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TRABAJO FIN DE MASTER

ENERGY INVESTIGATION OF A SEMI-DETACHED RESIDENCE IN MIDDLE SWEDEN

A STUDY ON HOUSEHOLD VENTILATION, ENERGY BALANCE AND POTENTIAL ENERGY EFFICIENCY MEASURES

7 ENERGÍA ASEQUIBLE Y NO CONTAMINANTE
9 INDUSTRIA, INNOVACIÓN E INFRAESTRUCTURA
11 CIUDADES Y COMUNIDADES SOSTENIBLES

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Cover picture: Photo of the building studied in the thesis; the contents concerning the energy investigation revolve around the left side semi-detached dwelling. Picture taken by the authors in one of the parameters measuring visits.

Preface

This work constitutes the end of my university studies in the field of Industrial Engineering. The contents presented in this document are the result of years of getting acquainted with engineering knowledge and ideas I am passionate about.

I would like to first and foremost thank my co-supervisor Roland Forsberg, who not only was my first contact in the development of this thesis, but also the person with most involvement in my progress. His aid in arranging house visits, handling metering devices and providing relevant documents proved invaluable and his enthusiasm was key for my success.

I am very grateful to Mr. and Mrs. Johansson who opened their house for me when needed, always with the same heartwarming hospitality. Their residence gave me the opportunity to work with an excellent case-study very relevant to the topic I was interested in.

Words of appreciation to Sana Sayadi for agreeing on supervising my simulations despite her workload, and to Magnus Mattsson for giving feedback and guidelines swiftly when requested.

Especial thanks to my relatives in Spain and exchange program mates in Sweden for being part of a growth experience abroad, both academically and personally. Their presence encouraged me to give my best in this work.

Abstract

Nordic houses have extended heating demand periods due to their climatology, in addition to some of the highest electricity consumptions in Europe. In Sweden, the residential sector accounts for 40% of the energy end use, and as such, it is imperative to evaluate plausible energy efficiency measures both in old and new buildings should the latest European Union regulations be met. Particularly, energy auditing practices are a step towards proposing robust changes. This work conducts an energy investigation over a semi-detached light-concrete house built in 2007, located in the municipality of Gävle in Middle Sweden. The study consists of several visits to conduct experimental measures in the ventilation system and indoor thermal conditions to map out the energy inflows and outflows of the dwelling. Results are contrasted with a simulated model using IDA-ICE software and the proposed energy efficiency measures are backed up with existing literature.

The results indicate that the house is proficiently insulated with transmission losses in the order of 12 000 kWh/year and its mechanical exhaust ventilation system regulated well enough to comply with indoor air quality standards above 0.35 $L/(s{\cdot}m^2)$, yet the overall energy demand remains above policy targeted levels. Measures like indoor temperature control and the implementation of heat recovery in the ventilation system are analyzed. In addition, a 5 kW_p PV system is designed to help alleviate electricity needs from the grid. Some alternatives, however, proved to be insufficiently appealing from an investment standpoint as in the case of thermal collectors. The measures report potential energy savings of 26% over the base model, with financial benefits of over 7 800 SEK/year, though with hefty investments with payback periods close to a decade.

This thesis ultimately aims to improve upon the energetic balance of its study dwelling, and it intends to contribute to the domestic energy auditing practices in a broader scope. Future work remains to be performed in the form of the development of more accurate auditing techniques for the removal of complex to meter variables that tend to fall under simplified assumptions.

Keywords: "Energy Efficiency Measure", "Detached-house", "Mechanical exhaust ventilation", "District heating", "Energy balance", IDA-ICE, light-concrete building.

Resumen

Debido a su climatología, los hogares nórdicos tienen extensos periodos de demanda energética en forma calor para interiores, junto con uno de los consumos de electricidad más altos de Europa. En Suecia, el sector doméstico es responsable del 40% del uso final de energía, y por ende, es imperativo plantear medidas de eficiencia energética plausibles si se desea alcanzar las últimas regulaciones de la Unión Europea. En concreto, las prácticas de auditoría energética son un paso hacia la propuesta de robustos cambios. Este trabajo realiza una investigación energética de un adosado construido en 2007, situado en la localidad de Gävle, Suecia central. El estudio consiste en varias visitas para obtener muestras de los parámetros térmicos y de ventilación del hogar, para así estimar los flujos de energía entrantes y salientes del domicilio. Los resultados son contrastados con un modelo simulado en el software IDA-ICE y las propuestas energéticas realizadas se apoyan con un trabajo bibliográfico extenso.

Los resultados indican que el domicilio estudiado está adecuadamente aislado térmicamente, con pérdidas en el orden de 12 000 kWh/año, y su sistema de ventilación por extracción mecánica está regulado para cumplir con los estándares de calidad de aire interior sobre 0.35 $L/(s \cdot m^2)$, aunque el consumo energético es superior al marcado por los reglamentos. Medidas como un control de la temperatura interior más riguroso y recuperación de calor en el sistema de ventilado han sido analizadas. Además, se propone una instalación fotovoltaica de 5 kW_p para aliviar la demanda de la red. Sin embargo, otras alternativas estudiadas han resultado ser poco atractivas para una inversión, como es el caso de los paneles solares termales. En conjunto, las medidas propuestas presentan un ahorro energético del 26% sobre el caso base, con beneficios económicos de 7 800 SEK/año, aunque con considerables inversiones iniciales y periodos de retorno de inversión cercanos a una década.

Esta tesis tiene como objetivo final mejorar el balance energético del domicilio, y pretende contribuir al conocimiento de auditorías energéticas residenciales en un alcance más amplio. Para futuros progresos, se sugiere el empleo de técnicas de medición más sofisticadas para eliminar variables complejas que se reducen en suposiciones simplificadas.

Palabras Clave: "Medida de eficiencia energética", "Adosado", "Ventilación mecánica de extracción", "Calefacción de distrito", "Balance energético", IDA-ICE, "Construcciones de cemento".

Laburpena

Haien baldintza klimatologikoengatik, Eskandinaviako herrialdeek behar energetiko handiko aldi luzeak izan ohi dituzte bero forman, Europako elektrizitate kontsumo altuenetarikoekin batera. Suedian, etxebizitzaren sektorea herrialdeko amaierako energia kontsumoaren %40-aren erantzulea da; horrenbestez, ezinbestekoa da energia efizientzia neurriak proposatzea Europar Batasuneko baldintzak bete nahi badira. Konkretuki, energia ikuskaritza praktikak aldaketa sendoak egiteko bidea izan daitezke. Lan honek energia ikerketa bat bideratzen du Gävlen eraikitako familia bakarreko etxebizitza batean, Suedia erdigunean. Ikerketa hainbat bisitetan oinarritzen da geletako tenperatura eta aireztatze parametroak lortzeko, ondoren sartu eta irtetzen diren energia fluxuak estimatzeko. Emaitzak IDA-ICE softwarean simulatutako modelo batekin konparatzen dira, eta proposaturiko neurriak aldez aurretik egindako lan bibliografiko sakon batean oinarritzen dira.

Emaitzek eraikina termikoki nabarmen isolatuta dagoela adierazten dute, 12 000 kWh/urteko galerekin, eta aireztatze sistemak parametro egokiak ditu etxe barruko airearen berritze kalitatea 0.35 $L/(s\cdot m^2)$ estandarraren gainetik egoteko. Hala ere, etxeko energia kontsumoa araudiek adierazitakoaren gainetik dago. Barne tenperaturaren kontrol zorrotzagoa edo bero berreskuraketa aireztatze sisteman ikertutako neurrien artean daude. Gainera, 5 kW_p -ko instalazio fotovoltaikoa aurkezten da sareko kontsumoa leuntzeko. Dena-dela, aurkitutako beste proposamen batzuk ez dira erakargarriak izan inbertsio bat burutzeko, hala-nola eguzki panel termikoak. Sistema osoa hartuta, %26-ko energia aurrezpenak lortu dira hasierako egoerarekiko, 7 800 SEK/urteko onura ekonomikoekin, nahiz eta hasierako inbertsioa handia den, eta honen berreskurapen aldiak hamarkada baten ingurukoak diren.

Tesi honek etxebizitzako balantze energetikoa hobetzea du helburu, eta energia ikuskaritzaren esparruaren adimena sustatu nahi du hein zabalago batean. Etorkizuneko aurrerakuntzentzat, neurketa teknika sofistikatuagoak erabiltzea proposatzen da aldagai konplexuak hobeto definitzeko eta sinplifikatzeko egiten diren suposaketak baztertzeko.

Hitz gakoak: “Energia eraginkortasun neurria”, “Familia-bakar etxebizitza”, “Erauzketa aireztatze mekanikoa”, “Distrituko beroketa”, “Energia Balantzea”, IDA-ICE, “Porlanezko eraikina”.

Nomenclature

Magnitudes

Symbol	Description	Unit/s
Q	Heat power	W, kW
E	Energy	kWh, MWh
P	Power	W, kW
U	Thermal transmittance	$W/(m^2 \cdot K)$
R	Thermal resistance	$(m^2 \cdot K)/W$
λ	Thermal conductivity	$W/(m \cdot K)$
d	Thickness of a layer	m
A	Surface area	m^2
Ψ	Thermal transmittance coefficient for linear thermal bridges	$W/(m \cdot K)$
L	Length of the linear thermal bridge	m
X	Thermal transmittance coefficient for point thermal bridges	W/K
T	Temperature	°C
h	Degree hours	°C·h
η	Efficiency	-
ρ	Density	kg/m^3
c	Heat capacity	$kJ/(kg \cdot K)$
v	Volumetric flowrate (air)	m^3/s, L/s
q	Volumetric flowrate (water)	$m^3/year$
p	Number of people	-
H	Hours	h
r	r-factor for solar radiation transmittance	-
c*	Cloudy factor for solar radiation transmittance	-
I*	Solar irradiation	
d*	Days with demand	days
S	Degree hours (correction)	°C·h
a	Annuity	SEK/year
i	Discount rate	-
I	Initial investment	SEK
τ	Time constant	s
V	Enclosed volume	m^3
C	Thermal mass	J/K

Abbreviations and acronyms

Characters	Full meaning
GHGE	Greenhouse Gas Emissions
EU	European Union
IEA	International Energy Agency
NZEB	Nearly-Zero Emission Building
EEM	Energy Efficiency Measure
HVAC	Heating and Ventilation and Air Conditioning Systems
BBR[1]	Swedish Boverket's regulation of Buildings
DUT[1]	Dimensional outside temperature
DVUT[1]	Dimensional winter outside temperature
IR	Infrared (radiation)
IDA-ICE	IDA Indoor Climate and Energy
MVHR	Mechanical Ventilation with Heat Recovery
PV	Photovoltaic
NPV	Net Present Value
PP	Payback Period
PV/T	Photovoltaic Thermal
SVEBY[1]	Swedish Agency for Standardization and Verification of Energy Performance in Buildings
SMHI	Swedish Meteorological and Hydrological Institute
ppm	Parts per million

[1] Despite the full meaning being translated, the original language (Swedish) acronym has been maintained.

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1 Introduction

1.1 Background

One of the primary concerns for the well-being and safety of the planet is global warming and its consequences. Buildings are a major contributor to climate change as they constitute more than 15% of greenhouse gas emissions (GHGE), accounting for 20% of the World's final energy use [1]. On top of that, the overall energy use is expected to increase in the future at a worldwide level [2]. Figure 1 illustrates the latest decades' final energy consumption breakdown in terms of share percentage by sector.

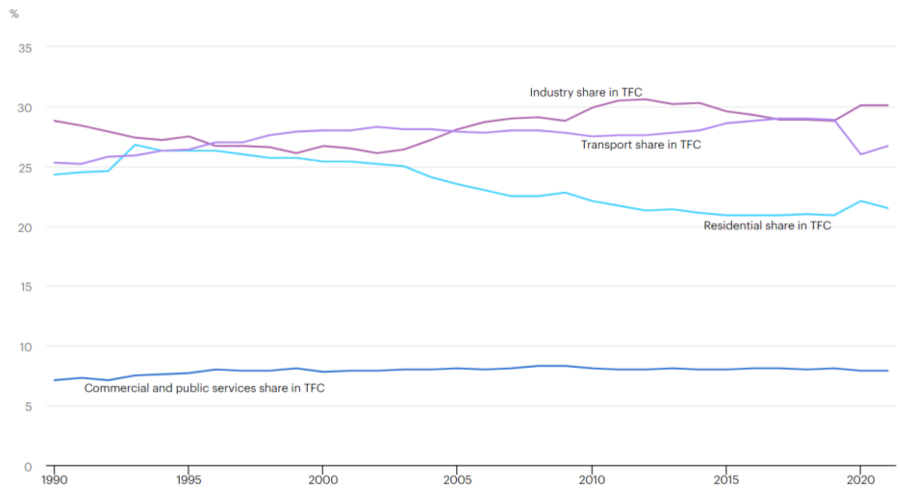

FIGURE 1.ENERGY SHARE OF TOTAL FINAL CONSUMPTION (TFC) BY SECTOR, WORLD, 1990-2021. SOURCE: IEA [1].

The impact of the building sector is even stronger in the European Union (EU), with the residential sector taking more than 40% of the end energy use and representing 36% of GHGE [3]. In response, the EU is seeking new measures to reduce energy and emissions with ambitious goals, reducing these by 30% and 40% respectively by 2030, compared to those figures from 1990 [4]. In addition, it intends to reach a 32% renewable energy share across the union and increase the share of renewable energy in residential buildings by 49% by the same year [5]. Particularly, the introduction of the Nearly-Zero Emission Buildings (NZEBs) by the Energy Performance of Building Directive (EPBD) in Europe will demand significant improvements if Sweden is to renew their Swedish Building Code "Boverket" for 2030 requirements, as in Nordic countries NZEBs must have a limited primary energy use of 45-60 kWh/(m^2·y), much of which is fulfilled by renewable energy production units on-site or nearby [6].

Nordic countries have long space heating demand periods that they have to cover with different energy mixes, with Sweden employing almost 24% of its total energy to the residential sector in 2021 [7]. Sweden's electricity supply comes primarily from renewable resources (most notably hydro power) and nuclear power. In addition, approximately 90% of multi-family buildings are connected to municipal district heating (DH) networks [8]. A full energy supply-end use Sankey diagram for other energy carriers than electricity is shown in Figure 2, for a full overview of the Swedish energy mix. Comparably, Sweden has equally ambitious future goals of those of the EU, with an expectation of reducing energy use in the country by 50% by the year 2050 in comparison to the 1995 reference year [9].

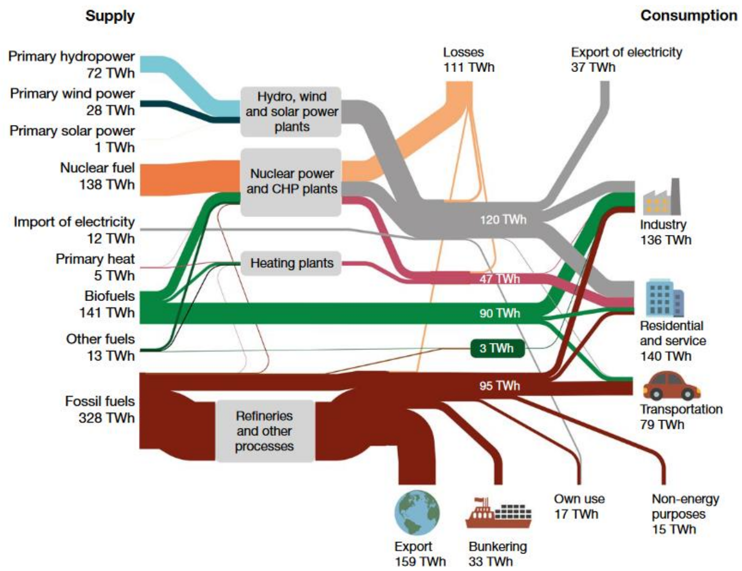

FIGURE 2. ENERGY SUPPLY AND USE IN SWEDEN 2020, TWH. SOURCE: SWEDISH ENERGY AGENCY [8].

As the housing demand peaked in 1960, the "million-houses program" was launched to construct one million dwellings during 1965-1975. It is important to note that most residences are considered to last 50 years before they need to undergo renovation [10]. In Sweden, single-family houses are of special interest as there are approximately two million detached and semi-detached dwellings using 30.2 TWh/year [9], making them responsible for 53% of the GHGE from the Swedish residential sector, equivalent to 2.62 $MtCO_2$/year in 2005 [11]. In perspective, these are only 15% of the total GHGE from the Nordic country (thanks to the developed use of renewable energies), but the energy use still represents the 40% statal total [12]. Space heating and hot water are the main energy sinks, constituting 60% of the energy demand [8]. However, it has been estimated that significant cuts of 10.8 TWh per year can be made in these two demands, giving the Swedish residential sector a potential to reduce its energy use by 20% or more [13].

Energy efficiency measures (EEMs) are more likely to be taken when conducting other home improvements, adopting these in packages [14]. Usually, two types of EEMs are of interest: energy saving windows (approximately 30% of the EEMs) and heat insulation (14% attic insulation and 8% walls insulation) [15]. However, previous pilot renovations to passive houses level led to projects with high costs and payback periods of 30-44 years, with questionable cost effectiveness [15]. Improvements in building heating and ventilation and air conditioning systems (HVAC) can result in up to 20% energy savings and have been reported to be more economically feasible than full building performance assessments [16]. Introducing improvements in the ventilation systems of domestic houses can help in lowering thermal energy needs, as air changes may account for up to half of the thermal losses [3], and the tendency to make buildings more airtight presents new challenges for cooling in summer periods [4]. However, these energetic challenges must not hamper indoor air quality (IAQ), as CO_2 concentrations above 5 000 parts per million (ppm) have detrimental effects on human health but much lower amounts of 1 000-1 500 ppm already constitute unacceptable living environments [3]. Thus, finding a system and parameters that balances both objectives is still to be elucidated and generalized. On the other hand, if EU 2030 targets are to be fulfilled, as mentioned previously the incorporation of renewable systems is of high interest as residential buildings with solar PV/T systems still remain a minority in Nordic climates, even with the prices of solar panels falling over the last decade [17]. For instance, solar thermal is predicted to contribute between 2.4% and 6.3% towards these targets [18]. However, the installations, maintenance and other costs associated to PV/T adoption are to this day a high investment [19], though the primary energy source change tendencies from Figure 3 over the last decades lead to promising prospects.

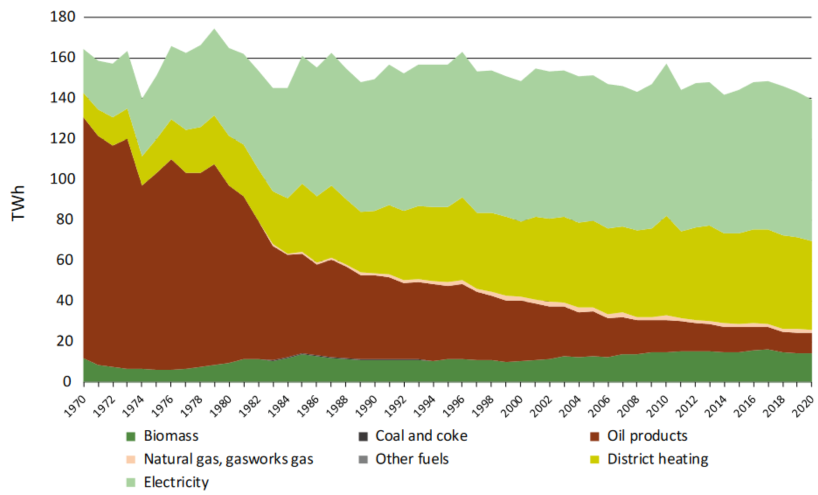

FIGURE 3. ENERGY USE IN THE SWEDISH RESIDENTIAL AND SERVICE SECTOR 1970–2020, TWH. AS THE USE OF FOSSIL FUELS DECAYS, INCREASED ELECTRICITY USE ALLOWS FOR RENEWABLE SOURCES IN CONJUNCTION WITH SUSTAINABLE DISTRICT HEATING NETWORKS. SOURCE: SWEDISH ENERGY AGENCY [9].

Nevertheless, although the importance of the topic is well understood and reported, studies on renovations and house energy audits are either scarce or research is scattered [20]. This thesis is a contribution to the knowledge around energetically improving the residential building sector in a cold climate with relatively low electricity prices, which makes for a unique study environment. Many of the papers found in the literature for Sweden conveyed studies in south Sweden, with the northernmost articles working in the province of Dalarna. This case-study in Gävle shall provide interesting results to compare, obtained from several visits to a 2007 single family detached-house that can benefit from a set of energy measures to accommodate for the future sustainable standards.

1.2 Literature Review

The literature review to both set the state of art that concerns this thesis work and to obtain acquaintance with previous methods and motivations was conducted by consulting several databases like Springer, Web of Science and Scopus; the results from academic search engines like Discovery and Google Scholar let to articles and reviews found in the aforementioned sites. For the majority, the results were filtered to be peer-reviewed and no older than ten years, giving priority to those that conveyed their own case-studies instead of reviews or state-of-art reporting. Due to the extent of it, the review is grouped in subsections, having used a set of research terms for it:

- **State of art for energy renovations**: "Energy measures/efficiency AND House AND Swe* / nord*", "Domestic Energy Measures", "Residential Energy AND Savings"
- **Issues regarding energy from ventilation:** "ventilation AND energy saving/efficiency", "resident*/famil* house ventilation", "indoor air quality AND house", "residential space heating/cooling"
- **Issues regarding energy from construction aspects:** "Nearly Zero", "Resident* Home/Buildings", "U-value" and "Energy savings"
- **Issues regarding energy alternatives (e.g. PV):** "House PV", "Solar single-family", "Renewable house energy"

1.2.1 The barriers, drivers and boost options for renovations

To understand the motivations and barriers for undertaking the introduction of energy efficiency measures in a house, several studies have conveyed surveys to get insight on the thoughts of owners. The article by Azizi et al. [21] indicates that energy renovations (ER) and EEMs often go hand-in-hand but not enough attention is put into their differences. Split into 3 main categories (thermal envelope, mechanical installations and renewable energy source), owners often adopt EEMs in a package when conducting an ER and the interactions are not considered, yet according to the authors these are influenced by a set of “personal" and "house-related” factors. After conducting a four section 5-point Likert Scale survey with over 1550 Swedish single-family house owners (yet only 29% responded and some age-groups were overrepresented), answers were statistically treated with Pearson’s chi-square test to elucidate whether the distributions of replies were due to chance or fit the expected frequencies. Figure 4 results indicate 60% of the respondents expressed interest in implementing an EEM, especially those consisting of replacing windows (29%) or installing a heat pump (26%), and 43% and 36% of the respondents showed interest in implementing at least one thermal envelope and HVAC measure, respectively. From the statistical analysis homeowners without children are more likely to undergo attic renovations, while those with long tenancy periods over 3 years are less interested in thermal envelope changes mostly due to the disruption of their daily activities. In addition, stay periods over 25 years incentivized owners to adopt new windows. Lastly, indoor environmental problems (IEPs) are a major driver for residents to adopt EEMs, with 46% of the respondents reporting some IEP in their house. Another survey performed in Denmark by M. Frontczak, R. V. Andersen, and P. Wargocki [22] on 645 persons stated that 54% of the respondents reported to have at least one indoor environmental quality problem at home. Most of them were cold floors (22%), too high temperature in the summer (20%) or too low in winter (14%), which are consequences of low efficient thermal measurements.

