

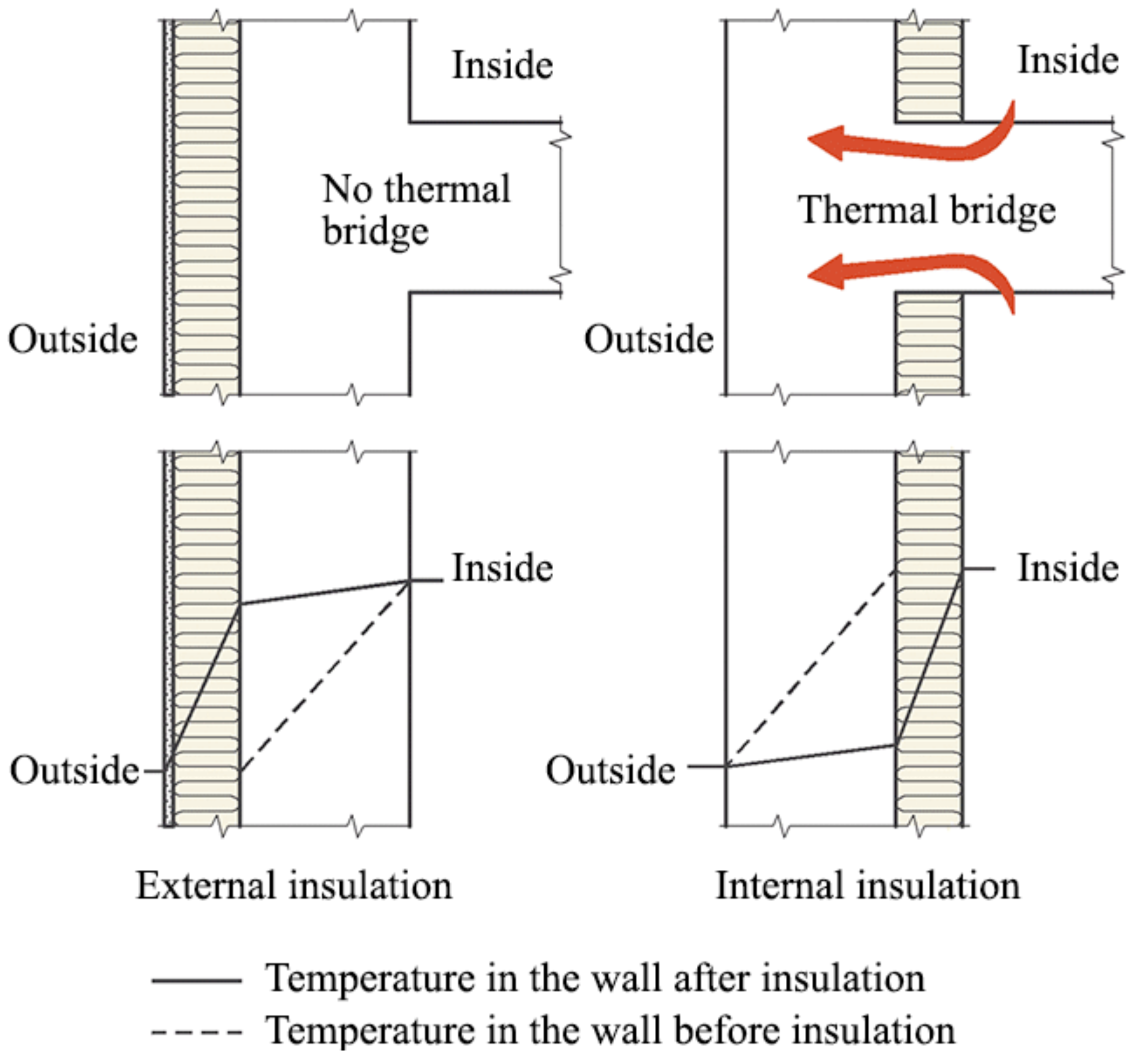


Figure 5.1: Effect on temperature variations of external- and internal insulation respectively (SINTEF Byggforsk, 2014a)

5.1 Concrete and its Use in Norwegian Construction

Concrete is a composite material created as a result of mixing water, cement, aggregate and additives. Once mixed, concrete is a fluid mass that is easily mouldable, but due to a chemical reaction between the water and cement, the mixture hardens into a solid stone-like material. This means that all shaping of the concrete must occur within the first few hours after mixing. When using concrete for construction, reinforcing with steel beams is common practice. The beams are cast into the concrete, due to the concrete's crisp nature. The crispiness makes concrete vulnerable to stretching forces, which the steel beams are able to sustain. Reinforced concrete is therefore a composite material where the concrete bear the pressure force and the steel beams the stretch.

The Norwegian cement industry started in the late 19th century, with the first factory starting production in 1890. Despite the production of cement, concrete was not widely accepted as building material until several years after the turn of the century. This was largely due to the lack of knowledge on how to properly assess and calculate its properties. However, due to the necessity for a robust and easy-to-mould material, concrete quickly became one of the most sought after materials, and is still widely used today (Nn.enclypedia.pink, n.d.).

5.1.1 Common Constructional Methods

Concrete walls can be constructed in several different ways, depending on purpose and architectural expression. Older concrete walls can often contain small amounts of insulation, and more worryingly have large heat loss through thermal bridges. There are three common concrete wall constructions in older Norwegian buildings: cast walls with either external- or internal insulation cast into the façade, cast walls with internal insulation, and concrete elements with insulation between a set of concrete slabs (also referred to as a sandwich element).

Cast Walls with Cast Insulation

This is perhaps the most straightforward manner of façade construction based on concrete (illustrated in Figure 5.2). The main portion of the façade consists of a bearing layer of reinforced concrete, and some form of insulation is then cast on either the internal- or external surface of the concrete mass. A layer of plaster then covers the insulation, in order to protect the insulating material. These walls are flexible when deciding on how to add additional insulation, however there are some concerns that should be addressed. Walls containing autoclaved aerated concrete (AAC) should be externally insulated. This is due to the plaster used on many older facades leading to moisture-damages with internal insulation. Preferably the AAC should be removed and replaced with modern insulating materials, which could reduce wall-thickness and still improve performance.

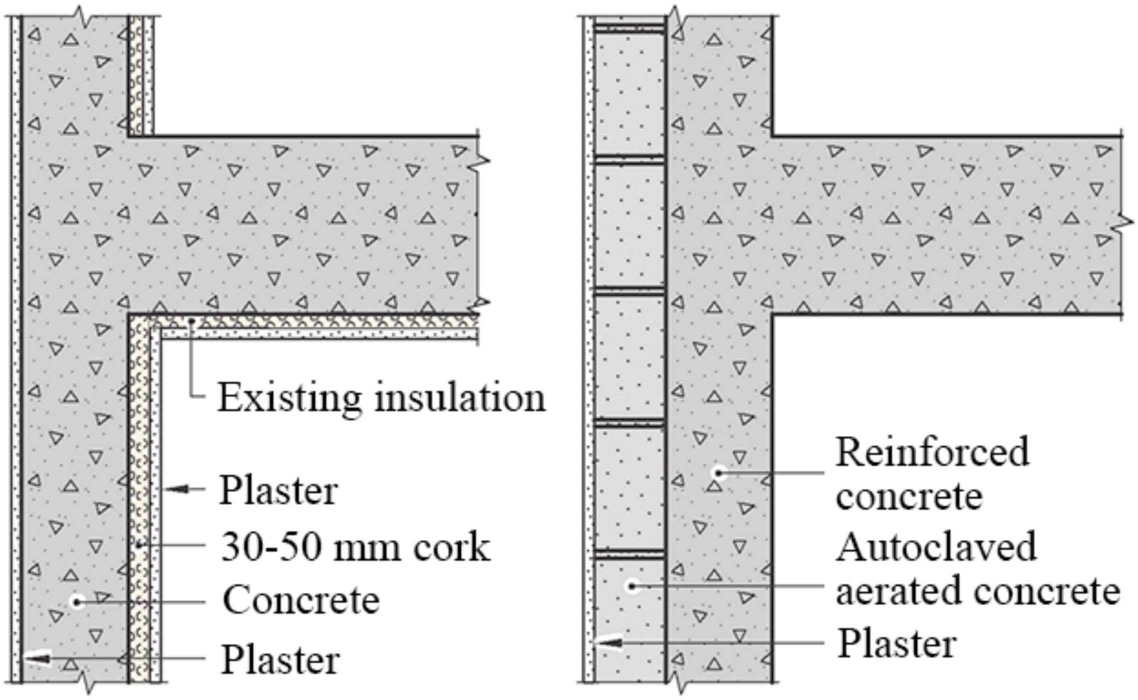


Figure 5.2: Horizontal cross section of cast walls with internal- (left) and external insulation (right) cast into the façade (SINTEF Byggforsk, 2014a)

Cast Walls with Internal Insulation

This method of constructing facades already consists of decent amounts of insulation within the light framed wall added internally, however the framed wall will cause thermal bridging unless properly blocked. Figure 5.3 show an example of how this method can be reasonably executed: the internal insulation is of good thickness for providing sufficient insulation, and the cold bridges are prevented from running directly throughout the façade by a layer of cork insulation. The thermal bridges will still have some effect on the overall thermal performance, but the blockage from the cork insulation is essential for restricting heat loss.

These facades are flexible in terms of additional insulation, and both internal and external methods are fairly easily implemented. For internal installation, the light wall can simply be opened and extended to allow for the fitting of additional insulation.

This could allow for the additional insulation to help break the thermal bridges, if the additional framing is moved so that new insulation overlaps the existing frame. This would allow the existing insulation to break the potential thermal bridges provided by the new framing, while the new insulation help break the thermal bridges of the existing framework. External insulation can be added directly onto the external surface, and facades with columns running partly (Figure 5.3) or entirely throughout the façade elements can cover these columns to avoid thermal bridging.

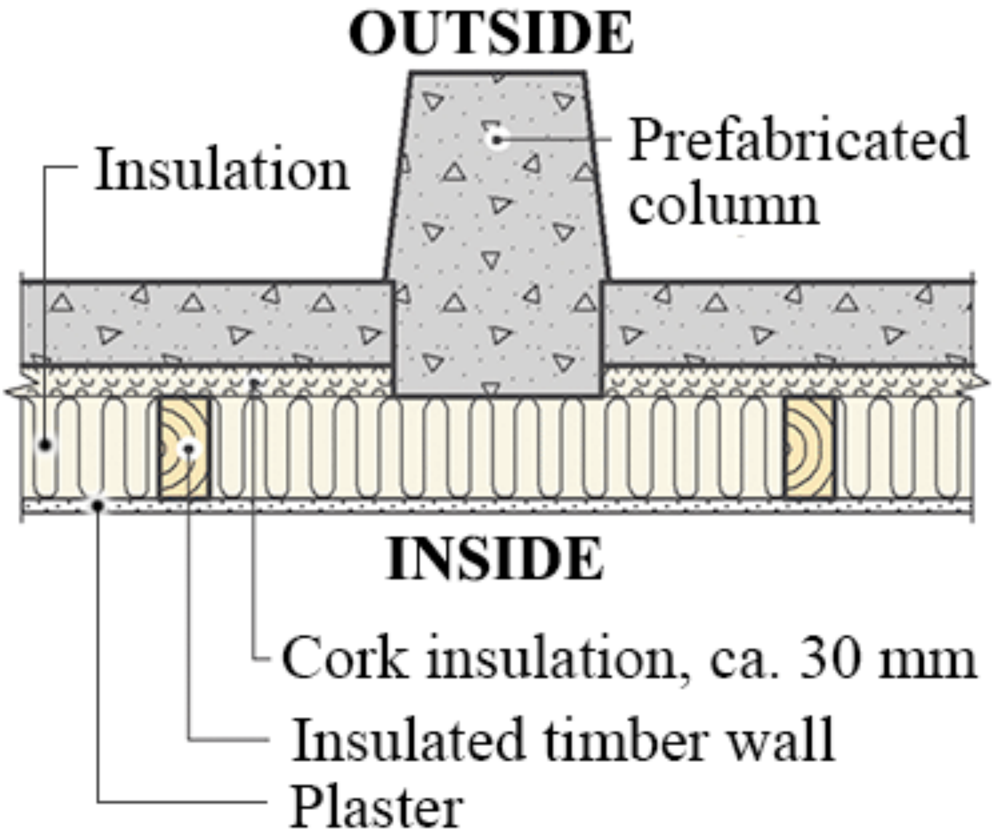


Figure 5.3: Horizontal cross section of a cast wall with internal insulation (SINTEF Byggforsk, 2014a)

Sandwich Elements

These elements are found in the more modern concrete structures, and are often fairly well insulated compared to the previously mentioned concrete facades. A layer of insulating material is 'sandwiched' in between two concrete slabs. One concrete slab can be of load bearing thickness if required. The insulation is usually continuous throughout the element, which severely limits the amount of thermal bridges in the façade. These elements provide no clear preference of internal- or external insulation other than those mentioned in Table 5.1.

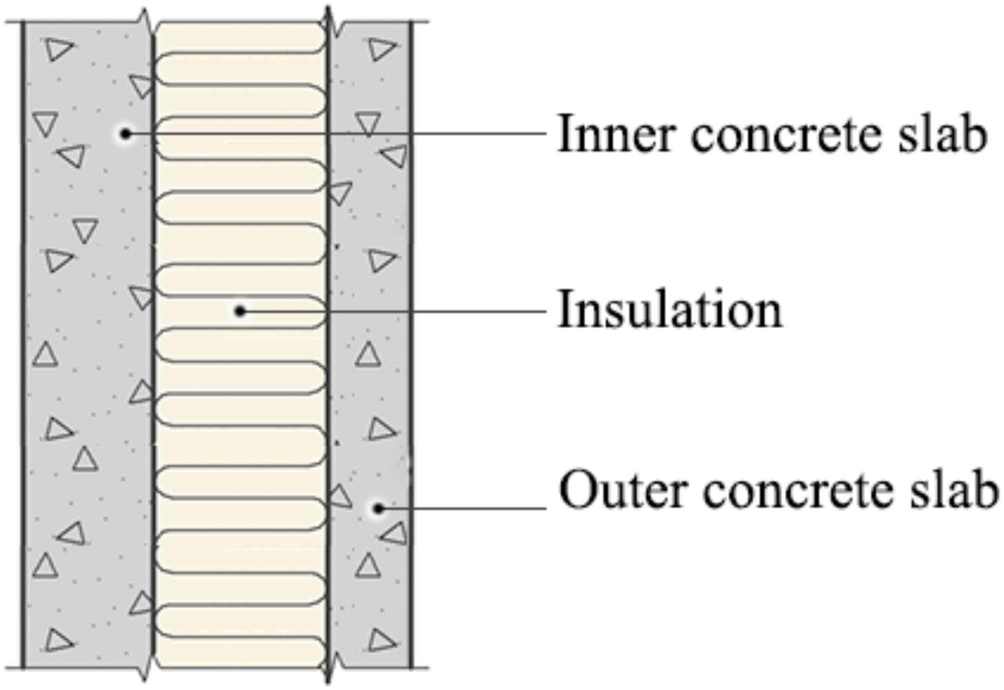


Figure 5.4: Horizontal cross section of a concrete sandwich element

5.1.2 Methods for Fitting Additional Insulation

There are mainly three relevant methods for fitting external insulation onto an existing concrete façade: insulation in timber framework, continuous insulation and plaster-covered insulation. These methods are similar for both internal and external application, however plaster-covered insulation is mainly used in external fitting. Deciding on method may depend on several factors such as preferred insulating material and available space.

Timber-framed Insulation

A timber framework is fastened to the concrete slab and will act as support for the insulating material. The insulating material protected by sheating and slats create space in between the insulating layer and the cover-material that is fixed to the timber-frame and slats. This option allows the timber-frame to provide a sturdy foundation for fastening the external cover.

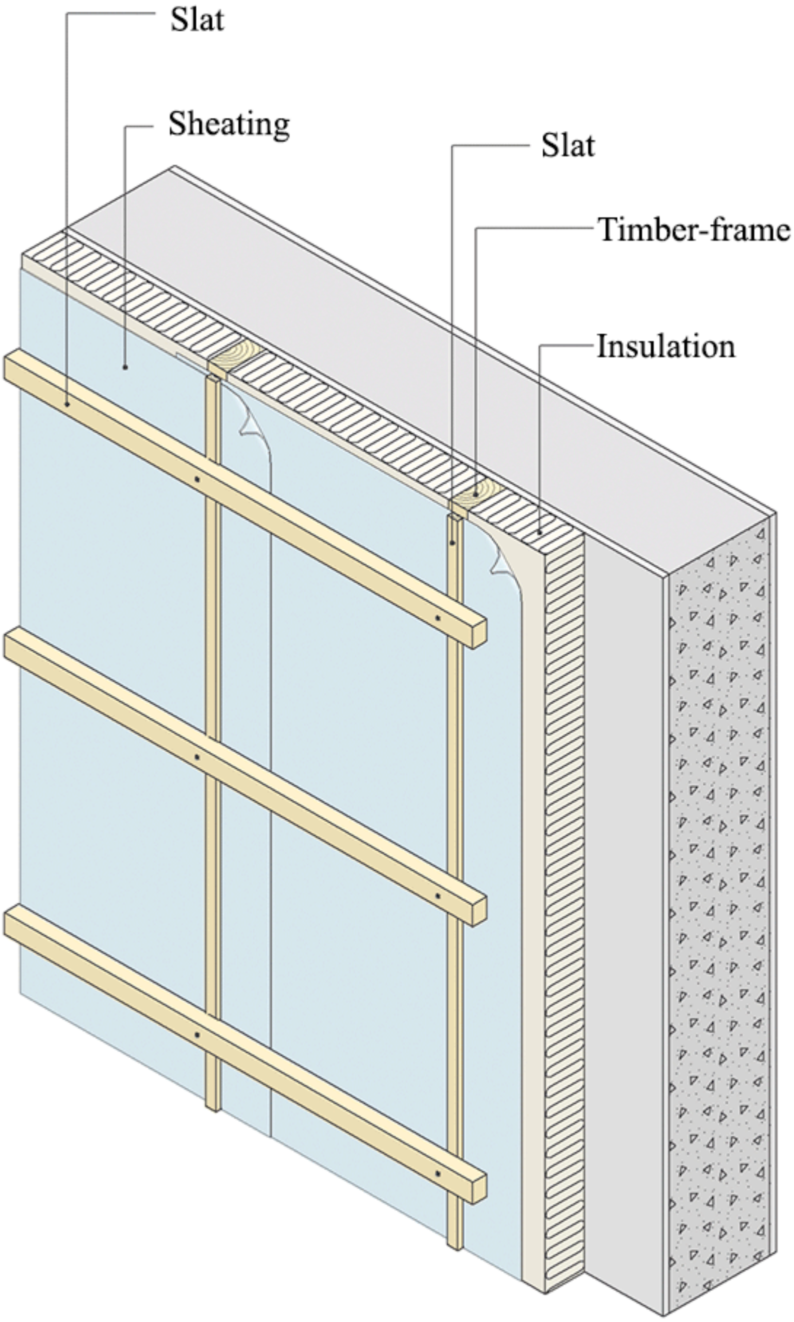


Figure 5.5: Concrete wall with added insulation and timber framework (SINTEF Byggforsk, 2014b)

Continuous Insulation

This method is based on mineral wool with high density and firmness, and can be utilised with very thick layers of insulating material. The insulation and cladding is usually attached to the concrete with long bolts, but solutions exist where the cladding and slats are attached to the roof structure. This method creates fewer thermal bridges compared to the timber-framed method, but requires certain types of mineral wool (or similar) material to be effective.

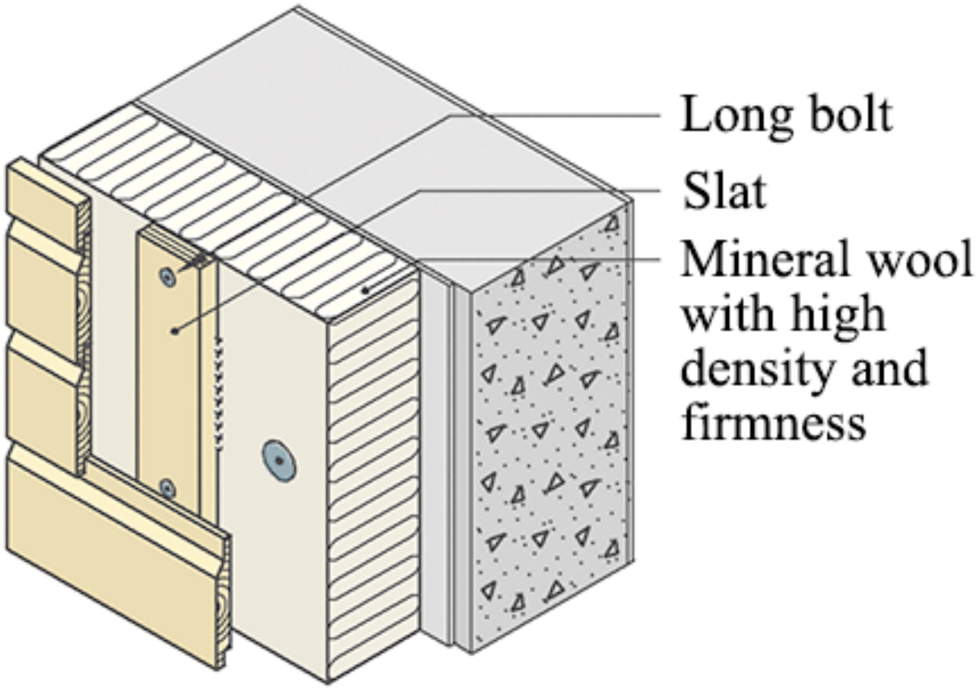


Figure 5.6: Externally fitted continuous insulation (SINTEF Byggforsk, 2014a)

Plaster-covered insulation

The final mentioned method is used when plaster is applied onto the insulating material to act as external cover. The insulation is fixed to the wall by a layer of adhesive mortar, which acts as a temporary attachment. The insulation is then nailed to the concrete with plugs, which are either made of plastic with a steel core or steel plugs with a head or cover made of plastic. These plugs are insulated in order to avoid creating unnecessary thermal bridges (Figure 5.7). A layer of mortar is then added in which a reinforcement grid is fitted (Figure 5.8). If necessary, another thin layer of mortar is added on top of this grid, before the outer plaster covers the façade.

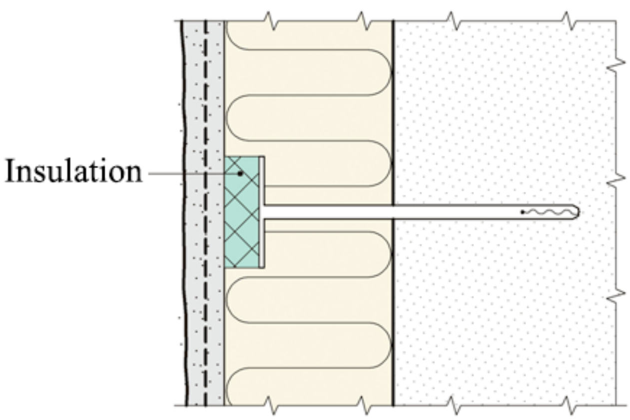


Figure 5.7: Insulated plug in a plaster-covered insulated wall (SINTEF Byggforsk, 2010)

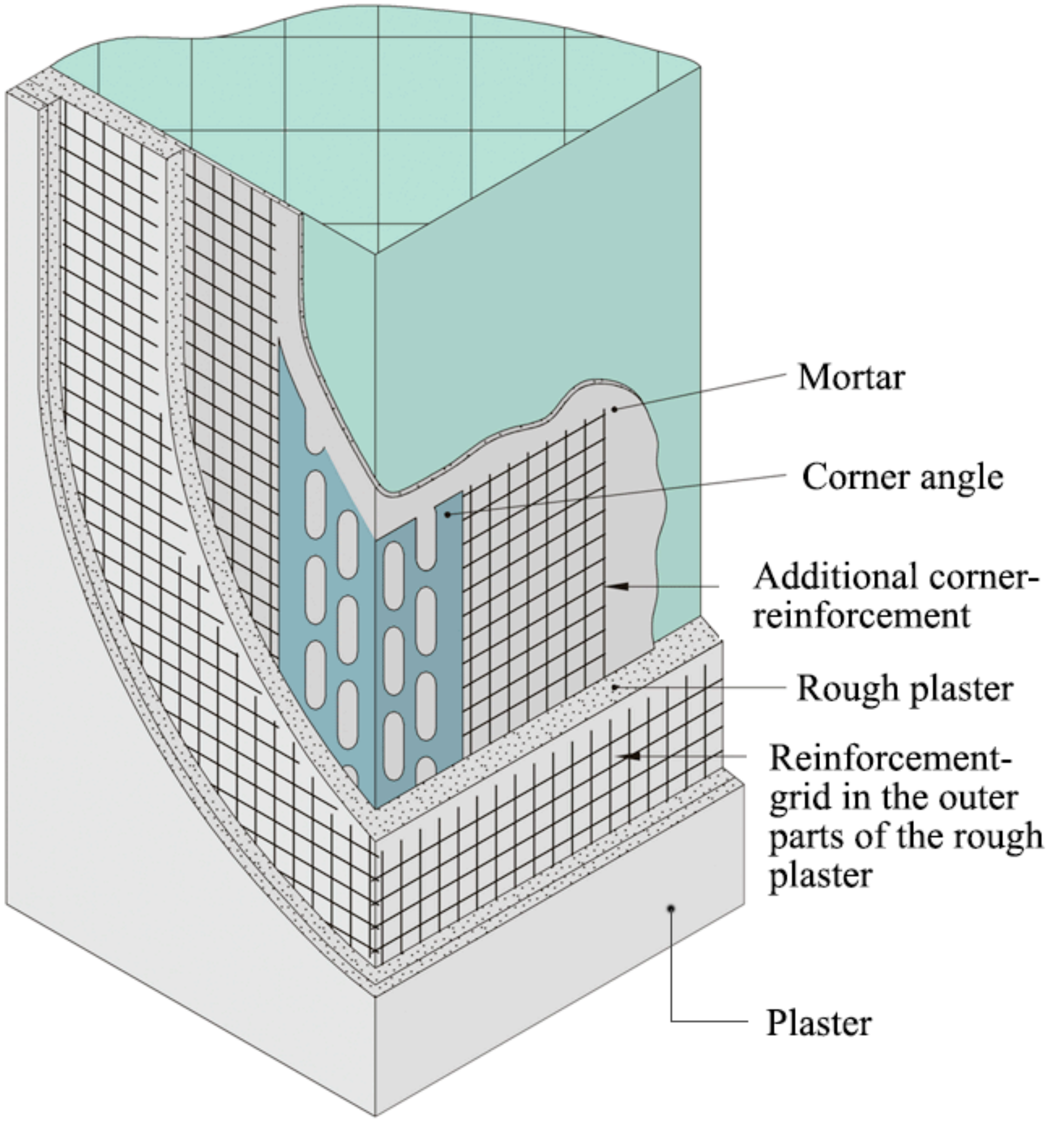


Figure 5.8: Corner of a concrete wall with plaster-covered insulation (SINTEF Byggforsk, 2010)

5.1.3 U-values of Facades Prior to and Following Additional Insulation

Table 5.2 show what U-values one might expect with for the original construction, and facades with additional insulation fitted. The table is based on construction and materials that used to be common, and may stray from what is today's standard. The table provide estimates, and all values must be properly calculated for all new projects. The values provided in Table 5.2 assume a timber-framed insulation method and mineral wool as the insulating material.

Table 5.2: Typical U-values for older wall types and materials, before and after additional insulation is added (SINTEF Byggforsk, 2014a)

Wall Type	Estimated U-value [W/m²K]				
	Original	Additional insulation[1] [mm]			
		100	200	300	400
Concrete Wall	3.8	0.40	0.21	0.14	0.10
Concrete wall insulated with:					
- 30 mm cork	1.07	0.31	0.18	0.12	0.10
- 40 mm cork	0.87	0.29	0.17	0.12	0.09
- 50 mm cork	0.73	0.27	0.17	0.12	0.09
Concrete wall insulated with:					
- 50 mm woodwool	1.12	0.31	0.18	0.12	0.10
- 75 mm woodwool	0.83	0.28	0.17	0.12	0.09
- 100 mm woodwool	0.66	0.26	0.16	0.12	0.09
Concrete wall insulated with:					
- 100 mm AAC	0.97	0.30	0.18	0.12	0.09
- 125 mm AAC	0.81	0.28	0.17	0.12	0.09
- 150 mm AAC	0.70	0.27	0.17	0.12	0.09
Concrete wall insulated with:					
- 100 mm LECA[2]	1.43	0.33	0.19	0.13	0.10
- 150 mm LECA	1.09	0.31	0.18	0.12	0.10
- 200 mm LECA	0.88	0.29	0.18	0.12	0.09

[1]Insulation with thermal conductivity of 0.033 [W/mK] is assumed

[2]Lightweight Expanded Clay Aggregate

5.2 Brick Buildings in Norway

Brick is a ceramic material created by searing or drying of clay, and has been widely utilised for centuries. Bricks first used in Norway in the 13th century, and would mainly be found in royal constructions such as castles and churches. Widespread use however, did not start until the mid 1700s when several brickworks started operation. Brick buildings became increasingly common and during the 19th century, the larger cities implemented regulations that forced new buildings to be constructed in brick (Wikipedia, 2016b).

5.2.1 Common Brick-laying Methods in Norwegian Construction

There are several methods of constructing a brick wall that still exists in the current buildings stock. These structures range from simple massive blocks of bricks to fairly complex patterns that include 'pipelines' or cavities. The different methods vary significantly, but all are treated in similar manner during rehabilitation.

Solid Walls

The wall is constructed by laying the bricks adjacent to one another without any gaps (Figure 5.9). This creates a heavy wall capable of being load bearing should it be required. A solid brick wall is usually constructed with anything from ½ to a 3-brick thickness. This method will not allow convectional heat transfer within cavities, however brick is poor insulation, so conductional heat transfer and thermal bridging is substantial.

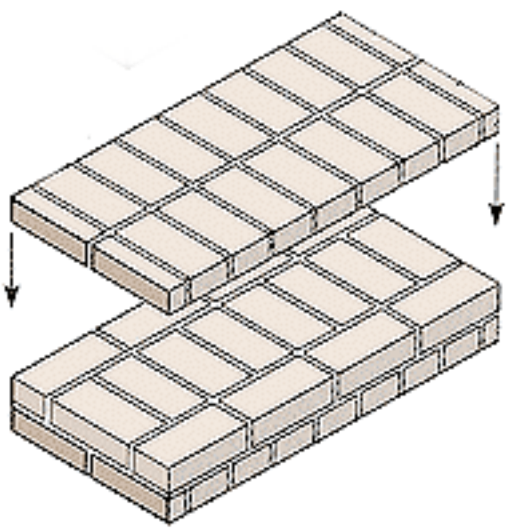


Figure 5.9: Solid wall with a 2-brick thickness (SINTEF Byggforsk, 2013a)

Trondhjem-brickwork

This type of brick wall is a cavity wall with channels of ¼-brick thickness separated by walls of ½-brick. Walls constructed with this method in 1 ¾ and 2 ¼ thicknesses (Figure 5.10), could replace solid walls of 1 ½ or 2-brick thickness respectively. This constructional method significantly improves the façade's insulating properties, compared to the solid brick wall (Table 5.3, chapter 5.2.2).