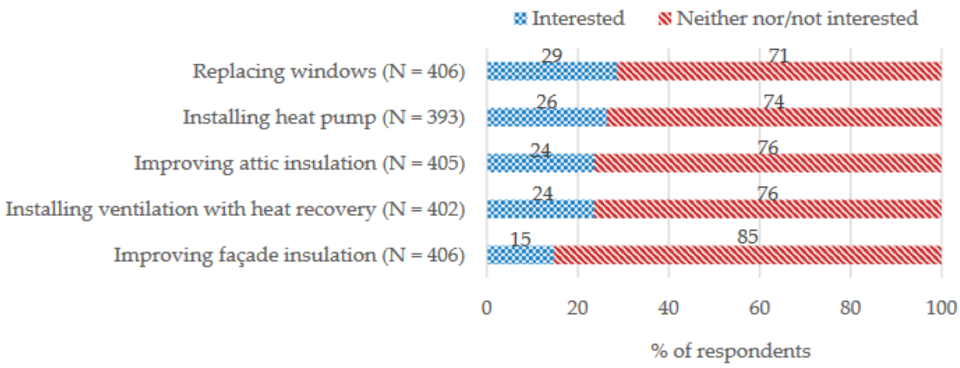

FIGURE 4. THE INTEREST OF HOMEOWNERS IN ADOPTING DIFFERENT ENERGY EFFICIENCY MEASURES (EEMS). SOURCE: AZIZI ET AL. [21].

Nevertheless, Azizi et al. remark that despite personal and house barriers, a better perception of information and knowledge would boost the adoption of EEMs, which can be tackled via different policies thus underlining the importance of these governmental instruments [21]. Nair et al. [23] concluded their study with a similar finding, highlighting that 64% of the respondents in their study were unaware of government support and that information campaigns announcing economic incentives would positively affect adoption decisions rates. This is very revealing as the 3 059 home interviews Nair et al. conducted to draw results were made in 2008, and thus, it is evident that despite the passing of a decade no advancements have been made in information channels. However, and very contrary to the results of Azizi et al., Nair et al. reported from their results that 70-90% of the respondents had no intention of adopting building envelope measures in the next 10 years, as they claimed to be satisfied with their house physical and thermal conditions, but they do acknowledge that there indeed exist personal and external influence factors too (e.g. marketing) when making renovation decisions [23]. Their method differs mainly on the fact that their 5-point Likert scale survey is of 6 parts (rather than 4) and that it did take into account the stratification of population in Sweden (i.e. south being noticeably more populated than north), as well as the obvious period difference (summer 2008). A new point this work reveals is that 66% of the respondents did not think that their energy costs were high, thus discouraging investment as annual energy cost saving is the major driver [23]. This statement is, however, probably not as prevalent due to the increase in energy prices over the last decades (as seen in Figure 5).

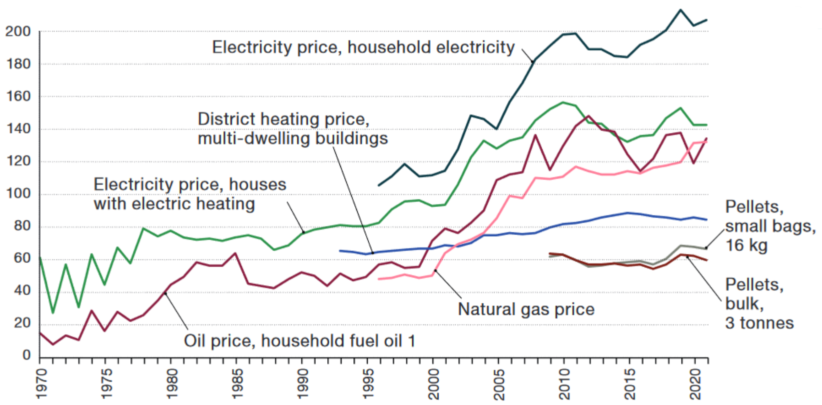

FIGURE 5. ENERGY PRICES FOR HOUSEHOLDS FROM 1970, INCLUDING TAXES AND VAT, IN 2021 PRICE LEVELS, ÖRE/KWH. SOURCE: SWEDISH ENERGY AGENCY [8].

R. Lundmark [15] supports the statement that for single-family buildings, energy efficiency improvements through renovations can net savings for the dwellers. The cost of these renovations is of interest for study, as there exists inflated costs to these processes, the so called "transaction costs" which ultimately act as an economic barrier for investment. Thus, a reduction (or even elimination) of these transaction costs would help the endorsement of more renovations. In fact, these costs are estimated to be 24 to 50% of the cost in single-family dwelling renovation projects [15]. In R. Lundmark's study, the measures of heat insulation and window changes are of most interest, as 30% of energy measures in Sweden are for windows while 22% is the sum of attic and wall insulation enhancements. After conducting a survey across Sweden with different steps and 2 848 respondents, the econometric model revealed that single-family owners can pay up to an additional 18 046 SEK for heat insulation and 21 106 SEK to install energy-saving windows [15]. Ultimately, Lundmark identifies the recurrent mention to a lack of information in the literature that may lead to these market failures, and in hand with Azizi et al. and Nair et al., he suggests more policies should be designed to overcome the barrier.

1.2.2 Literature regarding ventilation energy efficiency

Many mechanical ventilation systems in Sweden offer the owners control over the airflow with regulation panels. This raises the question of which should the actual regulated airflow be. According to the Swedish Boverket's regulation of Buildings (BBR), residential buildings should be ventilated at least 0.5 air changes per hour (ACH) or 0.35 $Ls^{-1}m^{-2}$ [13]. However, according to Hesaraki et al. [24], the Swedish regulation value is higher than what is necessary to keep an indoor CO_2 concentration under 1000 ppm, the threshold for what it is commonly considered acceptable for IAQ. Thus, heat wasting via excessive ventilation was identified. In their study, a range of airflows was tested in a recently renovated Swedish single-family house that had a similar exhaust ventilation system, both with an experimental approach and with a mathematical model. Their results show that a very low ventilation rate of 0.10 $Ls^{1}m^{-2}$ is not sufficient to keep acceptable CO_2 levels, but flows of 0.20 $Ls^{-1}m^{-2}$ did satisfy quality conditions, achieving 43% energy savings. However, it must be pointed out that CO_2 is not the only component to constitute foul indoor air, and this reduced flow may prove insufficient to remove other contaminants like airborne particles, which were not measured in the tests. On the other hand, their mathematical model showed that a third of the air renovation came from air leaks. Blecich et al. [25] reported that houses are being made more airtight in contrast, and consequently less ventilated. They concluded that mechanical ventilation heat recovery (MVHR) systems not only accomplish savings in the same magnitude, but are indispensable in the energy system of a passive house towards reaching NZEB status with a space heating load under 10 W/m^2. Their simulations of three different Croatian single-family houses showed that the better insulated dwellings with MVHR had reduced space heating demand hours and increased cooling demand hours, but had overall lesser energy needs: a passive house model experienced a heating demand decrease from 30.4 to 9.0 kWh/m^2 with MVHR. The 10 years payback period they report for these systems is also of high interest for a proposal of upgrading their mechanical ventilation system in the Gävle case-study, however, the fact that there exist significant climatic differences between Croatia and Sweden poses validity problems, potentially making this payback figure significantly different. A. Dodoo [26] reports similarly strong arguments for MVHR systems, suggesting potential of 80-90% heat recovery for ventilation in Nordic climates. In his investigation, 5 different configurations of air handling units (AHU) are tested in a multi-family building in the south of Sweden, reporting savings ranging from 16 to 29 kWh/m^2. A. Dodoo highlights that the cost-effectiveness of these systems varies depending on what primary energy the house uses, with better returns for systems that draw from district heating than from electric heat pumps [26].

Other than optimal airflow study and MVHR evaluation, ventilation strategies have also been recorded in the literature for optimal IAQ at efficient energy. Garman et al. [27] field-tested a bedroom with four different ventilation strategies in a case-study house in the province of Dalarna, Sweden. By comparing constant air volume (CAV) strategies (direct and indirect) and demand-controlled ventilation (DCV), both with intense and normal demands, they concluded that only CAV by indirectly extracting air from doorways instead of exhaust ducts did not satisfy acceptable CO_2 levels in the room. Moreover, DCV modes performed better at mitigating low humidity problems from the cold climate. It is important to note that CO_2 distribution is not uniform within a room ([24], [27]), and this stratification causes quality imbalances when people are present and when they are not [27]. However, Garman et al. remark that extracting air directly from bedrooms is rather unusual in Swedish homes as it is usually done from the kitchen and bathrooms, as in the case of the house for the thesis study. Moreover, the majority of the testing was made with Boverket's figures, which as reported by [24] could not be the most optimal.

Another aspect that is important to consider and that is usually only mentioned is the importance of natural ventilation even with the existence of a mechanical ventilation system. Y. Chen and L. Luo [28] constructed a questionnaire to analyze ventilation habits in residential buildings and concluded that there is potential for emissions reduction with proper natural ventilation: specifically, they report a CO_2 reduction of 1.61 kg per square meter for the summer temperatures in Shanghai[2] (26 °C to 28 °C interval) by opening the windows the necessary time daily to achieve thermal comfort. Nevertheless, there exists some controversy as they report that data analysis and simulation of samples reveal large gaps between monitoring data and simulation. Energy consumption was measured and simulated with a sample of buildings in Shanghai, and the Predicted Percent Dissatisfied (PPD) by Fanger [29] was used to assess comfort along with personal questionaries to residents. Another result drawn from the investigation is that by improving ventilation with design and structural approaches, residents are more likely to choose a more natural ventilation over other equipment such as air conditioning units [28].

Most of the aforementioned papers make heavy use of simulated models, all with a similar quantitative approach. A paper by E. Belias and D. Licina [30] constructs a model for different European cities to find correlations between outdoor air pollution, residential ventilation and IAQ. While the study does not evaluate energy as closely and focuses more on health effects, it is innovative in regards that the same

[2] The summer climatic differences between Shanghai and Gävle may raise validity issues regarding the application of this article for the thesis, as Gävle seldom exceeds temperatures of 24 °C. Nevertheless, there exist momentary indoor overheating problems in my case study dwelling when such outdoor temperature is surpassed, and the measure of the article should be comparable to this thesis work.

model was utilized for several locations, as opposed to other literature focusing on one single location. After studying different ventilation systems to those akin seen in [27], their findings report ventilative cooling (VC) can significantly reduce the energy demand for cooling between 10 and 36%, aligned with the results in [28]. Another important conclusion is that balanced ventilation with filtration and energy recovery achieved the best health and energy tradeoff, superior to the baseline of continuous exhaust mechanical ventilation without filtration [30].

1.2.3 Literature regarding energy efficient construction elements

When it comes to identifying the construction weaknesses that make buildings stay away from the NZEB category, the study performed by Boussa et al. [31] by modelling a set of EEMs in a typical Swedish multi-apartment argues that the majority of the heat losses in nowadays buildings occur due to the inefficiency of thermal insulation. This can be overcome by changing the type of windows or analyzing the different heating systems. In their article, it is stated that by taking passive EEMs such as reducing the U-values of the windows and improving the insulation, the space heating demand can be reduced up to 70%. Nevertheless, although the measures were effective and practical as they reach the requirements for NZEB (65 $kWh/m^2 \cdot year$) for every situation, they were taken based on different economic scenarios and not following some other technical parameters. In any case, this is interesting since it is shown how it is possible to economically renovate a multi-apartment building and transform it into a NZEB. In spite of that, to reach a Net-Zero energy consumption it would be necessary to implement a renewable energy source, such as photovoltaic (PV) panels, that will significantly increase the initial investment. However, as it has been mentioned before, it might be interesting to delve into more technical parameters, such as the type of insulation or the position of the windows [31]. The study of Misiopecki et al. [32], which defines how the thermal bridge has a significant contribution on the energy losses from the building envelope, corroborates that finding the most efficient window-to-wall interface that must be taken into account to reach the best energy efficiency and minimize the thermal bridging effects. Throughout the different simulations for 660 cases reporting linear thermal transmittance (LTT) values against windows positions, it was shown that wooden-framed walls were less sensitive to window position changes and higher for thicker walls. On the other side, concrete walls, which are the ones of this current project, showed significant LTT variation with preferable positions identified for optimal thermal performance. Regarding concrete walls that are insulated on the outside, putting the window in the middle of the insulation layer turns out to be the best choice, whereas for walls with insulation on the inside, the best spot for the window seems to be about 250 mm away from the wall. A significant insight of this is that improper window placement can lead to a 30% window's overall heat loss, so this must be taken into consideration. However, although the study provides an insight into how important the position of the window is, it would be useful to include a discussion about the relative cost of relative cost of different configurations, as this could help to make informed decisions not only from a performance point of view but also economic viability [32].

Apart from the position of the windows, the selection of the type of window must be considered too. Saadatian et al. [33] made a study analyzing both costs and environmental life-cycle assessment of 32 alternative window solutions (summarized in Figure 6). The alternatives included four framing materials (PVC, aluminum, wood and fiberglass) and eight glazing alternatives (with low versus high values for thermal transmittance and solar factors). The results were obtained by using the Pareto bi-objective optimization, balancing costs against environmental impacts, across three distinct European climate regions and encompassing different window orientations. It was shown that PVC is significantly advantageous because of the reduced initial investment, since the Life Cycle Cost (LCC) is notably lower, ranging from 36% to 64% compared to the aluminum framed solutions. Additionally, the study showed that for cold climates it was recommended windows with low U-values to reduce convective losses, as well as PVC or wood frames [33].

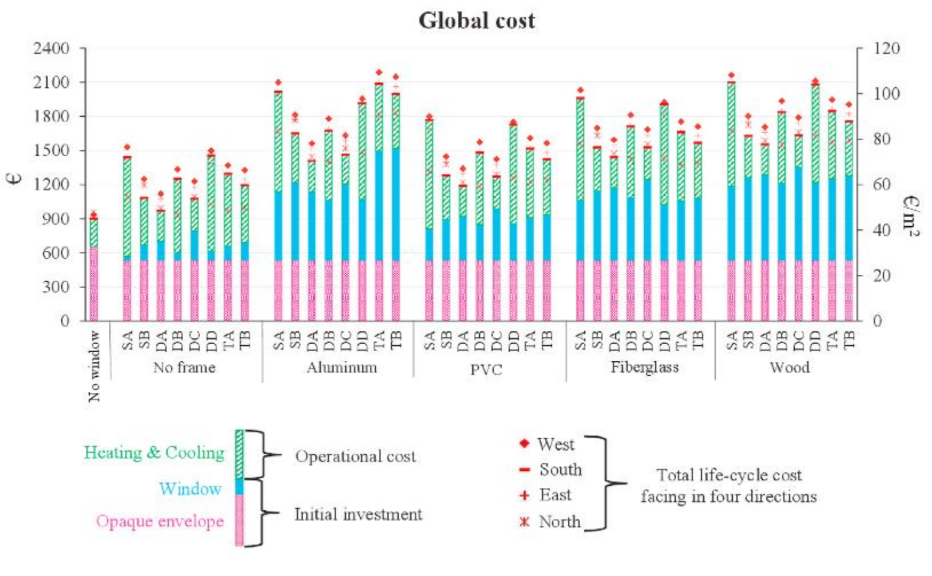

FIGURE 6. LIFE-CYCLE COST OF 30-YEAR USE OF THE OFFICE ROOM IN COIMBRA, COMPARING DIFFERENT WINDOW SYSTEMS FACING IN FOUR DIRECTIONS. SOURCE: SAADATIAN ET AL. [33].

Analogous to the improvements suggested for windows, choosing the correct insulation for walls can lead to very noticeable potential savings in the overall energy consumption [22]. Thus, research conducted by U. Y. Ayikoe Tettey and L. Gustavsson [34] in a concrete residential building in Sweden was initiated for seeking the material with the lowest primary energy use and CO_2 emissions. The criteria followed was the one based on BBR and passive house standards (comparison in Figure 7). It has been established that the materials used for external walls have the greatest impact on primary energy consumption and CO_2 emissions, followed by the foundation, roof and external cladding. The study showed that alternative constructions to concrete, which incorporate wooden construction frames, wooden external cladding, EPS for foundation insulation, and cellulose insulation for external walls and roof, can lead to approximately 36-40% reduction in primary energy consumption during production and 42-49% reduction in CO_2 emissions compared to the concrete alternative. Despite this research stands for the importance of the use of improved Cross Laminated Timber (CLT), it does not mention anything about the maintenance needs or the end-of-life related impacts of wood, that are key factors when considering a change of the building's envelope [34].

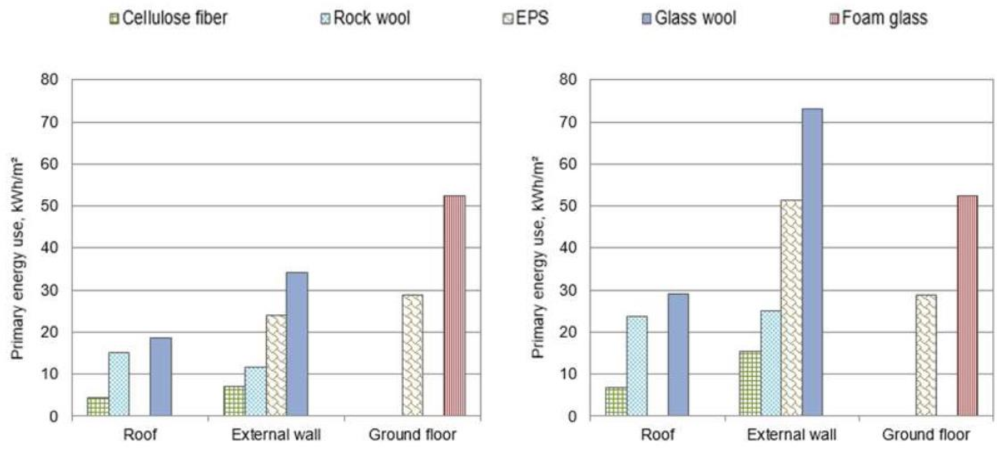

FIGURE 7. PRIMARY ENERGY USE FOR PRODUCTION OF THE VARIOUS INSULATION MATERIALS IN THE DIFFERENT BUILDING ENVELOPE PARTS TO THE BBR STANDARD (LEFT) AND PASSIVE CRITERIA PROPOSED BY U. Y. AYIKOE TETTEY AND L. GUSTAVSSON (RIGHT). SOURCE: [34].

1.2.4 Literature regarding support of solar energy, a holistic perspective

To complement the construction enhancements, green energy alternatives as a photovoltaic system are required to reach the ideal Net-Zero Building. However, the few daylight hours in Sweden during winter make it necessary to conduct a study like the one by Kabir et al. [35] to determine whether it is worthwhile or not. It must be taken into account existing government PV incentives, equivalent to 30% of capital investment, since thanks to them, a positive Net Present Value (NPV), profitability index (PI) and a Payback Period (PP) of 10.5 years is obtained in this research. Conversely, without government incentives, these systems exhibit negative NPV and low PI, rendering them economically unfeasible. Figure 8 quantitatively compares both scenarios in the form of estimated bill savings. Moreover, when choosing the battery type it must be taken into consideration that the efficiency analysis underscores the superior performance of lithium-ion batteries compared to traditional lead-acid batteries, with lithium-ion batteries achieving efficiencies of up to 97.1%. Nevertheless, although this analysis shows that it is possible to implement a profitable photovoltaic system in Sweden, some other parameters should be taken into consideration. One of these is the inclination of the solar panels and its correction factor K that will provide the mean corrected daily radiation, since the value used in the study by Kabir et al. [35] is the radiation measured in the horizontal plane.

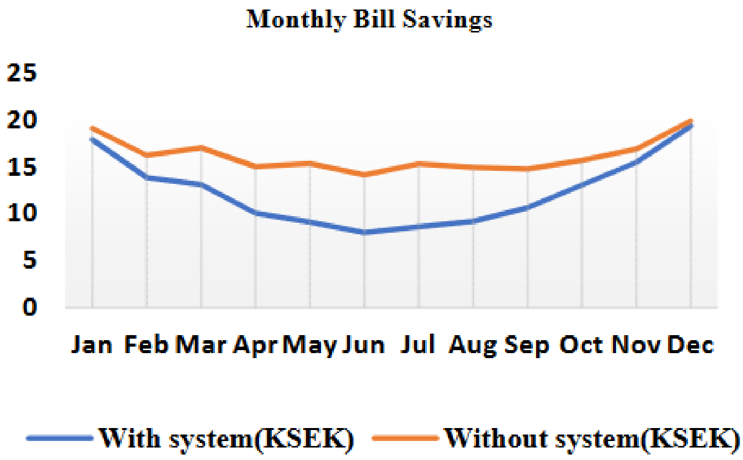

FIGURE 8. EXAMPLE OF POTENTIAL ANNUAL BILL SAVING FOR A 40 KWP SYSTEM WITH A 3KWH LITHIUM-ION BATTERY AT KARLSTAD. SOURCE: KABIR ET AL. [35].

Hyvönen et al. [17] further investigated PV storage alternatives and also concluded that without any external economic support, these storages in detached Nordic houses would only be profitable with high electricity market prices. In their paper, lithium-ion battery storage (LiB), hydrogen storage, and thermal energy storage (TES) were compared in a detached house in southern Finland. Despite increasing electricity market prices and the installation of PV system decreasing overtime, the results pointed out that LiB was the most profitable, with hydrogen storage and TES being noticeably more expensive than simply using grid electricity. The study employed a MATLAB model of a detached house with different energy supplies (e.g. district heating, PV, …) and different demand responses, using LCC[3], LCOE[4] and LCOS[5] as the economic magnitudes to assess profitability of the different storage techniques.

---

[3] Life Cycle Cost (LCC): it is an indicator for economic evaluations that takes a cradle-to-grave perspective to evaluate costs.
[4] Levelized Cost of Energy (LCOE): similarly to LCC, it takes a lifetime perspective. It is usually defined as the ratio between the sum of costs over lifetime and the energy produced in a lifetime, i.e. the average production cost over the device's lifetime.
[5] Levelized Cost of Energy (LCOS): it is analogous to LCOE, when applied to storage technologies.

However, Hyvönen et al. also bring up other non-strictly economic issues some of the storages have, like hydrogen systems having an overall poor efficiency and high components cost and sensible heat storage being unsuitable to convert energy back to electricity [17]. The results are considered to be valid for a case in Sweden, as Finland was the 3rd electricity consumer in Europe in 2019, only after Sweden and Norway. The models emphasized on the high heating demand of these Scandinavian countries, estimating an annual electricity consumption of 5 600 kWh (resulting in a daily average demand of 15.4 kWh), thus making the calculations for a 5 kW_p PV installation. Numerically, assuming a 20-year lifetime, a LiB storage would imply a 0.05-0.12 €/kWh LCOE, whereas H_2 storage and TES increase energy costs by 0.13-0.21 €/kWh and 0.21-0.59 €/kWh, respectively. A PV system of greater capacity (13.5 kW) and alternative charge-discharge cycles are discussed but ultimately the paper concludes that policy execution is needed if buildings are to achieve the 49% renewable energy fraction to comply with the 2030 EU guidelines.

There is also literature concerning solar power used for thermal purposes in hot water systems, rather than for electricity generation. L.R. Bernardo, H. Davidsson and E. Andersson [19] proposed an installation method to retrofit hot water boiler systems in single-family houses when committing to solar collectors' implementation (illustrated in Figure 9). Employing LCC, they reported approximately 50% of the 5 000 kWh/year of domestic hot water consumption could be saved in south Sweden, with a return on investment of 17 years, while conventional options seldom reach profitability in their 25 years lifetime. Regular installations often replace the existing boiler, while in this study the boiler is used for solar hot water storage by developing a coupling unit, thus saving costs. This coupling unit contained the required balance of the system, could work in charge and discharge at the right temperatures and needed no additional input pipes to connect [19].

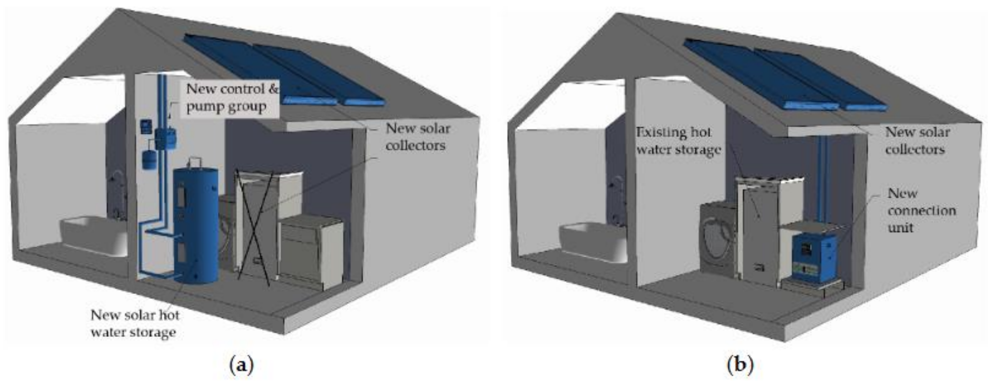

FIGURE 9. (A) CONVENTIONAL SOLAR DOMESTIC HOT WATER SYSTEM, COMMONLY FEATURING A SOLAR STORAGE WITH A HEATING COIL AT THE BOTTOM AND AN ELECTRIC HEATER AT THE TOP; (B) RETROFITTING THE EXISTING ELECTRIC WATER HEATER BY INSTALLING NEW SOLAR COLLECTORS VIA A NEWLY DEVELOPED CONNECTION UNIT. SOURCE: BERNARDO ET AL. [19].

According to the findings of the authors, the installation of domestic hot water systems is usually set to 6 250 € including Value Added Tax (VAT) at 25%. The full breakdown for this price tag is shown in Figure 10. However, the authors conclude that their retrofitting solution is very dependent on the house and boiler characteristics, and failed to meet the energy demands in winter, having to rely on an auxiliary heater. The payback period was deemed too long for today's market standards, although Sweden constitutes a worst-case scenario, with cheap electricity prices and relatively low annual solar radiation [19].

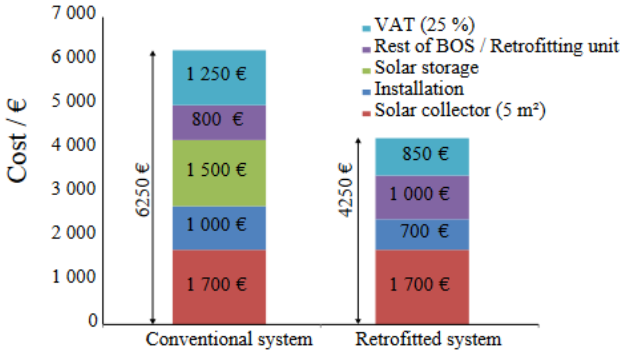

FIGURE 10. ESTIMATION OF COSTS BY [19] OF THE DIFFERENT PARTS OF THE CONVENTIONAL AND RETROFITTED SOLAR DOMESTIC HOT WATER SYSTEMS, INCLUDING VAT. SOURCE: [19].

Until 2011 there was a subsidy for solar thermal heating technology in Sweden, but the year this was removed, installations of such decreased to a third and continued decreasing thereafter [19]. Alternatively, combined photovoltaic thermal (PV/T) systems have also been proposed under the assumption these might be more profitable than having two separate systems. In the study by Kazanci et al. [36] they found that PV/T panels yield a solar fraction (i.e. the ratio between solar energy and the total energy as a sum of solar plus auxiliary energy) of 63% in Madrid and 31% in the neighboring Copenhagen. The study consisted of designing a single-family detached house, with the full renewable and HVAC system included, with the requirement to be functional in the aforementioned two cities, which have significantly different climatic conditions. While the conveyed TRNSYS model is purely hypothetical, the work of Kazanci et al. elucidates aspects of the design for sustainable domestic energy systems with commercial potential.

To sum up, several studies demonstrate that although there is interest in adapting energy-saving measures into residential dwellings, as heat pumps or window replacement, investment may be discouraged due to the belief that energy expenses are low and the general contentment with existing dwelling conditions. Though its cost-effectiveness varies depending on the major energy source employed, mechanical ventilation with heat recovery is also recognized as an effective way to improve indoor air quality and energy efficiency. Lastly, studies indicate that the use of renewable energy sources as PV systems, is essential to the construction of NZEBs; however, the financial sustainability of these systems is depending on government subsidies and an appropriate system architecture.

In conclusion, adopting energy efficiency measures in a residential dwelling in Sweden is affected by multiple personal and house-related factors. The main barriers include a lack of information and high initial costs, but government incentives and better awareness of the benefits can lead to the adoption of these measures. This has been the main motivation behind conducting the present study, aside from providing a new perspective on semi-detached houses, as there are not enough articles about them.

1.3 Aims

The aim of this project is to conduct a formal energy audit and from there to propose energy efficiency measures and energy source alternatives in a residential building located in Gävle, Sweden. The goal is to improve the primary energy number and energy class for the dwelling and leverage opportunities for both economic and environmental motivations. As an extended target for the thesis, this work also strives for obtaining results that are generalizable to other residential buildings that are not only detached or in Nordic climates.

Specifically, the work will be centered on thermal energy flows, since significant energy savings in buildings can be accomplished by enhancing technical features. Thus, the components to be analyzed will be the operation of the existing mechanical exhaust ventilation system, along with architectural and technical parameters that windows or insulation must meet for ranking higher in the energy scale.

This topic is interesting not only for the opportunity to improve a vital aspect in the building sector, which is one of the major energy users globally today, but also for evaluating the feasibility of such energy renovations from an economical perspective as the thesis intends to include a comprehensive financial report.

The study is, however, limited by the depth of the analysis and sample taking. Most critically, air quality is not tracked extensively with airborne particle or CO_2 meters; the measures that were actually taken for airflows and others are only punctual readings that will undergo some extrapolation error when extending simulations and calculations over longer periods. There may be concerns too on the climatic conditions in which the samples were taken, the first ones being conveyed in still cold February weather while the later ones being performed in warmer April.

1.4 Approach

The study combines on-field measuring, simulation, academic review and data analysis in order to quantitatively draw empirical conclusions. Nevertheless, it also includes some qualitative aspects such as verbal interviews with the dwellers. Although unconventional, hand-made calculations shall be performed along with IDA-ICE simulations, for verification and comparison proposes.

Data handling is performed means different Microsoft Office software (e.g. Microsoft Excel). All measuring techniques, devices and dwelling nuances are further explained under section 3. Methods. Figure 11 illustrates the approach idea schematically.

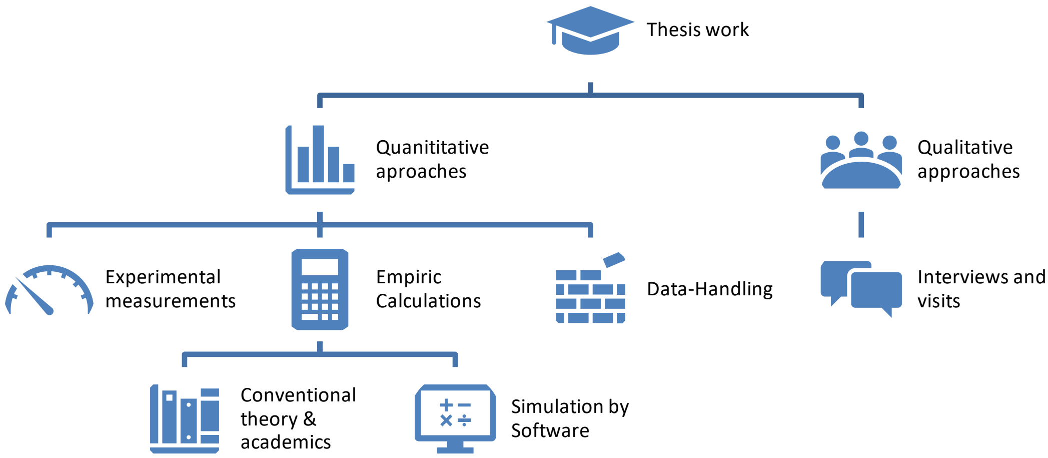

FIGURE 11. BREAKDOWN OF THE APPROACH TO THE THESIS TOPIC.

2 Theory

2.1 Energy audit

Energy auditing (or energy investigating) is an important tool to overcome energy efficiency gaps due to barriers like lack of knowledge about the energy system of the study environment. Specifically, its purpose is to identify general energy-saving areas or to propose energy-saving measures. As the audit progresses, both data collection and analysis become more detailed [37]. In the words of the European Energy Audit Standard (EN 16247-1), and energy audit is [38]:

> *A systematic inspection and analysis of energy use and energy consumption of a site, building, system or organization with the objective of identifying energy flows and the potential for energy efficiency improvements and reporting them.*

Today there are two international standards in the field of energy auditing; EN 16247 and ISO 50002. However, energy auditing methods can be tailored to the needs of the task, and they can be described in terms of scope, depth and purpose of the audit [37]. In this student thesis, the investigation is described based on the classification of energy audits provided by ASHRAE[6]; 3 levels are shown [37]:

- **Level I** is mainly based on information from economic accounts such as invoices. Other easily attainable information reviewing and possibly a short visit to the plant are also part of this first stage. At this level, the process is looking for measures that have low or no cost, with the proposal of a few initial hypothesis for study measures.
- **Level II** contains a more detailed audit and analysis of the study environment. At this point energy is usually divided into categories, either in activities, carriers or unit processes[7].
- **Level III** often involves an in-depth study, for example, a building simulation or optimization by using the data of the aforementioned steps.

[6] Acronym for American Society of Heating, Refrigerating and AC Engineers.
[7] The classification of unit processes is more common in the industry environment, while it lacks much meaning for the residential sector. In this thesis's case, a mix of by carrier and by activities is employed (e.g. district heating carrier energy being divided into transmission, ventilation, etc.).

2.2 Energy Balance

In a steady state (static) system, where no accumulation of energy is given, the energy inflows must correspond those out in order to obey energy conservation principles.

$$E_{in} = E_{out}$$ *Equation 1*

The more detailed development of equation 1 is known as the energy balance of a dwelling, and it is usually calculated for a year timespan. The usual breakdown on of the terms:

$$E_{in} = E_{space\ heating} + E_{solar} + E_{people} + E_{appliances}$$ *Equation 2*

$$E_{out} = E_{transmission} + E_{mech.\ ventilation} + E_{uncontrolled\ losses} + E_{hot\ water}$$ *Equation 3*

Where:

- $E_{space\ heating}$: Purchased energy to increase the indoor temperature to a comfort level (kWh/year).
- E_{solar}: Energy gains from the solar radiation entering the windows (kWh/year).
- E_{people}: Energy gains generated from the metabolism of the dwellers (kWh/year).
- $E_{appliances}$: Energy gains generated from the heat in electricity usage in household appliances (kWh/year).
- $E_{transmission}$: Energy losses by conduction-convection through the building envelope (kWh/year).
- $E_{mech.\ ventilation}$: Energy losses by the air changes performed by the mechanical exhaust system (kWh/year).
- $E_{uncontrolled\ losses}$: Sum of the energy losses by the air changes performed by activities like opening the windows and the existence of air leakage (kWh/year). This term shall also include losses by thermal bridges[8].
- $E_{hot\ water}$: Energy losses by the usage of heated up tap water.

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[8] Formally, losses by thermal bridges are a form of transmission loss that should be included in the other term. Nevertheless, as argued in the next point, it is more convenient to consider them in this category.

2.3 Transmission losses

Transmission losses occur through the building envelope due to the differences in indoor and outdoor temperature, as well as through air changes, where heated up air from the inside is exhausted outwards for new outdoor air. These last ventilation losses can be divided into controlled losses from the mechanical exhaust system and uncontrolled from natural ventilation (e.g. opening windows) and from air leaks (e.g. from window frame seams). The Dimensional Outdoor Temperature (DUT) method is proposed to calculate the power and energy of transmission heat losses; the power is obtained from the product of the loss factors and the difference in target indoor temperature and the minimum daily average temperature measured at the place in an extended period of time (most commonly 20 years):

2.3.1 Losses through the building envelope

Equation 4 describes de heat loss factor by transmission through the building envelope, i.e. the sum of the areas of the walls, roof and floor that enclose the inner environment:

$$H_t = \left(\sum U_i \cdot A_i\right) + \left(\sum \Psi_{TB\,k} \cdot L_k + \sum X_j\right) \qquad \text{Equation 4}$$

The first term corresponds to the product of the thermal transmittance U-value (W/m^2K) of the surfaces and their respective area (m^2). The second term corresponds to more localized heat transfer spots, the linear thermal bridges and punctual thermal bridges:

- $\Psi_{TB\,k}$: Thermal transmittance of the linear bridge (W/mK).
- L_k: Length of the linear thermal bridge (m).
- X_j: Thermal transmittance of the punctual bridge (W/k).

The power is drawn from the product of the loss factor and the (indoor T – DUT) difference:

$$P_{transm.\ loss} = \left(\sum U_i \cdot A_i\right) + \left(\sum \Psi_{TB\,k} \cdot L_k + \sum X_j\right) \cdot (T_i - DUT) \qquad \text{Equation 5}$$

The indoor temperature is considered to be 24 °C all year along, which is more accurate to this residence in Gävle rather than slightly higher than the standard 21 °C. The DUT is adjusted from the map found in Appendix G given by Prof. Forsberg, with a value of -22 °C for a light building in Gävle.

Calculating energy is a more daunting task as obtaining the number of hours to is not straightforward, mainly because outdoor dry-bulb temperatures are variable across the year seasons. The degree-hours concept is introduced to calculate the yearly energy loss; the degree-hours are the sum of the temperature difference (between indoor and outdoor) multiplied by the related time, accounting only for the times when outdoor temperature is smaller than the so-called balance temperature. This balance temperature is taken as the average indoor temperature the dwelling would have without internal heat generation sources, which usually provide extra 5 °C. Thus, balance temperature is usually 19 °C for older buildings (assuming a 24 °C temperature indoors) but lower for modern buildings; in the case of the dwelling in Gävle, since it is insulated more rigorously, it will be considered that the internal gains provide extra 6 °C. In practice, the degree hours are drawn from an outdoor dry-bulb duration diagram, recording all year temperatures every hour and ordering them in increasing order. A practical example for a duration diagram belonging to Gävle in 2023 is shown in Figure 12.

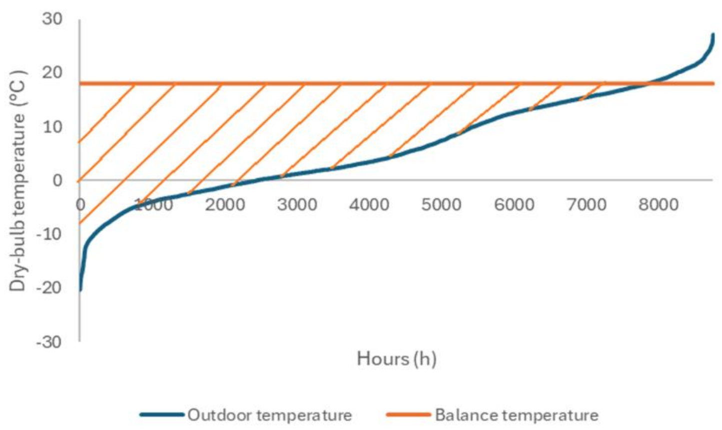


FIGURE 12. PLOT OF THE DURATION DIAGRAM FOR OUTDOOR DRY-BULB TEMPERATURE IN GÄVLE 2023. THE HATCHED AREA REPRESENTS HEAT DEFICIT THAT MUST BE SUPPLIED. NUMERIC DATA FOR THE PLOT EXTRACTED FROM SMHI FILES.

On the other hand, measuring thermal bridges is of high complexity. Thus, the term corresponding to it is simplified, and it shall be accounted for in a later energy term that will be obtained as a result of an energy balance:

$$E_{transmission} = \left(\sum U_i \cdot A_i\right) \cdot h \qquad \textit{Equation 6}$$

Where h is the number of degree-hours (°Ch). Translating its definition to a mathematical expression, where the operator "i" corresponds to one of each of the 8 760 hours in a year:

$$h = \sum_{i=1}^{T_{out_i} < T_{balance}} \left(| T_{out_i} - T_{balance} | \cdot 1\ hour \right) \qquad \textit{Equation 7}$$

Alternative methods exist like the one proposed by Prof. Fosberg, where estimated degree-hours are tabulated for each set of indoor and outdoor temperatures. However, while the values drawn in this method are good to compare, these tables are required to be updated to the correct time period.

2.3.2 Energy losses from ventilation

The ventilation losses can be expressed with another heat transfer coefficient according to the terminology of ISO 13789:2017:

$$H_v = \left[(1-\eta_T) \cdot F + F_{leakage}\right] \cdot \rho_{air} \cdot c_{air} \qquad \textit{Equation 8}$$

Where the first term within the square bracket corresponds to controlled losses from a mechanical system with heat recovery and the second term corresponds to uncontrolled air leaks:

- η_T: Efficiency of the heat recovery system. If no recovery system $\eta_T = 0$.
- F: Air flow through the controlled ventilation system (m^3/s).
- $F_{leakeage}$: Uncontrolled air flow (m^3/s).

The power is then drawn from the product of the coefficient and mean air temperature differences:

$$P_{vent.\ loss} = \left[(1-\eta_T) \cdot F + F_{leakage}\right] \cdot \rho_{air} \cdot c_{air} \cdot (T_{in} - T_{avg.out}) \qquad \textit{Equation 9}$$

However, the fact that the house concerning the thesis lacks a recovery system, that it is very complex to estimate the leakage losses and that exhaust flows have been measured one by one makes a simplified approach from equation 9 a more practical option:

$$P_{vent.\ loss\,(kW)} = v \cdot \rho_{air} \cdot c_{air} \cdot (T_{in} - T_{avg.out}) \qquad \textit{Equation 10}$$

Where:

- v: sum of the volumetric flowrates directly measured from the exhaust ducts (m^3/s).
- ρ_{air}: density of the air at an indoor temperature Tin (kg/m^3).
- c_{air}: heat capacity of air at indoor temperature Tin (kJ/kgK).

Energy is calculated with the same concept of degree-hours from the transmission losses section:

$$E_{vent.\ loss\,(kWh)} = v \cdot \rho_{air} \cdot c_{air} \cdot h \qquad \textit{Equation 11}$$

2.3.3 Uncontrolled losses

To account for the simplification of thermal bridges, air leaks and natural ventilation heat loss, as these are highly complex to measure, a new energy term $E_{uncontrolled}$ is proposed. The value of this term is unknown until the energy balance from section 2.2 is solved, and it is needed to ensure the equality of E_{in} and E_{out}.

$$E_{uncontrolled} = E_{in} - E_{transmission} - E_{vent.\ loss} - E_{hot\, water} \quad \text{Equation 12}$$

2.4 Hot tap water

Some of the tap water is heated up for domestic uses and then thermal energy is lost out the dwelling when water goes down the drain. However, invoices cannot track this volume of heated water, rather, the invoices from the water distribution companies charge for the total water use, both cold and hot. In the experience of Prof. Forsberg, it is safe to assume that a third of a regular houses water consumption is warm:

$$q_{hot-water}\left(\frac{m^3}{year}\right) \cong \frac{q_{total-water}}{3} \quad \text{Equation 13}$$

Energy within this heated up water is then calculated by:

$$E_{hot-water}\left(\frac{kWh}{year}\right) = \frac{q_{hot-water} \cdot \rho_{water} \cdot c_{water} \cdot \Delta T}{3600} \quad \text{Equation 14}$$

Where:

- $q_{hot-water}$: volumetric flow of hot-water use (m^3/year).
- ρ_{water}: density of water at an indoor temperature T_{in} (kg/m^3).
- c_{water}: heat capacity of water at indoor temperature T_{in} (kJ/kgK).
- ΔT: difference of temperature between the water coming from the inlet and the target hot temperature. Common values estimate temperatures of 5 °C and 55 °C, respectively.