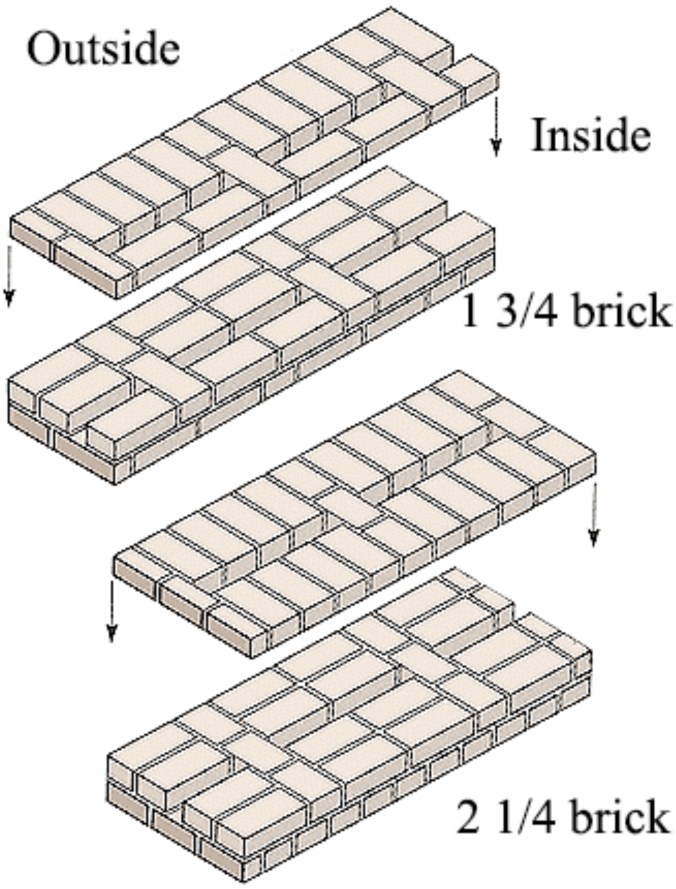


Figure 5.10: Trondhjems-brickwork of two common thicknesses (SINTEF Byggforsk, 2013a)

Bergen-brickwork

These walls contain vertical channels and could replace the solid walls without expanding the thickness of the wall. The method would therefore be material-efficient compared to both the solid- and Trondhjems-brickwork. However, both moisture- and thermal insulation suffered compared to Trondhjems-brickwork, due to the reduced depth of the outer layer. The wall is usually constructed with two ½-brick jambs separated by cavities of varying depth (Figure 5.11).

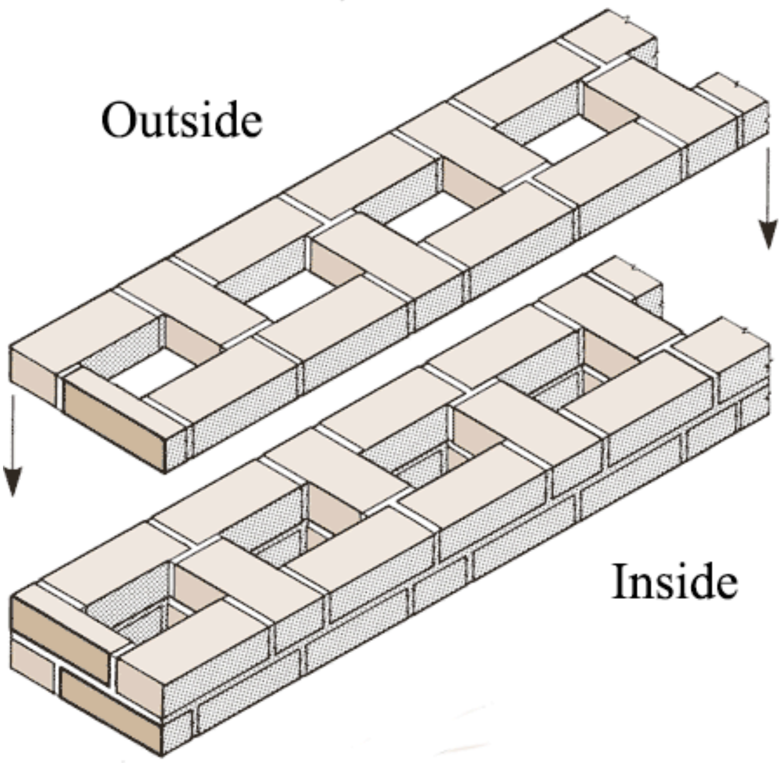


Figure 5.11: Bergens-brickwork with a 1 ½-brick thickness (SINTEF Byggforsk, 2013a)

English Cavity Wall

Similarly to the Bergens-brickwork, the English cavity wall consists of two ½-brick jambs, however there is a nearly continuous cavity throughout the wall. The jambs are held together with binders of either steel or brick. This method is mainly used in smaller buildings, and despite a more continuous cavity, insulation is still poor compared to modern wall-construction, as there is significant convectional heat transfer in the cavity.

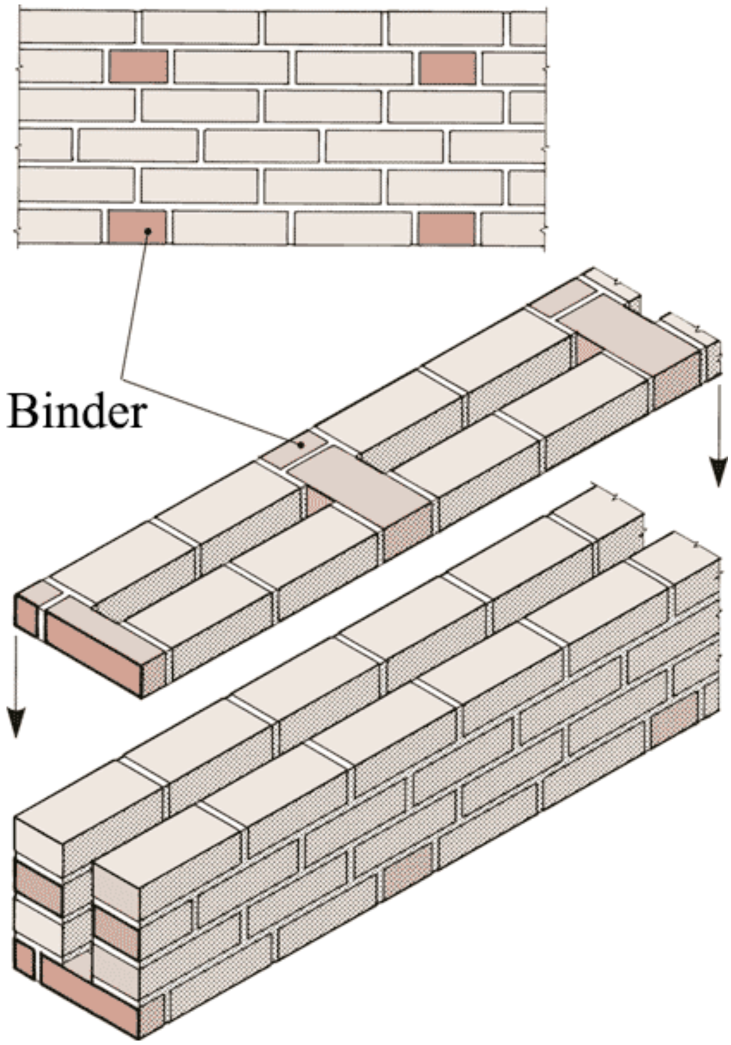


Figure 5.12: English cavity wall with brick binders (SINTEF Byggforsk, 2013a)

5.2.2 Insulating Brick Walls

When adding additional insulation to brick walls, identical methods to concrete walls, as shown in chapter 5.1.2 is used – with one exception. English cavity walls may also make use of blown-in cavity insulation due to the large and continuous void in between the jambs. This kind of insulation is not practical in any other brickwork, due to the small size of the accessible cavities. Typical U-values can be found in Table 5.3.

When insulating brick walls, external insulation is the superior choice due to bricks' proneness to frost damage. Internal insulation may prevent drying of the external brickwork that will allow moisture to freeze, which will cause cracks and damages. In rare cases this can be prevented by waterproofing with certain types of plaster, however it remains preferable to install external insulation whenever possible.

Table 5.3: Typical U-values for brick walls with additional timber-framed insulation

Wall type	U-value [W/m²K][1]				
	Original	Thickness of additional insulation [mm]			
		100	200	300	400
Solid wall	2.10	0.35	0.19	0.13	0.10
English Cavity wall filled with 50 mm insulation	0.50	0.23	0.15	0.11	0.09
1 ¾ brickwork	1.10	0.30	0.18	0.12	0.10
2 ¼ brickwork	0.85	0.28	0.17	0.12	0.09

[1]The thermal resistance of insulation and framing is assumed to be identical to that used in Table 5.2

5.3 Norwegian Timber Buildings

Timber is one of the most common building materials in Norwegian construction, and has been used in homes for centuries. Norway is largely covered by forests, which have made timber a plentiful resource. In addition to being a local and easily obtainable material, it is likely one of the most climate-friendly. Trees are important 'carbon sinks' that helps to limit the release of greenhouse gases. Growing trees absorb CO_2 from the atmosphere, which again is released upon biologic degradation or when burned. However, in Norway the rate of growth has eclipsed the felling, meaning that there is a net absorption of CO_2 in the Norwegian forests. This absorption is estimated at 25-30 million tonnes between 2005-10, totalling to approximately half of the yearly national CO_2 emission according to KLIF et al. (as cited by (Statsbygg, 2013)).

Timber has mainly been utilised in smaller buildings, as it was prohibited in use for any building over three floors until 1998 – meaning few large buildings mature for significant rehabilitation will have timber facades. However, there are still large quantities of older residential- and smaller commercial buildings constructed in timber.

5.3.1 Structure of Common Timber Facades

The methods for constructing a timber building have evolved drastically over the centuries; meaning methods for adding additional insulation will depend on the timber structure of the existing building. Timber facades can mainly be categorised as either log buildings or constructed with timber-framed facades. Log buildings are found in early timber structures, and is a traditional manner of constructing dwellings. This building method have also been modernised to some degree and is mainly found in both modern cabins, however there are examples of modern log houses. Timber-framed facades on the other hand are a very common practice in dwellings, and allows for insulation to be easily integrated into the façade structure. However, when adding additional insulation to a timber façade, whether it's externally or internally, it may often be combined with cavity insulation due to the constructional methods of the facades.

Log Buildings

Log buildings was the dominating method in Norwegian construction from the Viking age (late 8th century) until the mid 19th century (Wikipedia, 2016a). These buildings are constructed by laying logs horizontally on top of each other. The logs are layered in a manner that makes them lie level with the logs on the opposite parallel wall, while the adjacent walls are a half log-size higher. The logs are peeled, scribed and custom fitted to one another. They are then fitted together in notches where they overlap at the corners (Figure 5.13).

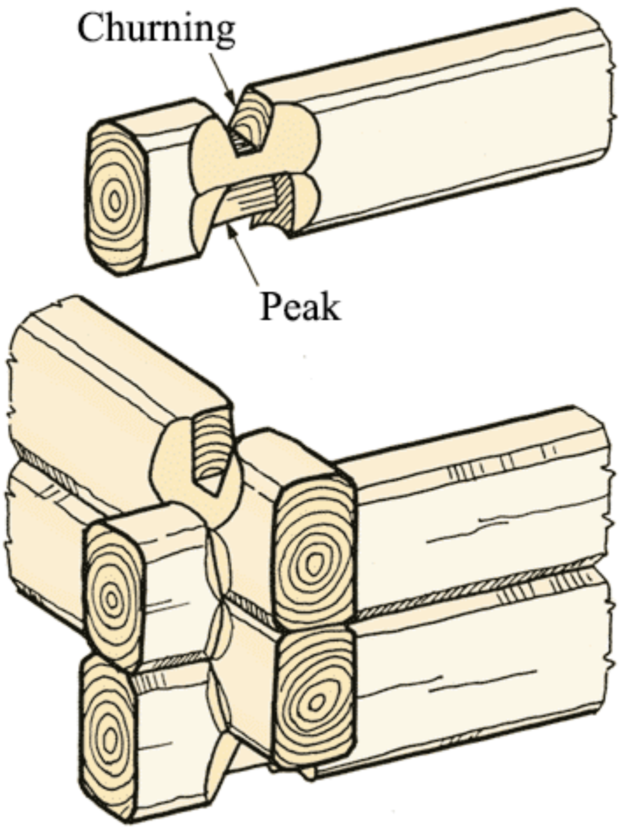


Figure 5.13: Constructional method of a Scandinavian log building (SINTEF Byggforsk, 2006)

Early Timber Framing

Timber framing was introduced to Norwegian construction in the late 18th century and was a common method until the 1920s, however were still some buildings constructed in this manner until the 1950s. Early timber framing consists of a framework made of beams and sleepers where the spacing is filled with vertical planks or beams (Figure 5.14). This method replaced the log buildings, as it required significantly less materials to complete. Additionally, the shrinking of timber is less along its length than its width, meaning that there was less trouble with stairs and chimneys. However, a well-constructed log building would become tighter with shrinkage, while timber-framed buildings will develop cracks in between the planks. This would somewhat slow down the advancement of the method until approximately 1870, when building cardboard was introduced as protective sheating (SINTEF Byggforsk, 2015). Up until then, the walls would only be insulated with newspaper stuck in between the façade and the internal cover.

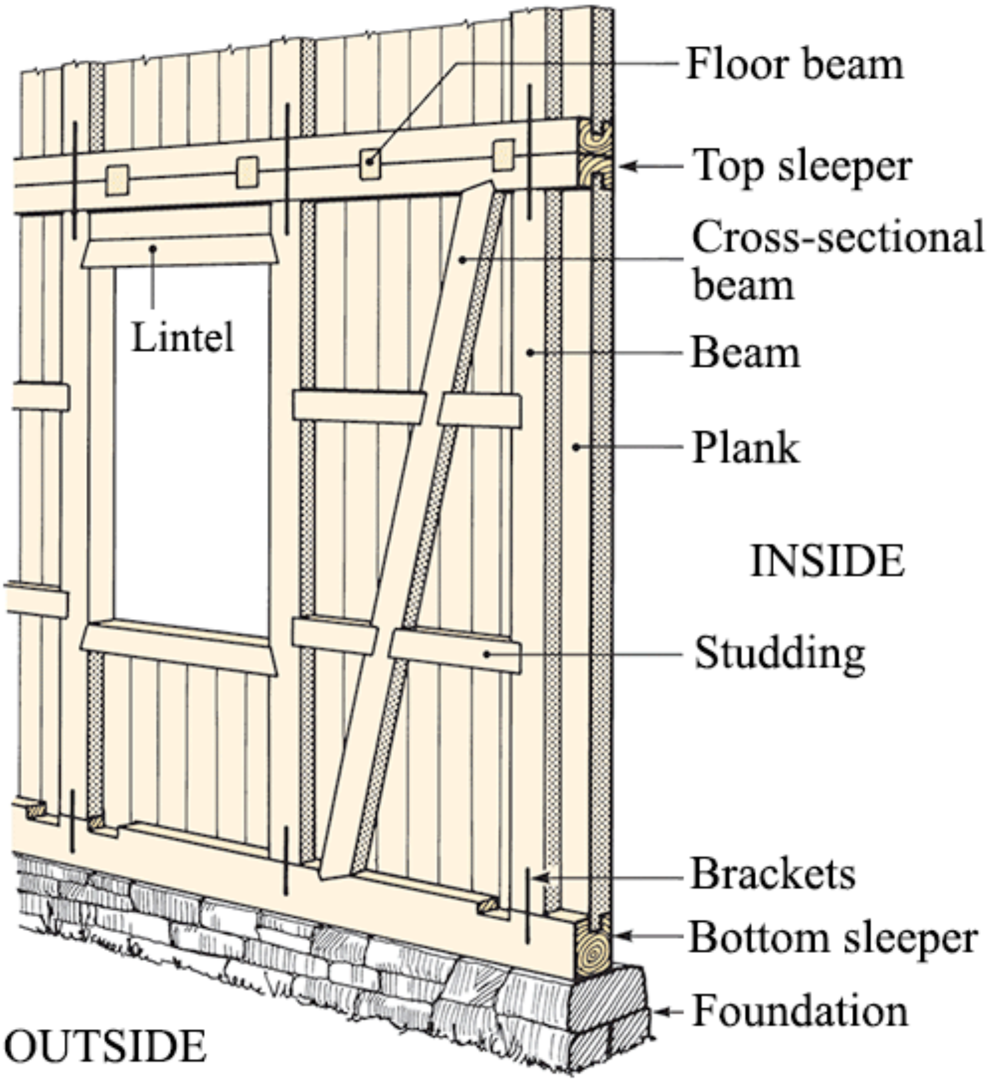


Figure 5.14: Early plank-filled timber framing without sheating or cover (SINTEF Byggforsk, 2015)

Modern Timber-framed walls

In more modern times, the timber-framed walls no longer have planks or beams in between the wall studs, but are rather filled with insulating material and sheating. As can be seen by Figure 5.15 the framework requires significantly less timber than the earlier counterpart, which also allows for faster construction. The insulation is fitted in between the wall studs, which often is covered by another, thinner layer of insulation and sheating, before being enclosed by the cladding. To avoid moisture damage either internally or in the construction itself, a protective vapour barrier is added behind the internal cover.

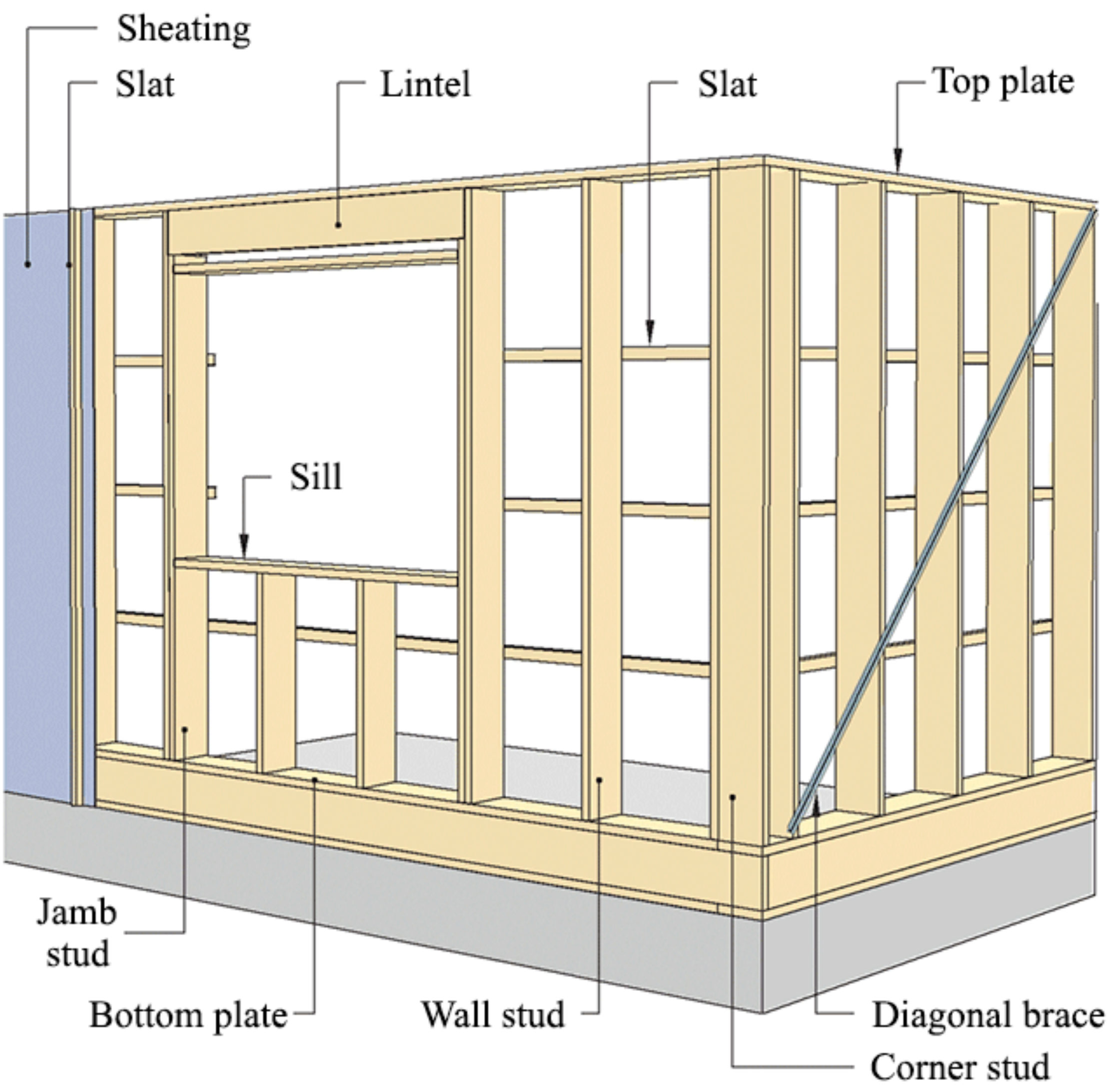


Figure 5.15: Modern timber framing without insulation or cladding (SINTEF Byggforsk, 2014c)

5.3.2 Fitting Additional Insulation Onto Timber Facades

Fitting additional insulation onto timber facades is different than concrete or brick in the manner that the method of installing insulation varies depending on the existing wall type. The differences between the timber walls are significant and do not always allow certain methods of insulating to be performed. When adding additional insulation to a timber wall, the developer must therefore be aware of the requirements set by certain wall types.

Log Buildings

Unless the exterior expression of the building is required to remain intact, it is preferable to add external insulation to log buildings. The most significant technical reason for this being favoured is the ability to prevent moisture damage, due to the logs being kept warm by the internal heat. However, there are several factors, as listed in Table 5.1, that also accentuate the preference for this method. Adding additional insulation to log buildings is somewhat similar to the timber-framed insulation seen in concrete or brick buildings. Insulation is added directly onto the logs and kept in place by studdings and slats, before cladding is secured for external protection. Due to the irregular surface of the log walls, the insulation is often divided into two layers (Figure 5.16). The first consists of a flexible layer of insulation, which is added first to even out the surface. Another layer can then be put on top of this to provide the desired amounts of insulation. Internal cover is optional, and can be omitted if there is a desire to maintain the original look of the wall.

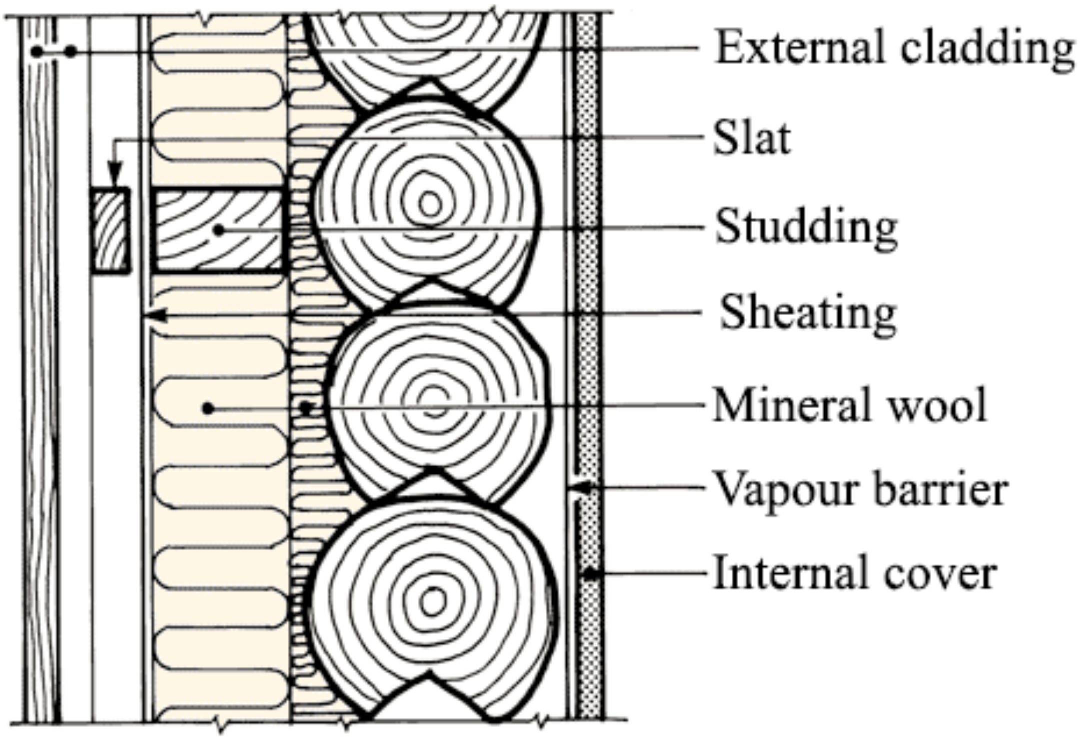


Figure 5.16: Externally insulated log wall (SINTEF Byggforsk, 2004a)

Should the external façade be protected against alternation for any reason, internal insulation is equally possible with log buildings. However, there is risk of moisture damage causing cracks in damp logs when outside temperatures reach freezing. This is due to the water expanding, which is avoided with internal insulation due to the logs' higher temperature. Internal insulation is done in almost the exact same manner as external, however the sheating is now installed onto the internal surface of the logs (Figure 5.17).

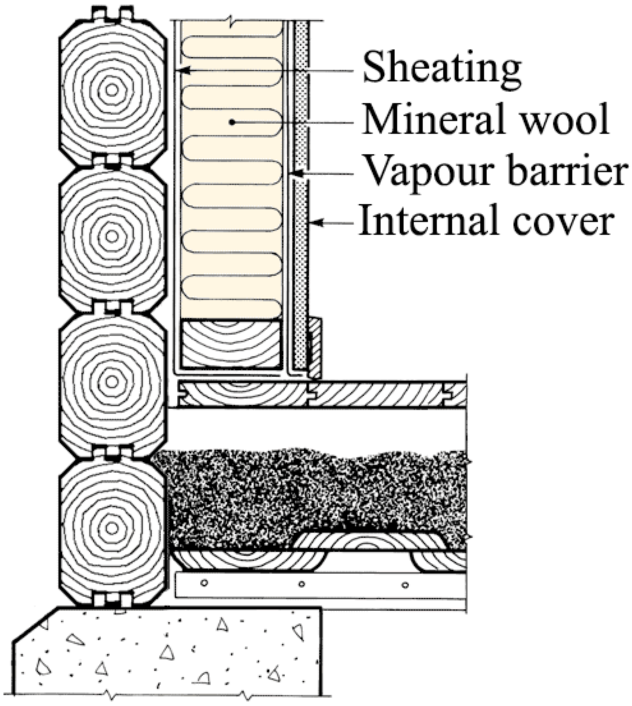


Figure 5.17: Internally insulated log wall (SINTEF Byggforsk, 2004a)

Table 5.4 show how insulation influences the U-value of log walls of varying thickness. Whether insulation is placed internally or externally seems to have little effect on the overall thermal performance, however when insulation is fitted internally thermal bridging through floor-separators and internal walls will still increase heat loss.

Table 5.4: U-values of insulated log walls (SINTEF Byggforsk, 2013b)

Log thickness [mm]	Insulation thickness [mm][1]	U-value [W/m²K]	U-value [W/m²K]
		Externally	Internally
50	0	2.00	2.00
	100	0.36	0.37
	200	0.21	0.21
	300	0.15	0.15
	400	0.11	0.11
100	0	1.20	1.20
	100	0.32	0.33
	200	0.20	0.20
	300	0.14	0.14
	400	0.11	0.11
150	0	0.84	0.84
	100	0.29	0.30
	200	0.19	0.19
	300	0.14	0.14
	400	0.11	0.11
200	0	0.65	0.65
	100	0.27	0.27
	200	0.18	0.18
	300	0.13	0.13
	400	0.10	0.10
250	0	0.54	0.54
	100	0.24	0.25
	200	0.17	0.17
	300	0.13	0.13
	400	0.10	0.10

[1]Insulation with thermal conductivity of 0.033 [W/mK] is assumed

Early Timber Framing

There are mainly two ways of externally insulate early timber-framed wall which is constructed in the manner explained in the previous subsection. There is normally an external cladding adjacent to a cavity, before the framing itself. This cladding should either be removed in order to fit the insulation and add proper sheating (Figure 5.18), or if left attached, insulation can also be blown into the cavity through the cladding itself. This should also be combined with an additional layer of external insulation fitted onto the existing cladding (Figure 5.19).

Alternatively, the wall can be insulated internally. This is done very similarly to log buildings, where the insulation is fitted in between studdings before being covered by a vapour barrier and an internal cover (Figure 5.20).