2.5 Purchased energies and energy gains

The sum of the purchased energy for space heating and the thermal gains from different sources account for the incoming energy to the dwelling E_{in}. Unlike in E_{out}. all the values in this section should be known and easily measured.

2.5.1 Purchased energy for space heating

The dwelling purchases electricity and is connected to a district heating network. Of these two, only the district heating is used for space heating, i.e. the house does not have a heat pump. Thus, only the figures from the invoice of district heating are relevant for the thermal energy balance that is being described so far. It is important to note that the raw number from the invoice is taken, when in reality there might be in-between efficiencies that diminish the figures.

2.5.2 Energy gains from people

Due to internal metabolism, the dwellers make a small contribution to the energy balance of the house. This heat generation from the body varies with the activity the person is doing, as well as depending on if the person is an adult or a child. The Swedish Agency for Standardization and Verification of Energy Performance in Buildings (SVEBY) estimates that adults generate about 100 W, while children generate 60W [39]. Other sources estimate adult sedentary activity to generate 126 W and seated activity 104 W. To account for the generation of the usual 2 adult dwellers, the value of 100 W is considered in the calculations:

$$E_{people} = p \cdot Q_{metabolism} \cdot H$$

Equation 15

Where in equation 15:

- p: number of adults in the house.
- $Q_{metabolism}$: generation of heat from the body due to metabolism (W)
- H: Number of hours spent in the household when there is heat deficit (h).

2.5.3 Energy gains from appliances

Due to efficiencies in household appliances, the use of electricity in different devices and machines generates heat that contributes to covering heat deficits within the house. While each household appliance has its own efficiency, SVEBY gives a 70% electricity-to-heat conversion guideline for the calculation [39]. As such:

$$E_{appliances} = E_{electricity} \cdot \eta_e$$

Equation 16

η_e being the conversion of electricity-to-heat.

2.5.4 Solar energy gains

Solar radiation through windows helps increase the indoor temperature in a greenhouse effect phenomenon. Rather than measuring direct, diffuse and ground radiation to evaluate the irradiation over the surfaces, charts are provided by Prof. Forsberg to directly obtain the solar energy per unit area and time.

$$E_{solar} = r \cdot c^{*} \cdot I^{*} \cdot A \cdot d^{*} \quad \text{Equation 17}$$

Where in equation 17:

- r: sun radiation factor/heat gain coefficient (-). As windows both reflect and absorb radiation, this coefficient accounts for the actual solar radiation fraction that goes through the window. Its value is dependent on the type of window construction (e.g. 2-glazed panes, special windows, etc.). It can be seen as the equivalent of the more commonly used g-SHGC value defined as [40]:

$$r \equiv g - SHGC = \frac{Solar\ energy\ radiated\ into\ the\ room}{Solar\ energy\ radiated\ from\ outside\ into\ the\ outer\ pane} \quad \text{Equation 18}$$

- c^{*}: cloudy factor (-). It accounts for how direct energy irradiation may become diffuse with the presence of clouds, thus diminishing the solar gains. It varies across different months.
- I^{*}: daily solar energy per unit area (Wh/m^2day).
- A: area of the windows (m^2).
- d^{*}: days of the month

It is important to note that the whole year should not be considered when inputting the days of the months, i.e. the contribution in summer months is not as impactful as the dwelling it is considered sufficiently warm. This consideration shall also extend to the calculations of internal gains from people and appliances, both gathered in Appendix A.

2.6 Normal year correction

For the current study, the average outdoor temperature is 6 °C, which corresponds to the year 2023 from SHMI files. However, due to the very fact that the data required for the calculations of the studied dwelling is taken from a specific year without considering potential fluctuations from year to year, it will be necessary to adjust these results with the so-called energy index. This index is the relation between the degree hours of the selected year and the degree hours of a normal year.

$$Energy\ Index = \frac{S_{standard\ year}}{S_{actual\ year}} \qquad \text{Equation 19}$$

The value of the degree hours of a normal year is considered the average value over a longer period of time (e.g. 30 years). The data file will be provided by SMHI, which represent the typical climate from a heating and cooling needs perspective and are based on the weather data of 1996-2023 for Gävle. Degree days are thus the difference between 17 degrees and the average value of the outdoor temperature per day.

2.7 Financial considerations: Net Present Value (NPV) and Payback Period (PP)

Net present value (NPV) method is used to determine whether an investment will be profitable in the future. The net present value of an investment is the sum of all future cash flows over the life of the investment, discounted to its present value, minus the initial investment. When a positive value for the NPV is obtained, the investment will be considered profitable. It is described by the following equation:

$$NPV = \frac{(1+i)^N - 1}{i \cdot (1+i)^N} \cdot a - I \qquad \text{Equation 20}$$

- i: Discount rate (-)
- N: Total number of periods (usually years)
- a: Savings per period, i.e. Annuity (SEK/period)
- I: Initial investment (SEK)

Since the NPV is very sensible to the chosen discount rate, the more straightforward Payback Period (PP) is also employed. Generally, this method will yield lower investment return years, as it does not consider the change in value of money over time.

$$PP = \frac{Initial\ Investment}{Annual\ cash\ flow\ or\ savings} \qquad \text{Equation 21}$$

3 Methods

The methodology for the development of the investigation consists of a linear four step procedure to gather theoretical knowledge, obtain measurements and handle data with simulation assistance for projected results.

3.1 Study object

A dual on-field calculation/measurements and simulation approach is taken on the topic by studying a 2007 detached residence in the city of Gävle, in middle Sweden close to the Baltic coastline. The outdoor conditions are those of the tundra climate, with dry winters and temperatures ranging from -10 °C to 5 °C when measurements were started in the late-winter season and temperatures between 0 °C to 10 °C when these were finished in mid-spring (a more accurate representation is found at Figure 13, drawn from software databases). It is regularly inhabited by 2 adults with occasional visits.

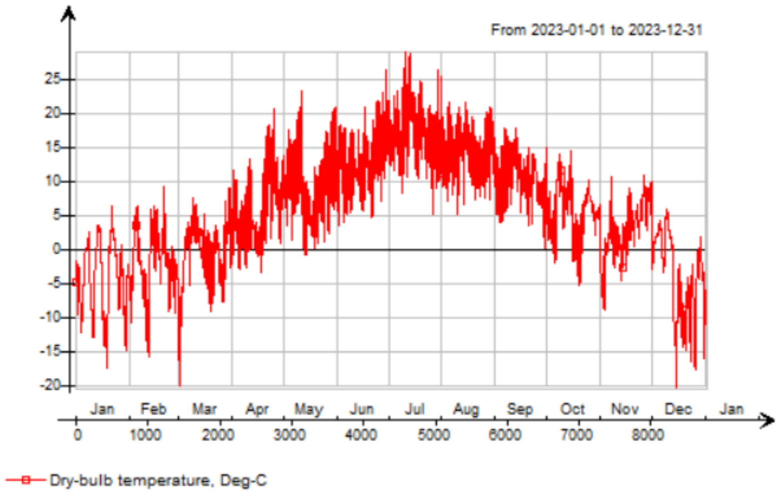


FIGURE 13. OUTDOOR DRY-BULB TEMPERATURE IN GÄVLE FOR 2023 FROM IDA-ICE DATABASES.

The dwelling is a 2-story residence adjoining another family's house as part of the same building, to which we did not have access, i.e. semi-detached. However, their ventilation system is independent and it consists of mechanical exhaust ventilation without heat recovery. The extract air terminals are mainly distributed in the top floor bathroom, ground floor bathroom, laundry room and storage room. There is also an ample fume extractor located in the middle of the kitchen area and several outdoor air supply vents scattered across the rooms. Upon arrival, the owners showed the status of the supply vents located in the lower floor, all of which were shut close and kept in that state during measuring exhaust flows. As many buildings in Gävle, the house is connected to the municipal district heating network. The dwelling draws heat energy from it to feed the radiant floor it has in both stories for floor heating. It does not make use of wall radiators for additional space heating.

It is important to emphasize the significant number of windows throughout the house, particularly those situated in the living room; these windows span approximately one wall that measures 10 meters in height and 5 meters in width, potentially resulting in substantial convective heat loss but also solar gain (illustrated in Figure 14). All walls are mainly composed of concrete and the main façade of the house has an orientation of -42º East. For detailed house plans, layout and building materials information (e.g. U values stated by the construction company) see Appendix E: Blueprints for the study house and Appendix F: House parameters from building plans.

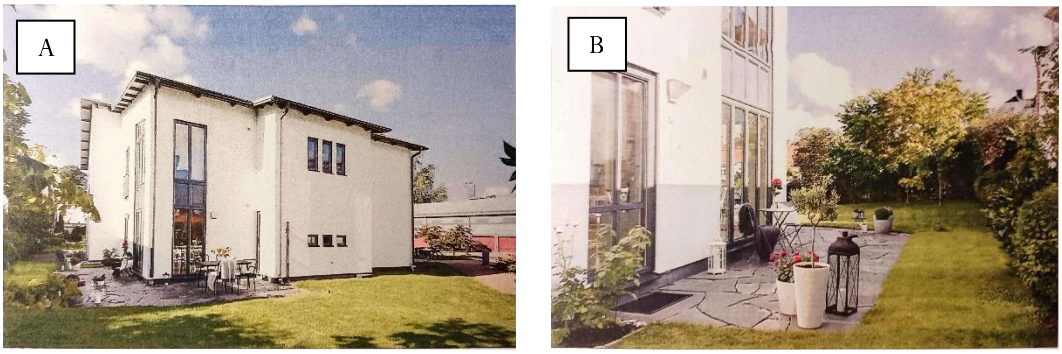


FIGURE 14. (A) HOUSE SIDE VIEW WITH THE LARGE WINDOW AREA IN THE CORNER, BELONGING TO THE DINING AREA. (B) DETAIL OF THE WINDOWS IN THE BACK SIDE OF THE DWELLING. PHOTOGRAPHER: BUILDING PLANS REPORTS (2006).

3.2 Materials

Air flow measures were taken with several airflow meters, depending on the geometry of the ventilation orifice, its location and the expected airflow:

- A SwemaFlow 233 volume flow hood metering device from the Swedish manufacturer SWEMA, for exhaust ducts where the hood made full wall contact. The hood is able to measure air flows ranging from 1 L/s to 65 L/s at temperatures between 0-50 °C, with an error of ± 3.5% and a precision of 0.1 L/s. Figure 15 illustrates the device model used.

FIGURE 15. SWEMAFLOW 233 LUFTFLÖDESSTOS. SOURCE: SWEMA.SE

- A SwemaFlow 4001 volume flow hood metering device for the fume extraction hood in the kitchen, as it had a surface and flows well over the capacities of the first mentioned device. Still, the 4001 model dimensions were not big enough to cover the full fume extraction section and some of the remaining surface was covered with paper. Figure 16 illustrates the device model used.

FIGURE 16. SWEMAFLOW 4001 LUFTFLÖDESSTOS. SOURCE: SWEMA.SE

- A VelociCalc Plus 8360 multi-function anemometer from the American manufacturer TSI. The tip of the probe was inserted for ducts that had insufficient wall contact or special geometry, namely the exhaust gate in the sauna room and the duct in the master room closet. Unlike the previous two devices, instead of measuring the flow directly, the device returned the pressure difference in the selected mode, which along with some charts from exhaust ducts manufacturers to get a K coefficient depending on the model, allows for flow calculation. In the selected mode, the anemometer could measure pressure differences between -2.5 and +2.5 kPa, with an accuracy of ± 0.002 kPa. Figure 17 illustrates the device model used.

FIGURE 17. VELOCICALC PLUS 8360 MULTI-FUNCTION ANEMOMETER. SOURCE: EBAY.COM

- Air-humidity (relative, RH), indoor temperature and CO_2 concentration were measured with a set of indoor climate loggers. The specific model was CL11 CO_2 Data Logger from ROTRONIC with a temperature measuring range from -20 to 60 °C and CO_2 concentration range from 0 to 5 000 ppm. The precision for the various measurements is ± 0.3 °C for temperature, ± 30 ppm for CO_2 concentration, and ± 2.5% for relative humidity. The data loggers were scattered in the living room, in the master bedroom and in the study, the latter two being located in the second floor. They conducted measurements every ten minutes from 23rd of April until 29th of April. Figure 18 illustrates one of the device models.

FIGURE 18. CL11 CO_2 INDOOR CLIMATE LOGGER. SOURCE: ROTRONIC.COM

- IR thermographies were conducted with a FLIR E75 thermal imaging camera. The device was capable of recording between temperatures of -20 °C to +650 °C with an accuracy of +/- 2%. The scope was configured with a surface emissivity of **ε** = 0.95, and the distance was set to 5-10 m although the auto-focusing of the camera was used for every snapshot. It must be mentioned that the day when the device was used was rather warm, with an outside temperature of 16 °C, and as a result, the thermal gradients in potential thermal bridge spots were attenuated. The thermographies are further analyzed in the following subsection. Figure 19 illustrates the camera model:

FIGURE 19. FLIR E75 THERMAL IMAGING CAMERA. SOURCE: RS COMPONENTS AB

Dimensional parameters of the residence were not needed to be taken as the owners provided an extensive collection of blueprints. Other important data like the U-value parameter for walls and windows was given too in construction reports from 2006 by the construction company.

Figures for energy balances were drawn from energy invoice overviews between 2020 and 2023, tracking down the energy from electricity and district heating in kWh as well as the water consumption in cubic meters. Additionally, a qualitative interview was conducted with the owners regarding thermal comfort and indoor air quality issues, to identify interesting spots within the residence. While this process did not give computable data such as a Likert scale questionnaire, it served to set the focus when conducting measures.

3.3 Procedure

Several visits were conducted to the semi-detached house with the owners present. The first visits served as printed documents collecting reunions and short interviews, while the subsequent ones a magnitude was measured in each, i.e. one day for airflow measures, another visit for IR camera snapshots, etc.

Airflows were measured with the exhaust system working under two modes: low flow regulation, and high flow regulation. At high flow, the system is designed to increase the potency of all exhaust ducts by the same factor, however, the devices measured different flow multipliers between x2-3 for the ducts in the house. Intake air was briefly evaluated by measuring one of the openings in the living room, as all incoming air vents are all equal in construction and manually regulated by gates the dweller must open. In the visits, the ones in the most open areas like the living room and dining space were shut, while the ones in the top floors were partially open. These conditions do not tend to change. Regardless, no rigorous evaluation of the supply system airflows was made, as in an exhaust air ventilation system like this, that same air flow can be expected also to enter the house and it is more interesting to evaluate the mechanical exhaust system itself.

Air temperature, relative humidity and CO_2 concentration were measured over a programmed 7-day timespan in the climate loggers. During this time, the owners were allowed to perform their daily activities with no alteration, although it was pledged that no windows would be open for too long near the loggers.

IR camera photos were taken at a period when outside temperature started warming up. While this was inconvenient for the quality of the thermographies, the interest of the measures was directed towards making a first impression on how severe the thermal bridges were in the residence, rather than to record the length and thermal constants of all bridges in detail. It serves as a baseline to input the degree of abundance of bridges in IDA-ICE to avoid leaving the setting sliders at predefined values.

IDA-ICE simulations were conducted after performing the U-Values and Energy balance calculations found in Appendixes A and B, in order to avoid bias in the calculation process. While uncommon, this methodology offers the reassurance of validating the software model and/or the correctness of the hand-made estimations. The economic calculations such as the NPV are drawn after reaching a consensus between all results.

3.4 Simulation parameters

On-field measures allow the engineer to map out rough estimates, while simulation tools allow verification of these. Conversely, the calculations from field measures help validate the model of the software. Hence, it is an excellent synergistic tool that saves temporal and financial resources. IDA-ICE (indoor climate and energy) from EQUA Simulation AB is one of those software. The developers of the software point out the following description of their product:

> *IDA ICE (Indoor Climate and Energy) is a new type of simulation tool that takes building performance to another level. It accurately models the building, its systems, and controllers – ensuring the lowest possible energy consumption and the best possible occupant comfort.*

Discrepancies have been reported between monitored values and simulated models in other case-studies [4]. To study such differences in the studied building, a replica of the dwelling is built in the multizone indoor-climate analysis IDA-ICE 5.0.0.1 software, using much of the data from Appendix A and Appendix B. The simulations are performed over a whole year with extrapolated parameters from the visits, having climate data for Gävle predefined from IDA-ICE databases, with the most relevant variables shown in Table 1.

TABLE 1. MAIN PARAMETERS OF THE CLIMATIC DATA FILE OF GÄVLE FOR IDA-ICE SIMULATIONS (2023).

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudiness, %
January	-4.1	86.2	24.8	7.8	0.8	0.6	72.3
February	-1.8	81.2	60.7	22.9	0.9	-0.5	64.2
March	-0.7	77.6	90.8	60.8	1.0	1.2	64.6
April	5.6	72.7	158.6	80.5	-0.1	0.4	56.2
May	9.9	67.8	228.0	99.7	-0.7	-1.0	49.7
June	13.3	70.4	234.3	102.9	-0.1	-0.3	53.6
July	17.7	65.2	191.1	127.7	1.2	1.0	55.9
August	14.4	77.4	105.0	99.3	1.0	0.6	70.3
September	10.2	81.0	113.9	55.2	-0.1	-0.1	62.8
October	5.4	81.5	67.0	30.9	1.6	0.6	61.3
November	3.0	86.8	48.4	8.3	1.1	1.6	68.5
December	-4.2	87.8	20.0	4.6	1.4	-0.2	73.8
mean	5.8	78.0	112.0	58.6	0.7	0.3	62.8
mean*8760.0 h	50532.7	682887.4	981139.1	513575.1	5960.4	3010.0	549900.0
min	-4.2	65.2	20.0	4.6	-0.7	-1.0	49.7
max	17.7	87.8	234.3	127.7	1.6	1.6	73.8

The dimensions of the model are built to scale with the provided blueprints; the resulting dimensioned replica is shown at Figure 20. However, there exists simplification in the geometry of the simulated dwelling, especially in the upper floor room ceilings that had many slanted facades. Instead, the roof was modeled as a single unit in the form of a new attic zone with no ceiling with the rooms below (to avoid extra surfaces where there should not be).

FIGURE 20. 3D MODEL OF THE DWELLING IN IDA-ICE SOFTWARE.

Nevertheless, the setpoints introduced (see Figure 21) for describing the indoor conditions are accurate as they are the ones obtained by means of the devices explained in section 3.2. In fact, IDA-ICE allows simulation for a range of acceptable temperatures, rather than a fixed temperature of 24 °C like the one employed in the energy balance calculations.

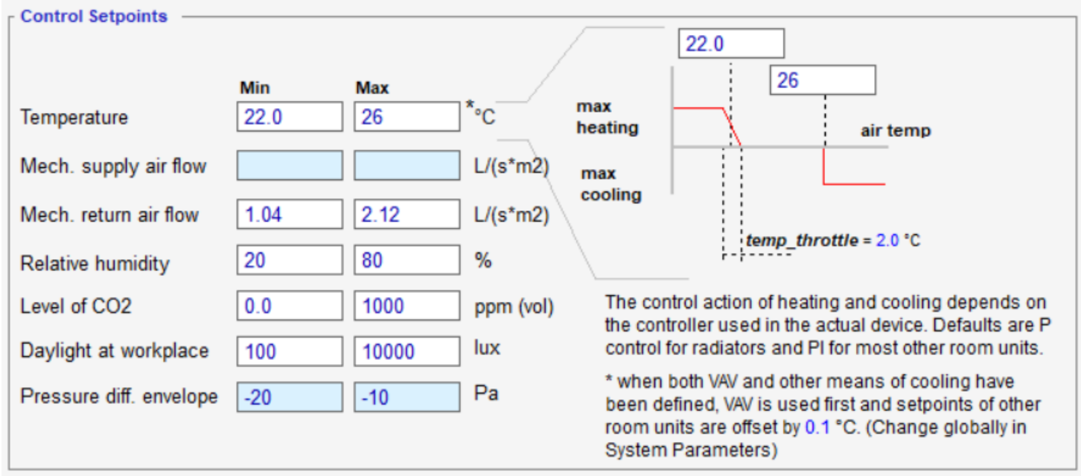


FIGURE 21. SCREENSHOT OF THE INPUT SETPOINT PARAMETERS TO DESCRIBE THE INDOOR ENVIRONMENT OF THE MODEL IN IDA-ICE.

For clarity purposes, it must be mentioned that a conversion of units for airflow had to be performed in order to input correct data, as the exhaust air experimental measures yielded flows in L/s and m^3/s (all these values can be found in Appendix A under Appendix Table 2) which must be converted to the indicated $L/(s{\cdot}m^2)$ from Figure 21. Hence, the floor area of the rooms with exhaust vents is needed, which is read directly from the dimensions of the model in Figure 20. For the example in Figure 21, which is the setpoint for the lower bathroom with a floor area of 4.13 m^2:

$$Setpoint\ flowrate\ (low) = 0.0043\ \frac{m^3}{s} \cdot \frac{1000\ L}{1\ m^3} \cdot \frac{1}{4.13\ m^2} = 1.04\ \frac{L}{s \cdot m^2}$$

$$Setpoint\ flowrate\ (high) = 0.0088\ \frac{m^3}{s} \cdot \frac{1000\ L}{1\ m^3} \cdot \frac{1}{4.13\ m^2} = 2.12\ \frac{L}{s \cdot m^2}$$

The floor areas for the rooms with exhaust ventilation vents are gathered in Table 2.

TABLE 2. AREAS AND AIRFLOW SETPOINTS FOR THE ROOMS WITH EXHAUST VENTILATION VENTS.

Zone	*Floor area [m²]*	*Low Setpoint [L/(s·m²)]*	*High Setpoint [L/(s·m²)]*
Upper Bathroom	12.040	0.42	0.86
Lower Bathroom	4.130	1.04	2.12
Laundry room	5.829	0.6	1.4
Dressing room	4.690	0.35	0.7
Sauna	4.132	1.69	3.78
Kitchen[9]	15.410	2.47	5.37

Naturally, the CO_2 maximum setpoint is set at a 1000 ppm for ensuring a healthy indoor air [13], while the lower one is set at 0 even though a null concentration is not achievable realistically.

[9] In the case of the kitchen, the setpoints only apply to the time of cooking, e.g. 30 minutes/day. The rest of the time they should have a value of zero as the hood is closed.

3.5 Measures

3.5.1 Solar PV panels

Renewable energy adoption has become a top concern for homes and society as people become more conscious of the need of sustainability and lowering greenhouse gas emissions. In this regard, the initiative to install solar panels in this home is a major step towards the generation of energy needed for a more sustainable and independent future. An On-Grid PV system uses solar panels, inverters, and an electric meter to produce electricity using solar energy, as seen in Figure 22.

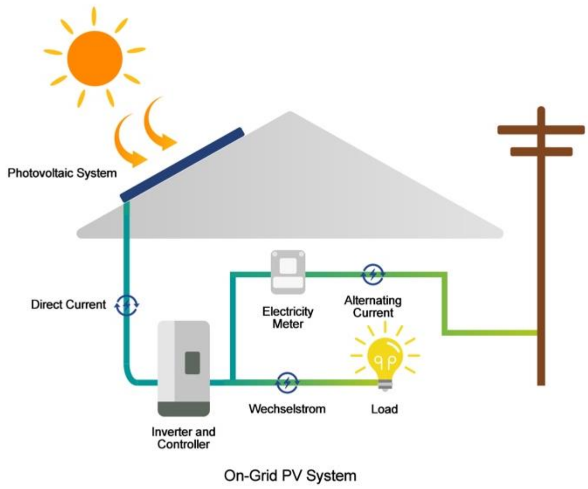


FIGURE 22. SCHEME OF A COMMON HOUSEHOLD ON-GRID PV SYSTEM. SOURCE: MAYSUNSOLAR.COM.

The chalet to be studied in Gävle, Sweden, has a latitude of 60.676° and a longitude of 17.151°. The roof of this dwelling has one side facing East at an angle of -42º and inclined at 12º from the horizontal line, which will determine the tilt angle for the PV modules. In addition to the solar panels, the installation of a PV solar system connected to the grid requires the selection of an inverter to convert direct current to alternating current for household appliance usage. Moreover, as a grid-connected system, the implementation of a monitoring system is essential to ensure efficient operation and performance monitoring.

The annual electricity consumption for this study is obtained from the average of the last four electricity bills and rounded up to 3 120 kWh, with an unknown specific daily or monthly distribution. To simplify the analysis, it is assumed that the electricity demand is evenly distributed throughout the year, resulting in a monthly consumption of 260 kWh.

The needs of the home were studied and analyzed, as well as the components that will be used. Finally, an approximate budget was calculated, and an analysis was conducted regarding the profitability of the investment.

3.5.2 Thermal collectors

Another option to take advantage of the solar resource is the implementation of thermal collectors. This technology consists of capturing radiation from the sun to convert it into thermal energy to increase the temperature of a fluid; Figure 23 illustrates this common household setup. For residential installations, non-concentrated thermal collectors are used. This means that the area that intercepts the solar radiation is the same as the area absorbing solar energy. Flat-plate collectors are the most typical type of non-concentrated collectors [41] and therefore they will be selected for the installation of this system in the studied dwelling. This type of collectors works by absorbing sunlight through a flat surface, which heats up water that is circulating through copper pipes inside of the plate. The main advantages are that they do not require complex tracking systems, making them more affordable and easier to install and maintain. Additionally, they are durable and have a long lifespan, providing a reliable performance over many years [41].

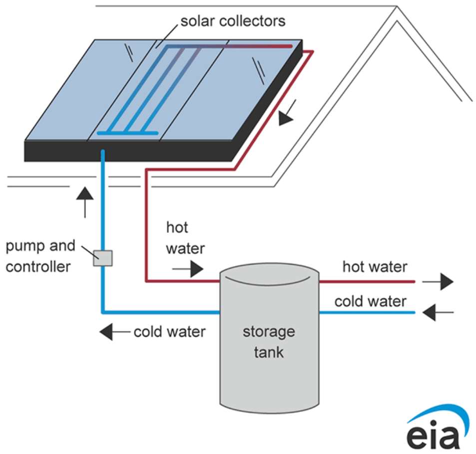


FIGURE 23. SCHEME OF A COMMON HOUSEHOLD THERMAL COLLECTOR INSTALLATION. SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION [41].

The panels would be located the roof of the dwelling, with a tilt angle of 12º and oriented to the East (-42º), as well as the PV panels. The recommended area of the collector per person is considered to be approximately from 1 m^2 to 1.5 m^2 to cover the domestic hot water consumption [42]. Considering this estimation, an area of the collector of 3 m^2 is required. By analyzing different alternatives, the selected model in the market is 1.5AR from AES Solar, with an overall area of 1.5 m^2 and an aperture area[10] of 1.38 m^2. Therefore, two collectors will be needed to comply with the requirements. For more technical details, see Appendix K: Thermal collects specifications sheet.

[10] The aperture area of a solar collector is the surface exposed to the sun that absorbs solar radiation to convert it into usable thermal energy. This area is where solar radiation hits the collector directly and is converted into heat.

For the correct sizing of the storage tank, it must be considered the average amount of hot water consumed per person each day. This value is pondered around 50 L per person, meaning that the optimal size of the storage tank is 100 L [43].

3.5.3 Heat exchanger unit in the exhaust ventilation system

To reduce the ventilation energy loss there exists two main alternatives for designing air heat recovery systems, those being return air recovery and heat recovery by heat exchangers [44]:

a) Return air recovery systems usually make use of ducts with dampers to redirect and mix airflows from inside return air and outside new supply air, i.e. the final supply air consists partly of returned exhaust air. Since the cost of these elements is reduced, it is a generally economical method for achieving heat recovery. However, even with filters, there exists concerns about air quality as the indoor return air into supply may transmit back pollutants and particles, and it rarely found in European countries.
b) Heat recovery by heat exchangers on the other hand are more costly due to the units needed but prove to be still feasible from a life cycle cost perspective, and it is the main system employed in Europe.

The one to be designed for the dwelling is a Mechanical Ventilation with Heat Recovery (MVHR), since it is a type of system that is gaining an increasing interest in buildings that are reaching for the NZEBs standards. This technology consists of providing fresh filtered air into a building and using the energy that has already been used in heating the property. Initially, polluted air is extracted from wet rooms as the bathroom or the kitchen. This air is then directed through a central heat exchanger which retains and recovers the heat that will be interchanged with the supply air that the unit is resupplying back into the living spaces [45].

4 Results

4.1 Energy Balance of the House

4.1.1 Energy in

The house receives mainly energy from the purchased district heating and from the solar radiation through the windows. However, the dwellers also contribute to this sum with the heat from their metabolism, as well as the various appliances around the residence with their electrical power. The sum of these energy sources, which are looked at closer in this subsection, indicates that the house received an estimated 29.85 MWh/year in 2023, a figure that must be matched latter on by the losses to guarantee energy balance. Full numeric reasoning is further developed under the subsections of Appendix A.

The historical purchases of district heating for space heating of the rooms are summarized in Table 3. Only the yearly figure is known, but it is accepted that there will be significant variations of this primary energy use across different seasons.

Table 3. Summary of the district heating bills for the house.

Year	*Energy (kWh/year)*
2020	17 226
2021	20 134
2022	18 769
2023	19 405

The average value was taken at 18 883.5 kWh/year, representing 63.3% of the total energy intake. The monetary value of these bills is unknown, so the cost of this purchase was estimated from the research in [46], where it is claimed that on average, in the years 2012-2017, a 20 MWh bill in a Swedish single family house implies a cost of 18 000 SEK, of which 3 600 SEK is a fixed fee similar to those in electricity bills (e.g. for contracted power). [46] also points out that privately owned networks have 3% more expensive bills than those connected to municipal networks. Particularly, Gävle has one of the most developed district heating networks run by Gävle Energi. Another student thesis by Asier Querejeta in 2023 [47] studied a detached house with a bill of 21.34 MWh/year of district heating with a known cost of 16 397 SEK, in the same municipality. Using this second source as reference due to its more updated state and closer proximity to this case, proportionally, a 18 883.5 kWh/year bill would imply a cost of 14 514 SEK, i.e. 768.36 SEK/MWh.

The solar gains through windows are summarized[11] in Table 4, categorized in orientations. The west orientation receives no solar gains as it is the façade attached to the adjacent house.

TABLE 4. SUMMARY OF THE ENERGY GAINS FROM SOLAR RADIATION THROUGH WINDOWS IN DIFFERENT DIRECTIONS.

	Direction	*Esolar (Wh/year)*	*Etot (MWh/year)*
2-pane special windows U = 1.25 W/(m2·K) r = 0.6	-132 (N)	571362	8.95
	-42 (E)	3334812	
	48 (S)	5039913	
	138 (W)	0	

The window parameters were given by datasheets of the building company. In the calculations, no major shading objects were identified, as the house has no large balconies or overgrown trees in the garden. The irradiation tables for the calculations were provided by supervisor prof. Forsberg and they correspond to a latitude of 60°(N), close to that of Gävle. Nevertheless, it is important to highlight that these sources are not precisely the solar hours of the municipality but were deemed to have enough resemblance. The result of 8.95 MWh/year indicates that the solar gains account for 30% of the energy intake, which is a rather significant share a Swedish house, and that is not counting the months with most solar radiation (mid-May to mid-September).

The internal gains from people living in the house, with a normal metabolic activity, provide 0.55 MWh/year[12], a smaller share than the previous two but that still contributes to an indoor temperature raise. Similarly, appliances provide an additional 1.46 MWh/year to the dwelling assuming 70% of the electricity use gets converted to heat[8]. Figure 24 illustrates the breakdown of all energy in sources.

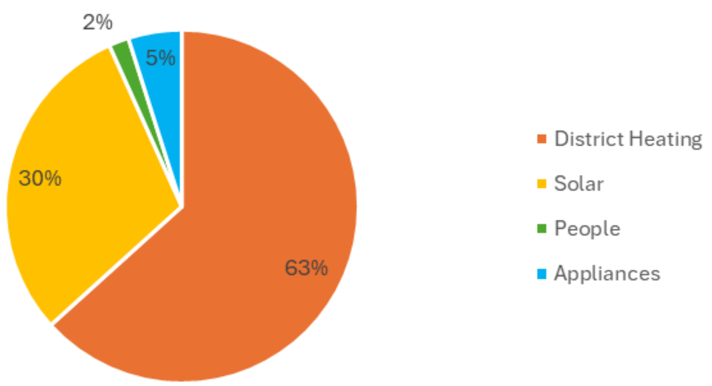


FIGURE 24. BREAKDOWN OF THE CONTRIBUTION OF DIFFERENT ENERGY INTAKES TO THE HOUSE.

[11] See Appendix A "Solar calculation" for a full chart collection (irradiance values, window areas, net energies, etc.)
[12] See Appendix A "Internal gains" for a full numeric reasoning behind the final yearly value.

4.1.2 Energy out

The energy losses of the house occur via transmission through the building envelope, hot water through the drain, heat lost in the air changes and other uncontrolled losses like natural ventilation and air leaks.

A summary of the heat powers and energy losses by transmission through elements like walls is shown in Table 5. The maximum power loss results in 5 514 W through different elements. Converting this power magnitude to energy is not trivial and it introduces some error via the assumption of the appropriate duration hours, thus, the historical degree-hour approach is employed following the procedure explained in the theory section 2.3.1. The result of energy losses in the order of 12.65 MWh/year are in accordance with the expectations for a house with this envelope area and insulation characteristics. Altogether, transmission losses are the source of 42% of the total energy losses of the house[13]. However, it must be remarked once more that transmission through localized thermal bridges is not included in this figure.

TABLE 5. SUMMARY OF THE TRANSMISSION LOSSES THROUGH DIFFERENT SURFACES.

	Power (W)	**Energy (kWh)**
External walls	2243.300	5148.111
Windows	1980.300	4544.556
Roof	484.380	1111.595
Wood floor	514.209	1180.050
Tiles floor	152.158	349.184
Door	140.070	321.444
Total	**5514.417**	**12654.940**

The mechanical exhaust ventilation system can report different heat losses depending on the flow regulation. In Table 6, the figures for the two extremes at lowest and highest regulations are shown.

TABLE 6. SUMMARY OF THE AIR FLOWS AND ASSOCIATED HEAT ENERGIES OF DIFFERENT VENTILATION MODES.

Regulation	*Total exhaust flow (m^3/s)*	*Total Power (kW)*	*Total Energy (kWh/year)*
Low	0.059	3.349	3157.204
High	0.128	7.132	6793.357

[13] For the full element-by-element heat transmissions discussion, refer to Appendix A “Transmission losses”, and its complementary Appendix B for the argumentation of the relevant coefficients to be used.

Thus, the ratio between highest and lowest is 2.169. By design of the system, this value should be 2.00, although the exhaust hood from the kitchen has its own control, which is probably the source of this discrepancy. For all the visits, the owners set their regulation to low. It could be argued that high regulation is also employed at specific times. However, estimating this time, even with the dwellers' best guesses, would introduce more uncertainty than just assuming permanent low regulation. Hence, for the final balance it is considered that the exhaust air losses are in the order of 3.16 MWh/year, accounting for 11% of the total energy losses[14]. This share is not as significant as initially anticipated and will spark a debate for the viability of a heat exchanger system in the upcoming discussion sections.

The water use from bills is shown in Table 7, as well as the energy needed to heat it up from 5 °C to 55 °C, regular setpoints suggested by SVEBY. Additionally, it is considered that only one third of the water is heated up.

TABLE 7. SUMMARY OF THE WATER CONSUMPTION AND THE HEAT ENERGY ASSOCIATED TO IT.

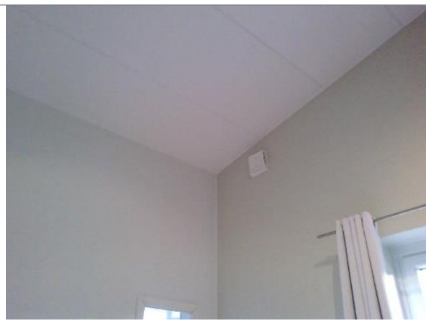
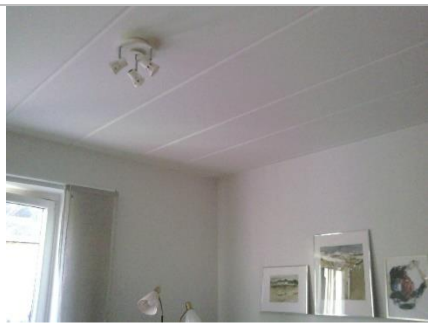
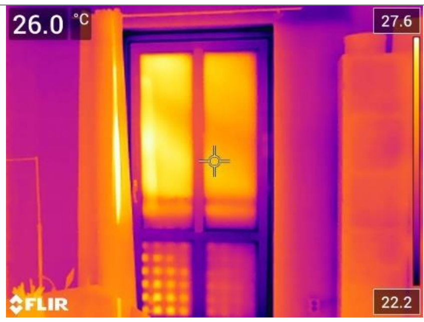
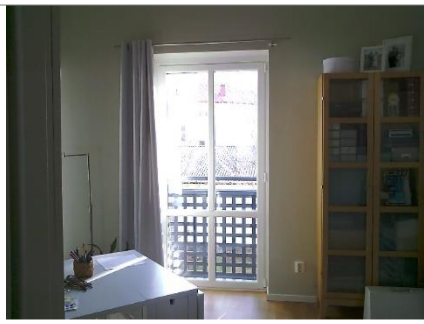
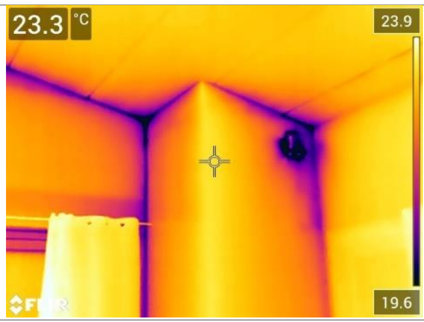
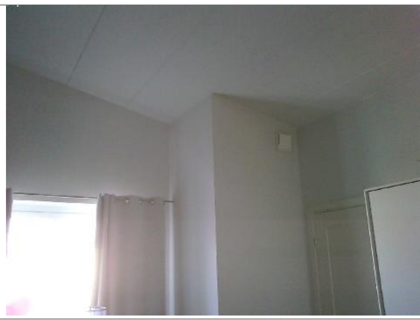
Year	*Total m³*	*Warm m³*	*Heat energy (kWh/year)*
2018	89.000	29.667	1722.315
2019	80.000	26.667	1548.148
2020	81.000	27.000	1567.500
2021	82.000	27.333	1586.852
2022	74.000	24.667	1432.037
2023	73.000	24.333	**1412.685**

There is a remarkable decrease in water consumption, and consequently, a decrease in the energy invested to heat up one third of that volume. This is due to behavioral changes of the dwellers (e.g. shorter showers). For practical uses, the latest value of 73 m^3 water/year was taken, 24.33 m^3 of which were heated with 1.41 MWh/year.

Adding these water, ventilation and envelope losses results in 17.22 MWh/year, not matching the energy intake of 29.85 MWh/year. The difference between the balance is explained with the remaining uncontrolled energy losses, magnitudes that were not measurable without advanced techniques. This includes thermal bridges, natural ventilation by opening the windows for air changes and localized air leak points. The combination of these accounted for 12.61 MWh/year, or in other words, 42% of the total energy losses. The dwellers reported that they opened the windows 30 minutes/day for ventilating, except in the winter season, when the windows would remain closed at all times. The IR camera did show the existence of thermal bridges, most notably in the joints of the ceiling of the second story and the roof.

[14] For the full development of the ventilation energy losses and the measured flows by exhaust vent, refer to Appendix A "Ventilation energy losses".

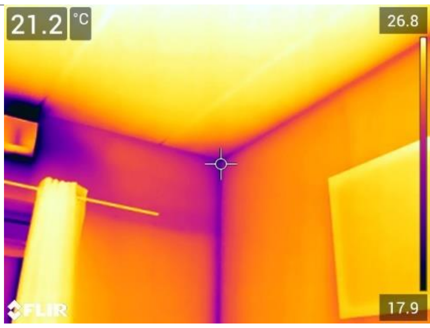
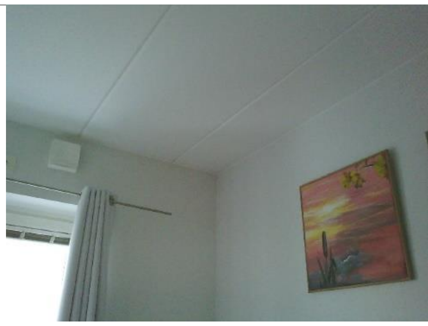
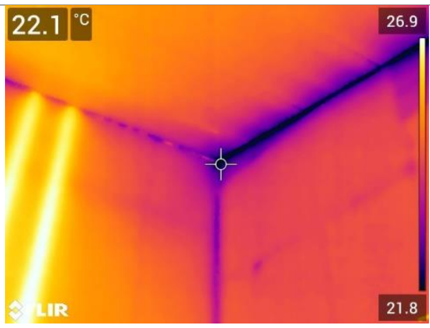
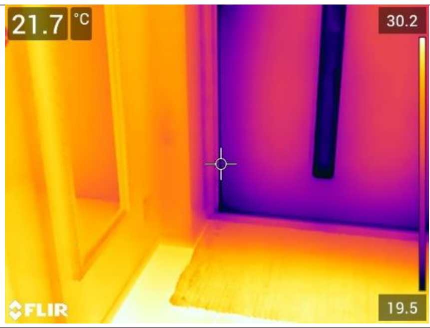
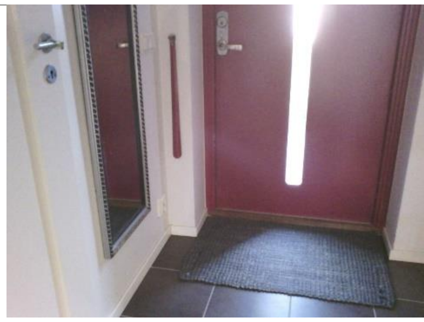
TABLE 8. VISUAL RESULTS OF THE MOST RELEVANT THERMAL BRIDGES DETECTED WITH THE IR CAMERA.

Description of the thermal bridge	IR camera view	Regular camera view
SET-A **Master bedroom in the second story. Joint of the wall with the roof**		
SET-B **Second story of the open dining area. Joint between the walls and the roof**		
SET-C **First floor living room corner. Connection between walls, right wall belongs to the attached façade**		
SET-D **Seams in the frame of the window locates in the second story office/studio**		
SET-E **Smaller thermal bridges and intake air pass between the master bedroom and closet walls**		

The identified bridges were overall not too severe. As seen in the pictures from Table 9, in most cases the thermal gradients are only of 5-6 °C. Additionally, in some parts where thermal bridges would be expected, good insulation was found, such as in the case of picture set-A left wall-roof joint and in the case of picture set-E roof joints. It is also noticeable the presence of the floor heating, as seen by the much warmer ceiling in set-C, which is also the floor of the second story. For the upcoming IDA-ICE simulations, the thermal bridges sliders will be set to "Typical" for the aforementioned reasons.

Similarly, the IR camera also allows for the identification of some air leaks. These look very similar to joints with thermal bridges but are characterized by shapes that have tail-like trails, sign of colder airflow through the surface.

TABLE 9. VISUAL RESULTS OF THE MOST RELEVANT THERMAL BRIDGES DETECTED WITH THE IR CAMERA.

Description of the air leak	IR camera view	Regular camera view
SET-F **Air intake with gates that are not fully shut in the first story bedroom**		
SET-G **Air trails in the ceiling of the office room in the second story**		
SET-H **Air leaks in the seams of the main front door in the first story**		

The air leaks seemed localized and could not be experimentally quantified. In light of these results, these observations lead to believe the evaluation of 12.61 MWh/year for this category is abnormally elevated and the deduction method for their estimation is uncertain. It shall be the subject of further discussion in section 5.1.

Figure 25 how each type of loss contributes to the 29.85 MWh/year leaking out of the house interior.

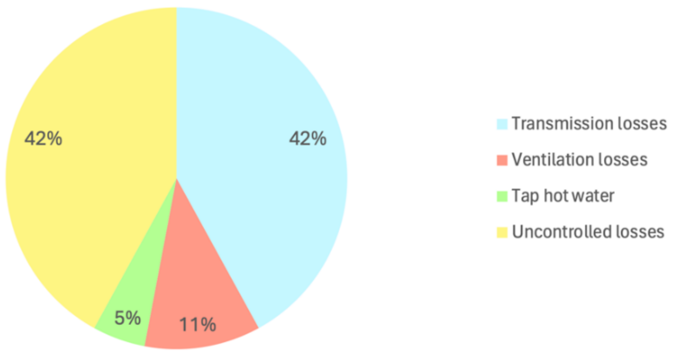


FIGURE 25. BREAKDOWN OF THE LOSSES OF DIFFERENT ENERGY FLOWS OUT THE HOUSE.