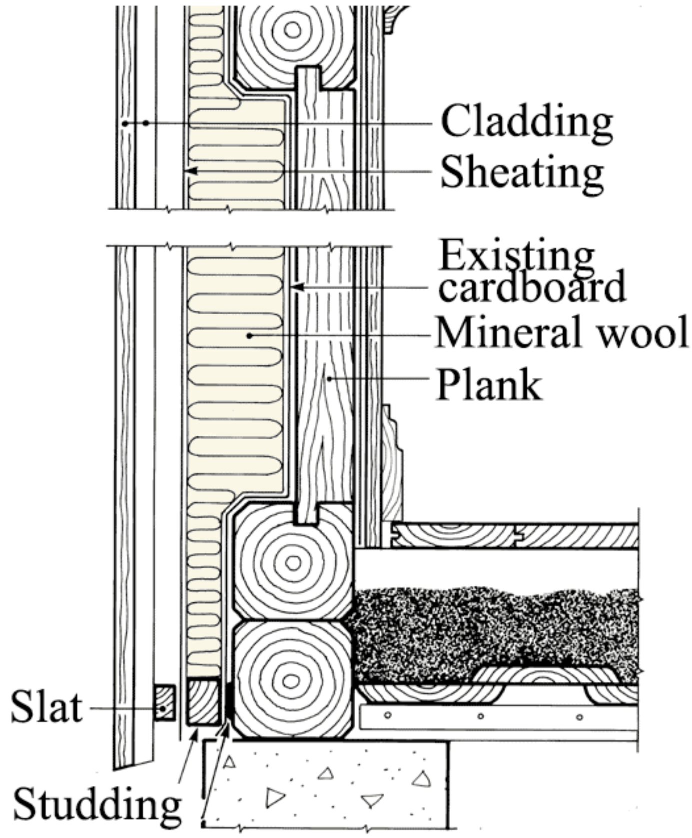


Figure 5.18: Externally insulated timber-framed wall. The cladding have been removed and replaced after insulation (SINTEF Byggforsk, 2004a)

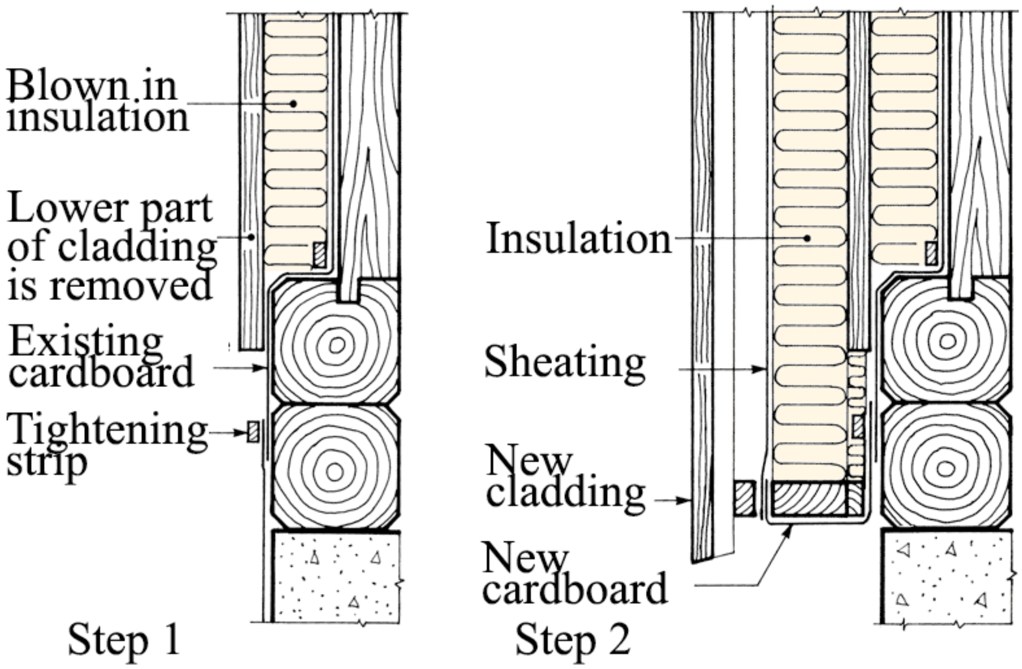


Figure 5.19: Early timber framing insulated with both blown in insulation and an additional layer (SINTEF Byggforsk, 2004a)

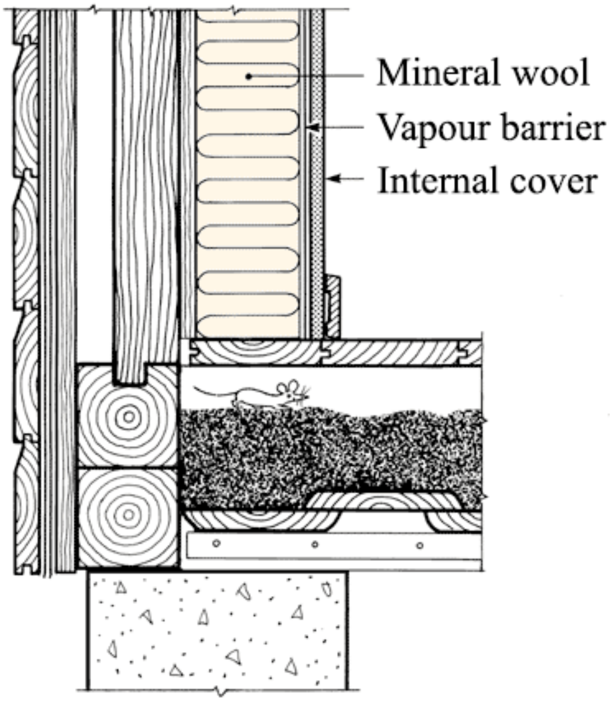


Figure 5.20: Internally insulated timber-framed wall (SINTEF Byggforsk, 2004a)

Table 5.5: U-values of insulated timber-framed walls (SINTEF Byggforsk, 2004a)

Insulation method	Studding thickness [mm][1]	U-value [W/m²K]
External insulation or blown-in insulation and external insulation	0 (original wall)	0.82
	98	0.24
	198	0.16
	298	0.12
	348	0.10
Internal insulation	0 (original wall)	0.82
	98	0.28
	198	0.18
	298	0.13
	348	0.12

[1]This is the additional thickness created by the stud framing. For total insulation thickness, the insulation between sleepers must also be added.

Modern Timber-framed Walls

When adding additional insulation to a modern timber-framed wall, internal or external cladding is removed (depending on where the additional insulation is to be placed), before the framing is extended and filled with insulation. This method is almost identical for external- (Figure 5.21) and internal insulation (Figure 5.22), due to the structure of the timber-framed walls. In walls where there is no existing insulation or with an insulating material other than mineral wool, it may be advantageous to use blown-in insulation. This method will have to be combined with additional insulation methods if the aim is energy efficient building facades.

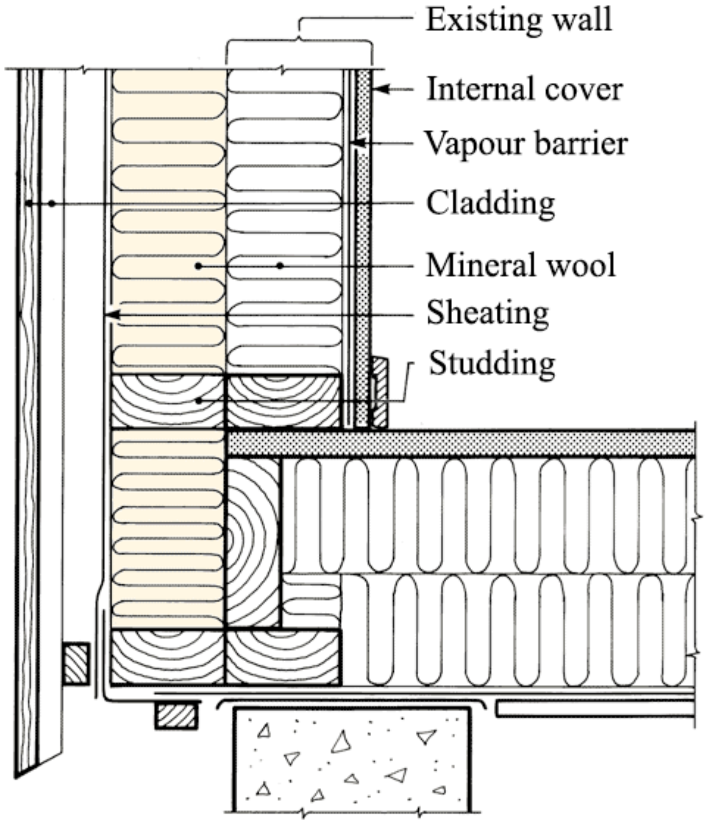


Figure 5.21: Externally insulated modern timber-framed wall (SINTEF Byggforsk, 2004a)

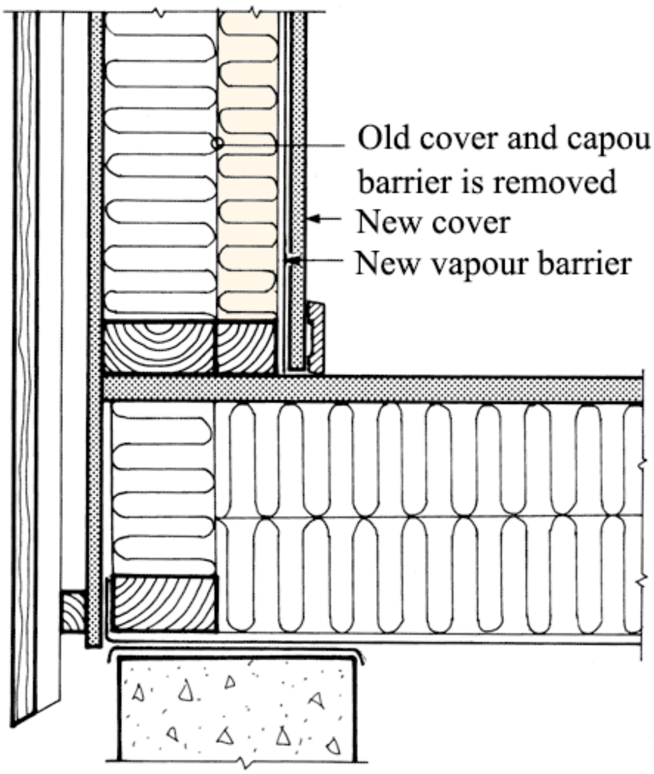


Figure 5.22: Internally insulated modern timber-framed wall (SINTEF Byggforsk, 2004a)

Table 5.6: U-values of insulated modern timber-framed walls (SINTEF Byggforsk, 2004a)

Insulation Method	**Original wall**	**Studding thickness [mm]**				
		0	98	198	298	348
External- or internal insulation with the following old insulation in the cavity:						
- Empty cavity	1.52		0.36	0.22	0.15	0.13
- 100 mm mineral wool	0.50		0.26	0.18	0.13	0.12
- Filled with sawdust	0.79		0.31	0.20	0.14	0.13
- 50 mm wood wool or 30 mm sewn mineral wool mats	0.81		0.31	0.20	0.14	0.13
External- or internal insulation combined with blown-in insulation	1.52		0.24	0.17	0.13	0.12
Blown-in insulation	1.52	0.46				

6 Choosing the Appropriate Insulation Material

The materials used in building insulation have drastically evolved from when the concept was first introduced. Going from newspaper to mineral wool have made a significant impact on thermal comfort in Norwegian homes. Since Norway is subject to a large climatic variations and temperature ranges, the building envelope of Norwegian buildings are carefully designed to survive the local conditions. The cold winters crave significant thermal protection, which means insulation is one of the most important features in Norwegian façade construction.

6.1 Conventional Insulation Materials

Most modern buildings use either mineral wool or plastic insulation in their facades, due to their good insulation properties and reasonable pricing. Mineral wool is a common term for glass- and rock wool, which is usually installed as mats inside the facades, but can also be utilised as blown in insulation. Both types of mineral wool have similar thermal resistances, but rock wool is a more dense and rigid material. This means that while both are adequate for insulation purposes, they may be utilised differently depending on desired applications (i.e. load bearing insulation). Plastic insulation is a common term for polystyrene and polyurethane foam (PUR), and is delivered as blocks for instalment in facades. There are two different types of polystyrene: expanded polystyrene (EPS) and extruded polystyrene (XPS). They are produced in a slightly different manner, which results in the XPS having a thin plastic cover, while EPS have a partially open pore structure. This difference affects the overall reaction to moisture and temperature, but in the proper conditions the thermal resistance is fairly similar (Figure 6.1 and Figure 6.2). PUR does is created by a chemical reaction and have significantly better insulating properties than polystyrene (Figure 6.1) and can be delivered as blocks or blown in on-site to fill crevices (i.e. around windows and doors). However, PUR is also sensitive to moisture (Figure 6.2), which means it could be considered a worse option in cases where significant moisture is unavoidable.

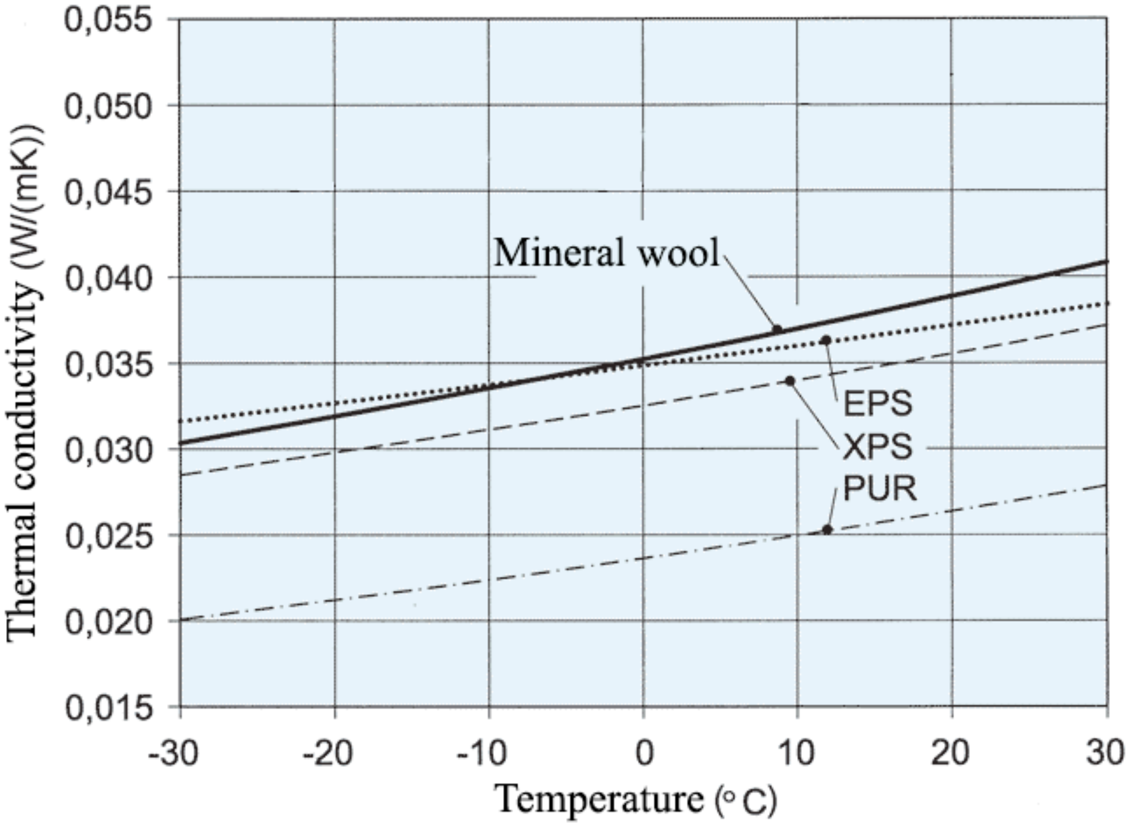


Figure 6.1: Thermal conductivity as a function of the average temperature in the dry material (SINTEF Byggforsk, 2004b)

As the figures show, to minimise the thermal conductivity of a insulating material, it should be kept dry and cold. This would also suggest that external insulation will somewhat improve the overall thermal performance. However, if for some reason the material is exposed to moisture, the cold may cause damage due to water freezing. Therefore adequate vapour barriers are paramount for achieving a well-insulated façade.

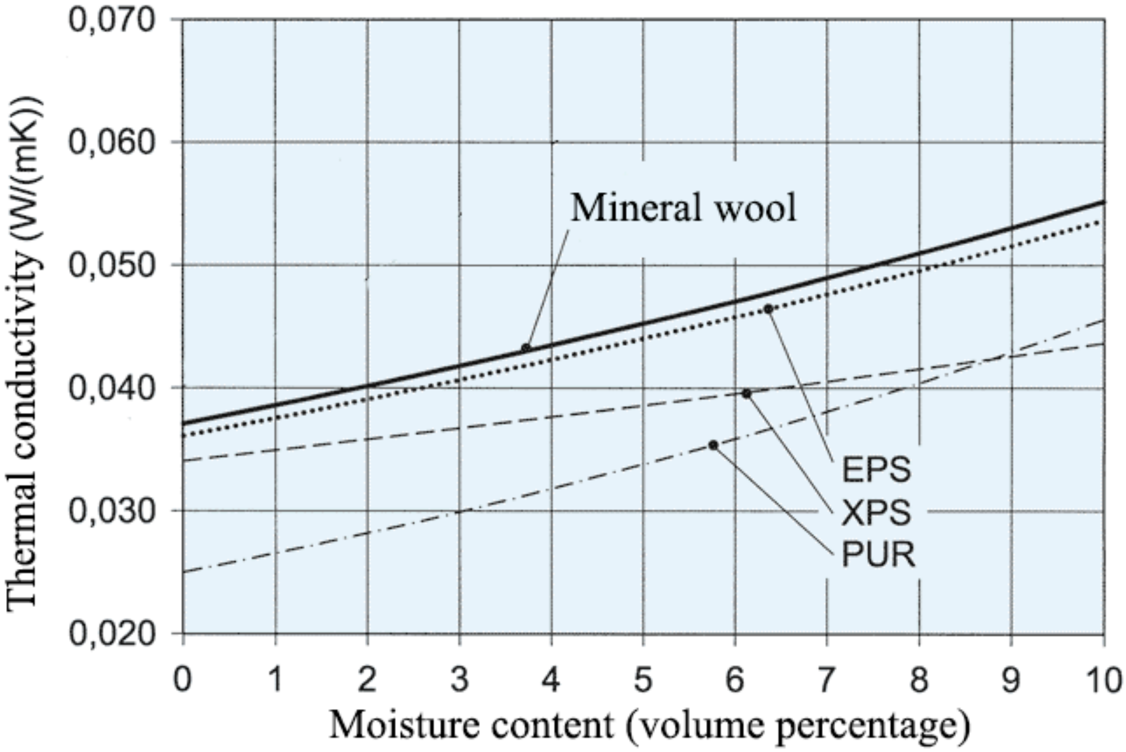


Figure 6.2: Thermal conductivity as a function of moisture content (SINTEF Byggforsk, 2004b)

6.2 Thermal and Economical Properties of Vacuum Insulation

In recent years, a new insulating material has been explored in vacuum insulation panels (VIP). These panels consist of a porous core sealed by a steam- and airtight foil, where there are near-vacuum conditions in the core material. This allows vacuum panels to be 5 to 10 times more effective insulators compared to conventional materials such as mineral wool. There are however significant challenges when utilising this kind of insulation method. The panels lose significant thermal resistance if punctured (will rise from approximately 0.004 to 0.02 W/(mK)), which means the panels are not flexible when fitting to existing wall geometry, and therefore require both significant care and skill during installation.

In addition to being challenging to install, the panels will suffer from thermal bridging around the edges. This is due to the panels being laid adjacent to each other, which will cause small gaps in between the insulation. As can be seen in Figure 6.3 this has substantial impact when the panels are small, but are less significant if they are kept at larger sizes. However, this needs to be considered in any case where vacuum insulation is a realistic option.

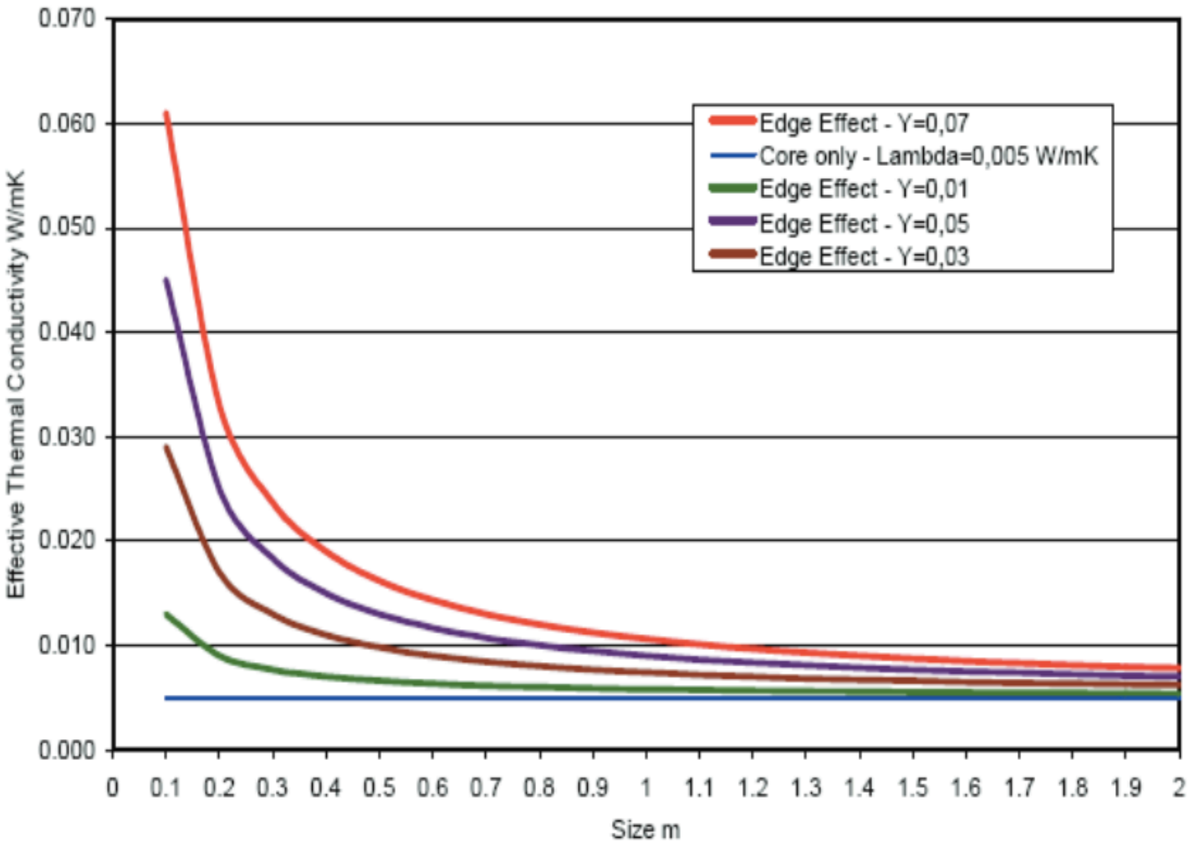


Figure 6.3: The effect of panel size and thermal bridging of the edges on the effective thermal conductivity (Y= linear thermal bridging value) (Grynning et al., 2009)

While the previously mentioned challenges are restricted to proper installation, a considerable, and yet unavoidable factor is the lifetime decay of vacuum panels. Due to increased pressure over its lifetime of 25 years, existing reports suggest that the thermal conductivity of vacuum panels will increase from 0.004 to 0.008 W/(mK) (Grynning et al., 2009). This means that the insulation will only be about half as effective at the end of the predicted lifetime. This cause significant issues on several fronts, as the thermal performance will gradually change. Additionally, the insulation must be replaced after approximately 25 years, which would require additional investments.

Vacuum insulation is also significantly more expensive than conventional insulating materials, which leads to it being rarely used. The one advantage of vacuum insulation is the vastly superior thermal conductivity, which allows for drastically thinner insulation thicknesses. Which is why this kind of insulation may actually be economically superior in special cases. When internal insulation is the only option, the use of vacuum insulation can help retain internal floor area. Any building owner would appreciate retaining as much space as possible, as building prices are often calculated on the basis of the available floor area.

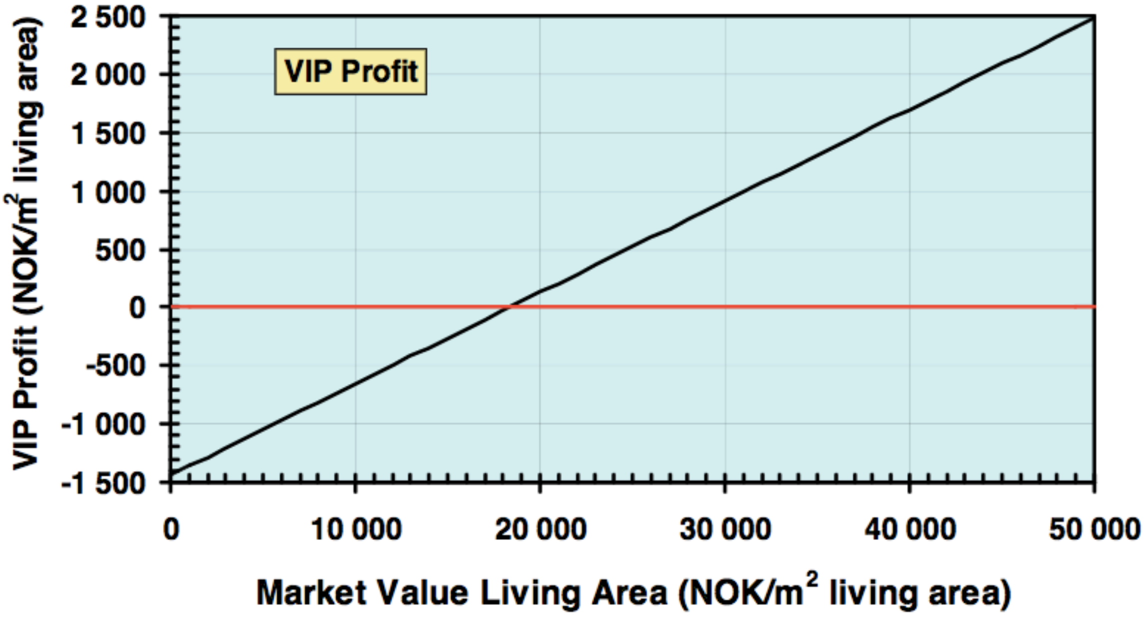


Figure 6.4: Profit in NOK for an example house with reduced wall thickness 20 cm due to VIP (10x10 m, with a floor height of 2.5 m) (Grynning et al., 2009)

As Figure 6.4 demonstrates, the value of the retained floor area will be highly impactful on the overall cost, and VIP will be highly profitable in areas with high real estate prices. Prices in the Norwegian market are high, especially in the urban areas of the largest cities, where external insulation may be difficult and prices are high. This is the case where vacuum insulation may be a good option, both in terms of energy efficiency and overall economical investments.

7 The Difference on Thermal Bridging Between Internal and External Insulation Methods

As mentioned in previous chapter, the placement of the additional insulation may significantly influence the thermal performance of a building element. This is due to the thermal bridging that occurs when elements of higher thermal conductivity leads directly from the warm side (internal space) to the colder side (external area). Thermal bridging allows heat flow to move around or through an insulating element, reducing its effectiveness. Figure 7.1 show two identical wall constructions simulated in THERM, however one is insulated externally, while the other is fitted with internal insulation. The insulating construction consists of a timber framework fitted with EPS insulation panels. The thickness of the insulation is identical in both cases, however the internal insulation is only fitted towards the façade construction – this is common practice when the developer wishes to retain the maximum amount of internal area.

The figure shows the heat flux vectors through the building element, and in an ideal case these vectors remain uniform in length and direction throughout the element. Such a case would suggest that there are no paths around (or through) insulating elements, and the insulation can perform at maximum effectiveness. This is clearly not the case in either example, just as it would never be in reality. However, the results clearly show a significant difference between the two cases. The externally insulated example has fairly uniform heat flux through the concrete element, but there is some clustering around the timer framework as the higher thermal conductivity of wood allows heat to 'bridge' through the EPS insulation. This suggests some thermal bridging occurs due to this framework, however when comparing to the internally insulated case, this seems minimal.

The heat flow through the internally insulated element is far from uniform in either length or direction, and most of the heat seems to flow through the internal divider and into the façade element, completely avoiding the insulation. There is also some clustering around the timber frames, just as in the previous case. This building element would clearly suffer from significant thermal bridging, which in the case of nZEB could provide substantial challenges.

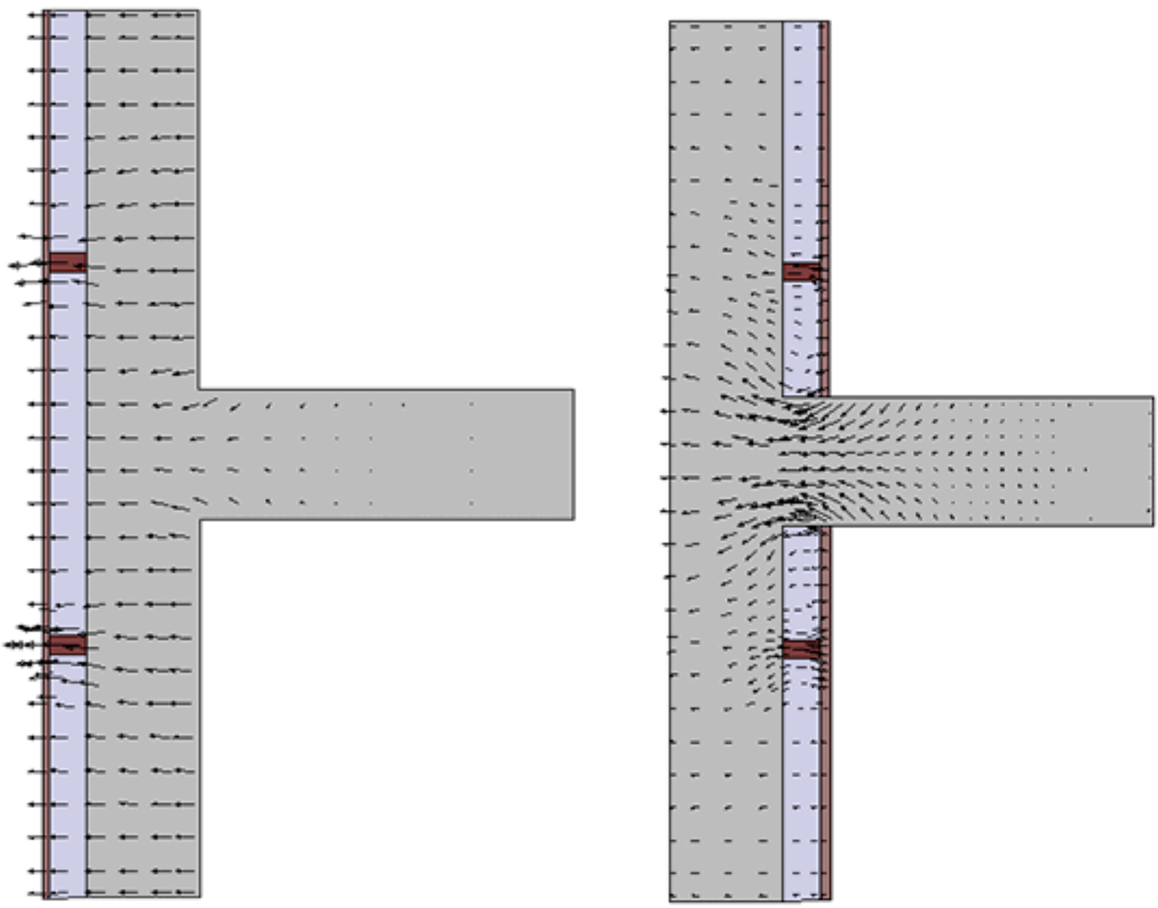


Figure 7.1: Heat flux vectors through a concrete wall (seen from above) with external- (left) and internal insulation (right)

Figure 7.2 show the temperature distribution in the same wall elements, which again show the significant difference in uniformity. Uniform heat flow would cause a uniform temperature distribution. This figure underpins the suggestion that the thermal bridging through an externally insulated element (left) far less significant than that through an internally insulated element (right). In addition, the temperature distribution highlights another worrying problem with internal insulation – moisture damage. Several common façade materials (i.e. brick, logs) could suffer extensive damage from moisture expanding when frozen, and with the external façade element all in negative degrees, freezing will occur. A non-insulated element would be heated by the internal temperature and suffer less (if any) such damages, it is therefore paramount to properly waterproof such facades.

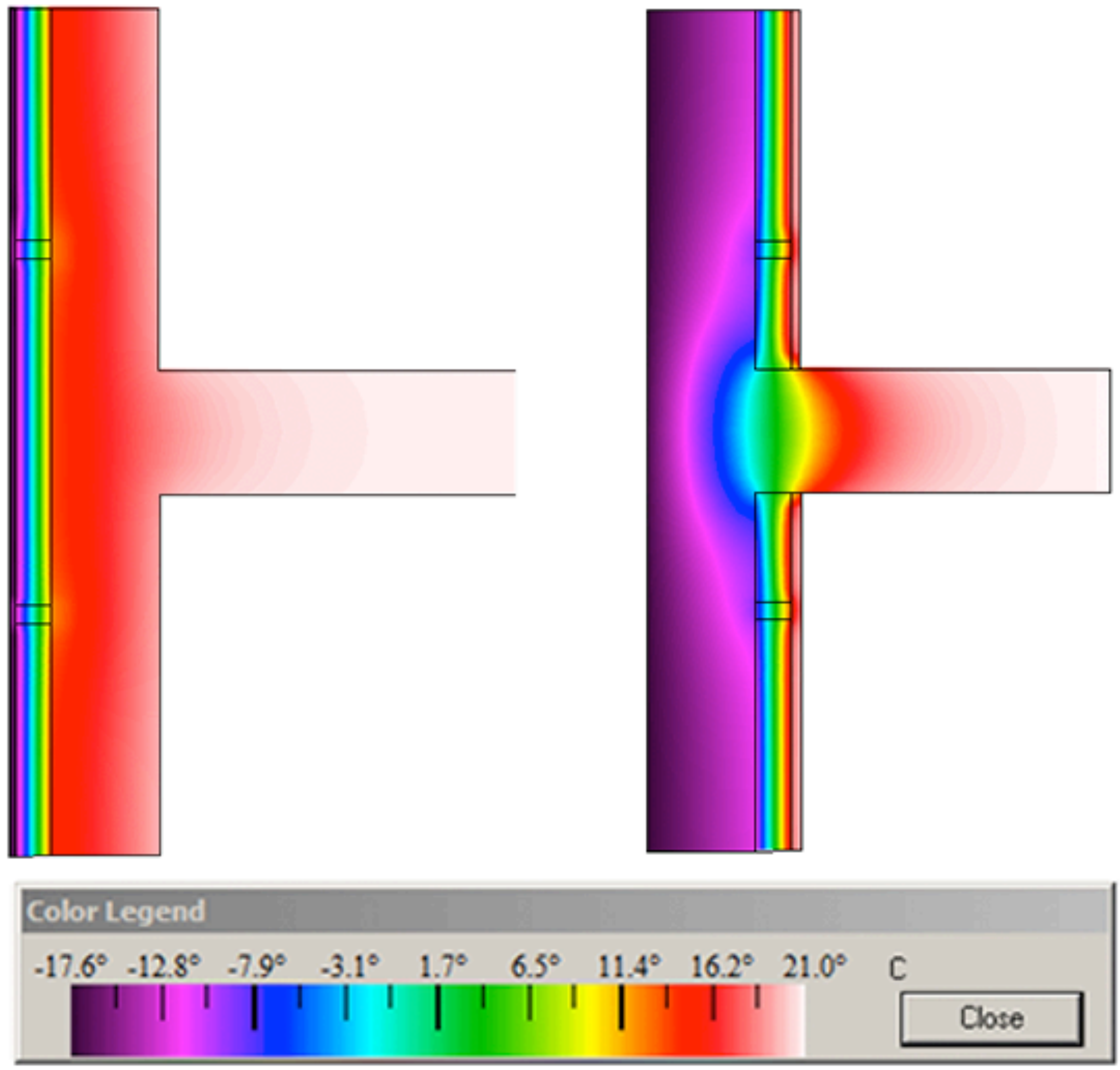


Figure 7.2: Temperature distribution through a concrete wall (seen from above) with external- (left) and internal insulation (right)

In non-solid walls, such as cavity walls, the heat will often travel along the binders and the wall will suffer from significant thermal bridging despite being insulated. Figure 7.3 show a simulated example, where the cavity have been filled by mineral wool, however the brick binders create an easy path for heat flow. Interestingly, the internal divider does not seem to cause much thermal bridging due to the cavity insulation 'breaking' the path. The heat will then travel along the easiest path, which in this case is through the binders. The temperature distribution shows how some areas of the internal surface (covering the binders) is significantly colder than the rest.

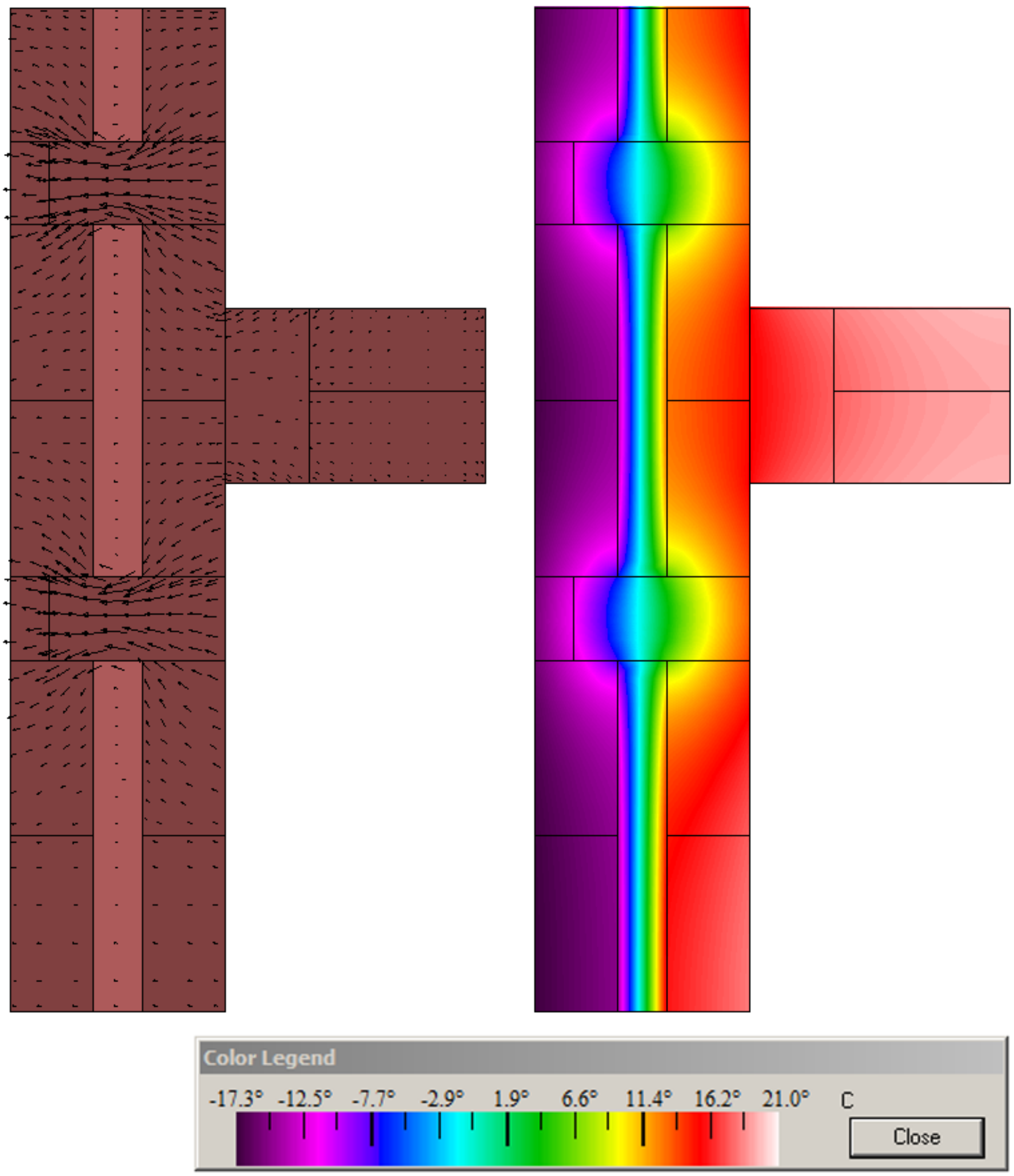


Figure 7.3: Heat flux vectors and temperature distribution through an insulated cavity wall (seen from above)

The results shown in Figure 7.3 might suggest that internal insulation may actually be as effective if installed as to ‘break’ the thermal bridges provided by the brick binders. However, as Figure 7.4 show, the heat flow is not restricted to linear flow, and the heat will instead flow through the internal divider and brick binders to form a significant thermal bridge. The problem of varying internal surface temperature is solved, but despite no linear bridging, the wall element will suffer from considerable thermal bridges. These results suggest that in order to properly minimise the effects of thermal bridging, some external insulation is necessary.

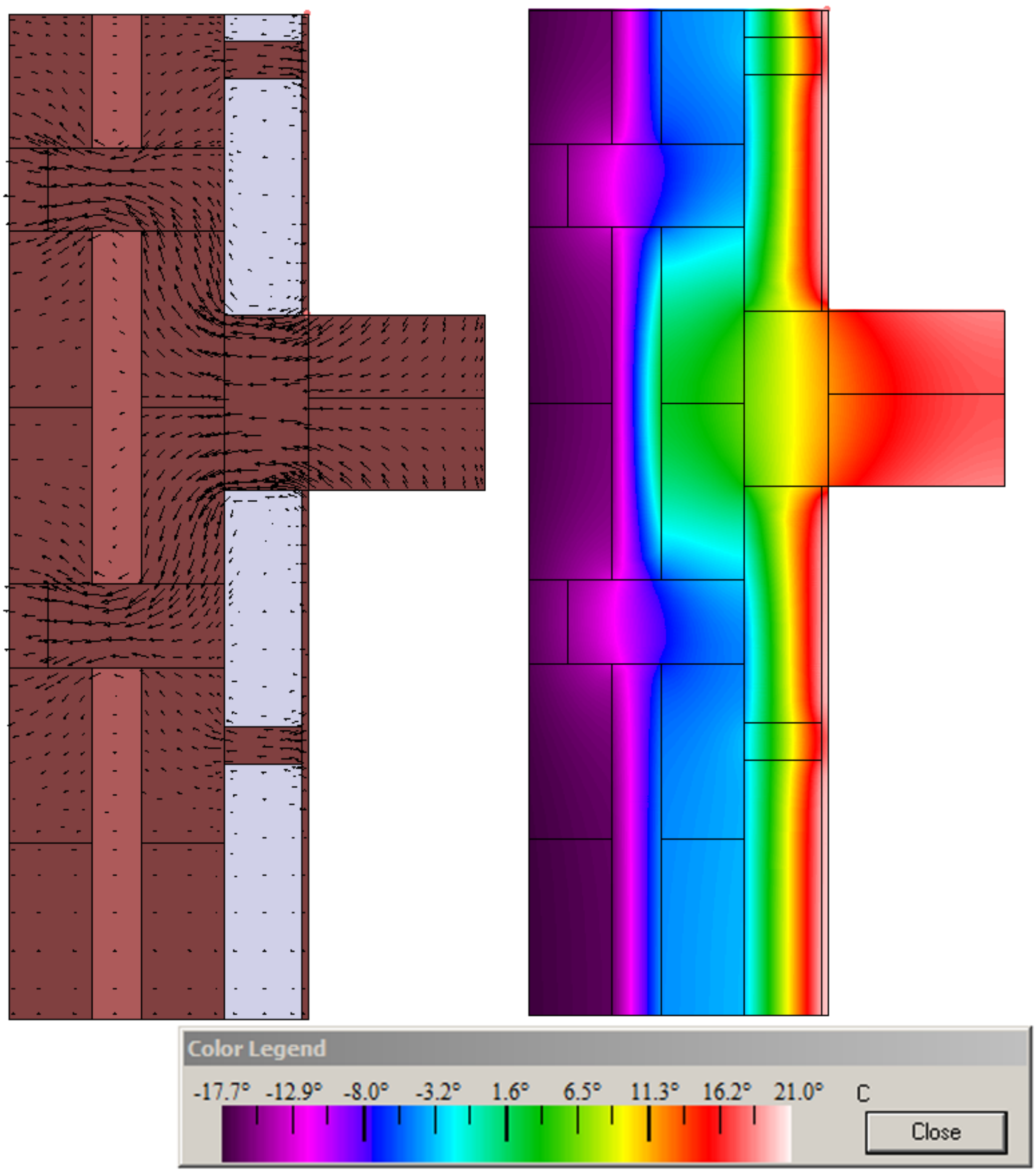


Figure 7.4: Heat flux vectors and temperature distribution through a cavity wall (seen from above) with both cavity- and internal insulation

8 How Building Shape Influence Energy Efficiency

Contrary to new development, rehabilitation is highly restricted to the existing building shape. Complex building shapes can create significant difficulties when refurbishment aims for nZEB standards, due to the increased heat loss from the building envelope. This chapter aims to explore significance of the building shape and compactness to the overall energy demand, in order provide a quantitative measurement for building shape that may indicate whether rehabilitation to nZEB is feasible. This will be done through data analysis of results from building energy simulations in SIMIEN.

8.1 The A/V Ratio

Heat loss is directly influenced by the compactness of the building, which makes it highly beneficial to be able to compare it numerically – which is why the A/V ratio has been introduced. The A/V ratio shows the relationship between the external surface area (A) and the internal volume (V). The ratio gives an indication of the compactness of a building and a high A/V ratio suggests an unpropitious shape for low-energy buildings. Since this ratio rarely is adjustable in cases of rehabilitation, it could prove to be a significant stumbling block in a developer's ambition for an nZEB refurbishment project.

The A/V ratio is also affected by the size of the building. The fabric U-values, shape and orientation of the building can be identical, but a smaller building will have a greater heating demand due to its unfavourable A/V ratio (McLeod et al., n.d.). This suggests that smaller buildings must take greater consideration to its shape than larger ones, and a successful rehabilitation to nZEB of detached dwellings may be highly dependant on its compactness.

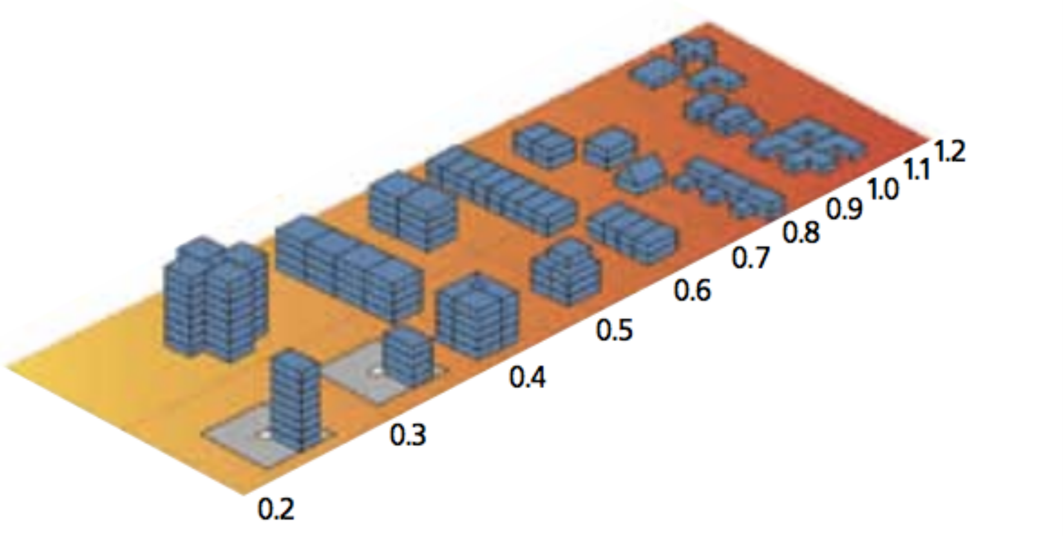


Figure 8.1: Influence of form and size on the A/V ratio (McLeod et al., n.d.)

Figure 8.1 provides a visual exemplification of building shapes and their corresponding A/V ratios, and gives an indication of the necessary shapes or size required to achieve favourable compactness. McLeod et al. (n.d.) suggests that an A/V ratio ≤0.7 m^2/m^3 provides a propitious foundation for passive house design. Despite nZEB being a more ambitious and strict concept than passive house, the building fabric is likely to be similar to the passive house buildings. This is due to the diminishing returns of insulation, and aiming for fabric U-values below that of passive house is unlikely to be cost effective. Therefore factors such as buildings shape will have to be considered of increased importance in nZEB.

8.2 Simulating Buildings of Varied Compactness

In order to properly investigate the extent of influence from the buildings shape (A/V factor), a set of buildings of varied sizes and shapes have been created for simulation in SIMIEN. The buildings are based on those used in SINTEFs theoretical groundwork for NS3701:2012 (2012), which is the Norwegian standard that provide the criteria for passive- and low energy commercial buildings. The buildings used in this report are based on the office buildings provided in the mentioned SINTEF publication. There are four different buildings shapes, which provide a scale of A/V factors to consider. Every shape is also simulated in three different sizes: 1000 m^2, 600 m^2 and 300 m^2, exactly as done in the theoretical groundwork done by SINTEF (2012). This report does however only provide an ideal rectangular shape, and so the remaining shapes are created with identical average fabric U-values and glazing to façade ratio. This is to isolate the A/V ratio as the only variable, which will allow for proper investigation of its influence on the total building energy demand.

8.2.1 Building Shapes Used in the SIMIEN Simulations

The buildings provided by the SINTEF report have glazing on every wall and are oriented along the optimal East-West axis, which are both properties that are carried over to all the simulated buildings. The ratio of glazing on each wall is held constant (see Table 8.1) and all buildings have their longest façade facing south. The 'shoebox' shape is taken directly from the report, and all other building shapes are based on its properties.

Table 8.1: The ratio of glazing to facade on the original 'Shoebox' buildings

Floor area	Wall orientation	Part of façade covered by glazing
1000 m^2	North or South	50.8 %
	East or West	15.8 %
600 m^2	North or South	39.7 %
	East or West	10.6 %
300 m^2	North or South	26.5 %
	East or West	7.9 %

All the buildings are simulated twice – once with all the factors suggested in Table 4.1 on the 'minimal end' of the scale and the other on the 'optimal end' of the scale. This will allow the simulation to provide a likely area in which the energy demand will lie if improvements on the building fabric are made according to the suggestions provided in this report.

The Base Case – 'Shoebox'

The first case building shape is provided by SINTEF (2012) and is considered the base case in this study. The building is a rectangle and the area is distributed over two floors (see Figure 8.2). This shape is often referred to as a 'shoebox' due to the geometrical similarity, and is considered the optimal shape for energy efficient buildings. This is due to how the compactness translates to a low A/V-ratio, and the will allow for a significant part of the outer façade to face south. This provides opportunity for optimal utilisation of solar radiation, which will reduce the demand for both heating and lighting, and if combined with proper shading will not significantly affect cooling demand.

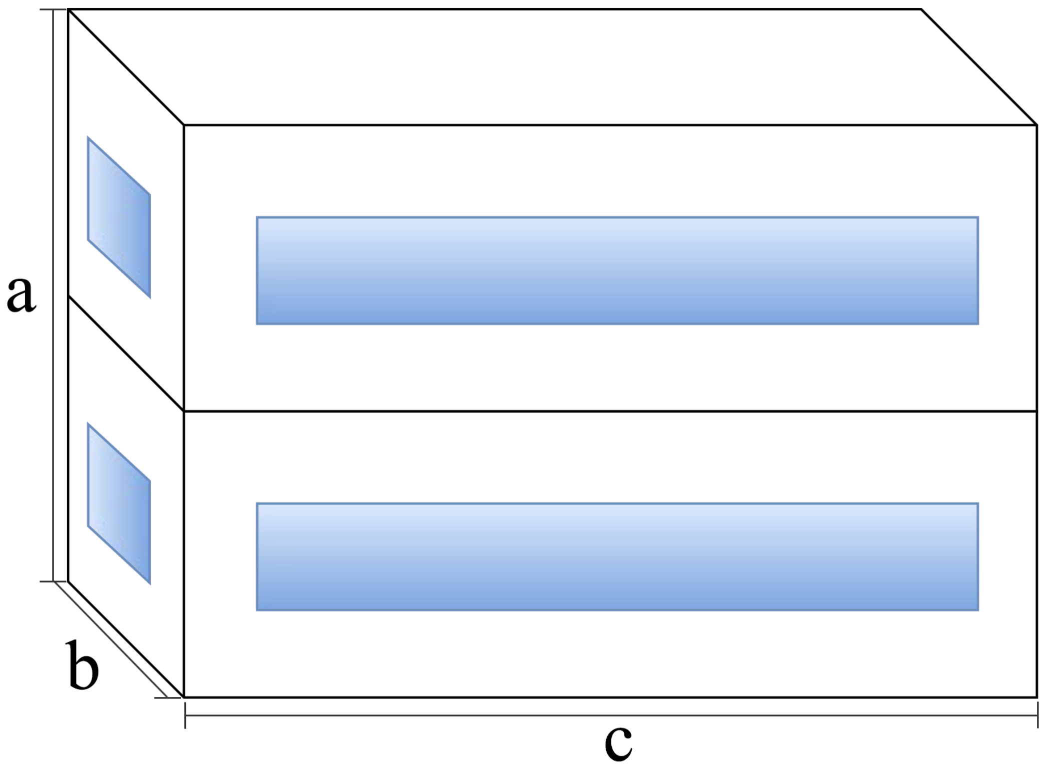


Figure 8.2: The general shape of the 'Shoebox' buildings

Figure 8.2 show the general shape of the 'shoebox' buildings design, and two lengths will be adjusted to create the different sizes used in this study. The height of each floor will remain constant throughout simulation, while the length and depth of the building will vary. The three buildings are created with the dimensions showed in Table 8.2.

Table 8.2: Dimensions used in simulations of the ‘shoebox’ buildings

Building size [m^2]	Length of side [m]			A/V ratio [m^2/m^3]
	a	b	c	
1000	6.3	20	25	0.497
600	6.3	15	20	0.551
300	6.3	10	15	0.651

‘L-shaped’ Buildings

This building shape was created to represent a less compact design compared to the shoebox alternative and significantly worse than the optimal shoebox design. The floor area remains identical, and the average fabric U-values are kept as well. This shape aims to represent a lot of common buildings’ compactness, as it is non-optimal, yet not too complex. Figure 8.3 show the general shape of the building design, and the dimensions of each case is presented in Table 8.3.

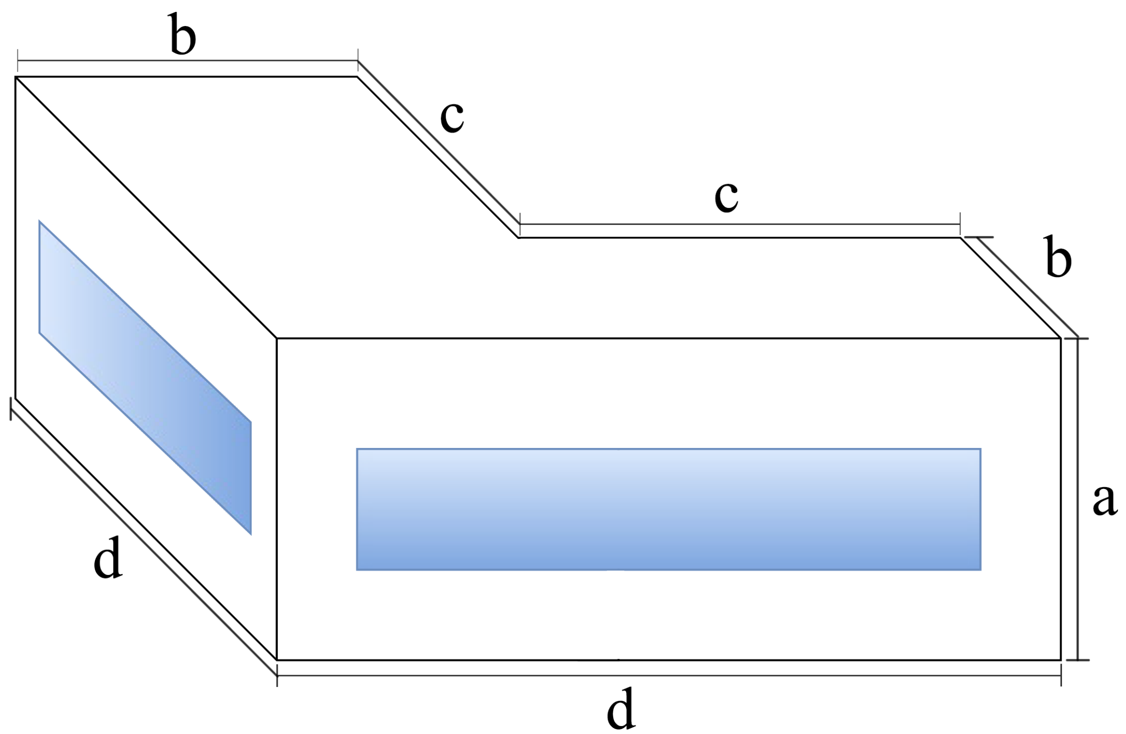


Figure 8.3: The general shape of the ‘L-shaped’ buildings

Table 8.3: Dimensions used in simulations of the 'L-shaped' buildings

Building size [m²]	Length of side [m]				A/V ratio [m²/m³]
	a	b	c	d	
1000	3.15	20	15	35	0.775
600	3.15	15	12.5	27.5	0.818
300	3.15	10	10	20	0.902

The A/V ratio in these buildings have taken a significant leap from those of the base case design, and is a result of both shape and the reduction from two to a single floor. This also shows the significance of distributing the floor area over several floors, which reduces the external area of the building.

The Worst-case Scenario – 'C-shape'

The C-shaped buildings provide a case that represents complex buildings shapes with very little compactness. This will provide the worst-case scenario in terms of building shape, and will still retain the same U-values and floor areas as the previous scenarios. Figure 8.4 illustrate the general shape of these buildings, and the dimensions used in simulation are shown in Table 8.4.

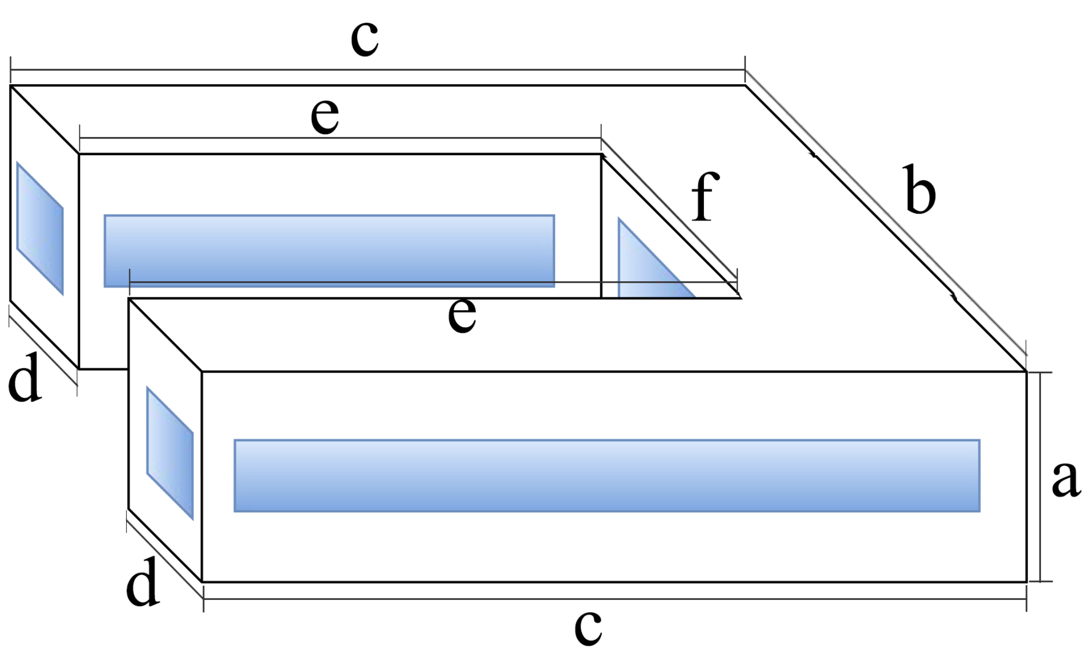


Figure 8.4: The general shape of the 'C-shaped' buildings

Table 8.4: Dimensions used in simulations of the 'C-shaped' buildings

Building size [m^2]	Length of side [m]						A/V ratio [m^2/m^3]
	a	b	c	d	e	f	
1000	3.15	40	40	10	30	20	0.855
600	3.15	30	40	5	30	20	0.968
300	3.15	30	20	5	15	20	1.068

The range of A/V ratios in this case somewhat overlap with that of the L-shaped buildings, which underpins the influence of building size to the overall compactness of the building. The largest building in this case is actually considered more compact than the smallest of the L-shapes, at least in terms of the A/V ratio.

8.3 Simulation Results

Building energy simulations have been done as if the buildings stand in Oslo, which is the practice done by SINTEF in their theoretical groundwork. Oslo is used as a base case scenario, and legislation will be based upon this climate, but adjusted according local climates.

Figure 8.5 shows the results of the 18 simulations, where delivered energy is plotted against the buildings' A/V ratio. The plot shows a clear trend of increased energy demand with increased A/V ratio, which fits with the assumption that compactness is a significant factor in nZEB. The plot also shows how the compactness is increasingly important when the building envelope is less energy efficient, as the curve of the 'minimal' case seems significantly steeper than the 'optimal' case. As nZEB is a concept that aims to maximise energy performance of the building, the figure show how in some cases it may be very tough to achieve this standard due to the A/V ratio. However, the moderate escalation in energy demand for the 'optimal' case provides some optimism for feasibility in sub-optimal building shapes as well. These buildings would require extraordinary attention to building fabric design, and would probably prove to be costly – but theoretically achievable.

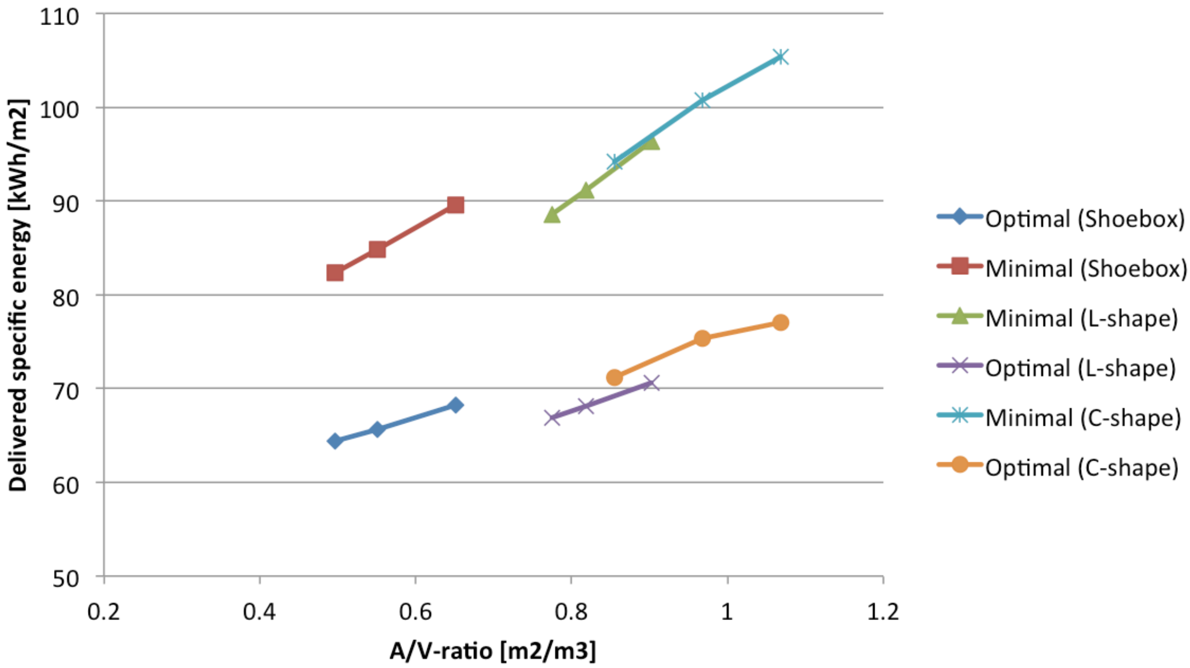


Figure 8.5: Relationship between energy demand and A/V-ratio for two different building fabric cases (results from SIMIEN simulation)

The plot also seems to imply that the relationship between building compactness and energy demand is linear, which suggest that all gains in terms of compactness will positively affect energy performance. By calculating the Pearson product-moment correlation, a clear statistical significance is confirmed (Table 8.5). The PPMC coefficient is extremely high, and suggests that there is little doubt that there is little doubt that there is a linear relationship between the two variables – in both cases there is more than 99.9 % certainty of linear correlation (Table 8.5).