4.2 Simulations by IDA-ICE of the base model

The results returned by IDA-ICE shall be commented on and compared to those of the previous section for validity purposes. Specially, it is interesting to look at hard to measure and calculate magnitudes like the thermal losses by infiltration and by thermal bridges. Table 10 shows the energy balance for the house in the span of a year.

TABLE 10. OUTPUT ENERGY BALANCE RESULTS OF IDA-ICE FOR THE SIMULATED MODEL.

kWh (sensible only)

Month	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
1	-1830.0	-0.9	-685.7	0.0	-1319.4	124.6	218.7	105.6	3387.3	-0.0	0.0
2	-1559.8	-1.2	-409.5	0.0	-1091.8	113.1	197.1	95.4	2657.7	-0.0	0.0
3	-1667.1	-5.7	-102.7	0.0	-1165.2	126.0	215.6	105.6	2494.2	-0.0	0.0
4	-1263.0	-10.2	418.0	0.0	-840.7	122.6	215.6	102.3	1261.1	-0.0	0.0
5	-1163.2	-27.0	901.8	0.0	-706.8	104.3	215.6	105.7	588.6	-0.0	0.0
6	-985.1	-7.5	989.8	0.0	-574.4	72.7	209.4	102.2	206.6	-0.0	0.0
7	-912.5	-8.0	1033.5	0.0	-508.3	52.9	221.8	105.7	27.8	-0.0	0.0
8	-714.6	29.2	561.5	0.0	-502.5	115.8	215.6	105.6	180.3	-0.0	0.0
9	-835.2	1.2	249.0	0.0	-606.4	123.7	212.5	102.2	756.5	-0.0	0.0
10	-1151.0	2.7	-165.0	0.0	-852.7	125.9	218.7	105.6	1717.6	-0.0	0.0
11	-1281.2	-0.6	-419.0	0.0	-931.0	121.3	209.4	102.1	2199.1	-0.0	0.0
12	-1812.9	6.0	-715.9	0.0	-1322.5	124.5	221.7	105.6	3394.9	-0.0	0.0
Total	-15175.7	-22.0	1655.9	0.0	-10421.6	1327.3	2571.6	1243.5	18871.6	-0.0	0.0
During heating (MIXED h)	-11676.6	530.6	-2268.3	0.0	-9126.7	933.6	1910.2	818.9	18872.2	0.0	0.0
During cooling (MIXED h)	-2562.5	-587.9	3143.0	0.0	-790.0	217.8	368.5	268.2	0.0	0.0	0.0
Rest of time	-936.6	35.3	781.2	0.0	-504.9	175.9	292.9	156.4	-0.6	-0.0	0.0

There is certainly discrepancy in many of the numbers, although these figures are in the same order of magnitudes, and as such, the output by IDA-ICE was not deemed disproportionate. Figure 26 illustrates the comparison with the calculations explained in the previous subsections:

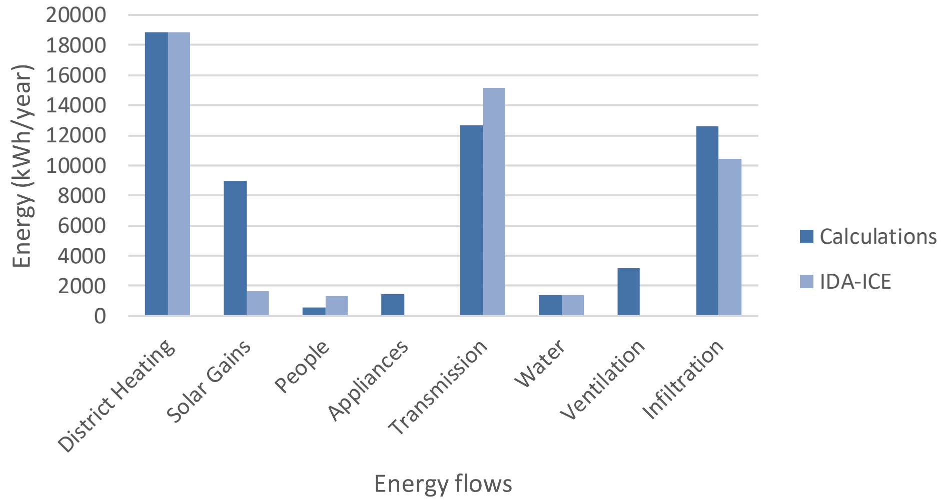


FIGURE 26. VISUAL COMPARISON OF THE NUMBER DISCREPANCIES BETWEEN EMPIRICAL METHODS AND SOFTWARE SIMULATION.

Further analysis reveals the source for some of the differences:

➢ Envelope & Thermal Bridges, as the name suggests, are not only the losses under the label "transmission losses" from section 4.1. Instead, it also includes the thermal bridges that were moved to "uncontrolled losses". The full breakdown of this figure is shown in Table 11. While the floor, windows and door figures match those of the hand calculations, the roof losses are very underestimated at 662.5 kWh/year. These mismatches were however expected for several reasons:

a) The roof/ceiling geometry is modeled as a separate zone garret, rather than blending in with the corresponding second floor rooms.
b) The model has some extra interior walls that could not be removed due to computing complexity limitations.
c) The method of estimating energy from power is different. For calculations is practical to use methods like DVUT, but IDA-ICE can integrate power for every time step more accurately. Moreover, indoor temperature is dynamic in IDA-ICE.

The most interesting result here is however the thermal bridges energy loss figure, reporting losses of 6 374.6 kWh/year. Admittedly, it is still rather arbitrary inputting the degree of the thermal bridges in IDA-ICE, only using a slider that categorizes the quality of the bridges ranging from "Very Good" to "Very Poor". Judging from the images taken with the IR camera visually, most thermal bridge layouts were set to "Typical" with occasional layouts set to "Good" where no significant gradients could be appreciated in the thermographies.

TABLE 11. OUTPUT TRANSMISSION LOSSES THROUGH DIFFERENT SURFACES RESULTS OF IDA-ICE FOR THE SIMULATED MODEL.

Month	Walls	Roof	Floor	Windows	Doors	Thermal bridges
1	-695.6	-91.3	-214.4	-796.0	-67.7	-761.1
2	-571.0	-75.6	-226.7	-676.4	-53.0	-633.5
3	-598.6	-74.6	-257.5	-738.4	-52.6	-683.9
4	-420.2	-49.1	-248.1	-590.3	-32.5	-513.2
5	-360.2	-38.1	-277.2	-585.9	-22.0	-465.8
6	-292.5	-30.1	-235.3	-549.8	-15.1	-412.1
7	-269.6	-26.7	-222.0	-519.1	-10.3	-383.9
8	-235.0	-25.6	-91.5	-434.9	-15.3	-347.3
9	-299.6	-36.7	-104.7	-427.6	-23.6	-370.7
10	-439.5	-58.9	-113.7	-547.4	-39.4	-499.5
11	-496.6	-67.7	-131.8	-579.1	-46.4	-538.8
12	-678.1	-88.3	-213.5	-795.4	-68.1	-764.9
Total	-5356.5	-662.5	-2336.4	-7240.3	-446.0	-6374.6
During heating	-3997.9	-613.6	-1643.6	-5078.0	-426.1	-4994.9
During cooling	-1012.2	-23.1	-627.9	-1704.3	-0.7	-898.5
Rest of time	-346.4	-25.8	-64.9	-458.0	-19.2	-481.2

- Window and Solar gains exhibit a noticeably lower value at 1 655.9 kWh/year. In principle, this is a more standard value for a Swedish residence than the calculated 8 950 kWh/year. However, there are negative values that should not be possible, and hence, the software must be combining the solar gains with the transmission losses. Since transmission through windows does not match calculations closely either, the results are not comparable. On top of that, summer period months are included in that figure, making the validity of this output rather doubtful.

- The magnitude of infiltration and openings was another figure of interest when conveying the simulation. It is reported at 10 421.6 kWh/year, which would exceed initial expectations from the handmade calculations. Nevertheless, the inputs for these are rather arbitrary too, as the exact Cd factors for air flow in openings (which determines the ratio of flow $Q_{real}/Q_{theoretical}$) were unknown and left as default (Cd = 0.65 [-]). The ACH value for wall air infiltration was halved from that of the default (ACH = 0.05 L/(s·m^2 ext. surf.)), as no major leaks were seen.

- Occupants, equipment and lighting energies are rather accurate as these are inputs from bills and SVEVY guidelines too.

- The final "local heating unit" magnitude, which represents the additional energy supplied by the floor heating via district heating, matches rather accurately the invoices at 18 871.6 kWh/year, despite reduced energy gains from solar.

Looking at the results of the base model, when implementing a sensitivity analysis it will be best to analyze the energy improvements in a relative-comparative manner with percentages, rather than with absolute values.

On the other hand, another valuable output given by IDA-ICE simulations are metrics regarding thermal comfort. Thermal comfort measures the degree of acceptance of a temperature range indoors for living. It is usually evaluated with Fanger's comfort indexes, most common one being Predicted Percentage of Dissatisfaction (PPD). As the name suggests, PPD illustrates the share in percentage of total occupant hours when the dwellers feel discomfort with the ambient temperature. In other words, the larger PPD percentage in a timeframe, the greater the discomfort. By definition, PPD starts off at 5% and can get as high as 100%. The following Figure 27 graphs illustrate the discomfort a person may have in the living room of the house, which was deemed the most representative zone as not only has the largest surface area and most openings to other zones, but it is also bound to be the most frequented zone.

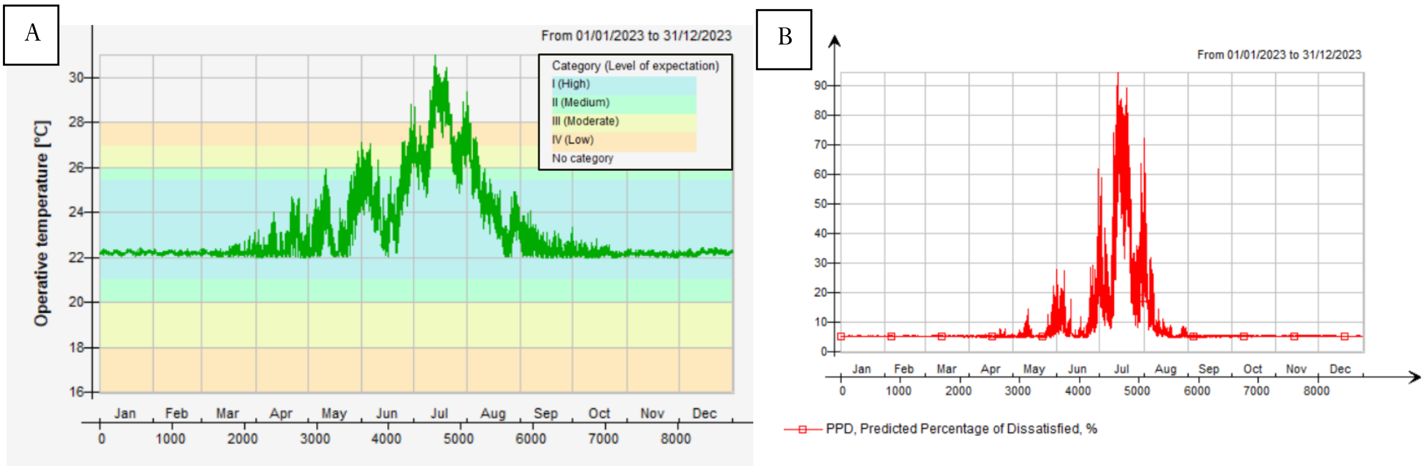


FIGURE 27. (A) TEMPERATURES DISTRIBUTION ACROSS THE SIMULATED YEAR 2023 IN THE LIVING ROOM AND THE PERCEIVED ACCEPTANCE. (B) PPD VALUES FOR THE LIVING ROOM OF THE HOUSE IN THE SIMULATED 2023 YEAR.

The results show that the minimum setpoint temperature of 22 °C can be kept at all times in the cold season with the floor heating system. However, since the house lacks any AC cooling system, temperatures may rise as high as to 30 °C in the summer period, which induces discomfort percentages of well over 70%. In terms of energy, summer is a non-concerning period as heat purchase is reduced, but these PPD results show that it might be interesting to implement a cooling system for comfort even if this is not an energy efficient measure (if anything, it increases overall energy consumption). However, an argument could be made too for natural ventilation to obtain cooling without an AC system, as owners suggested that windows were only opened for 30 minutes each day, except in the winter season.

4.3 Energy systems and Energy efficiency measures

4.3.1 Installation of PV panels

To implement a solar PV system cost-effectively at the residence selected, the configuration of the panels and the model of the inverter and the monitoring system were analyzed so the efficiency and savings of the installation are maximized.

Solar cells

Regarding the selection of PV panels, the software WINSUN was employed. This program requires data regarding the building, including its location, the tilt angle of the photovoltaic module's placement, ground reflection, horizontal shading, and orientation. Additionally, factors such as the power rating of the photovoltaic cells and the available installation area are required.

Firstly, the latitude and longitude were determined. For the selected chalet (located on Gävle, Sweden), the latitude is 60.676°(N) and the longitude is 17.151°(E). Additionally, it is noted that the roof has one face oriented to the East (-42º) that is inclined at a 12º angle with respect to the horizontal line. This inclination will correspond to the tilt angle of the PV modules. While the available effective area of this roof face exceeds 117 m^2, it's important to ensure that the solar panels fit within the designated space.

For the generation target, the annual electricity use is established at 3 120 kWh. An additional 1 100 kWh will be added to this demand to account for the electricity use of the implemented MVHR system, which will be explained in subsequent sections. However, the specific daily or monthly distribution of this usage is unknown. Therefore, for the purposes of this analysis, it is assumed that the electricity demand is evenly spread throughout the year, resulting in a monthly demand of 360 kWh.

For the simulation, a horizontal shading of 10º and a ground reflection factor of 0.3 are chosen, along with a 95% electrical system efficiency (accounting for 5% losses from production to final use), which are close to default values.

TABLE 12. SUMMARY OF THE MOST IMPORTANT WINSUN INPUTS FOR OUTPUT RESULTS.

Winsun user inputs

Variable	Value	Unit
Tilt	12	[°]
Direction	-42	[°]
Ground reflection	0.3	[-]
Horizontal shading	10	[°]

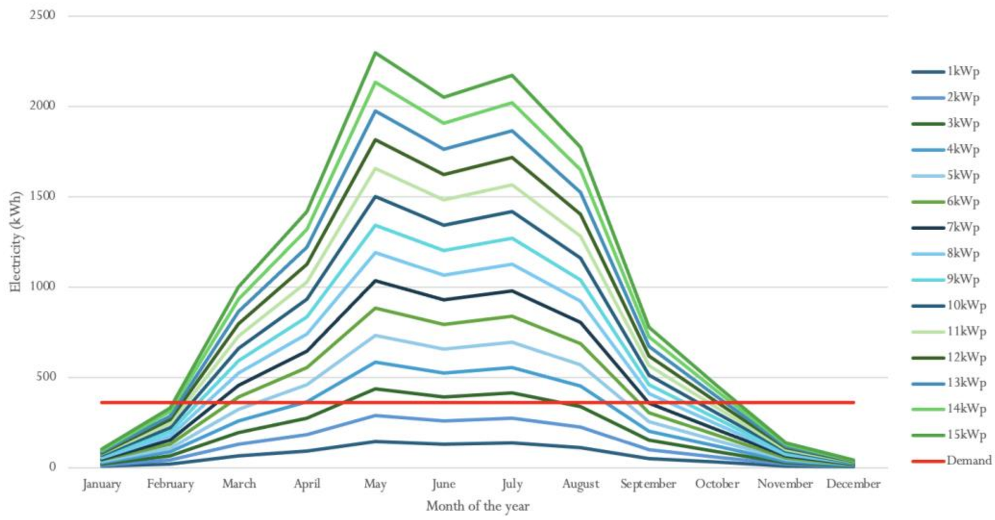


FIGURE 28. ENERGY PRODUCTION CURVES FOR SYSTEMS WITH DIFFERENT RATED POWER.

As a design criterion and following the principle of avoiding overproduction of electricity, a PV system capable of meeting the demand from March to September is selected, leaving some margin for covering some spring and autumn demand partially. Judging by the PV energy production curves constructed from Winsun outputs in Figure 28, attempting to meet the winter months' demand result in high excess for the summer period, thus, a 5 kW_p system is the reached compromise. After searching the market for alternatives, Model **TSM-DEG18MC.20** is suitable for the design, a monocrystalline silicon panel with a power output of 500 W. These panels, square in shape, cover an area of 2.4 m^2. Their temperature coefficient[15] is -0.25% and its efficiency stands at 20.7%, which refers specifically to the conversion efficiency from radiation to electricity. For additional details, see Appendix H: Solar panel specifications sheet.

- 0.5 kW_p
- 2.4 m^2/module

$$\text{Number of modules} = \frac{5\ kW_p}{0.5\ kW_p} \approx 10 \text{ modules}$$

$$\text{Area occupied} = 10 \text{ modules} \cdot \frac{2.4\ \text{m}^2}{\text{module}} = 24\ \text{m}^2$$

According to WINSUN, the system will produce **4 042 kWh/year**, helping to decrease the quantity of electricity acquired from the grid.

[15] The temperature coefficient of a solar panel is a measure of how the efficiency of the panel changes in response to changes in ambient temperature. It is typically expressed as a percentage change in efficiency for each degree Celsius change in temperature. A negative temperature coefficient indicates that the efficiency of the plate decreases as the temperature increases.

Inverter

Since it is necessary to change direct current into alternating current so that it can be used by home appliances or added to the electrical grid, inverters are essential to the installation process. Insulated-gate bipolar transistors (IGBTs) are used as switches in inverters to convert direct current into alternating current, which produces symmetrical square waves. Using the pulse width modulation (PWM) concept, these square waves are transformed into sine waves (see Figure 29). To replicate the properties of an ideal sine wave, this procedure involves varying the average value by modifying the duty cycle of the square waves [48].

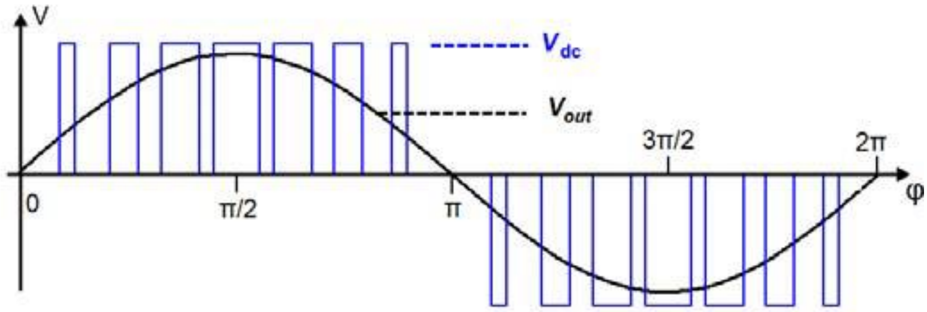


FIGURE 29. PWM MODULATION TO CONVERT DC TO AC. SOURCE: SATYAMSETTI ET AL. [49].

As it has been explained before, the house where the project will be implemented will require a power of the inverters of 5 kW. Thus, model **5K-2P-N** from Sol-Ark will be chosen, since it provides an output for intelligent load management. For further information, refer to Appendix I: Inverter specifications sheet.

Additionally, the device selected includes one Maximum Power Point Tracker (MPPT) input. The Maximum Power Point (MPP) is the operating point on the characteristic curve[16] where the solar panel delivers the maximum power to the load. In Figure 30, it corresponds to the point marked in red. Knowing the meaning of MPP, the MPPT input of an inverter aims to ensure that the operating point of the panels is always at the MPP [50].

[16] The characteristic curve of PV panels is a graphical representation of the relationship between current and voltage produced by a solar panel under different operating conditions. The two components are the Short Circuit Current (I_{sc}) and the Open circuit voltage (V_{oc}).

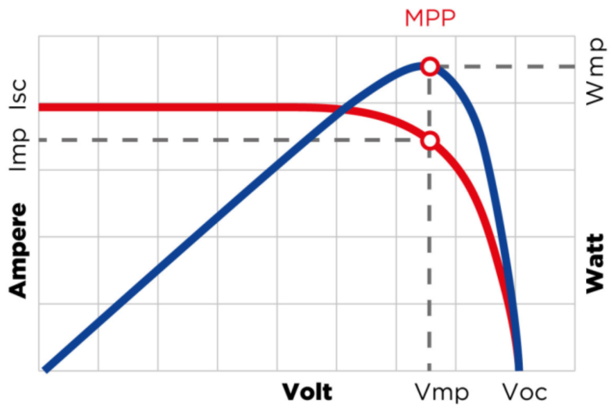


FIGURE 30. I-V AND P-V CHARACTERISTICS CURVES OF A REGULAR PV PANEL. SOURCE: NASTEC [50].

Monitoring System

A PV meter is utilized for measuring the electricity output of the solar installation. It offers the most precise measurement of the usable electricity a PV system generates, capturing even minor losses in production as energy flows between system components [51]. For this solar installation, the device **METSEPM530 by Schneider Electric** was selected. It measures energy, active and reactive power, voltage, current, frequency, power factor and up to 15th harmonic. For more technical information, see Appendix J: Monitoring system specification sheet.

Economic evaluation

According to the National Survey Report of PV Power applications in Sweden, the mean price for the installation for the last 10 years is around 17 500 SEK/kW$_p$ [52] (estimated from the reference in Figure 31), resulting in 87 500 SEK for the current project. Nevertheless, considering the Grön Tekink [53], a tax reduction provided by the Swedish Government of a 20% on material and installation costs for solar panels, the final cost of the installation will be **70 000 SEK**.

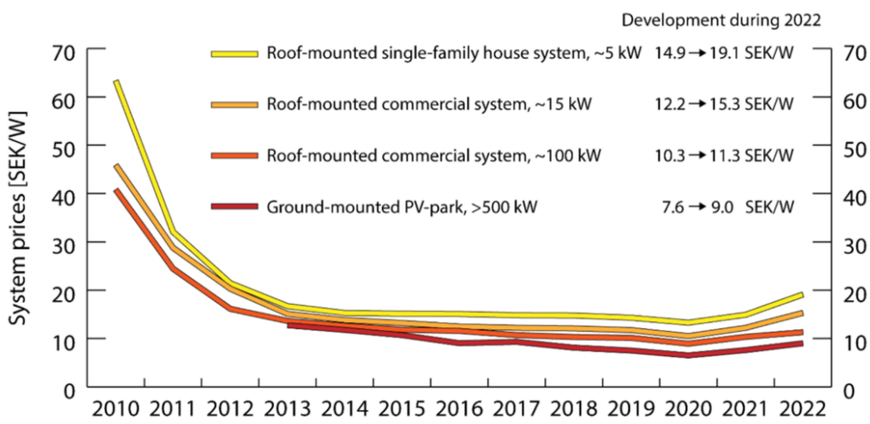


FIGURE 31. EVOLUTION OF PRICES FOR DOMESTIC PV INSTALLATIONS IN SWEDEN. SOURCE: NATIONAL SURVEY REPORT OF PV POWER APPLICATIONS IN SWEDEN [52].

As it can be observed in Figure 32, the excess above the demand curve corresponds to the amount of solar energy exported to the grid that represents a 41% of the total energy produced.

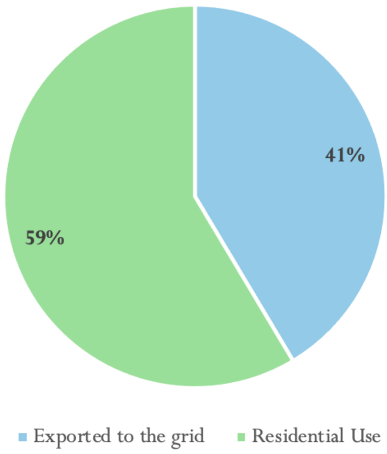


FIGURE 32. SHARES OF THE ENERGY END USE GENERATED BY PV.

According to Nord Pool [54], the average price for selling electricity in 2023 was around 1 SEK/kWh including taxes, although this value changes according to the year. Moreover, the electricity purchased from the grid was 2.46 SEK/kWh. In this way, the amount of money saved per year is calculated as follows:

$$\text{Savings} = 4\,042\ \frac{\text{kWh}}{\text{year}} \cdot \left(\frac{59}{100} \cdot 2.46\ \frac{\text{SEK}}{\text{kWh}} + \frac{41}{100} \cdot 1\ \frac{\text{SEK}}{\text{kWh}}\right) = 7\,523\ \frac{\text{SEK}}{\text{year}}$$

According to the savings and considering that the overall cost for the installation is 70 000 SEK, the payback will be calculated as follows:

$$\text{Payback} = \frac{70\,000\ \text{SEK}}{7\,523\ \frac{\text{SEK}}{\text{year}}} = 9.30\ \text{years}$$

To gain a more holistic understanding of the investment's financial viability, the Net Present Value equation with a 5% discount rate [55] has been used to provide a more comprehensive and financially rigorous evaluation for this long-term investment. This way, the installation would turn profitable by the 13th year.

$$\text{NPV for 12 years} \rightarrow \frac{(1+0.05)^{12} - 1}{0.05 \cdot (1+0.05)^{12}} \cdot 7\,523\ \frac{\text{SEK}}{\text{year}} - 70\,000\ \text{SEK} = -3\,321.76 < 0$$

$$\text{NPV for 13 years} \rightarrow \frac{(1+0.05)^{13} - 1}{0.05 \cdot (1+0.05)^{13}} \cdot 7\,523\ \frac{\text{SEK}}{\text{year}} - 70\,000\ \text{SEK} = 667.85 > 0$$

4.3.2 Installation of thermal panels

For the current project, the possibility of installing thermal panels to further take advantage of the solar energy is considered and fulfill the needs for hot tap water. It was proposed to use a system comprising 2 collectors with a combined area of 3 m^2 which will be coupled with a 100 L storage tank. For the collectors, flat-plate collectors of the model 1.5AR from AES Solar were chosen.

For simulating and obtaining the output of the solar thermal system, the online calculation tool T*SOL was used [56]. The configured parameters for the simulation are the following ones:

- Location: Gävle, Sweden (60.66° (N), 17.16° (E))
- Annual hot water consumption: 1 480 kWh/year
- Area of the collector: 3 m^2
- Inclination: 12°
- Orientation: -42° (E)
- Size of the storage tank: 100 L
- Annual global irradiation: 960 kWh/m^2
- Average outer temperature: 6 °C

By running this simulation, an output of 915 kWh per year can be obtained from the flat-plate collectors. This value represents nearly 65% of the total annual hot water consumption. The remaining 35% is met by the existing district heating system. The distribution of energy generation is depicted in Figure 33, based on an average energy demand.

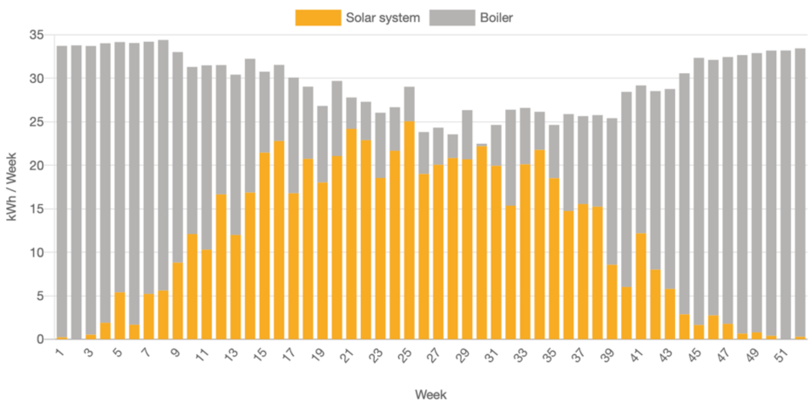


FIGURE 33 ANNUAL HEAT GENERATION OF THE THERMAL COLLECTOR SYSTEM. SOURCE: T*SOL [56].

The average price per MWh of district heating was 768.36 SEK [47]. After taking this data into account, the savings obtained from installing solar collectors is:

$$\text{Savings} = 768.36\,\frac{\text{SEK}}{\text{MWh}} \cdot 0.915\,\frac{\text{MWh}}{\text{year}} = 703.96\,\frac{\text{SEK}}{\text{year}}$$

By analyzing the market, the average price of the total thermal installation of a 3 m^2 flat-plate collectors is approximately 20 000 SEK [57]. Because of this, the payback will result in:

$$\text{Payback} = \frac{20\,000 \text{ SEK}}{703.96 \ \frac{\text{SEK}}{\text{year}}} = 28.41 \text{ years}$$

On the other side, if we use the Net Present Value equation with a 5% discount rate [58], the installation appears to never be profitable as it results in an asymptotical function. Evaluating for an already not reasonable 50-year period.

$$\text{NPV for 50 years} \rightarrow \frac{(1+0.05)^{50} - 1}{0.05 \cdot (1+0.05)^{50}} \cdot 703.96 \ \frac{\text{SEK}}{\text{year}} - 20\,000 \text{ SEK} = -7\,148.58 < 0$$

4.3.3 Heat exchanger unit in the exhaust ventilation system

To design a heat exchanger unit, the model proposed by P. Blecich et.al [25] is considered in the study, which was originally designed for Croatian house models with similar insulation and air leakage parameters, although with smaller heating needs. The schematics of the systems are illustrated in Figure 34.

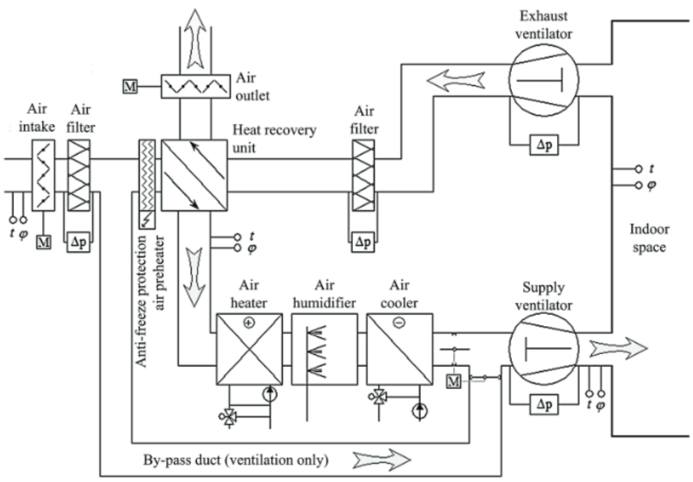


FIGURE 34. PROPOSED HEAT EXCHANGER NETWORK WITH MECHANICAL EXHAUST VENTILATION. SOURCE: [25].

The MVHR makes use of the already existing mechanical exhaust ventilation system and connects the air intake with a bypass duct for additional ventilation that redirects fresh air and with the heat recovery unit itself. The air heating, air humidifying and air cooling units downstream the heat exchanger proposed by [25] are not strictly necessary for the case study in Gävle, but there are arguments in favor of each.

- The air cooler could be removed altogether as the cooling demand is not a major concern in the energy investigation conducted. Nevertheless, as seen in section 4.2, there arise some discomfort in the summer period and the house could benefit from such unit. As stated, calculations for cooling are out of the scope of the investigation but it is a plausible solution that is more easily integrated than separated AC units, should the owners decide the proposal is suitable to their needs.

- The air humidifier is recommended and would probably be installed in a final design as the winter climate in Gävle is rather dry. In addition, the indoor climate loggers revealed that there is stratification of relative humidity between different zones of the dwelling and this unit would help achieve a more uniform environment.

- The air heating unit is in principle not needed as the radiant floor provides the distribution of heat the house requires. Nevertheless, [25] suggests that the MHVR system may be coupled to other energy sources such as ground heat exchangers, ground to-water heat pumps, solar PV and solar thermal, the latter two of which have been discussed. As such, a combination of floor heating and air heating could be considered.

The system also includes an air outlet for excessive air volume and filters in the intake and exhaust streams to ensure air supply with acceptable levels of pollutants. The heat recovery unit is a flat plate air-to-air heat exchanger with thermal efficiency (more commonly referred as heat recovery efficiency, η_Q) of 0.80. Due to the limitations of not having a blueprint for the piping of air ducts, the heat exchanger is not dimensioned. Heat recovery efficiency is described as:

$$\eta_Q = 1 - \frac{\text{Annual need of heat with recovery}}{\text{Annual need of heat without heat recovery}} \qquad \textit{Equation 22}$$

The ventilation losses if the house did not implement any actions would equate to 3 157 kWh/year as indicated in section 4.1.2. However, the MHVR must be designed taking in mind the interrelation with other measures. As proposed in the upcoming section 4.3.4, a behavioral measure like reducing indoor temperature would decrease the ventilation energy losses, specifically to 2 772 kWh/year when recalculating for 22 °C indoor instead of 24 °C. If this last figure is taken as the annual need of heat without the MHVR from the losses of low regulation exhaust ventilation, the new heating need would equate to 554.4 kWh/year. Financially the savings achieved with the district heating price orientation of [47]:

$$\text{Savings} = (2\,771.8 - 554.4)\frac{\text{kWh}}{\text{year}} \cdot \frac{1\text{ MWh}}{1000\text{ kWh}} \cdot \left(768.3\,\frac{\text{SEK}}{\text{MWh}}\right) = 1\,703.7\frac{\text{SEK}}{\text{year}}$$

Another work of Blecich et al. [59] suggests that the cost of the MVHR system per unit of floor area is estimated at 50 €/m^2, whereas costs between 40 and 80 €/m^2 have been reported. Hence, for sum the area of the rooms that already have the exhaust ducts (46.23 m^2, adding all room areas from Table 2) the estimated investment cost with the lower cost of 40 €/m^2 (since some of the components are already in place) would be of 21 598.66 SEK[17]. The associated Payback Period:

$$\text{Payback Period} = \frac{21\,598.66\ \text{SEK}}{1\,703.7\ \frac{\text{SEK}}{\text{year}}} = 12.68\ \text{years}$$

Using the same 5% discount rate for consistency, the definition of NPV indicates that the system would be profitable by the 21st year.

$$\text{NPV for 20 years} \rightarrow \frac{(1+0.05)^{20} - 1}{0.05 \cdot (1+0.05)^{20}} \cdot 1703.7\ \frac{\text{SEK}}{\text{year}} - 21\,598.7\ \text{SEK} = -366.8 < 0$$

$$\text{NPV for 21 years} \rightarrow \frac{(1+0.05)^{21} - 1}{0.05 \cdot (1+0.05)^{21}} \cdot 1\,703.7\ \frac{\text{SEK}}{\text{year}} - 21\,598.7\ \text{SEK} = 244.7 > 0$$

Regarding the comfort from this measure, the temperature at which air is supplied can be calculated with the relationship between heat recovery efficiency η_Q and temperature efficiency η_T, which is usually slightly lower. The relationship between these varies with location. Figure 35 shows the conversion for Stockholm and its surroundings.

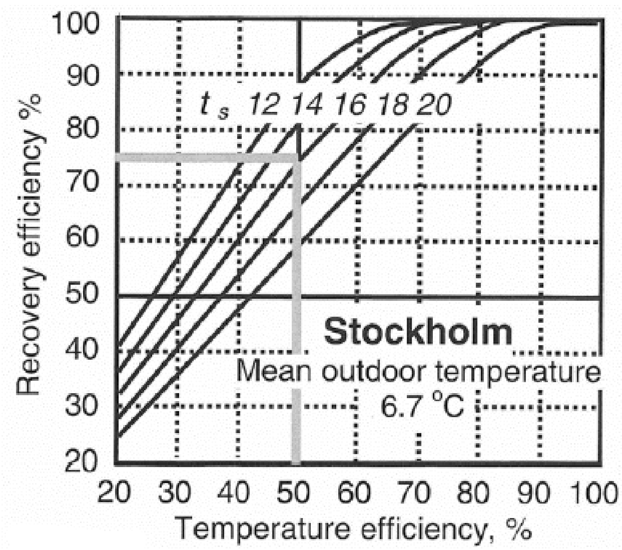


FIGURE 35. RELATIONSHIP BETWEEN HEAT RECOVERY EFFICIENCY AND TEMPERATURE EFFICIENCY FOR STOCKHOLM. SOURCE: [44].

[17] Currency Exchange from Euro to Swedish Crowns at 1€ = 11.68 SEK as of 07/05/2024 by Google Finance Analytics.

For a temperature efficiency of 0.7, which is a normal value for a direct recuperative heat exchange system, the supply temperature would then be around 20 °C which would then be heated up to indoor temperature. At the same time, by definition, the temperature efficiency is expressed as:

$$\eta_T = \frac{t_{rec} - t_0}{t_e - t_0}$$ *Equation 23*

Where, t_{rec}, t_o and t_e are the supply, outside and exhaust temperatures, respectively. For an exhaust at 24 °C and same outdoor mean temperature and temperature efficiency, a supply 18.8 °C is obtained with the empirical formula.

4.3.4 Complementary behavioral measures

Behavioral measures are designed to assess and improve the energy consumption habits of the individuals inside a building since the implementation of efficient practices can lead to significant long-term energy savings. Besides, no additional technological devices are required so its investment is almost zero.

For this project, it has been considered to reduce the indoor temperature from 24 °C to 22 °C since it has been reported by several authors that for every degree reduced there is potential for up to a 5% in energy savings regarding heat consumption, being one of the most economical behavioral measures [60]. Apart from reducing energy consumption, according to the Swedish Work Environment Authority, 22ºC is approximately the most comfortable temperature inside a dwelling [61]. Additionally, during the visits to the dwelling, we personally felt that the temperature was too high inside the house, which influenced the decision to implement this behavioral measure.

To analyze how many degrees should the indoor temperature be reduced, the current average indoor temperature must be obtained. Therefore, ROTRONIC brand indoor climate loggers were placed in the living room, in the master bedroom and in the study, the latter two being located on the second floor. They conducted measurements every ten minutes from 23rd of April until 29th of April, obtaining the indoor temperature, CO_2 concentration and relative humidity.

Figure 36's graph represents the measured indoor temperature [ºC] of the three rooms every five minutes next to each other for comparison:

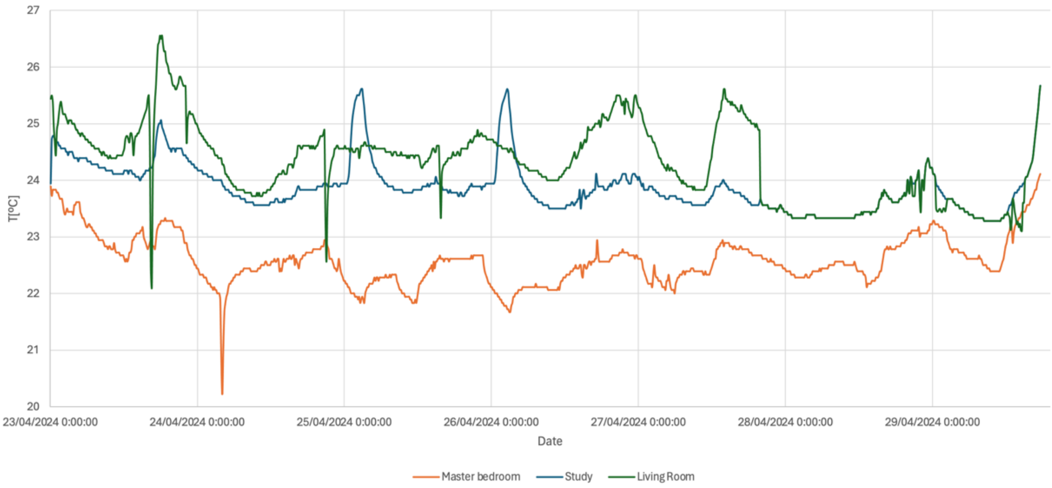


FIGURE 36. MEASURED INDOOR TEMPERATURE OF THREE ROOMS FROM 23RD OF APRIL UNTIL 29TH OF APRIL.

From the evolution of the indoor temperature over a few days, the average temperature in the living room obtained is 24.58 °C, while in the study and master bedroom, it's 23.89 °C and 22.58 °C respectively. These results yield an overall house average temperature of 23.68 °C inside. However, this data was collected in April, and during winter the indoor temperature is expected to rise slightly as dwellers look for a warmer comfort in contrast to colder outdoor temperatures. Additionally, considering the stratification since the lower floor always tends to be warmer than the upper floor, there will be errors in every average calculated. Therefore, an indoor temperature of 24 °C is assumed for simplification, so a 10% of energy savings can be obtained by implementing this measure.

For the heating energy required, it has been applied the normal year correction by means of the degree days, since it is more representative of an average year in Gävle. The energy index calculated in the subsection of Appendix A "Normal year correction" was 0.947, meaning that 2023 was a year with a higher heating demand than in a normal year. As a consequence, the heating demand for a normal year is 18.03 MWh/year[18]. Therefore, the saving per year taking accounting that each MWh of district heating was 768.36 SEK is:

$$\text{Energy saving} = 0.10 \cdot 18.03\ \frac{\text{MWh}}{\text{year}} = 1.80\ \frac{\text{MWh}}{\text{year}}$$

$$\text{Economic saving} = 1.80\ \frac{\text{MWh}}{\text{year}} \cdot 768.36\ \frac{\text{SEK}}{\text{MWh}} = \mathbf{1\ 385.35}\ \frac{\textbf{SEK}}{\textbf{year}}$$

[18] See Appendix D "Calculations for decreasing 2 °C the indoor temperature for a full development of the energy losses, parallel to that found in Appendix A for the baseline case of 24 °C.

The reducing electricity bills from heating is due to the reduction in losses by ventilation and transmission. With normal year correction, losses by ventilation are cut down to 2 624 kWh/year and the ones associated to transmission are 10 270 kWh/year[14]. Consequently, the final energy balance once this measure is applied is shown in Figure 37.

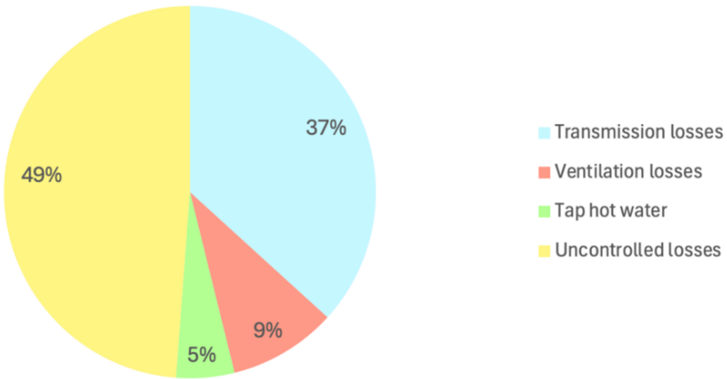


FIGURE 37. ENERGY BALANCE AFTER REDUCING 2 °C THE INDOOR TEMPERATURE.

4.4 Air quality assessment. CO_2 concentration analysis

The data obtained from the indoor climate loggers included the CO_2 concentration, which is an indicator of indoor air quality. An elevated concentration can be a signal of poor ventilation that con lead to affect the health and comfort of the residents, causing symptoms such as fatigue or headaches. The recommended concentration for indoor environment is from 400-1000 ppm [24]. However, this does not guarantee perfect air quality as other gaseous and particulate contaminants still need to be evaluated.

Thus, from the 23rd of April until the 29th of April, CO_2 concentration was measured in three different rooms of the house. The results are shown in Figure 38:

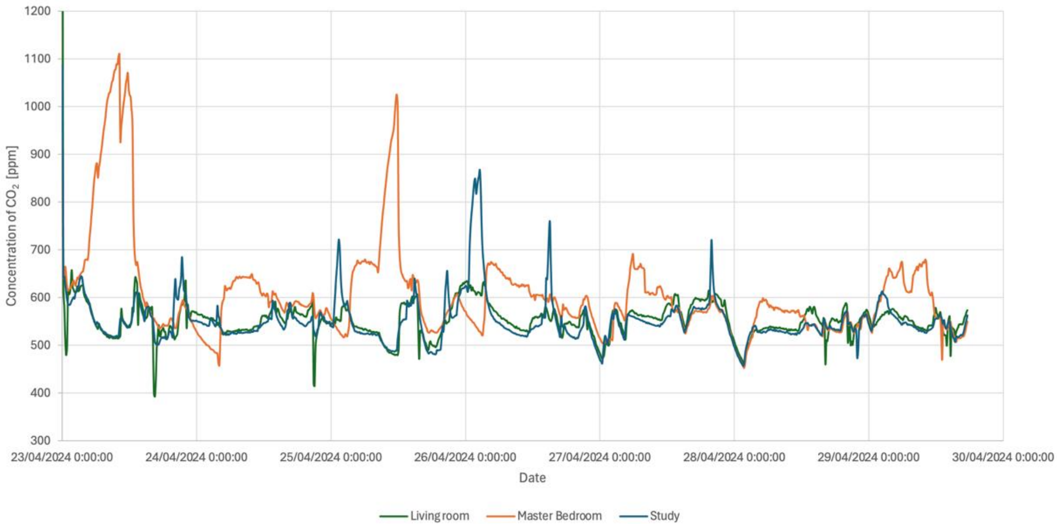


FIGURE 38 MEASURED CO_2 CONCENTRATION OF THREE ROOMS FROM 23RD OF APRIL UNTIL 29TH OF APRIL.