Table 8.5: Linear correlation hypothesis test of A/V-ratio to delivered specific energy

Building fabric	Sample size	Critical value (α = .05)	Critical value (α = .001)	r-value	Significance
Optimal	9	0.66638	0.89826	0.92394	**Yes**
Minimal				0.95267	**Yes**

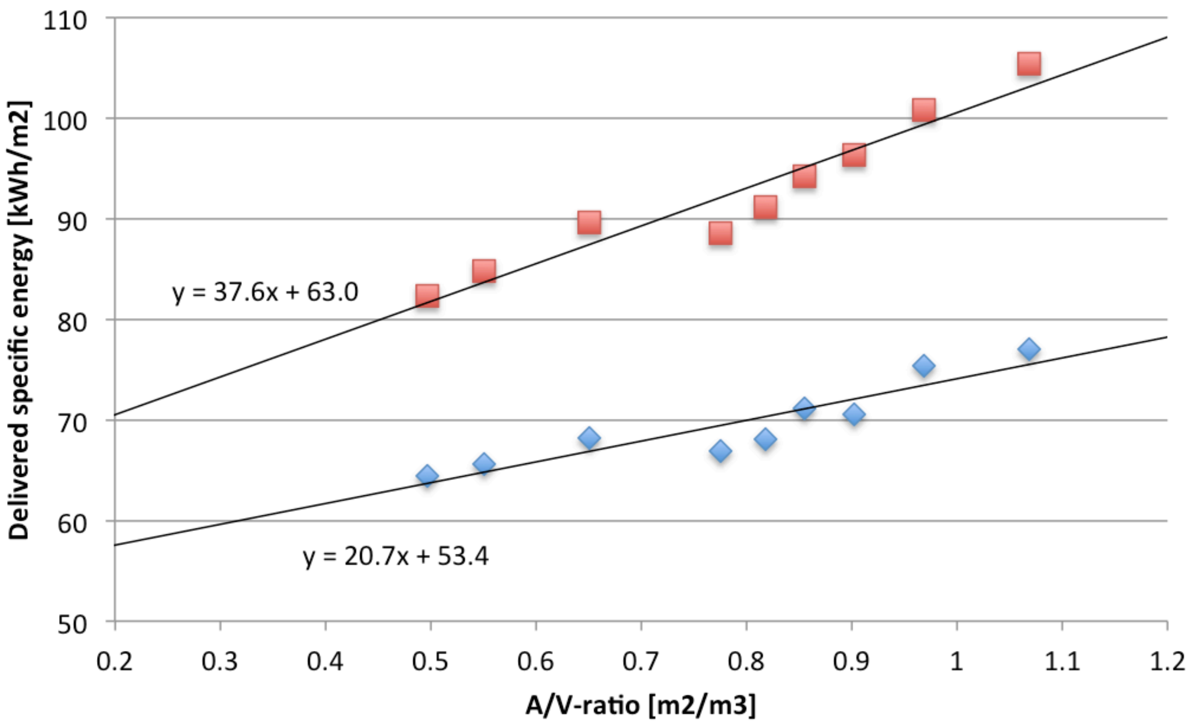


Figure 8.6: Linear approximation of energy demand as a function of A/V-ratio for the two building fabric cases

Figure 8.6 show a linear approximation of the relationship between the A/V ratio and the delivered energy in both cases. This figure seems to underpin the suggestion from the previous statistical analysis of a linear correlation. There will always be some degree of variance, as can be seen in the approximation, but all data points remain fairly close to the linear suggestion. This approximation also quantifies the importance of the building fabric, as the expression for the 'minimal' case show a significantly greater slope. The first data plots (Figure 8.5) imply the same, but the linear approximation shows the extent of this difference. The 'minimal' case is vastly more sensitive to building shape, and rise 82 % faster than the 'optimal' case. The plot also show how the two cases never come close in terms of energy demand, which suggests that building shape rarely compensates for poor building fabric.

The difference in demand between the two linear approximations in Figure 8.6 also follows a linear pattern (Figure 8.7), which is also confirmed by the PPMC hypothesis test (Table 8.6). The specific difference in energy demand is unsurprisingly linearly increasing, due to the difference in slope between the two linear expressions. The plot also shows that the relative difference increase with the A/V factor, further reinforcing the suggestion that building fabric is the dimensioning factor.

Table 8.6: Linear correlation hypothesis test of the measurements between the 'optimal' and 'minimal' cases

Data	Sample size	Critical value (α = .05)	Critical value (α = .001)	r-value	Significance
Specific difference	9	0.66638	0.89826	0.97356	**Yes**
Relative reduction				0.92714	**Yes**

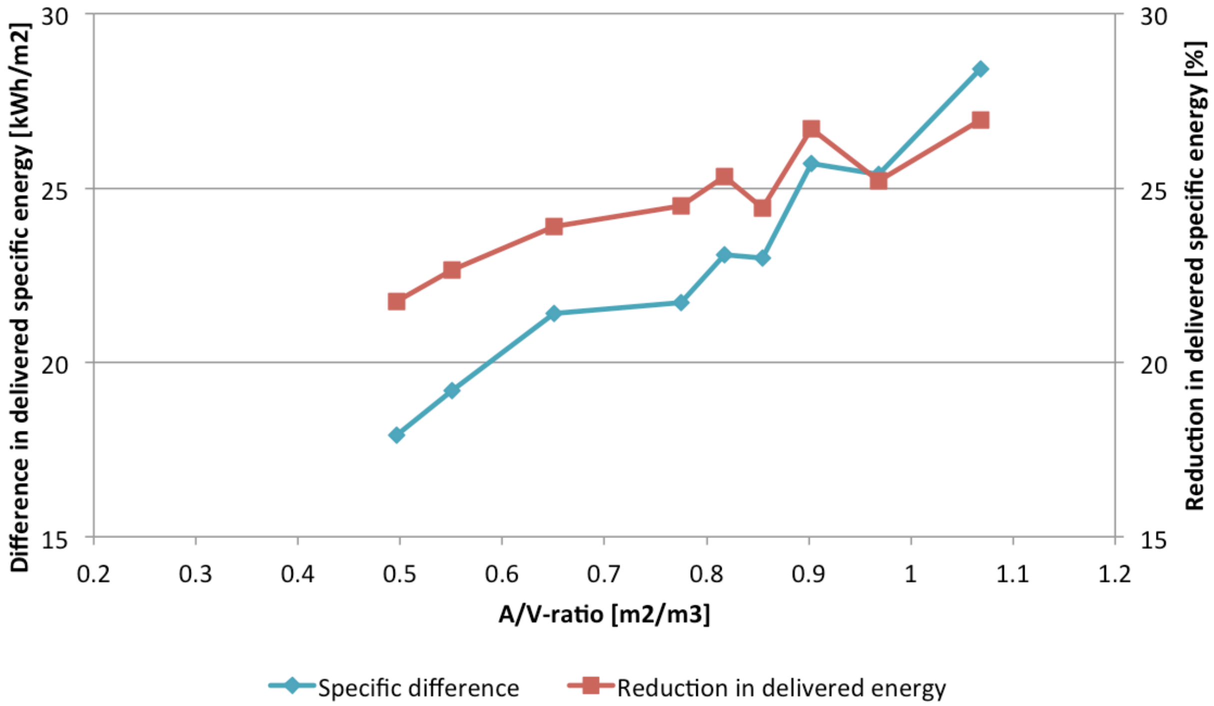


Figure 8.7: Difference in energy demand between the two building fabric cases. Both specific value (blue) and relative reduction (red) is included

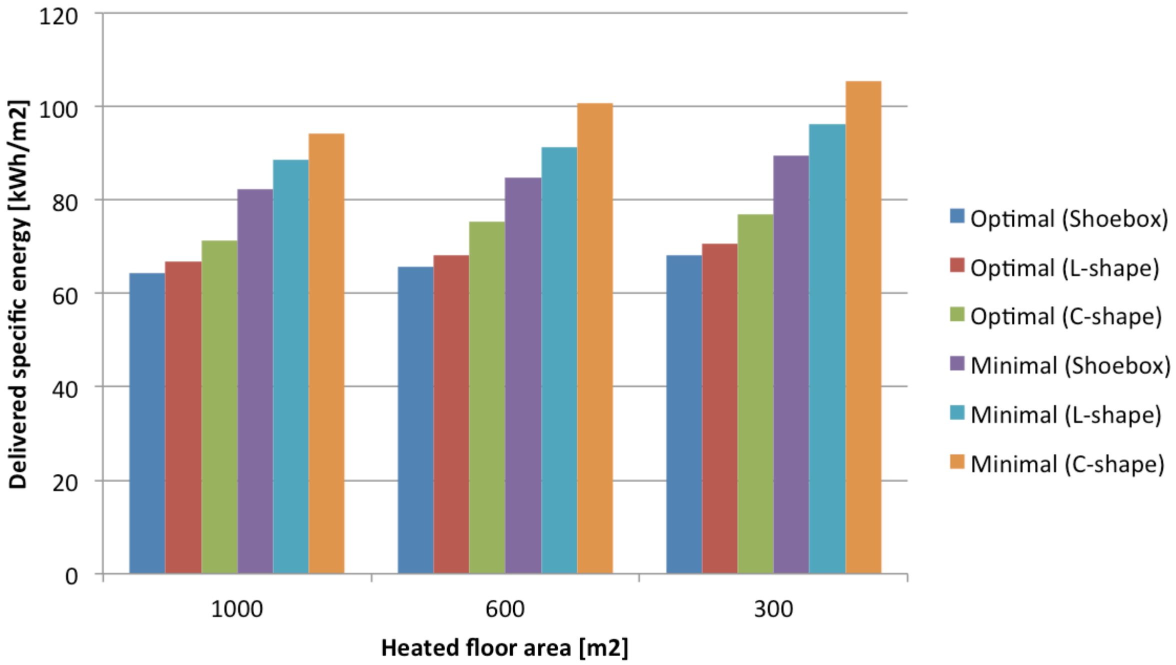


Figure 8.8: Energy demand for the simulated building shapes and fabric cases, sorted after heated floor area

Sorting the data into groups according to floor area show an almost identical trend of energy demand for all groups (Figure 8.8) – the energy demand increase with shape and fabric design. These results suggest that size alone may be a poor indication of energy performance, as the largest changes comes with building shape and fabric U-values. It would therefore be beneficial to consider the building shape and achievable U-values rather than the overall building floor area when considering rehabilitation towards nZEB, as contributing factor of the building size is already incorporated into the A/V ratio. This ratio will also reward buildings with several floors, and as can be Figure 8.5 the reduction of building floors from two to one, in combination with a slight change in shape, produce a noticeable gap in the A/V ratios of the base case and the following 'L-shaped' case. Contrastingly the 'C-shape' A/V ratios overlap with those of the previous 'L-shaped' case – where there is no alteration in the number of floors.

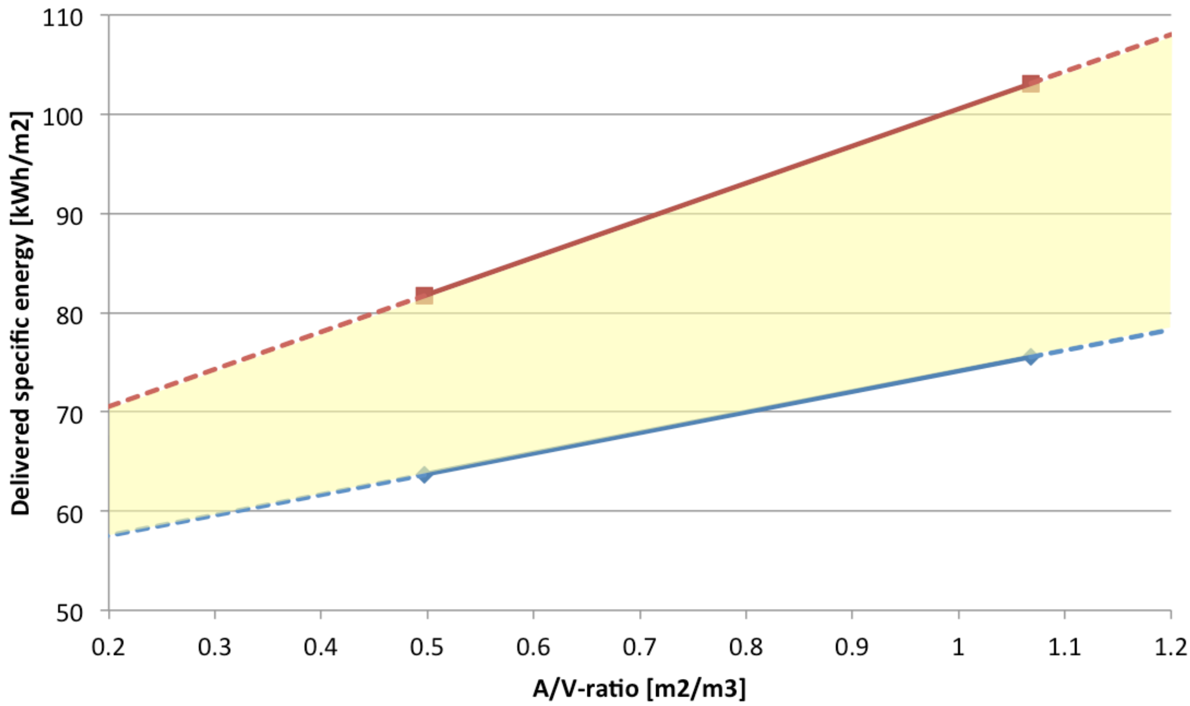
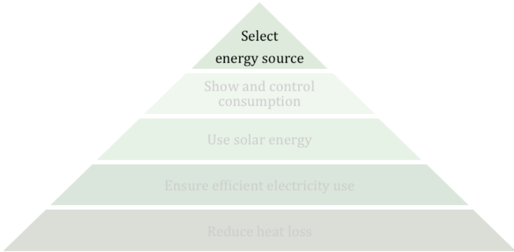


Figure 8.9: Probable area of energy demand after improving building fabric

The results suggest that delivered specific energy is highly correlated to both building fabric design and the building shape, and Figure 8.9 show the probable range of building energy demand based on the U-value ranges provided in Table 4.1 and the A/V ratio. The linear approximation (as shown in Figure 8.6) is used as upper- and lower limits due to the cases being on either extreme of the building fabric scale. The continuous lines represent the simulated range, and due to the significant linear correlation (Table 8.5), this line has been protracted in either direction to include an increased range of A/V ratios. This range is based on a office building operated 'as normal' (see Appendix A for details), but with a rehabilitated envelope – which means further energy efficiency measures may still improve performance.



9 Choice of Heat Source as an Energy Efficiency Measure

While most heat sources do not directly affect the building energy demand, the energy balance calculation will take into consideration the origin of such source as to determine whether it should be considered an energy efficiency measure. As stated in chapter 2.3.3, the suggested definition of nZEB will consider biofuel and district heating to be a more sustainable energy source, and therefore suggest energy factors that will be beneficial in a building energy balance. Biofuel and district heating have been granted energy factors of 0.37 and 0.43 respectively (Table 2.5), which means that heating demand covered by these sources will be reduced by 63 % and 57 % when calculating the energy balance. The heat pump is assumed to have a COP of 3.5, which is chosen due to being used in some recognised reports (Ramstad, 2011). The proposed nZEB definition use an import/export balance, which means that utilising an energy source with lower energy factor will be calculated as an energy efficiency measure rather than production. Alternatively to these heat sources, heat pumps may be utilised to reduce energy demand. Heat pumps run on electricity, which has an energy factor of 1 (Table 2.5), but as they required less electric energy per delivered heat energy, it will be considered an energy efficiency measure in an import/export balance.

Table 9.1: Influence on energy balance for some suggested heat sources

Building	Combined heating demand [kWh (kWh/m^2)]	Heat Source	Coverage of total heating demand [%]	Energy factor / COP* [-]	Net delivered energy [kWh (kWh/m^2)]	Reduction [%]
Minimal large 'shoebox'	28296 (28.3)	Ground source heat pump	93.4 %	3.5*	9419 (9.4)	66.7
		District Heating	100 %	0.43	12167 (12.2)	57.0
		Biofuel	93.4 %	0.37	11646 (11.6)	58.8
Optimal large 'shoebox'	13012 (13.0)	Ground source heat pump	95.7 %	3.5*	4117 (4.1)	68.4
		District heating	100 %	0.43	5595 (5.6)	57.0
		Biofuel	95.7 %	0.37	5167 (5.2)	60.2
Minimal large 'C-shape'	38045 (38.0)	Ground source heat pump	93.1 %	3.5*	12745 (12.7)	66.5
		District heating	100 %	0.43	16359 (16.4)	57.0
		Biofuel	93.1 %	0.37	15730 (15.7)	58.7

Table 9.1 presents the effect the heat source has on total heating demand in a few buildings simulated in SIMIEN (same as in chapter 8) – where combined heating demand is the sum of space-, water- and ventilation heating. District heating is assumed to cover the total combined heating demand, as the heat is delivered from a central location, a boiler is not required to be sized according to peak demand to cover the entire heating system. The biofuel boiler and the ground source heat pump is dimensioned to cover 40 % of the peak load, which translates to approximately 90 % of the total annual load (Appendix B), and the peak load is assumed to be covered by an electric boiler. SIMIEN does however only provide boiler-sizing for this heat source when hot water is not included, but in this report it is assumed that the heat source is dimensioned to cover both the water heating and 40 % of the remaining peak load. As can be seen by the results in the table, the percentage-wise reduction of heating demand remains very similar regardless of building fabric and –shape, ranging 57-68.4 % depending on heat source. The heating demand in the buildings simulated in this study makes up between 22.6 % and 47.5 % of the total energy demand, depending on building fabric and –shape, which means that the introduction of such an energy source could reduce delivered energy (as defined in import/export balance) by 13-32 %.

Despite the options being relatively close in terms of demand reduction, the investment price may differ greatly. Districting heating also requires an existing infrastructure to be in place, but if this is the case, it could prove to be the most cost efficient. The water based heating system would be connected to the existing grid and a substation would be installed, but the maintenance can largely be left to the district heating supplier. Biofuel systems are likely the other cost effective system of the three, and is very flexible compared to the other two. It can be placed in building without the availability of district heating or the outdoor space for heat wells (for the ground source heat pump). Ground source heat pumps require a substantial investment, but are also the most effective in terms of energy demand reduction. This option may prove to be cost effective over time, but do require both significant up-front investment and available outdoor space.

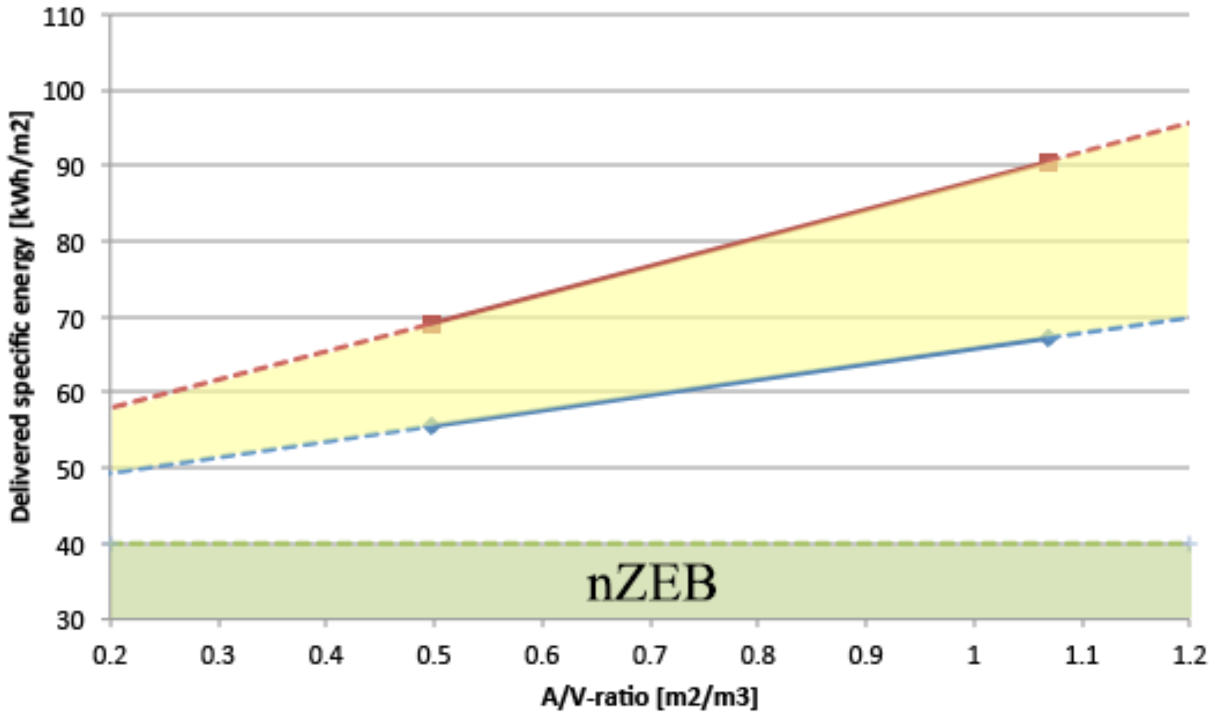


Figure 9.1: Approximation of energy demand after adjusted for new heat source. The green area represents nZEB energy goals

If the cases studied in previous chapter integrate an improved energy source, the assumed energy demand would significantly decrease. Figure 9.1 show an approximate plot adjusted for an upgraded heat source and clearly show an improved efficiency for every case. The difference between the two limits of the (yellow) area also shrink, which suggest that the installation of such a heat source would make greater impact on a building with worse building fabric. This follows previous results, as the percentage-wise reduction from a new heat source remains fairly similar regardless of building fabric design. The plot does also show that while this energy measure creates a significant improvement, the energy demand remains higher than the requirements of nZEB – meaning additional energy efficiency measures, and/or on-site production is required to meet this standard.

10 CASE STUDIES OF AMBITIOUS HIGH ENERGY PERFORMANCE BUILDINGS

In order to understand how the buildings of the future may perform, a selection of four energy-ambitious building projects have been chosen for further investigation. Two buildings that fall into the category of passive house have been chosen in order to analyse the improvements required in the immediate future. Additionally, two projects with extraordinary ambition with regards to energy efficiency have been chosen in order to understand the gap between nZEB and today's standard. Figure 10.1 show the load/generation balance for the four chosen buildings.

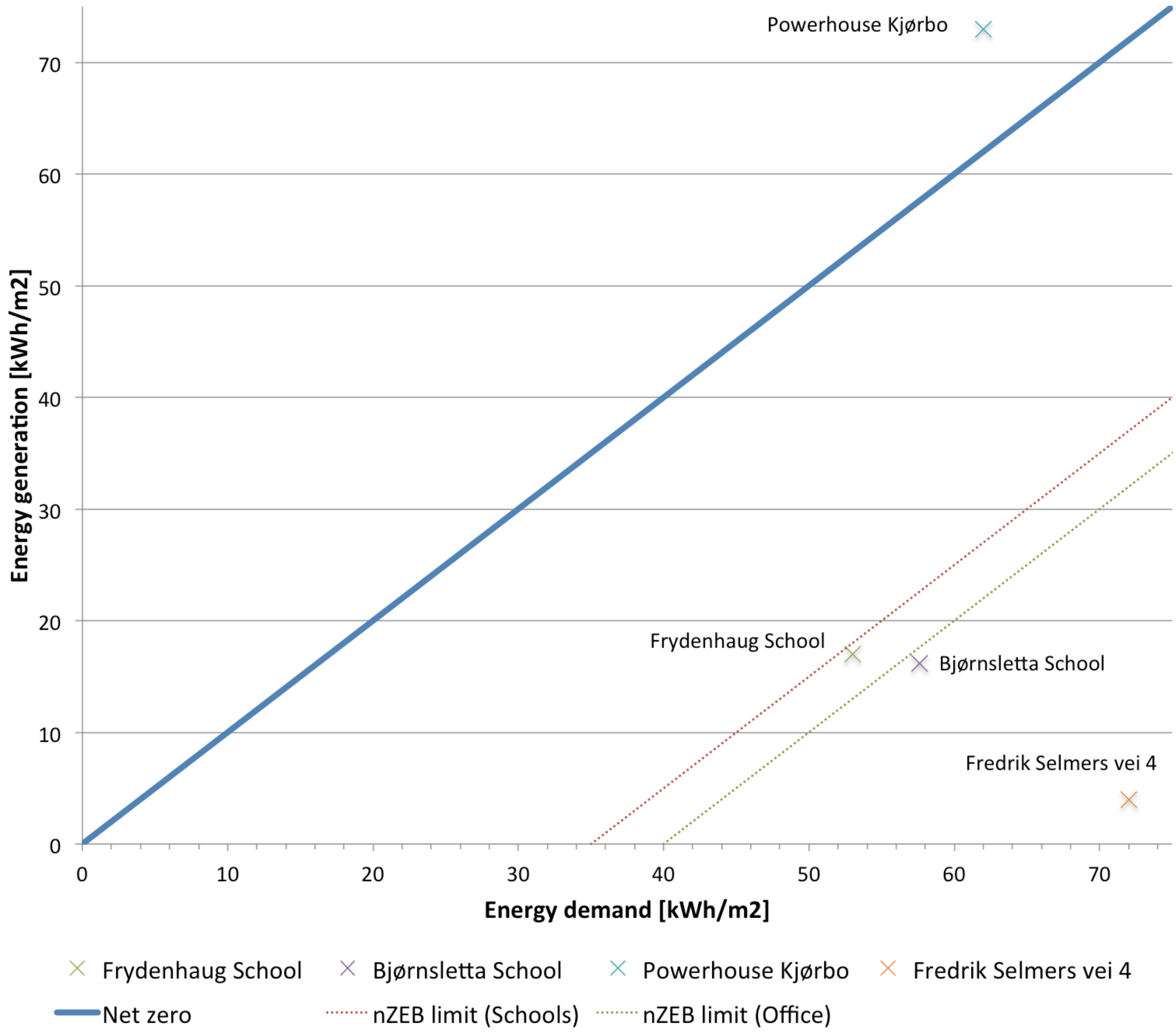


Figure 10.1: Load/generation balance for the four case studies

10.1 Bjørnsletta School

Figure 10.2: Exterior of Bjørnsletta School

Bjørnsletta has been built as the first school in Oslo to meet the requirements for passive house set by NS 3701. The school was finished and first taken into use fall 2014, and had a budget of 450 MNOK (46502 NOK/m^2). The school is a combined elementary- and lower primary school, accommodating approximately 800 students and consists of three wings in addition to a sports centre. However, this case study does not include the sports centre. The project have focused largely around designing a well insulated and low-infiltration building, and as presented in Table 10.1, the building fabric is highly energy efficient. The school's heating is provided by a geothermal heat pump that covers approximately 90 % both the space- and hot water heating demand, and an electric boiler to cover peak load.

Table 10.1: Building fabric properties for Bjørnsletta School

Building Fabric	Upper Limit for U-value [W/m² K]		
	TEK10	NS 3701	Bjørnsletta School
Outer Walls	0.18	0.10-0.15*	0.10
Glass/Windows/Doors (incl. frame)	1.20	0.80	0.80
Roofs	0.13	0.08-0.12*	0.065
Floors Adjoined to Ground	0.15	0.08-0.12*	0.10
Air changes from infiltration at 50 Pa [1/h]	1.50	0.60	0.30

*typical values, not requirements

The ventilation is demand-controlled with active supply air vents that provide accurate regulation of the system. The heat recovery system is also very efficient at an efficiency of 83 %. Lighting is typically one of the largest energy posts in a low energy building and Bjørnsletta have therefore installed daylight controls and LED-lighting. Energy readers have also been installed on all energy posts so that the use can be thoroughly monitored.

The school's net energy demand is 57.6 kWh/m^2, with 41.4 kWh/m^2 imported from the grid. As can be seen in Figure 10.1, Bjørnsletta does not qualify for nZEB for the school category, but is still a very energy efficient building categorised as a passive house.

10.2 Frydenberg School

Figure 10.3: Exterior of Frydenberg School

Frydenberg was finished in 2014 and is an elementary school for kids with disabilities in Drammen that accommodates 100 students and 110 employees. The school was built according to passive house standards (Table 10.2), but the additional environmental focus has pushed to project to a possible nZEB standard. The project cost was 175 MNOK (35817 NOK/m^2), with 1.9 MNOK in grants from Enova. The building's heating demand is mostly covered by a ground source heat pump (52 %) and 150 m^2 of solar thermal collectors (28 %), with the peak load covered by an electric boiler. The solar thermal collectors also contribute to cooling during the summer. Excess thermal energy is stored in energy wells dug 250 m into the ground.

Table 10.2: Building fabric properties for Frydenhaug School

Building Fabric	**Upper Limit for U-value [W/m^2 K]**		
	TEK10	NS 3701	Frydenberg School
Outer Walls	0.18	0.10-0.15*	0.12
Glass/Windows/Doors (incl. frame)	1.2	0.8	0.8
Roofs	0.13	0.08-0.12*	0.09
Floors Adjoined to Ground	0.15	0.08-0.12*	0.08
Normalised thermal bridge value [W/m^{2}K]	0.06	0.03	0.03
Air changes from infiltration at 50 Pa [1/h]	1.50	0.6	0.29

*typical values, not requirements

In order to reduce the energy demand for ventilation, demand-controlled systems have been installed with efficient heat recovery (84 %) and a combo-battery for both air heating and -cooling supplied by the energy wells. The lighting is highly efficient LEDs with movement sensors and a possibility for users to dim lighting levels. There are also monitoring equipment for continual oversight over SFP, COP (for heat pump) and all energy posts. The net energy demand for the school is 53 kWh/m^2, however the anticipated delivered energy is below 37 kWh/m^2 – meaning the building would most likely meet nZEB requirements for school buildings (≤ 36 kWh/m^2). Due to the building being recently finished, the actual annual energy use cannot yet be presented, however the results so far have been classified as 'satisfying', and it seems likely that the building will fall into the nZEB category as visualised in Figure 10.1 (with 36 kWh/m2 delivered energy).

10.3 Fredrik Selmers vei 4

Figure 10.4: Exterior of Fredrik Selmers vei 4

Fredrik Selmers vei 4 is a building in Oslo, currently occupied by the Norwegian Tax Administration. The building is originally from 1982, but was rehabilitated between 2010 and 2013 in order to drastically improve its energy performance, as well as an expansion and enhanced utilisation of the office space. The building frame has been reused, while the facades have been demolished and rebuilt with sustainable and recycled materials. Additional insulation has been added to both the basement and roof. These measures have drastically reduced energy demands and the building meets passive house standards, but has some way to go in order to reach nZEB levels (Figure

10.1). The building's heating energy demand is completely covered by local energy production, as defined in chapter 2.3.3, with 30 % from district heating and 70 % covered recycling the excess heat from the computer hall via a heat pump.

Table 10.3: Building fabric properties for Fredrik Selmers vei 4

Building Fabric	Upper Limit for U-value [W/m² K]		
	TEK10	NS 3701	Fredrik Selmers vei 4
Outer Walls	0.18	0.10-0.15*	0.16
Glass/Windows/Doors (incl. frame)	1.20	0.80	0.80
Roofs	0.13	0.08-0.12*	0.12
Floors Adjoined to Ground	0.15	0.08-0.12*	0.07

*typical values, not requirements

The building has focused on good insulation and demand-controlled systems in order to reduce the energy demand to the lowest possible levels. As can be seen in Table 10.3, the fabric U-values are all lower than the requirements set in TEK10, and close to the typical levels set in NS 3701, despite being a rehabilitation project.

The project cost was 500 MNOK (13094 NOK/m^2), with 18.5 MNOK support from Enova for their ambitious energy measures. This additional cost for refurbishing to passive house standard is estimated to be 40 MNOK above a TEK10-standard project, which reduce the energy demand from 150 kWh/m^2 delivered energy, to the 68 kWh/m^2 required in the current building. The building's BRA is 34832 m^2, meaning the decision to rehabilitate to passive house standard saves approximately 2.86 GWh per year, or 2.86 MNOK (assumed cost of 1 NOK/kWh). This means that the additional investment of 21.5 MNOK will be recouped in 7.5 years, making it a worthy long-term investment. Had there been no support from Enova, the payback period would increase to 14 years, however still considerably lower than any building's predicted lifetime.

10.4 Powerhouse Kjørbo

Figure 10.5: Exterior of Powerhouse Kjørbo

Powerhouse Kjørbo finished in 2014 and is a unique project as it is the world's first rehabilitated energy-plus-house. This means that the building produce more energy on-site than the building requires, allowing it to export surplus electricity to the grid. The building has installed a large amount of solar panels that produce more than 200 000 kWh per year, or almost 39 kWh/m^2, a significant surplus compared to the delivered energy demand of 28 kWh/m^2. The building is expected to be a net zero-energy project, meaning over the building's lifetime, the surplus energy production will offset the embodied primary energy in the construction process. The building's heating demand is covered by a set of heat pumps – both a ground source heat pump and a heat pump that recycles the heat produced in the server room is used. Hot water demand is covered by an additional heat pump, and the building is connected to district heating as a back-up solution in case of heat pump failure.

A lot of effort has also been put into installing accurate demand-controls to make sure no energy is spent unnecessarily. Lighting is adjusted according to natural lighting levels, and efficient adjustable solar shading reduces the cooling needs during the summer. A tight and well-insulated building envelope helps limit the heating demand, and the heat pumps further reduce heating energy needs. In addition to the efficient technical solutions, the building-operation crew have been educated in all the building's equipment in order to allow for optimal operation.

11 Solar Technologies and Their Role in Refurbishment to nZEB

11.1 Photovoltaic Systems as On-site Electricity Production

Photovoltaic (PV) cells absorb and convert solar radiation to electricity by utilising the energy of photons. The cell consists of two oppositely charged semiconductor layers pressed together. The positive (p-type) semiconductor has excess positively charged ‘holes’, while the negative (n-type) semiconductor contains superfluous electrons. The opposite charges create an electric field at the p-n layer junction, which prevents electrons from flowing from the n-type to the p-type. Instead, an external circuit provides a path for the electrons’ movement between the semiconductor layers. This circuit connects to both a front- and back contact, which allows the electrons to both enter, and complete the circuit respectively. As the amount of electricity produced is directly proportionate to the amount of absorbed radiation, an anti-reflective layer commonly encloses the layers, in order to maximise the amount of absorbed radiation. A protective barrier of glass or plastic is then added to avoid damage to the inner components (see Figure 11.1).

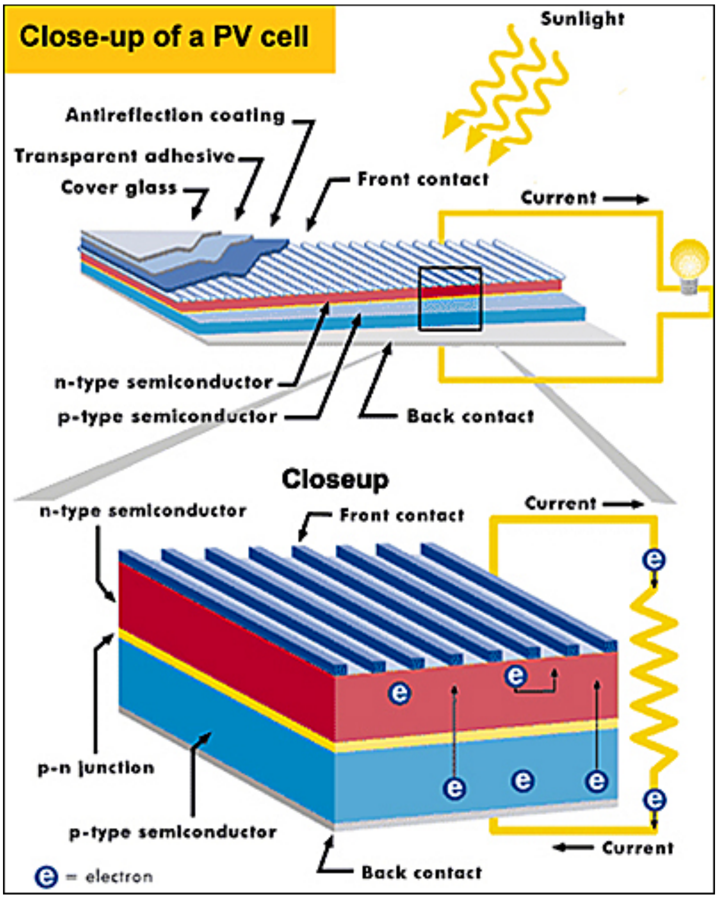


Figure 11.1: Layers of a photovoltaic cell (Solar Cell Central, n.d.(a))

The voltage over the two semiconductors causes electrons to gravitate towards the negative surface, where they become available for the external circuit. Similarly, the 'holes' in the positive layer move towards the positive layer, anticipating inbound electrons. In metals, semiconductors and insulators electrons are confined by atomic force to a limited few bands of energy, and therefore cannot lastingly inhabit other regions. The energy difference between the *conduction band* (free electron flow) and the *valence band* (outer electron) is referred to as the *band gap*. In the conduction band, the energy contained within the electrons is sufficient for them to move freely without being bound to any particular atom. Contrary, the valence band refers to the outermost electron shell, where the electrons are confined to their orbits by the nuclear force of a single atom. The band gap determines the conductive properties of a substance, and the two factors have an inverse relationship – increased gap correlates to less conductivity. Insulators contain gaps that are 'too large' to allow electronic flow, while a conductor's bands often overlap. Materials with band gaps in between these extremes are referred to as semiconductors (Figure 11.2).

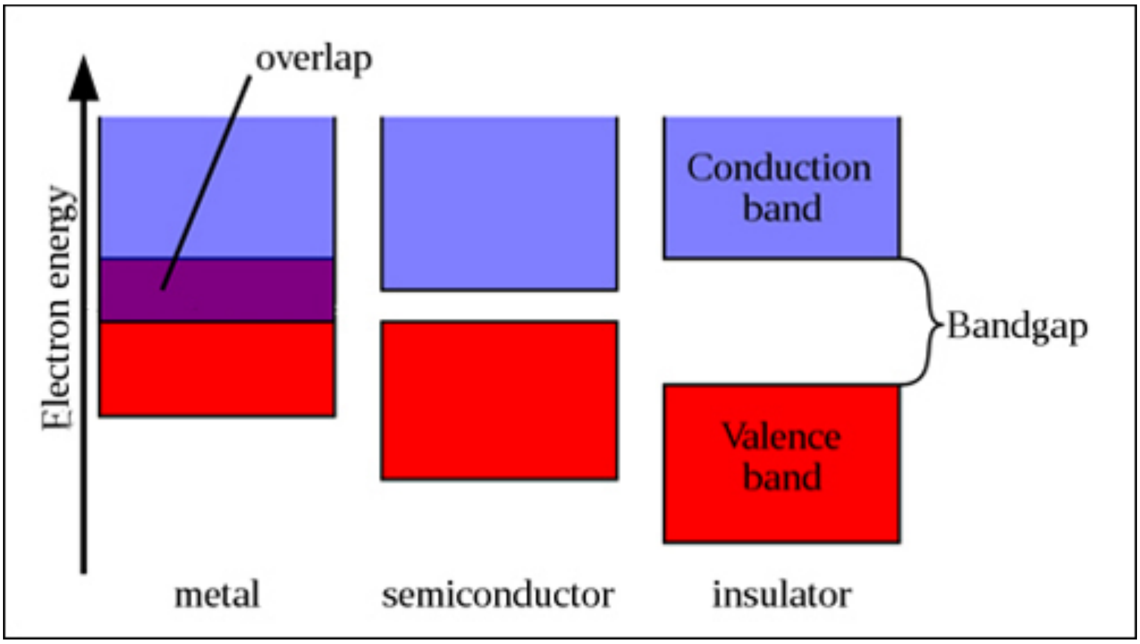


Figure 11.2: Band gaps (Solar Cell Central, n.d.(b))

In order for the electrons to move in between the bands, additional energy needs to be applied. In photovoltaic cells, the electrons absorb the energy from photons in order to make the leap across the bands. In order for this leap to take place, the energy contained within the photon must equal or surpass the band gap energy – any lower and the photon will pass straight through the cell. Any excess photon-energy is dissipated in the form of heat.

The power produced by a single cell is relatively small, only a couple of watts, therefore the cells are placed together to form modules (commonly referred to as panels), which provides power at a more useful voltage and current. The modules are similarly arranged into arrays in order to provide the desirable power output. This is called a crystalline silicon cell, and is the dominant technology within the solar sector, accounting for approximately 90 % of the installed market in 2011. These cells are also among the most competent, with efficiency ranging between 15 % and 23 % (Solar Cell Central, n.d.(a)). While this technology allows for great efficiency, it also requires a considerable area to be allocated to the system. Other technologies have been, and are under development that requires less space or is more seamlessly integrated into the environment or building façade. For example, some newer types of solar cells are made from thin films of semiconductor materials, which allows the cells to be installed in less obvious places. However, these cells have about half of the efficiency of the more common crystalline cells.

On-site production

While the electricity production happens in the photovoltaic arrays installed onto the building, there are several other components required in order to make use of the produced electricity. Figure 11.3 shows a slightly simplified illustration of a photovoltaic system installed in a residential building. The arrays are installed on the roof (1), where they produce electricity for use within the dwelling. The panels generate DC (direct current), which is then led into an inverter (2). Since DC is unusable with common household appliances, the inverter transforms it into AC (alternating current). The AC is the distributed by an electrical panel (3) in order to satisfy the any connected loads (4). Some systems also contain a battery backup that will charge in periods of overproduction. This backup is meant to take over as the main electricity source during nights or blackouts. Another attractive feature of photovoltaic systems is the ability to connect to the existing power grid (6) in order to sell surplus electricity in periods of overproduction (and when the battery is fully charged). The net meter (5) turns backwards, practically giving the user retail rates for their surplus electricity.

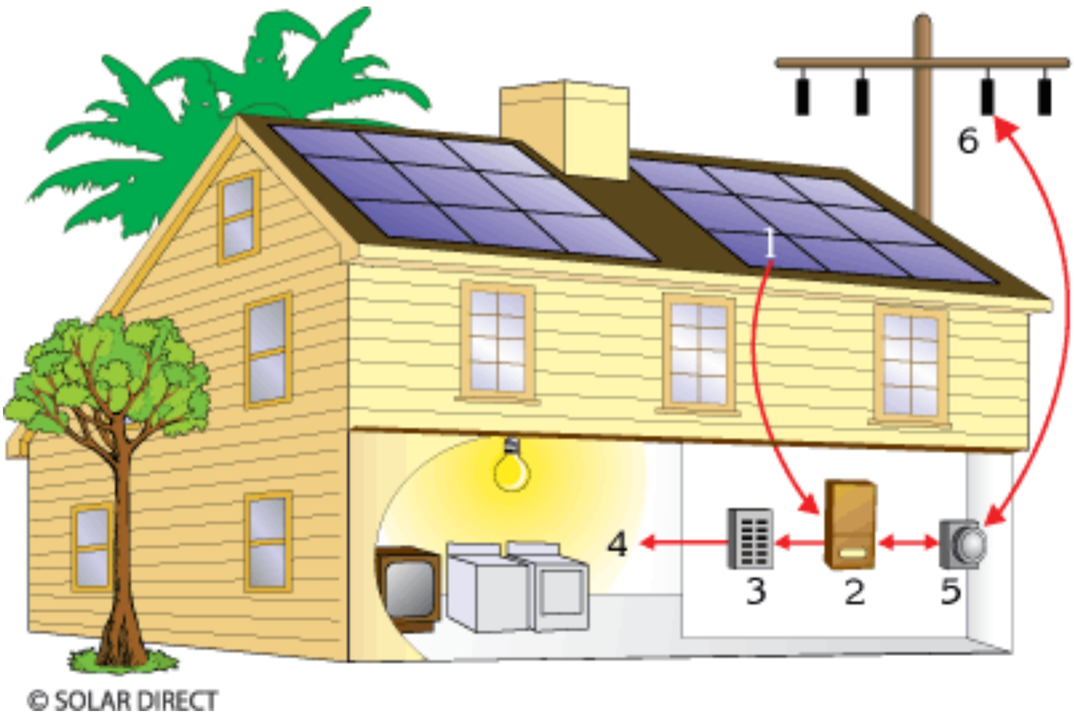


Figure 11.3: On-site photovoltaic system (Solar Direct, n.d.)

11.2 Solar Thermal Collectors for Direct Utilisation of Solar Irradiation Energy

Solar thermal collectors make direct use of the heat stored within the solar irradiation. The collectors absorb solar irradiation, before transferring the heat to a working fluid flowing through the apparatus. The heated working fluid is then transferred in pipes through a heat tank, where it acts as a direct heat source. A controller connected to the pump makes sure the flow through the collector panel remains proportionate to the energy demand of the hot water tank. Hot water demand is varying and the controller is necessary to make sure the temperature remains at desired temperatures. The thermal collectors may not be able to deliver the required heating demand at all times, therefore a boiler is also connected to the water tank in order to secure reliable hot water delivery. The thermal collectors are restricted to water heating purposes, and therefore are highly suitable in buildings with high proportions of domestic water heating demand or hydronic heating. Building where hot water demand is low (i.e. office buildings), PV panels will generally prove to be the better option.

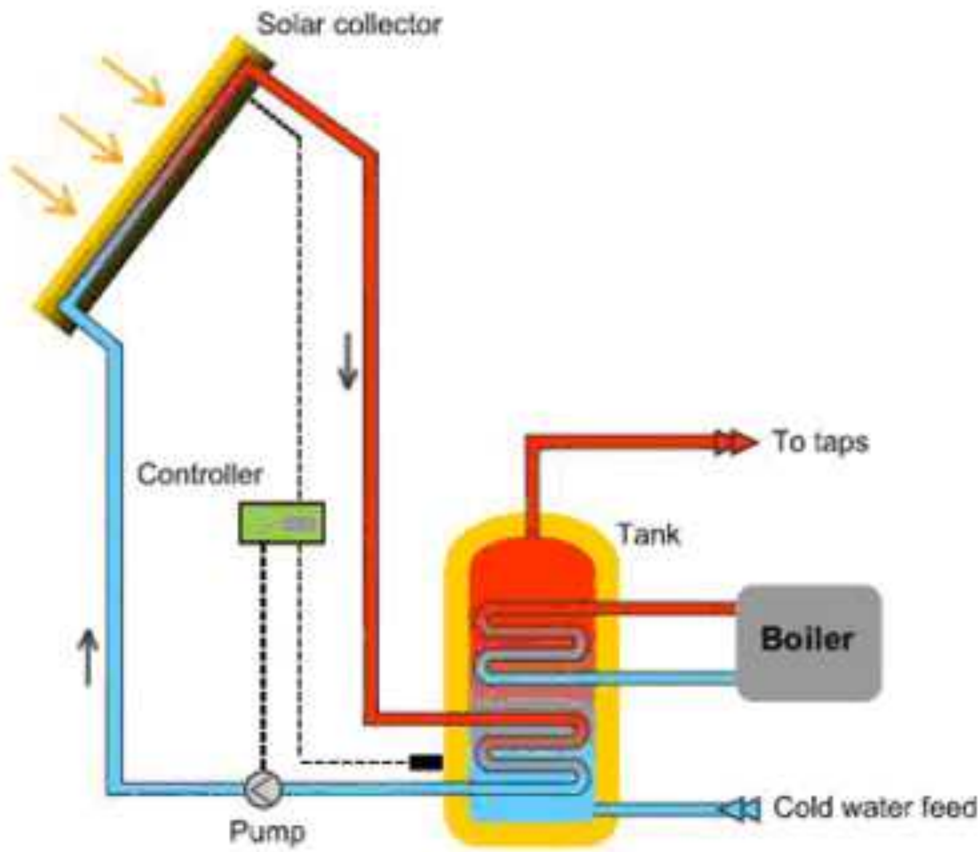


Figure 11.4: Solar thermal collector system (Stenkjaer, n.d.)

There are mainly two kinds of solar thermal collectors – flat plate collectors and evacuated tube collectors. Both systems will work as previously described, however the design and properties of the collector panel differ.

Flat Plate Collectors

Flat plate collectors (FPC) can be produced with and without convection barriers between the absorber and the glass cover. This barrier will reduce the heat loss from convection in the cavity between the cover and absorber (see Figure 11.5), but due to not being completely transparent, the irradiance on the absorber will be slightly reduced.

A working fluid will flow through an absorber made from a material of high thermal conduction with a matte black coating, which is heated by the solar irradiation. The working fluid is then being led into the hot water tank. This works exactly as described earlier in the process as visualised in Figure 11.4.

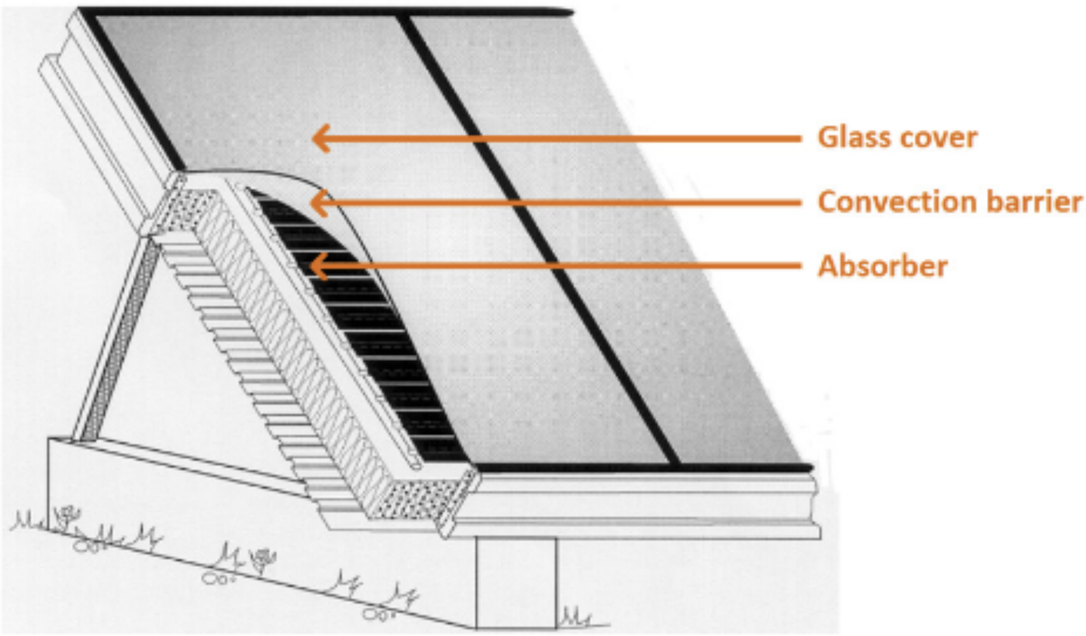


Figure 11.5: Illustration of a flat plate collector with convection barrier (Trier, 2012)

Evacuated Tube Collectors

Evacuated tube collectors (ETC) are composed of several evacuated glass tubes that containing an absorber plate and a heat pipe. These collectors can work in on of two ways: direct flow (like FPCs) or by means of the heat pipe principle. The latter allows only a small amount of fluid to be sealed within the tube. While the direct flow works like previously described, the heat pipe principle can be divided into four steps (Stenkjaer, n.d.):

1. The fluid is evaporated by the solar irradiation.
2. The vapour rise to the top of the collector, where is meets a colder pipe in which a liquid flow through.
3. The vapour is condensed, thus transferring the latent heat to the liquid within the top pipe.
4. The condensed fluid in the evacuated tubes runs back down to the bottom, where the process repeats.

The two methods require a slight difference in system design, which is presented in Figure 11.6.

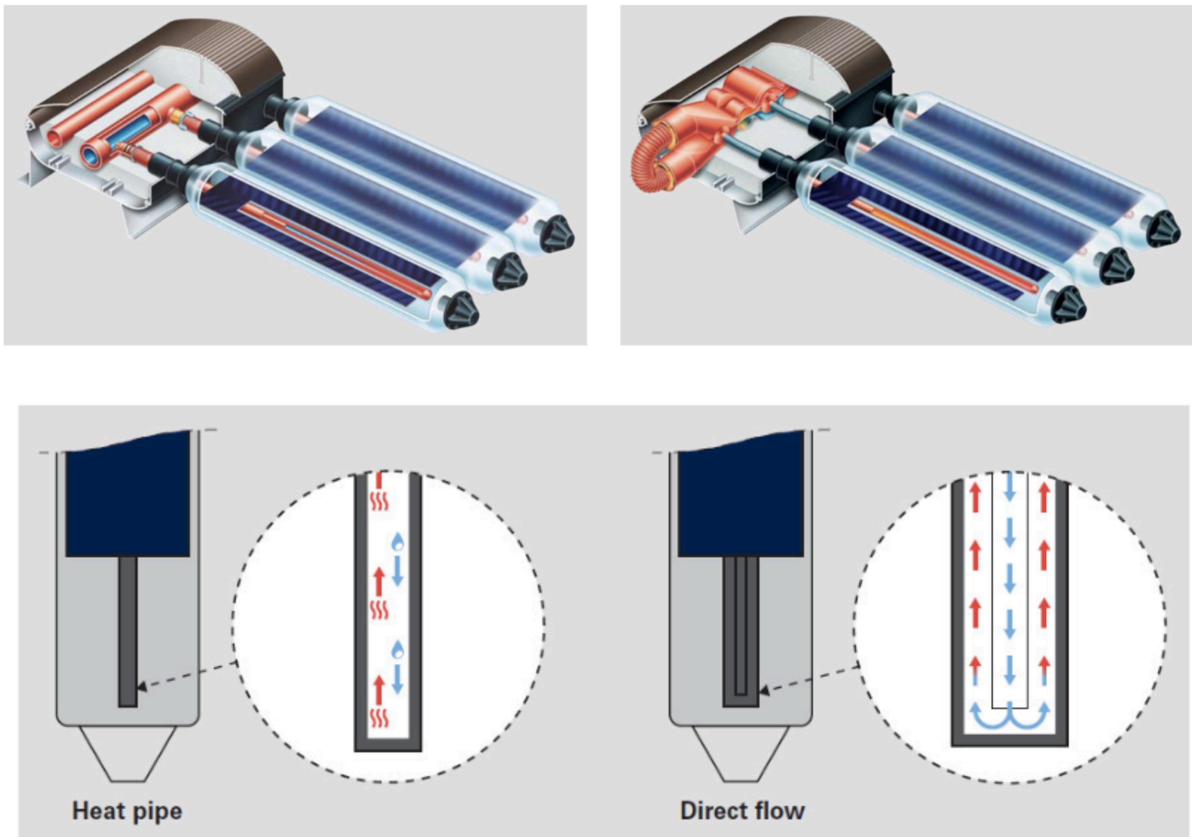


Figure 11.6: Heat pipe (left) and direct flow (right)

Often there are also installed concave mirrors underneath the tubes that reflect the solar irradiation passing in between the collectors back onto the absorber. This will allow a greater area of the ETC to be contributory to the overall performance.

Comparison of FPC and ETC

A solar collector's performance varies depending on temperature conditions, and the different solutions react differently. ETC is the best option in high collector temperatures, however FPC with convection barrier (high perf. FPC) also works well at medium to high temperatures. FPCs without convection barriers (medium perf. FPC) does however prefer lower temperatures (Figure 11.7).

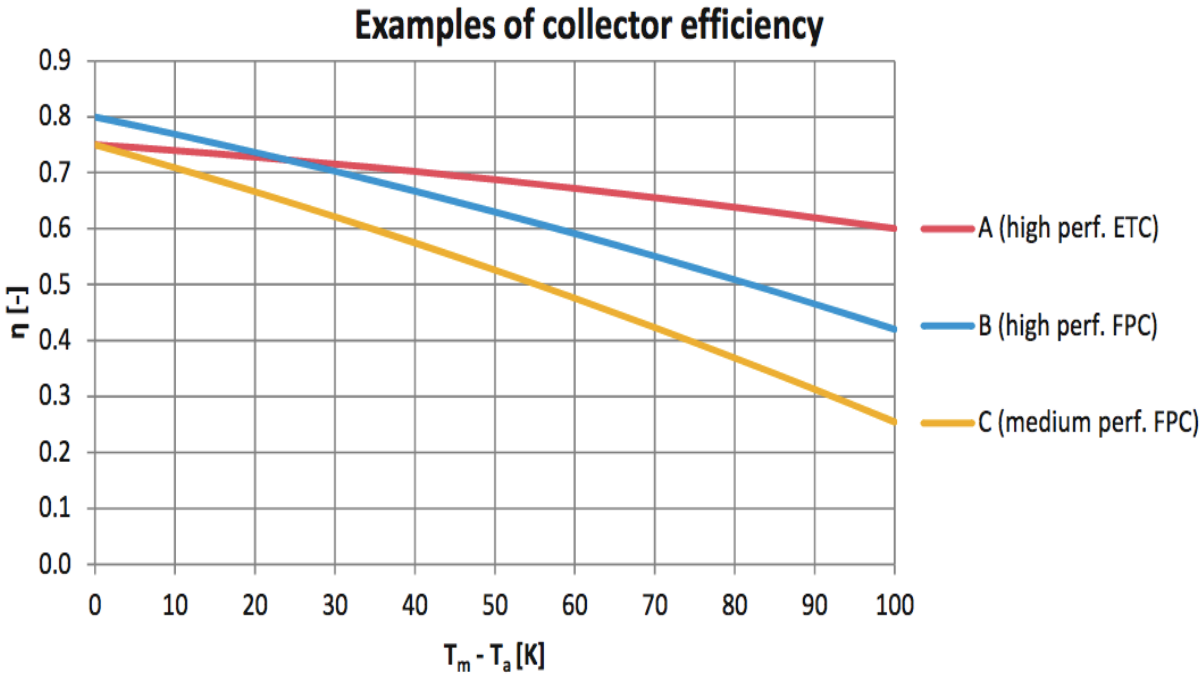


Figure 11.7: Collector efficiency based on aperture area as a function of temperature difference between collector fluid (T_m) and ambient air (T_a) (Stenkjaer, n.d.)

However, while the efficiency based on aperture area is greatest in most cases for ETC, the gaps in between the tubes make the gross area of the arrays significantly larger that the aperture area (30-70 %). FPC only has about 5-10 % difference in gross- and aperture area, making it a more space efficient option. This allows FPC power output per gross area to surpass ETC at low and medium temperatures (Figure 11.8).

FPC is the cheaper of the two options, and the panels can be produced in significantly larger sizes than the ETC, which makes installation easier in large systems. When deciding on which collector technology to use, in addition to price, one should therefore consider both available space and operating temperature.

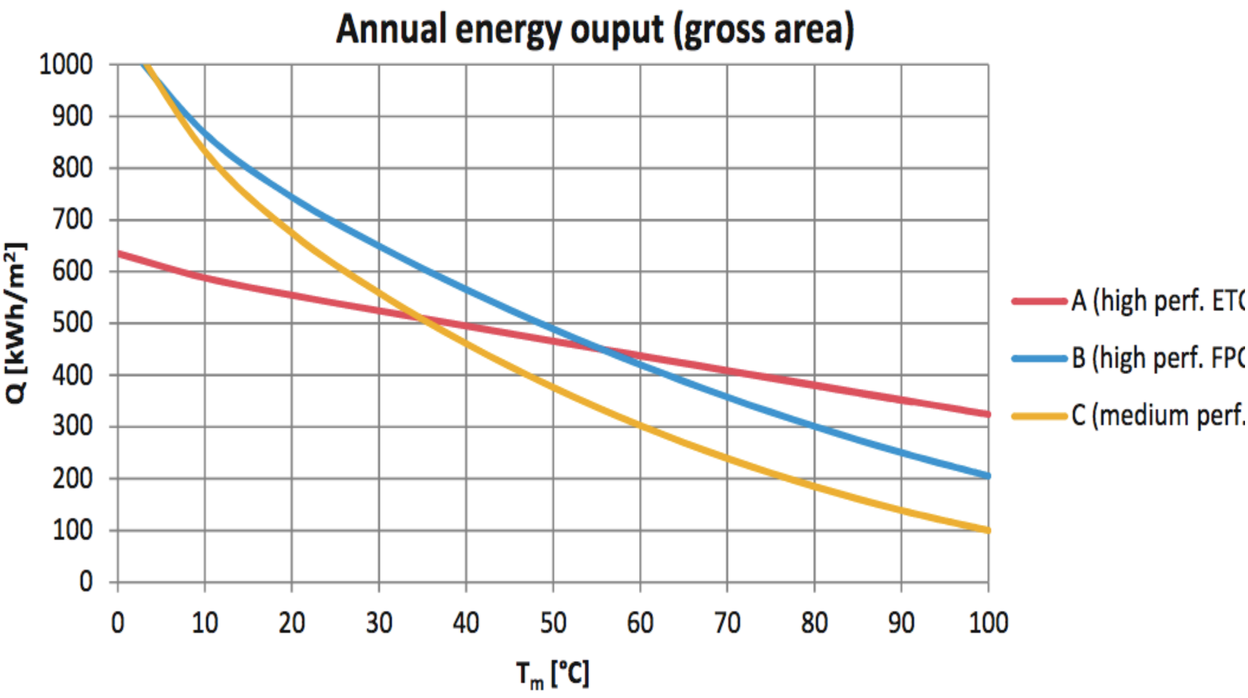


Figure 11.8: Annual solar power output as a function of mean temperature (T_m) (Stenkjaer, n.d.)

11.2.1 Solar District Heating

In addition to being a significant energy saving measure in individual buildings, solar thermal collectors may be used in a district heating network. There are mainly two ways of connecting the solar thermal plant to the network: centralised and distributed. Figure 11.9 show a centralised solution where the solar collectors deliver heat to a centralised heating plant, which then distributes heat to both buildings and large heat stores. Large enough stores may allow the solar collectors to contribute more than 50 % of the total system-wide demand. (Solar district heating, n.d. (b))

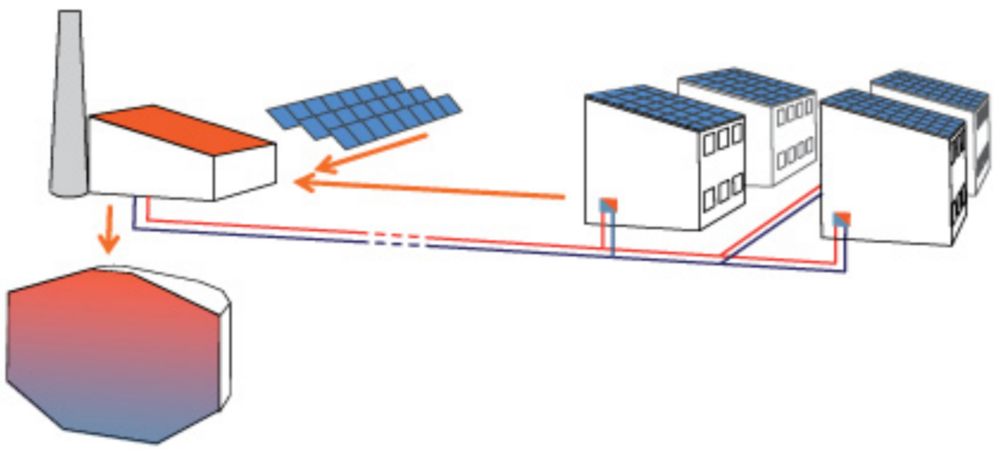


Figure 11.9: Centralised solar district heating (Solar district heating, n.d. (a))

In a distributed solar district heating system, the collectors are instead placed in suitable locations as to feed directly onto the district heating grid's primary circuit. These systems often utilise the DH network as storage.

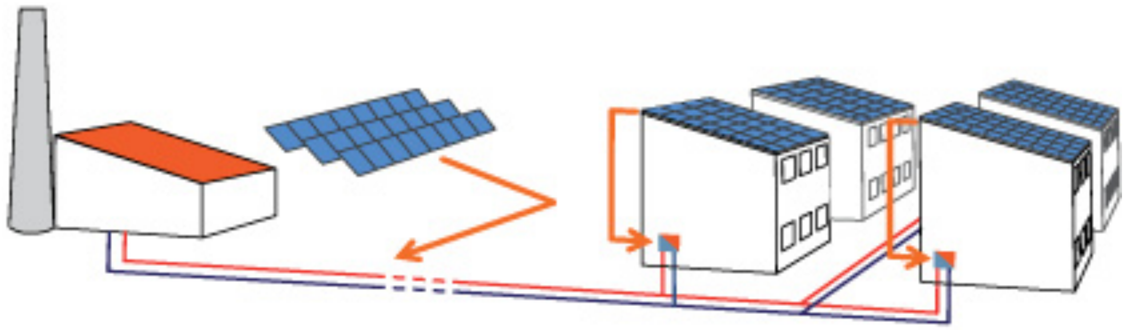


Figure 11.10: Distributed solar district heating (Solar district heating, n.d. (a))

Solar district heating is still an early market development, but may help improve the sustainability of DH systems. In terms of effect on nZEB rehabilitation, an increased ratio of renewables into the DH grid would lower the energy factor of building connected to the grid – creating a more favourable energy balance calculation.

11.3 Solar Energy Technologies' Role in nZEB

Solar technologies will take on the role of on-site energy production in projects aiming to meet the requirements set by nZEB standards. Solar technologies are popular as on-site production due to the ease of installation and lack of required space. It is also a well-tested technology, with few geographical restrictions.

In a refurbishment project, these technologies are requires to close the gap between a buildings energy demand, and the maximum allowed delivered energy. As exemplified in Figure 11.11, the on-site production needs to be identical to or greater than 22 kWh/m^2. This value is taken from a random example, and the required amount will vary in every case.

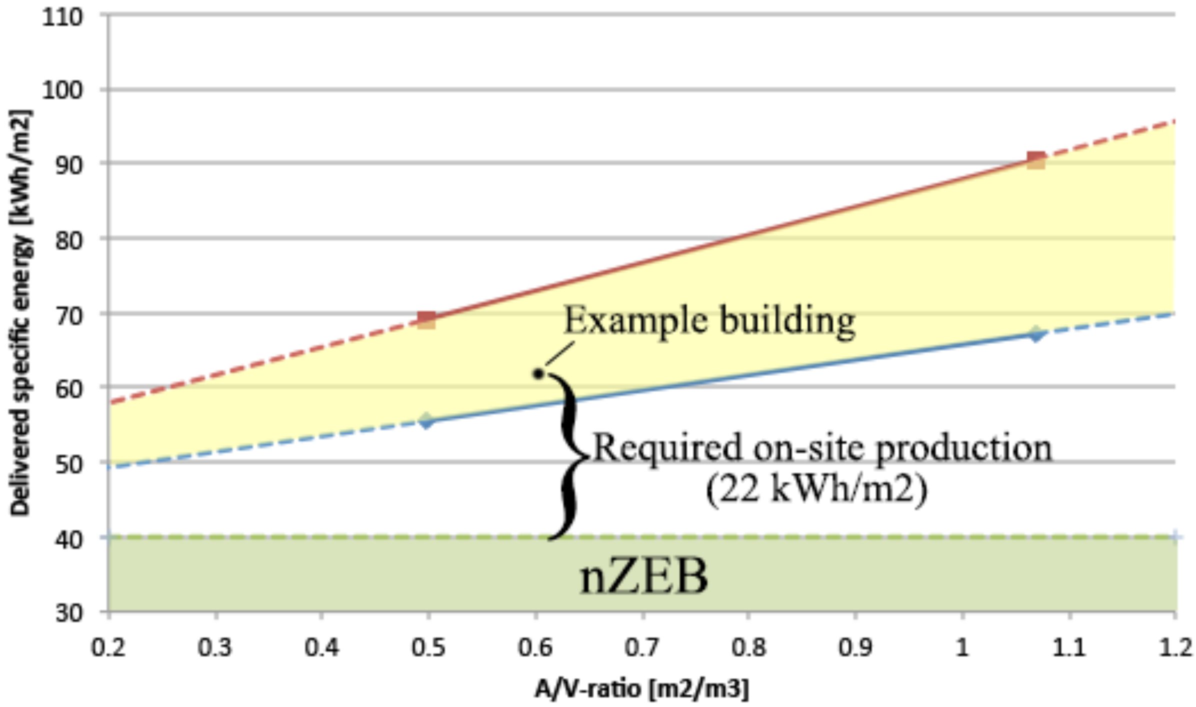


Figure 11.11: Required on-site production from solar technologies in an example building (represented by the black circle)

Previous chapters have suggested that on-site production is almost always necessary when building after nZEB standards. The case studies do however suggest that there are abnormalities in which it may not be. Powerhouse Kjørbo require 28 kWh/m^2 of delivered energy (excluding PV production), and could be classified as nZEB even if the on-site solar production is removed. However, this project has gone to great lengths to adjust control systems and installing highly energy efficient equipment. This may not be desirable in a lot of cases, due to the required maintenance and inspection criteria. Therefore solar technologies may prove to be the preferred option in most projects.

12 Conclusion - Feasibility of nZEB in Rehabilitation Projects

The strict requirements set for nZEB buildings require careful execution of rehabilitation projects in order to it to be successful. The question of whether nZEB is technically- and economically feasible as a new standard in energy efficient building rehabilitation is a complicated one, and the answer may not be straight forward. Rehabilitation projects set significant restrictions on the practicable solutions, and severe challenges must be overcome. As explored in earlier chapters, the building shape remains a substantial factor on building energy demand, and is rarely altered during rehabilitation. A building with unpropitious shape will significantly cripple the chance of achieving a functioning nZEB result. While some projects may allow for building extension that may change the shape favourably, surrounding environments and buildings may hinder many projects from implementing such improvements. Restrictions on building shape, in the form of a recommended limit of A/V ratio seems like a necessity when analysing the feasibility of achieving nZEB standards in rehabilitation. As A/V ratios greater than 0.7 is considered unfavourable in the construction of passive houses (McLeod et al., n.d.), a similar limit may be appropriate for nZEB as well. The building fabric and construction of nZEB is likely to be similar to that of a passive house, due to the diminishing gains of fabric insulation. The factors driving a building project towards nZEB will instead be energy sources and -production, which is not unnecessary in passive house projects.

In order to minimise the heating demand, large amounts of insulation is required. Projects with significant space restrictions may struggle to achieve an adequate building envelope, leading to massive requirements on energy production. Achieving a low U-value is paramount when constructing nZEB buildings, and as previously explored, the required insulation may be between 250 and 400 mm. External insulation is highly recommended, but in cases where this proves impossible, it is likely that other factors may make up for the increased thermal bridging. However, the installed insulation would need to surpass the minimum requirement of 250 mm, and would likely be required to be at least 300 mm.

Despite having favourable building shapes and insulation properties, the building will yet struggle to achieve nZEB standards without additional reduction of the net delivered energy. Energy factors for sustainable heat sources will allow the heating demand input of the energy balance to be significantly reduced, further reducing the requirement for on-site electricity production. Especially in urban areas, the space available for on-site production may be limited, and sustainable heat sources will reduce this demand. Implementing a sustainable heat source as a requirement for nZEB rehabilitation projects seems appropriate, and will prove valuable in energy balance calculations by reducing calculated heat energy demand by approximately 60 %.

While all the mentioned factors will reduce the energy demand to efficient levels, it remains unlikely to be sufficient for nZEB requirements. On-site production seems necessary, but the demand can be significantly reduced if all other factors prove favourable. Meeting the previously suggested requirements would likely demand an on-site electricity production between 10-40 kWh/m^2, based on the results presented in Figure 9.1.

Figure 12.1 is visual representation of the suggested initial requirements for nZEB rehabilitation. The aim is for the figure to provide a useful tool for anyone considering the feasibility of such a project. By moving downward along the arrows, one can approximate the feasibility of achieving nZEB. The structure is intentional, as each new level may to some degree compensate for sub-optimal values in the previous, while being slightly more adjustable. For example, a building with an A/V factor of 0.7, would likely require the higher end of the insulation thickness. A building with unable to implement large thicknesses of insulation may offset some of the heating energy demand by installing a sustainable heat source. On-site electricity production in the shape of PV panels is on the bottom, as it may compensate for any unfavourable values in the levels above – if climatic circumstances and available space allows.

In addition to the orange 'requirement fields', a green field have been added to the figure. This field represents the building energy factors not explored in this study – mainly controls and energy efficient equipment. Improvements within this field may also help offset deficiencies in other fields, similarly to PV. Powerhouse Kjørbo is a great example of a project where this field have been highly regarded throughout the project – significantly reducing building energy demand. In conclusion, nZEB rehabilitation is definitely achievable, but requires some initial criteria to be met if it is to be economically feasible. By meeting the requirements suggested in the figure below, data suggest a successful rehabilitation to nZEB can be accomplished.

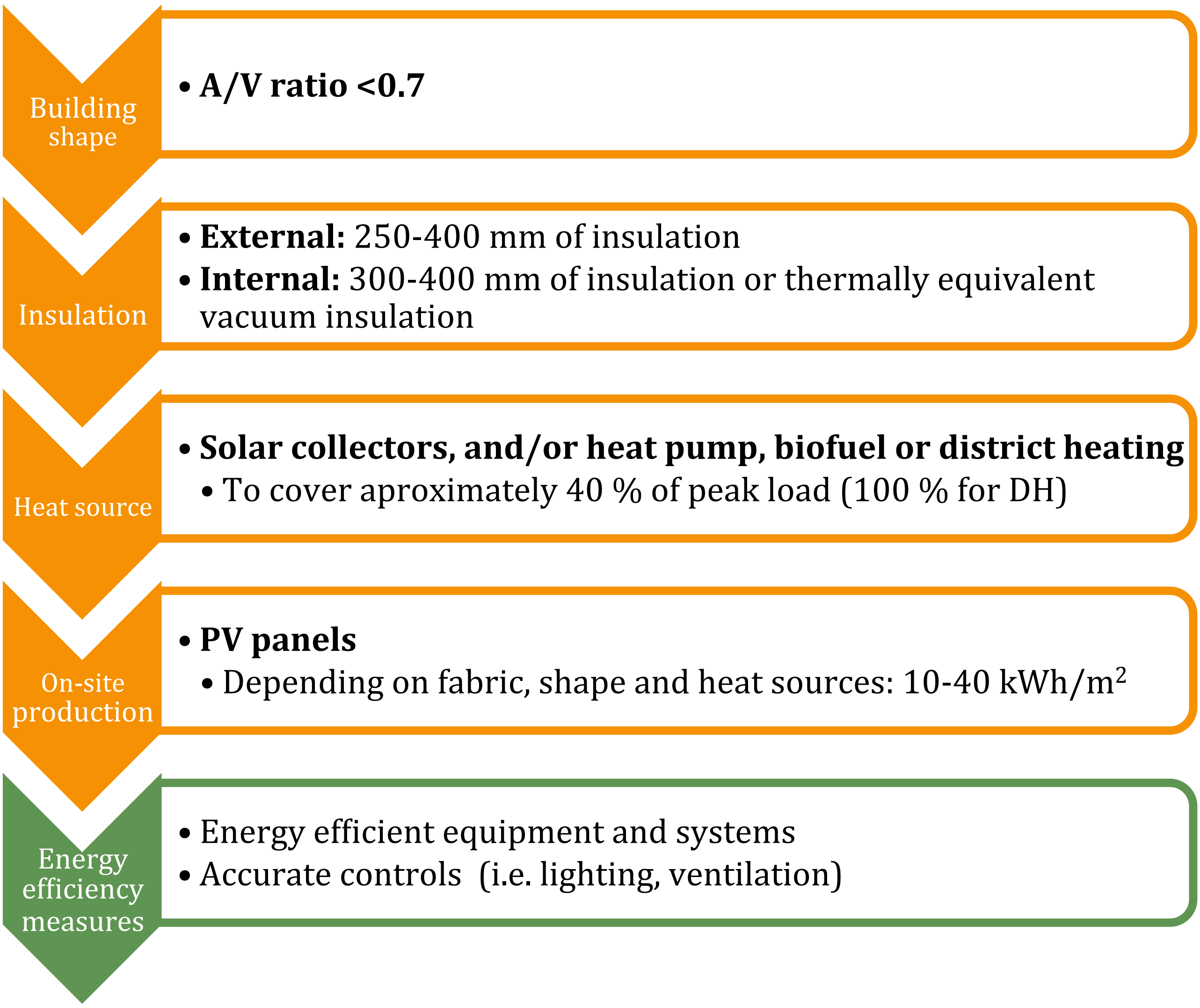


Figure 12.1: Suggested requirements for nZEB rehabilitation projects

13 Recommendations for Further Study

13.1 Energy Efficiency Measures Within the Building

As mentioned earlier, this study focuses on the building envelope and energy delivery. Further study into measures on energy efficiency of equipment and systems as well as appropriate controls could significantly improve on, alter or underpin the results in this study. The case studies show that these measures may provide significant energy efficiency improvements, but without significant data for analysis, this needs further investigation. It could be highly useful for anyone considering a nZEB project to know what factors to prioritise, both in terms of building envelope, energy sources and energy efficiency measures. Therefore such a study would provide 'the other half' of this current study.

13.2 Database of Building Elements

This study was originally intended to culminate into a database for use in rehabilitation projects, however due to the vast amount of work it would require, it was simply not enough time. However, this study should provide the main elements required to construct a database or reference guide. Such a guide could prove to be a valuable tool for any consulting engineer or architect in the early planning stages of nZEB projects.

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15 APPENDICES

APPENDIX A – PRINCIPAL ASSUMPTIONS USED IN THE SIMIEN SIMULATIONS

The assumptions used in this study are identical to those used by SINTEF in their simulations for passive house buildings (SINTEF, 2012). These assumptions are presented below:

Distribution of primary and secondary spaces		
Room type	**Primary(P)/Secondary(S)**	**Ratio of total area [%]**
Office cells	P	20
Office landscape	P	30
Corridor	S	15
Canteen	P	5
Meeting rooms	P	10
Misc. rooms	S	20
Total primary spaces		**65**
Total secondary spaces		**35**

Assumptions for airflow rate calculations	
Occupant density	5 m^2 per person
Air flow rate for materials	3.6 m^3/hm^2
Occupant presence primary spaces	60 %
Operating hours	3120 p/a

These assumptions produce the following input data:

Airflow rate in primary spaces: $25/5 + 3.6 = 8.6\ m^3/hm^2$

With 60 % presence: $0.6 \times 8.6 + 0.4 \times 3.6 = 6.6\ m^3/hm^2$

Average airflow rate for the entire space becomes: $6.6 \times 0.65 + 3.6 \times 0.35 = 5.6\ m^3/hm^2$

*This is rounded up to **6 m^3/hm^2** in the simulations.*

Outside of operating hours it is assumed that the system continues one hour after, and begins two hours before normal operating hours. The average airflow rate outside of operating hours becomes:

6 x (3 hours x 5 days) / (12 hours x 5 days + 2 x 24 hours) = 0.83 m^3/hm^2

*This is rounded up to **1 m^3/hm^2** in the simulations.*

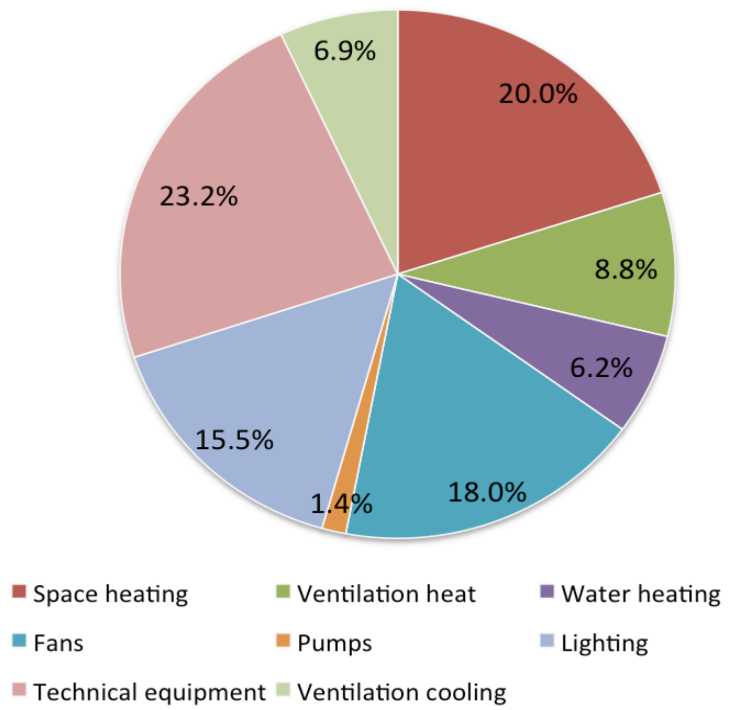
Appendix B – Summary of SIMIEN Results

Minimal Large 'Shoebox'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	16191 kWh	16.2 kWh/m²
Ventilation heat (heating element)	7094 kWh	7.1 kWh/m²
Water heating	5011 kWh	5.0 kWh/m²
Fans	14580 kWh	14.6 kWh/m²
Pumps	1129 kWh	1.1 kWh/m²
Lighting	12528 kWh	12.5 kWh/m²
Technical equipment	18792 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	5575 kWh	5.6 kWh/m²
Total net energy demand	**80901 kWh**	**80.9 kWh/m²**
Delivered energy	**82321 kWh**	**82.3 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
15 kW (40 %)	92 %

[1]Excluding tap water

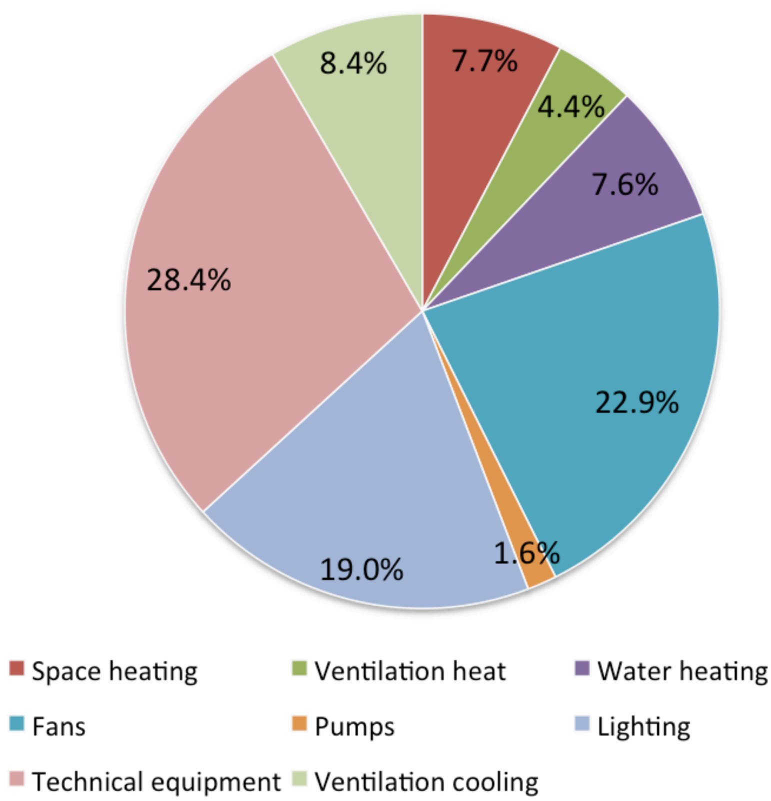


Optimal Large 'Shoebox'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	5113 kWh	5.1 kWh/m²
Ventilation heat (heating element)	2888 kWh	2.9 kWh/m²
Water heating	5011 kWh	5.0 kWh/m²
Fans	15130 kWh	15.1 kWh/m²
Pumps	1070 kWh	1.1 kWh/m²
Lighting	12528 kWh	12.5 kWh/m²
Technical equipment	18792 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	5575 kWh	5.6 kWh/m²
Total net energy demand	**66108 kWh**	**66.1 kWh/m²**
Delivered energy	**64356 kWh**	**64.4 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
11 kW (40 %)	93 %

[1]Excluding tap water

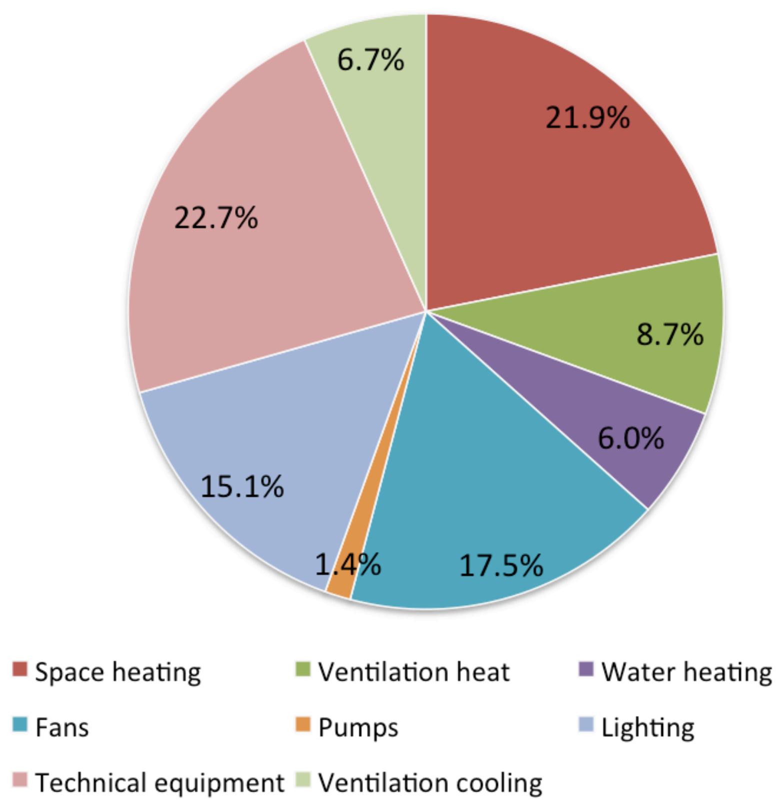


Minimal Medium 'Shoebox'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	10889 kWh	18.1 kWh/m²
Ventilation heat (heating element)	4319 kWh	7.2 kWh/m²
Water heating	3007 kWh	5.0 kWh/m²
Fans	8697 kWh	14.5 kWh/m²
Pumps	677 kWh	1.1 kWh/m²
Lighting	7517 kWh	12.5 kWh/m²
Technical equipment	11275 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	3345 kWh	5.6 kWh/m²
Total net energy demand	**49725 kWh**	**82.9 kWh/m²**
Delivered energy	**50862 kWh**	**84.8 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
9 kW (40 %)	92 %

[1]Excluding tap water



Optimal Medium 'Shoebox'

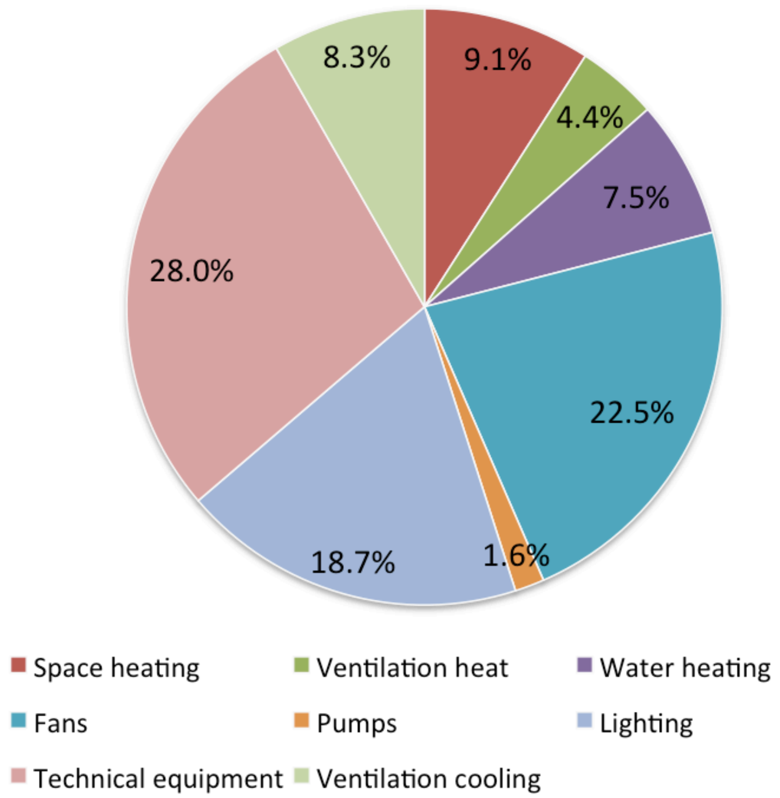
Energy budget

Energy post	**Energy demand**	**Specific energy demand**
Space heating	3662 kWh	6.1 kWh/m²
Ventilation heat (heating element)	1782 kWh	3.0 kWh/m²
Water heating	3007 kWh	5.0 kWh/m²
Fans	9050 kWh	15.1 kWh/m²
Pumps	643 kWh	1.1 kWh/m²
Lighting	7517 kWh	12.5 kWh/m²
Technical equipment	11275 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	3345 kWh	5.6 kWh/m²
Total net energy demand	**40280 kWh**	**67.1 kWh/m²**
Delivered energy	**39374 kWh**	**65.6 kWh/m²**

Coverage of heating demand[1]

Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
7 kW (40 %)	92 %

[1]Excluding tap water

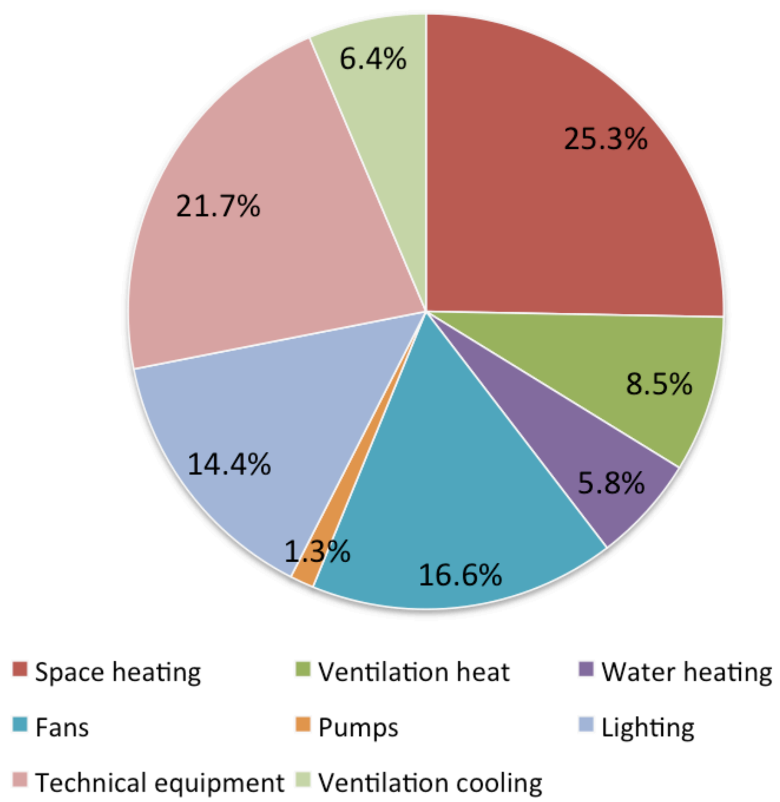


Minimal Small 'Shoebox'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	6588 kWh	22.0 kWh/m^2
Ventilation heat (heating element)	2217 kWh	7.4 kWh/m^2
Water heating	1503 kWh	5.0 kWh/m^2
Fans	4310 kWh	14.4 kWh/m^2
Pumps	339 kWh	1.1 kWh/m^2
Lighting	3758 kWh	12.5 kWh/m^2
Technical equipment	5638 kWh	18.8 kWh/m^2
Space cooling	0 kWh	0.0 kWh/m^2
Ventilation cooling (cooling element)	1672 kWh	5.6 kWh/m^2
Total net energy demand	**26026 kWh**	**86.8 kWh/m^2**
Delivered energy	**26870 kWh**	**89.6 kWh/m^2**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
5 kW (40 %)	91 %

[1]Excluding tap water

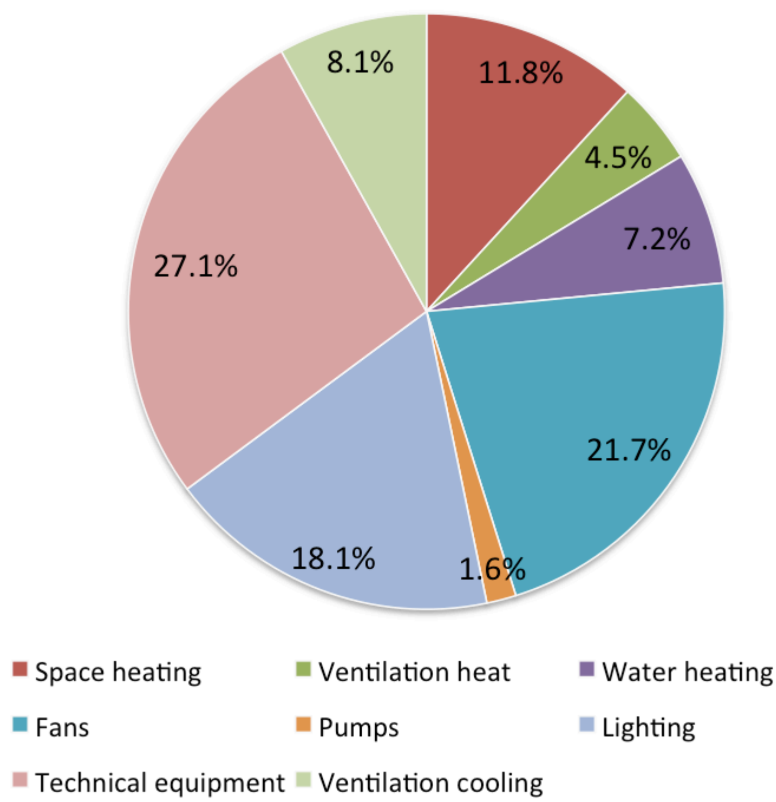


Optimal Small 'Shoebox'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	2446 kWh	8.2 kWh/m^2
Ventilation heat (heating element)	927 kWh	3.1 kWh/m^2
Water heating	1503 kWh	5.0 kWh/m^2
Fans	4496 kWh	15.0 kWh/m^2
Pumps	324 kWh	1.1 kWh/m^2
Lighting	3758 kWh	12.5 kWh/m^2
Technical equipment	5638 kWh	18.8 kWh/m^2
Space cooling	0 kWh	0.0 kWh/m^2
Ventilation cooling (cooling element)	1672 kWh	5.6 kWh/m^2
Total net energy demand	**20765 kWh**	**69.2 kWh/m^2**
Delivered energy	**20462 kWh**	**68.2 kWh/m^2**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
3.8 kW (40 %)	92 %

[1]Excluding tap water

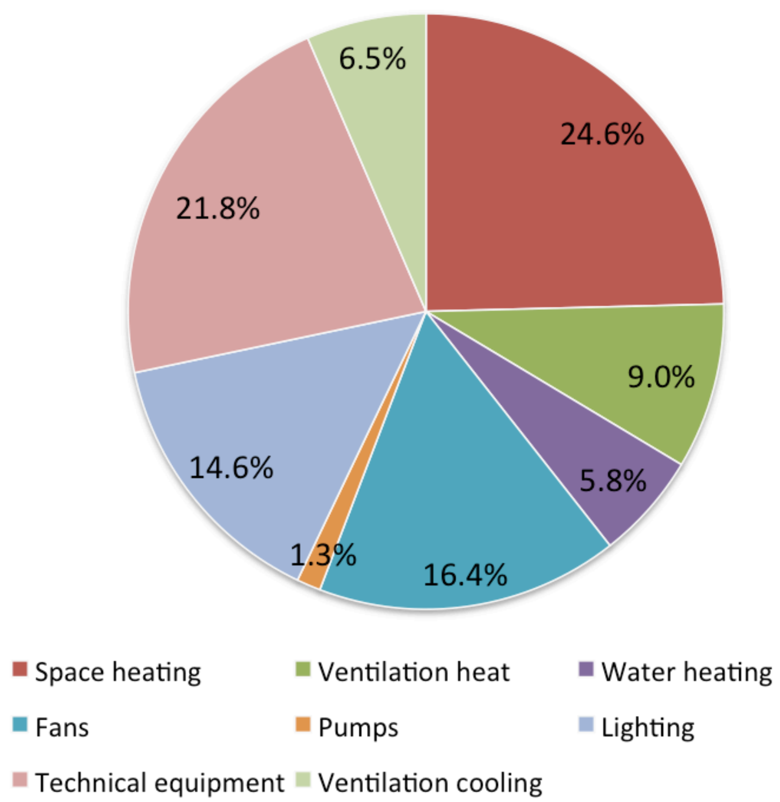


Minimal Large ‘L-shape’

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	21186 kWh	21.2 kWh/m²
Ventilation heat (heating element)	7758 kWh	7.8 kWh/m²
Water heating	5011 kWh	5.0 kWh/m²
Fans	14084 kWh	14.1 kWh/m²
Pumps	1129 kWh	1.1 kWh/m²
Lighting	12528 kWh	12.5 kWh/m²
Technical equipment	18792 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	5575 kWh	5.6 kWh/m²
Total net energy demand	**86063 kWh**	**86.1 kWh/m²**
Delivered energy	**88633 kWh**	**88.6 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
15 kW (40 %)	93 %

[1]Excluding tap water

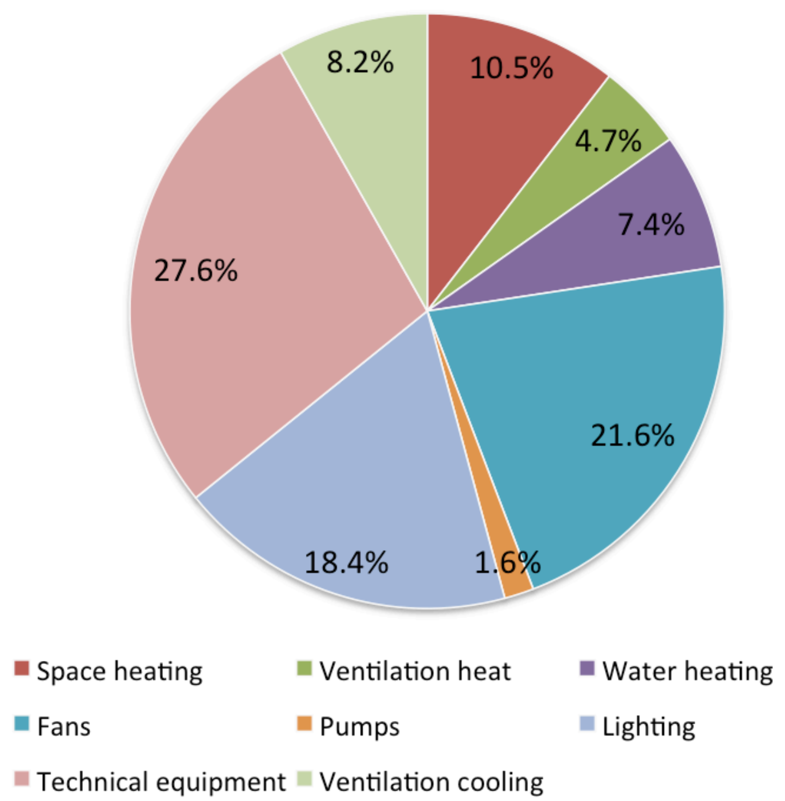


Optimal Large 'L-shape

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	7170 kWh	7.2 kWh/m²
Ventilation heat (heating element)	3233 kWh	3.2 kWh/m²
Water heating	5011 kWh	5.0 kWh/m²
Fans	14730 kWh	14.7 kWh/m²
Pumps	1081 kWh	1.1 kWh/m²
Lighting	12528 kWh	12.5 kWh/m²
Technical equipment	18792 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	5575 kWh	5.6 kWh/m²
Total net energy demand	**68120 kWh**	**68.1 kWh/m²**
Delivered energy	**66856 kWh**	**66.9 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
11 kW (40 %)	92 %

[1]Excluding tap water

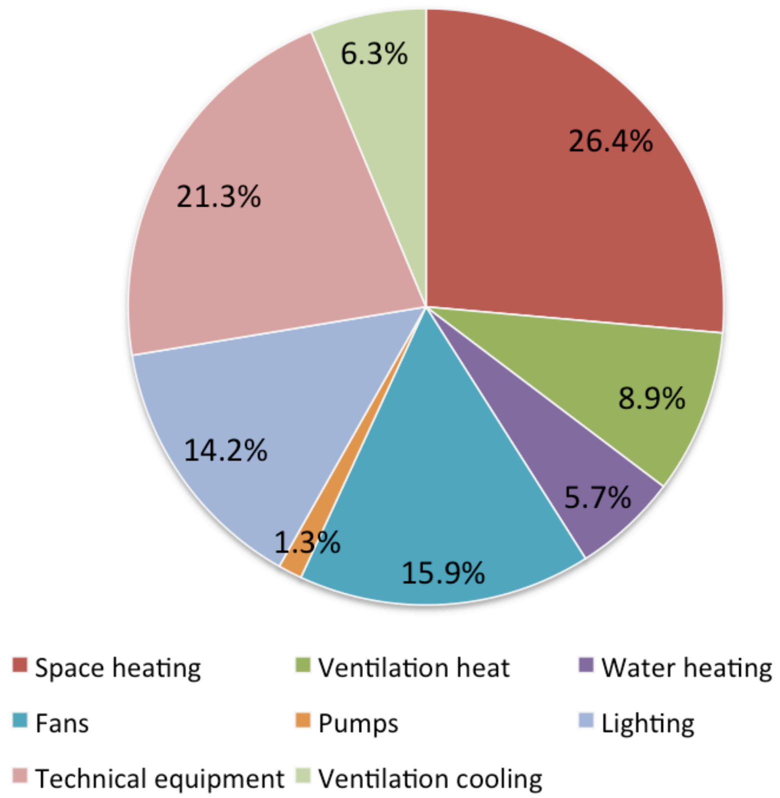


Minimal Medium 'L-shape

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	13955 kWh	23.3 kWh/m²
Ventilation heat (heating element)	4712 kWh	7.9 kWh/m²
Water heating	3007 kWh	5.0 kWh/m²
Fans	8396 kWh	14.0 kWh/m²
Pumps	677 kWh	1.1 kWh/m²
Lighting	7517 kWh	12.5 kWh/m²
Technical equipment	11275 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	3345 kWh	5.6 kWh/m²
Total net energy demand	**52883 kWh**	**88.1 kWh/m²**
Delivered energy	**54720 kWh**	**91.2 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
10 kW (40 %)	92 %

[1]Excluding tap water

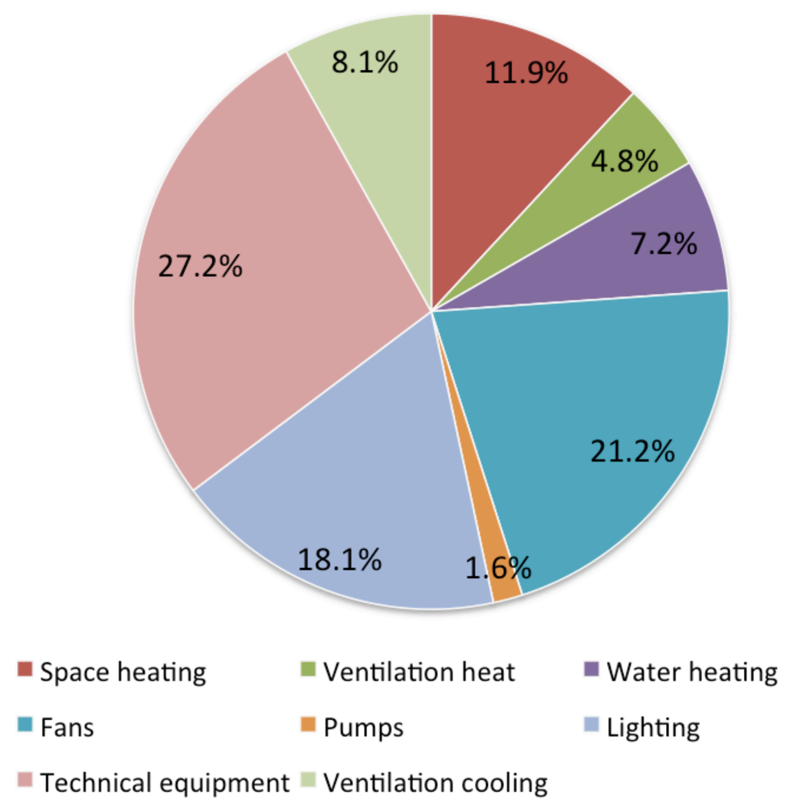


Optimal Medium 'L-shape

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	4919 kWh	8.2 kWh/m^2
Ventilation heat (heating element)	1972 kWh	3.3 kWh/m^2
Water heating	3007 kWh	5.0 kWh/m^2
Fans	8790 kWh	14.6 kWh/m^2
Pumps	649 kWh	1.1 kWh/m^2
Lighting	7517 kWh	12.5 kWh/m^2
Technical equipment	11275 kWh	18.8 kWh/m^2
Space cooling	0 kWh	0.0 kWh/m^2
Ventilation cooling (cooling element)	3345 kWh	5.6 kWh/m^2
Total net energy demand	**41473 kWh**	**69.1 kWh/m^2**
Delivered energy	**40862 kWh**	**68.1 kWh/m^2**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
7 kW (40 %)	92 %

[1]Excluding tap water

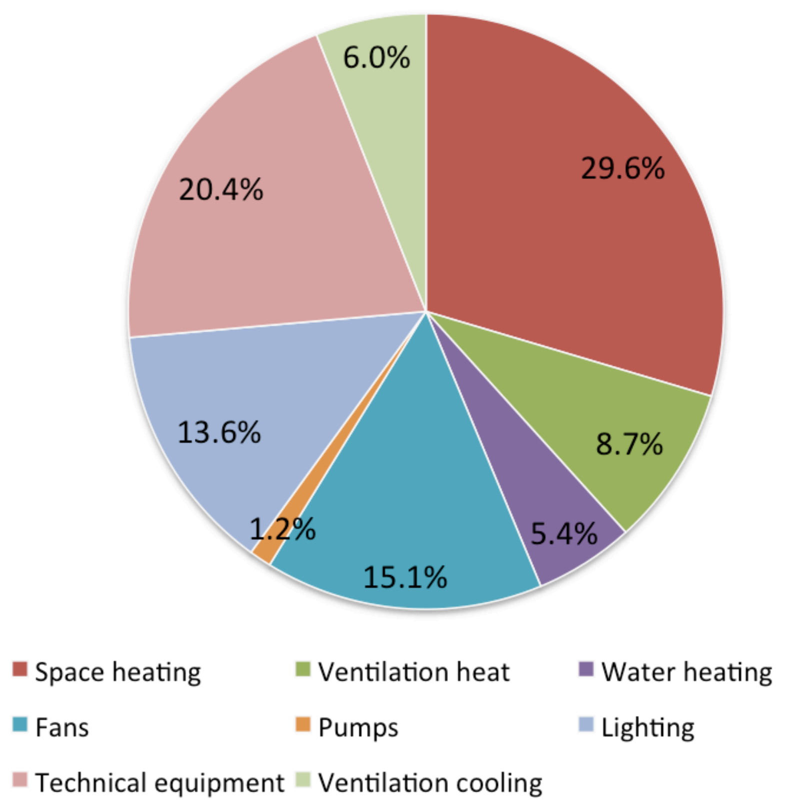


Minimal Small 'L-shape

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	8199 kWh	27.3 kWh/m²
Ventilation heat (heating element)	2400 kWh	8.0 kWh/m²
Water heating	1503 kWh	5.0 kWh/m²
Fans	4167 kWh	13.9 kWh/m²
Pumps	339 kWh	1.1 kWh/m²
Lighting	3758 kWh	12.5 kWh/m²
Technical equipment	5638 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	1672 kWh	5.6 kWh/m²
Total net energy demand	**27677 kWh**	**92.3 kWh/m²**
Delivered energy	**28883 kWh**	**96.3 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
5 kW (40 %)	91 %

[1]Excluding tap water

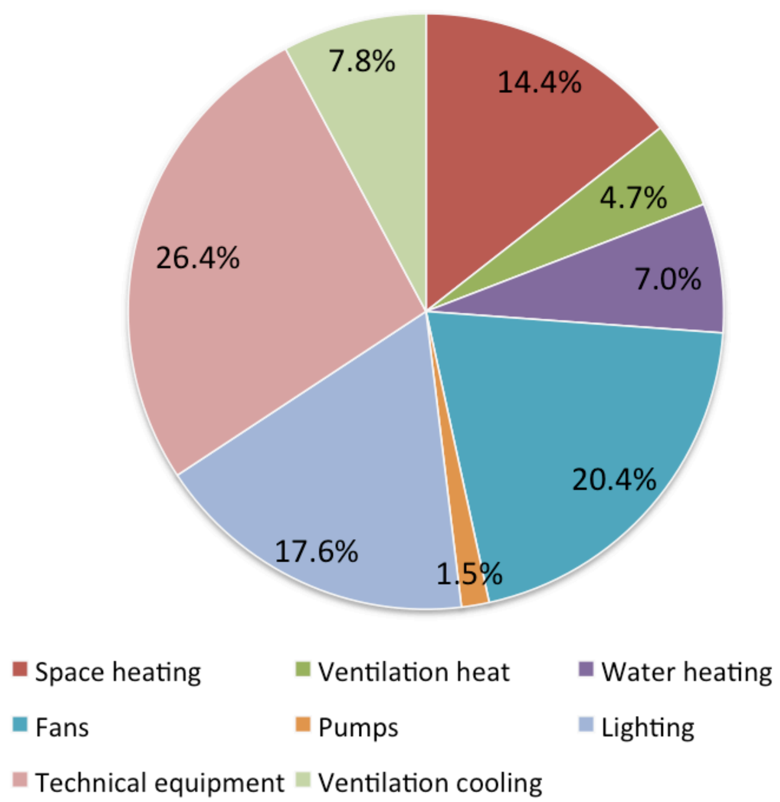


Optimal Small 'L-shape

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	3081 kWh	10.3 kWh/m²
Ventilation heat (heating element)	1014 kWh	3.4 kWh/m²
Water heating	1503 kWh	5.0 kWh/m²
Fans	4357 kWh	14.5 kWh/m²
Pumps	324 kWh	1.1 kWh/m²
Lighting	3758 kWh	12.5 kWh/m²
Technical equipment	5638 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	1672 kWh	5.6 kWh/m²
Total net energy demand	**21349 kWh**	**71.2 kWh/m²**
Delivered energy	**21190 kWh**	**70.6 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
3.7 kW (40 %)	91 %

[1]Excluding tap water

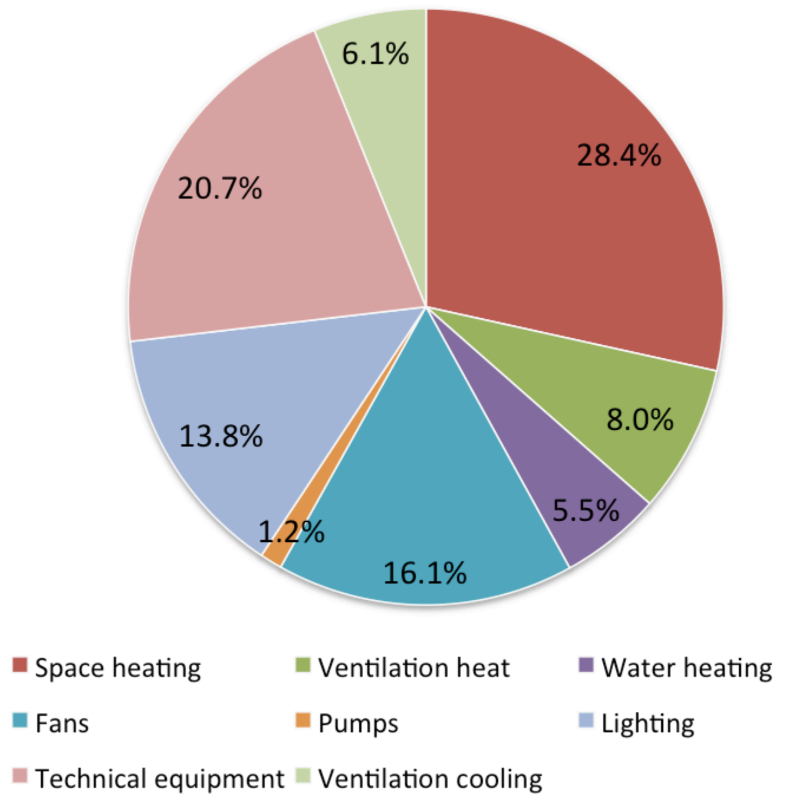


Minimal Large 'C-shape'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	25749 kWh	25.7 kWh/m^2
Ventilation heat (heating element)	7285 kWh	7.3 kWh/m^2
Water heating	5011 kWh	5.0 kWh/m^2
Fans	14587 kWh	14.6 kWh/m^2
Pumps	1129 kWh	1.1 kWh/m^2
Lighting	12528 kWh	12.5 kWh/m^2
Technical equipment	18792 kWh	18.8 kWh/m^2
Space cooling	0 kWh	0.0 kWh/m^2
Ventilation cooling (cooling element)	5575 kWh	5.6 kWh/m^2
Total net energy demand	**90655 kWh**	**90.7 kWh/m^2**
Delivered energy	**94218 kWh**	**94.2 kWh/m^2**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
17 kW (40 %)	92 %

[1]Excluding tap water

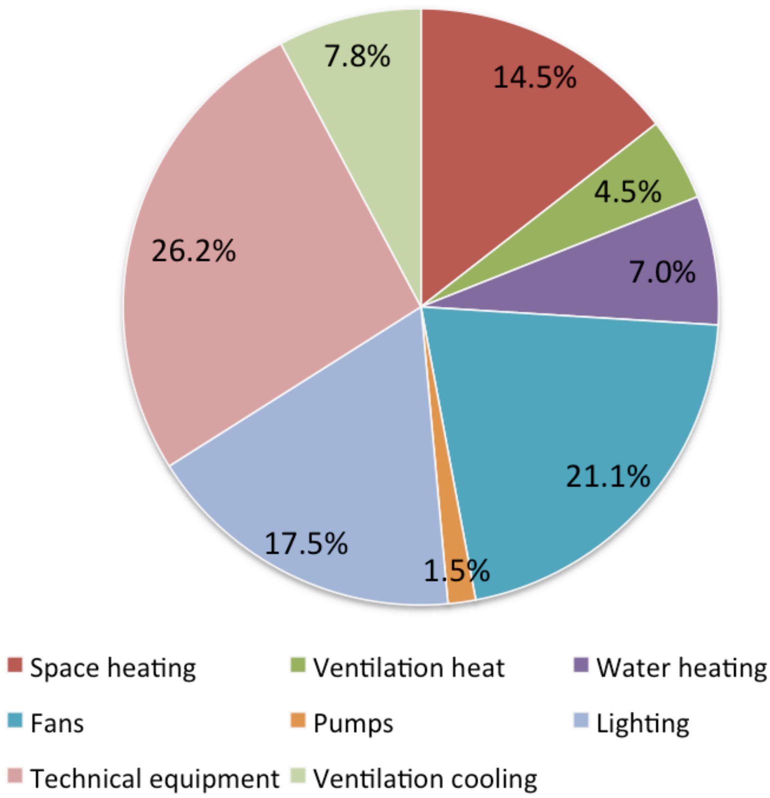


Optimal Large 'C-shape'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	10431 kWh	10.4 kWh/m²
Ventilation heat (heating element)	3199 kWh	3.2 kWh/m²
Water heating	5011 kWh	5.0 kWh/m²
Fans	15118 kWh	15.1 kWh/m²
Pumps	1072 kWh	1.1 kWh/m²
Lighting	12528 kWh	12.5 kWh/m²
Technical equipment	18792 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	5575 kWh	5.6 kWh/m²
Total net energy demand	**71726 kWh**	**71.7 kWh/m²**
Delivered energy	**71212 kWh**	**71.2 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
13 kW (40 %)	92 %

[1]Excluding tap water

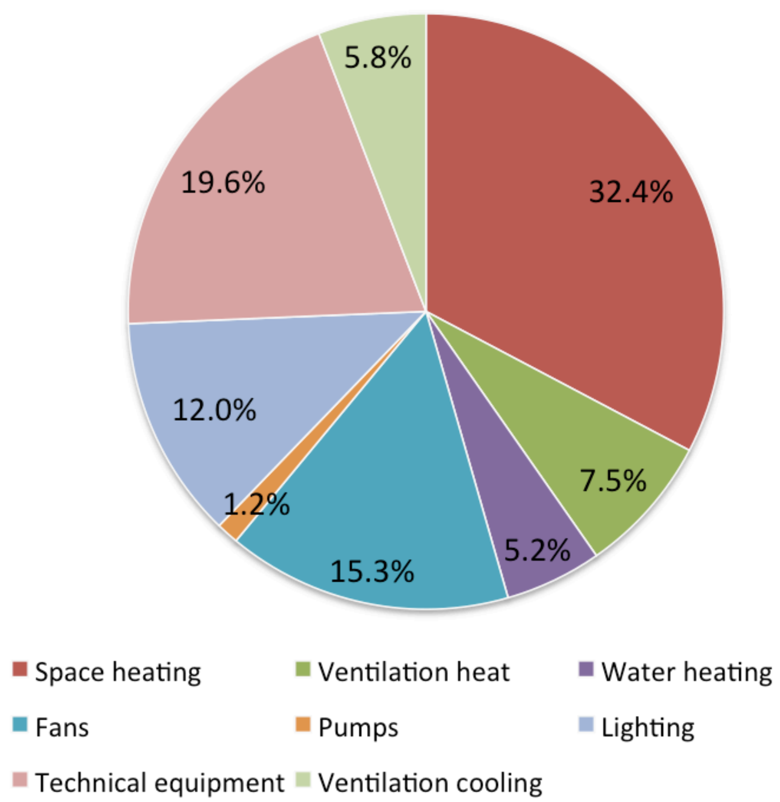


Minimal Medium 'C-shape'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	18661 kWh	31.1 kWh/m²
Ventilation heat (heating element)	4325 kWh	7.2 kWh/m²
Water heating	3007 kWh	5.0 kWh/m²
Fans	8826 kWh	14.7 kWh/m²
Pumps	677 kWh	1.1 kWh/m²
Lighting	7517 kWh	12.5 kWh/m²
Technical equipment	11275 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	3345 kWh	5.6 kWh/m²
Total net energy demand	**57633 kWh**	**96.1 kWh/m²**
Delivered energy	**60507 kWh**	**100.8 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
12 kW (40 %)	91 %

[1]Excluding tap water

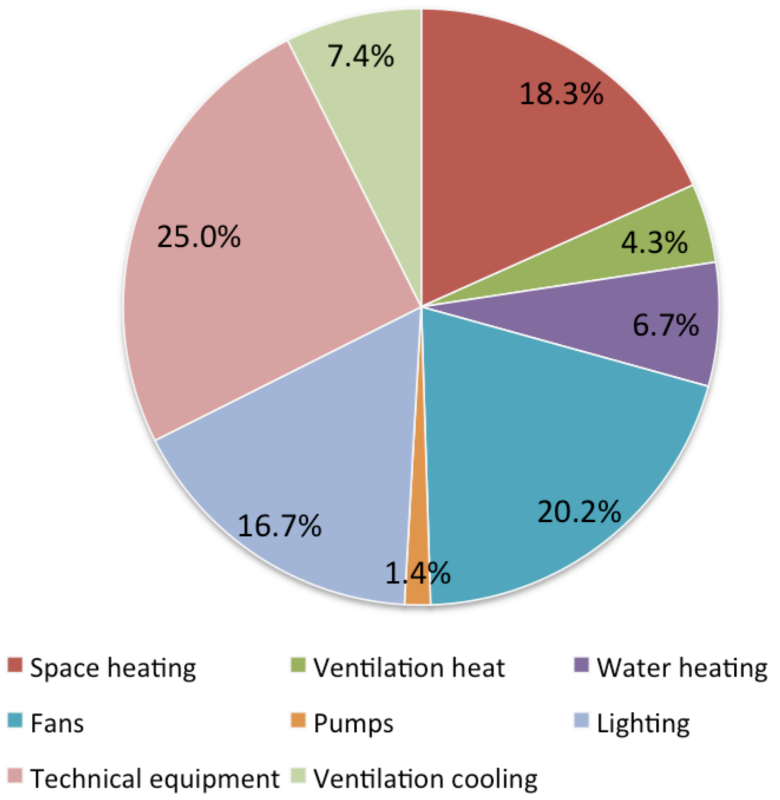


Optimal Medium 'C-shape'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	8243 kWh	13.7 kWh/m^2
Ventilation heat (heating element)	1935 kWh	3.2 kWh/m^2
Water heating	3007 kWh	5.0 kWh/m^2
Fans	9122 kWh	15.2 kWh/m^2
Pumps	643 kWh	1.1 kWh/m^2
Lighting	7517 kWh	12.5 kWh/m^2
Technical equipment	11275 kWh	18.8 kWh/m^2
Space cooling	0 kWh	0.0 kWh/m^2
Ventilation cooling (cooling element)	3345 kWh	5.6 kWh/m^2
Total net energy demand	**45088 kWh**	**75.1 kWh/m^2**
Delivered energy	**45240 kWh**	**75.4 kWh/m^2**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
9 kW (40 %)	92 %

[1]Excluding tap water

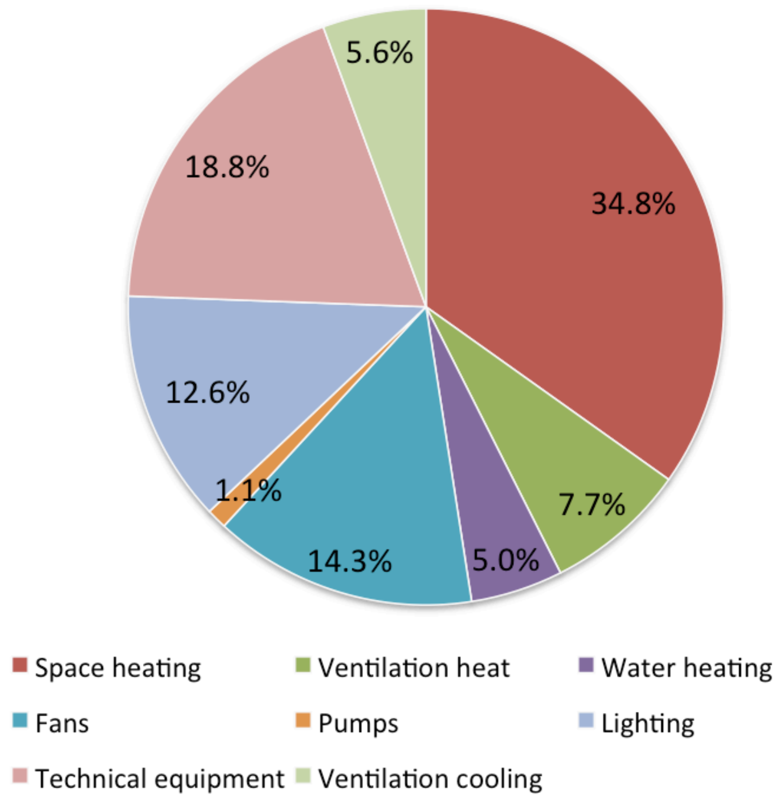


Minimal Small 'C-shape'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	10411 kWh	34.7 kWh/m²
Ventilation heat (heating element)	2314 kWh	7.7 kWh/m²
Water heating	1503 kWh	5.0 kWh/m²
Fans	4285 kWh	14.3 kWh/m²
Pumps	339 kWh	1.1 kWh/m²
Lighting	3758 kWh	12.5 kWh/m²
Technical equipment	5638 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	1672 kWh	5.6 kWh/m²
Total net energy demand	**29921 kWh**	**99.7 kWh/m²**
Delivered energy	**31628 kWh**	**105.4 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
6 kW (40 %)	91 %

[1]Excluding tap water



Optimal Small 'C-shape'

Energy budget		
Energy post	**Energy demand**	**Specific energy demand**
Space heating	4552 kWh	15.2 kWh/m²
Ventilation heat (heating element)	1009 kWh	3.4 kWh/m²
Water heating	1503 kWh	5.0 kWh/m²
Fans	4460 kWh	14.9 kWh/m²
Pumps	324 kWh	1.1 kWh/m²
Lighting	3758 kWh	12.5 kWh/m²
Technical equipment	5638 kWh	18.8 kWh/m²
Space cooling	0 kWh	0.0 kWh/m²
Ventilation cooling (cooling element)	1672 kWh	5.6 kWh/m²
Total net energy demand	**22917 kWh**	**76.4 kWh/m²**
Delivered energy	**23099 kWh**	**77.0 kWh/m²**

Coverage of heating demand[1]	
Boiler/heat pump size (coverage of peak)	Coverage of total heating demand
5 kW (40 %)	90 %

[1]Excluding tap water