The highest average of all rooms is the master bedroom, with 608.71 ppm, while the living room and the study have similar concentrations being 553.36 ppm and 553.12 ppm respectively. Although all areas have an average value below the 1 000 ppm limit, Figure 38 reveals a significant increase in the concentration, with occasional peaks above the limit in the master bedroom during the morning hours. Even though these peaks rarely exceed 1 000 ppm and are not considered as a health risk, it would be preferable to mitigate them. Therefore, it is recommended to open the windows for longer periods in the master bedroom. Additionally, the installation of an MVHR system will further enhance air quality by providing adequate air humidity levels and controlled air mixing, leading to a reduction in these CO_2 concentration peaks.

4.5 Primary energy number and energy grade

To put into perspective the sustainability of the energy use and losses of the house in study, it is interesting to employ standardized indicators that can be compared in predefined scales. For instance, in one of the construction documents it is specified that the house belongs to an "E" energy class, but it is not elaborated in which scale. Most likely, this grade belongs to the Energy Performance Certificate found in Boverket's building code. This scale consists on seven classes based on the energy use requirements, taking into account factors like building code, BBR (BFS 2011:6) and depend on the type of building, if it is electrically heated or not, and where in Sweden it is situated [62]. Energy use is described in the energy performance certificate in terms of energy performance measures. Energy performance measures (EP) indicate how much energy is consumed by heating, air-conditioning, hot tap water and the building's property electricity. This figure is accounted for a one-year timespan and is divided by the floor area (thus the unit is $kWh/m^2 \cdot year$). An E class means that EP is $> 135\%$ - $\leq 180\%$ of the requirement for a new building.

However, since 1st of January 2019, energy performance is to be expressed in primary energy number EP_{pet} in kWh/m^2_{Atemp}. The primary energy number (EP_{pet}) describes the specific energy use of entities, multiplied by a weight factor for each energy carrier, according to the building regulations:

$$EP_{pet} = \frac{\sum_{i=1}^{6} \left(\frac{E_{sh,i}}{F_{geo}} + E_{sc,i} + E_{DHW,i} + E_{fe,i} \right) \cdot WF_i}{A_{temp}}$$

Equation 24

Where the terms of Equation 24 mean:

- $E_{sh,i}$ is space heating energy from energy carrier i [kWh/year].

- $E_{sc,i}$ is space cooling energy from energy carrier i [kWh/year].
- $E_{DHW,i}$ is domestic hot water heating from energy carrier i [kWh/year].
- $E_{fe,i}$ is facility (or property) energy from energy carrier i [kWh/year].
- $WF_{,i}$ is weight factor for energy carrier i [-].
- A_{temp} is the total area of the floors enclosed [m^2].
- F_{geo} is a geographic factor to account for the location. For Gävle, $F_{geo} = 1.1$ [-].

The weighting factors are for building regulations imposed in 2020 as follows:

TABLE 13. WEIGHTING FACTORS FOR DIFFERENT ENERGY CARRIERS. SOURCE: BBR.

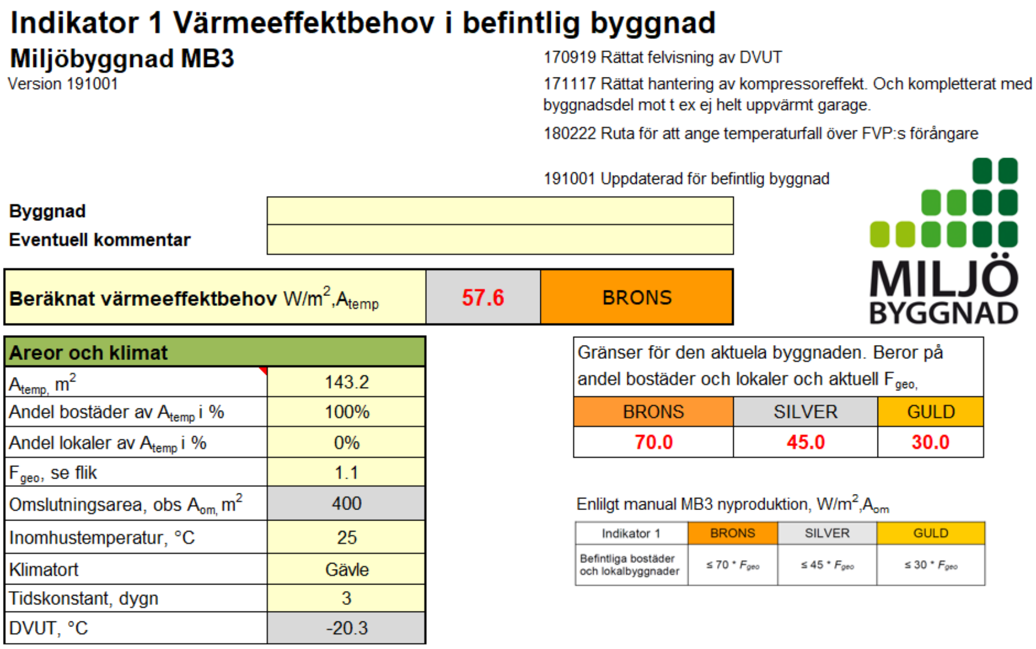
Carrier	Weighting factor [-]
Electricity	1.8
District Heating	0.7
District Cooling	0.6
Biofuels	0.6
Fossil Oil	1.8
Fossil Gas	1.8

Substituting the figures for the house in Gävle yields:

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{18883.5}{1.1} + 0 + \ 1412.7\right) \cdot 0.7 + 3117.5 \cdot 1.8}{143.2} = 130.01\ kWh/m^2$$

Looking at the chart that mark the limits of EP_{pet} in BBR (BFS 2011:6), a single family house with an $A_{temp} > 130$ m^2 should have an energy performance of 90 kWh/m^2 [63], meaning the house does not meet the requirements by a difference of 44%, should no EEMs be implemented.

Another interesting indicator and scale to look at is that proposed by “Miljöbyggnad” Environmental Certification of Building. This scale measures different components in energy, indoor environment and material, and assigns them one of three tiers depending on the result (gold, silver or bronze). The Excel workbook *Indikator 1 Värmeeffektbehov i befintlig byggnad* by Miljöbyggnad MB3 offers a straightforward way of inputting the case-study data for an output (Figure 39 and Figure 40).



Indikator 1 Värmeeffektbehov i befintlig byggnad

Miljöbyggnad MB3

Version 191001

170919 Rättat felvisning av DVUT

171117 Rättat hantering av kompressoreffekt. Och kompletterat med byggnadsdel mot t ex ej helt uppvärmt garage.

180222 Ruta för att ange temperaturfall över FVP:s förångare

191001 Uppdaterad för befintlig byggnad

MILJÖ BYGGNAD

Byggnad	
Eventuell kommentar	

Beräknat värmeeffektbehov W/m^2,A_{temp}	57.6	BRONS

Areor och klimat	
$A_{temp,}$ m^2	143.2
Andel bostäder av A_{temp} i %	100%
Andel lokaler av A_{temp} i %	0%
F_{geo}, se flik	1.1
Omslutningsarea, obs $A_{om,}$ m^2	400
Inomhustemperatur, °C	25
Klimatort	Gävle
Tidskonstant, dygn	3
DVUT, °C	-20.3

Gränser för den aktuela byggnaden. Beror på andel bostäder och lokaler och aktuell $F_{geo,}$

BRONS	SILVER	GULD
70.0	45.0	30.0

Enlilgt manual MB3 nyproduktion, W/m^2,A_{om}

Indikator 1	BRONS	SILVER	GULD
Befintliga bostäder och lokalbyggnader	≤ 70 * F_{geo}	≤ 45 * F_{geo}	≤ 30 * F_{geo}

FIGURE 39. RESULT OF THE ENERGY CLASSIFICATION TOOL BY MILJÖBYGGNAD.

As such, the tool reports a rating between bronze and silver for its standards with a heating need of 57.6 W/m^2. It must be pointed out that the program does not allow to choose the DVUT, but rather it draws it from a concept known as "time constant of the building", τ (*Tidskonstant* cell in Figure 39). The time constant is a magnitude that considers the heat stored in the building structures. It can be expressed as:

$$\tau_b = \frac{C_{internal}}{H_t + H_v} \quad [s]$$

Equation 25

Where $C_{internal}$ is the thermal mass, enclosed within the envelope's thermal insulation.

$$C_{internal} = \sum \rho_m c_m V_m$$

Equation 26

The terms ρ_m, c_m and V_m being the density, heat capacity and volume of the respective materials. Figure 40 shows the additional inputs the tool needed to return an output. Full calculations of the time constant τ can be found in Appendix C "Time constant calculations".

Transmissionsförluster		
Byggnadsdel	Delarea	U-värde
	m^2	$W/K,m^2$
Fönster, typ 1	34.44	1.25
Fönster, typ 2	0	0
Fönster, typ 3	0	0
Yttervägg, typ 1	164.2	0.169
Yttervägg, typ 2	0	0
Yttervägg, typ 3	0	0
Tak, typ 1	117	0.09
Tak, typ 2	0	0
Tak, typ 3	0	0
Grundkontruktion, typ 1	63.51	0.176
Grundkontruktion, typ 2	18.583	0.178
Källarväggar typ 1	0	0
Källarväggar typ 2	0	0
Källargolv, typ 1	0	0
Källargolv, typ 2	0	0
Ytterdörr, typ 1	2.1	1.45
Ytterdörr, typ 2	0	0
Byggnadsdel mot t ex garage	0	0
	0	0

Köldbryggor		
Om köldbryggor anges i %:		10.0%
Om köldbryggor specificeras:	Längd, m	psi, W/m,K
Bjäklagskanter	0	0
Sockel	0	0
Tak-yttervägg	0	0
Fönstersmygar	0	0
	0	0
	0	0

U_{medel} för kontroll, $W/m^2 A_{om}/K$	0.272

Ventilationsförluster för FTX	
FTX aggregat typ 1	
Luftflöde, l/s	59
Temperaturverkningsgrad	0%
FTX aggregat typ 2	
Luftflöde, l/s	0
Temperaturverkningsgrad	0%
FTX aggregat 4	
Luftflöde, l/s	0
Temperaturverkningsgrad	0%

Ventilationsförluster om F el FVP finns	
Frånluftsflöde, l/s	0
Frånluftens temperaturfall FVP	0
VP:s kompressoreffekt i W	0

Luftläckage genom klimatskärmen	
Lufttäthet, $l/s,m^2 A_{om}$ vid 50 Pa	0.1
Luftläckageflöde, l/s	2.0

FIGURE 40. EXTRA INPUTS TO RETRIEVE THE CLASSIFICATION FROM THE TOOL BY MILJÖBYGGNAD.

5 Discussion

5.1 Energy balance from calculations

The results for the energy balance reveal the inflows and outflows in the dwelling and help identify potential measures. The adoption of district heating integrates with a radiant floor that provides uniform space heating, though the thermal cameras and loggers did reveal that the second story is usually a few degrees cooler than the lower plant. This is probably due to the effect of large solar gains through windows, which were significantly larger than initially anticipated. According to the academic materials by lecturer S. Sayadi in Högskolan i Gävle, a Swedish villa usually receives 1 000 to 3 000 kWh/year of solar energy [64]. However, the dwelling of the study had an ample window area of 34.44 m^2, a large portion of it concentrated in the lower floor dining room (see blueprints in Appendix E). Moreover, most household appliances are located in the lower floor and owners spend more time there, both of which contribute to a raise in temperature in a smaller scale. It must be highlighted that the district heating energy comes from a sustainable source as Gävle's network draws power from the waste heat of a large paper factory nearby.

The biggest energy losses occur by unavoidable convection through the building envelope. Though this may be improved upon by changing the insulation of the walls, supervisors M. Mattsson and R. Forsberg commented that the existing layers were rather proficient enough. A rough economic analysis revealed that the external walls area, 164.2 m^2, would be too costly even to reduce these losses. In fact, there are only 13% larger transmission losses through the walls than through the aforementioned smaller window area than, and thus, an insulation renovation was not considered. Conversely, the U-value for windows at 1.25 W/m^2K is above the average, though Sayadi et al. suggest that to reach NZEB status, houses may need values closer to 0.65 W/m^2K [65], yet there are not many manufacturers that provide these values.

Tap water consumption at 73 m^3/year implies a water consumption of 200 L/day, i.e. 100 L/person daily with two dwellers, 33% of which is assumed to be heated up to 55 °C. This consumption is lower than the Swedish average water use reported by the national Statistiska centralbyrån (SCB), which reported a 155 L/person daily use in 2020 [66]. Remarkably, as seen in Table 7, water use was reduced by almost 22% in the past six years, just by behavioral changes according to the owners.

Energy losses by ventilation can dramatically increase or decrease depending on the regulation of the flow. A total exhaust flow at low regulation resulted in a flow of 0.059 m^3/s. BBR suggests a minimum 0.35 $Ls^{-1}m^{-2}$ for healthy indoor conditions. Converting units to compare both figures:

$$\text{Ventilation rate} = \frac{0.059 \frac{m^3}{s} \cdot \frac{1000\ L}{1\ m^3}}{143.2\ m^2 \text{ of floor area}} = 0.412\ \frac{L}{s{\cdot}m^2} > 0.35\ \frac{L}{s{\cdot}m^2}$$

Thus, it is sufficient to comply with the minimum standards. However, it must be mentioned that part of the calculation includes the exhaust hood which is not strictly part of the system and in reality the value may be lower than BBR's recommendation. Nevertheless, this is not a concern as the 143.2 m^2 are divided into the two house floors which are assumed to not be occupied at the same time. As such, the higher regulations should only be used in punctual events, i.e. when a crowded family meeting is due.

The uncontrolled losses in the form of natural ventilation, air leaks and thermal bridges account for the energy losses missing in the balance. Considering that the thermal bridges and leaks were not too severe as judged by the IR material, the figure for these losses seems to be somehow inflated. A possible leak that was not considered could exist in the floor heating system, were part of the water or heat through the pipes might be lost to the ground. The reason for the large nature of their share in the balance could not be fully elucidated in the timeframe for the elaboration of this report, and so future considerations for measuring these losses more accurately are commented in 6.2 Outlooks.

5.2 Comparison with simulation results

There exist noticeable differences between the output of the base IDA-ICE model and the performed empiric calculations. Table 14 summarizes the discrepancies by category.

TABLE 14. COMPARISON BETWEEN THE ENERGY BALANCE FIGURES OBTAINED FROM EMPIRICAL CALCULATIONS AND FROM IDA-ICE SIMULATION.

	Energy flow	Calculations (kWh/year)	IDA-ICE (kWh/year)
Energy In	District Heating	18883.5	18871.6
	Solar Gains	8946.1	1655.9
	People	546.6	1327.3
	Appliances	1458.8	-
Energy Out	Transmission	12654.9	15175.7
	Water	1412.7	1422.3
	Ventilation	3157.2	-
	Infiltration	12610.0	10421.6

Many of the sources for these differences lie on how IDA-ICE yields results by default. For instance, solar gains are reported as "Windows & Solar", with some months having negative values, that is, losses instead of gains which should not be possible. The total electricity use of appliances + lighting matches that of bills but the 70% conversion to heat is not shown. Lastly, transmission losses include thermal bridges in IDA-ICE, meaning the numbers in “Transmission” and “Infiltration” do not match that close in reality. In addition, there is error too in the form of calculating with methods like DVUT against an integration process of the software.

Overall, the numbers are in the same orders of magnitude but the discrepancies are too large to reach a consensus between empirical calculations and software. As such, concerning effective conclusions, the results obtained by the former are regarded first and foremost, since the proposed measures were based on those figures too.

5.3 Effectiveness and cost discussion of the measures

5.3.1 Installation of PV panels

Installing solar PV panels offers a saving of 7 523 SEK per year with a payback of approximately 9 years. Bearing this information, the initial investment can be recovered within a reasonable period, featuring the economic viability for the installation of the PV system. Although the payback period spans a considerable duration, the lifespan of the panels must be considered to evaluate the profitability of the system. As solar panels require minimal maintenance once installed and they have a typical lifespan of 25 to 30 years [67], the system will start to become profitable from the 13^{th} year, so it will produce significant savings in the electricity invoices for almost 2 decades. Furthermore, the payback period can be shortened considering that electricity costs are expected to increase over time due to inflation or other factors [68], therefore the yearly saving of 7 523 SEK may rise.

In conclusion, with the economic saving per year and a relatively brief payback period, the installation of solar panels is considered to be a prudent investment.

5.3.2 Installation of thermal panels

It is important to acknowledge that flat-plate collectors lower carbon emissions and depend less on non-renewable energy sources, which helps with sustainability initiatives. Furthermore, the district heating system that already exists improves energy security and resilience by offering a dependable backup.

However, although the environmental advantages may seem attractive, the installation of a 3 m^2 flat-plate solar thermal collectors presents a challenge because of the 35-year economic payback period. This arises due to the little yearly savings of about 554.71 SEK, so this measure is unfeasible from a financial perspective since the lifespan of thermal panels is 25 years [69].

It has been considered that although the installation of the thermal panels is an attractive environmental measure that enhances energy independency, it can result in potential economic losses since it is not foreseen to yield prove to be a profitable system.

5.3.3 Heat exchanger unit in the exhaust ventilation system

The use of a heat exchanger is common in systems that already have an exhaust mechanical ventilation system as some of the exhaust fans are already installed. As such, it seemed practical to install the missing components to retrieve some of the heat in the exhausted air. The suggested system would retrieve 2 217 kWh/year of heating, with savings in district heating of 1 703.7 SEK/year. These savings are moderate, resulting in a payback period of 12.68 years. According to A. Dodoo [26], the heat exchange unit has a lifetime of 25 years, while the ducts are expected to last 50 years with occasional cleaning maintenance. On the other hand, the NPV is borderline infeasibly high at 21 years, however, this method is very sensitive of the internal rate of return used, and for that reason, the result of the payback period is to be prioritized.

Another aspect to be discussed is that this system, unlike the previous two, needs some electricity feeding to move the fans and units like the humidifier. The Passive House Institute [70] set a referent value of electricity consumption is 0.45 W/(m^3_{space}/h). Therefore, with an enclosed volume of 377.05 m^3 read from the IDA-ICE model[19], it is estimated 1 486.3 kWh/year would need to be employed. This result is more critical than a longer payback period, as electricity is a more valuable energy carrier than heat energy. However, this figure does not take into account that the exhaust fans are already in-place and that their consumption was already taken into account in the balance, so realistically, the system would only add about 75% of that consumption, 1100 kWh/year. This electricity could be covered with the large PV surplus, but for the worst-case scenario, it will be considered a running cost with purchased electricity in Table 15.

Ultimately, the benefits of the system are not very remarkable. While it blends well with the proposed measures and already in place infrastructure, and is environmentally sustainable, the economic appeal is limited. The reason for this is that the ventilation losses still were only 9% of the losses in the house without measures, and thus, the saving were bounded.

[19] This space volume does, however, only take into account the volume where an effective ventilation is needed. Thus, it assumes a room height of 2.5 m for the lower floor and 2.6 m for the upper floor. Additionally, it does not consider the storage room volume nor the stairs passage area. The system is assumed to be running the full 8760 hours of the year.

5.3.4 Complementary behavioral measures

Implementing a reduction of 2 ºC in the indoor temperature leads to a 10% in the heating energy demand per year which leads to a saving of 1 378.43 SEK per year without any investment, which results in a very attractive measure to consider.

Moreover, a 22 ºC indoor temperature offers a greater thermal comfort than a 24 ºC temperature, that can lead to overheating.

It is regarded that reducing the temperature in a location can be a beneficial measure from an energy point of view, as it reduces energy consumption, and can improve the thermal comfort of the dwelling's occupants by any investment.

5.4 Effect of the measures

As it currently stands, the house owners employ 18 883.5 of kWh/year of district heating and 3 117.5 kWh/year of electricity, which have an associated estimated cost of 14 514 SEK and 7 669 SEK, respectively. This results in an estimated yearly energy bill of 22 183 SEK.

The proposal of thermal solar collectors is discarded as the NPV is prohibitively high and the NPV results in a function that converges in a negative profit value. Besides, the savings in kWh are not substantial. Mayhap different results would have been obtained if a combined PV/T model similar to the one by Kazanci et al. [36] was proposed, and allowing the solar thermal to be used for domestic hot water with the system proposed by [19].

Thus, this section summarizes the effect of the other three plans. PV panels constitute for an active energy measure, meaning rather than reducing the total energy use they compensate for some of it with a more sustainable alternative. On the other hand, a MVHR system and a reduction of temperature are passive measures since they directly help reduce consumption. The PV panels would cover 4 042 kWh/year of the electric demand, though unevenly spread in different months. The MHVR system is capable of saving 2 217 kWh/year of thermal energy, cutting down the need of district heating. Similarly, the reduction of temperature saves an additional 1 790 kWh/year in heating needs.

The payback of the PV installation is in line with the numbers explored in the literature review [35]. Similarly, from the literature review insights, the storage of excel solar energy in batteries was not considered as these were reported not to be cost-effective without subsidies ([17], [35]). Interestingly, the proposed design did not have space constraints as there was enough roof surface for a larger panel extension. This leaves the option to the owners to expand their system freely should their energy needs increase.

The MHVR not only achieves energy savings but contributes to the thermal comfort and air quality. Different flow regulations could still be chosen, and should the cooling unit be implemented, the house would now have a solution for summer overheating issues. However, the MHVR increases the electricity consumption in order to operate the extra units (mainly humidifier, and heating/cooling unit should it be finally implemented) and fans, and the cost of this electricity usage increase was not accounted for when estimating the financial saving, which ought to be subtracted as a running cost. This remark is accounted for in the final figures for Table 15. Overall, the energy reductions from this measure are more reduced than those reported in source articles ([25], [26]).

Although not an explicit measure, the findings in choosing of the ventilation flow intensity and the associated energy cost matches that of [24]. At low regulation, the house had acceptable CO_2 levels and recommend ACH levels, so it was not needed to tweak the system more thoroughly. On the other hand, a reduction in indoor temperature was deemed to be studied in more detail, as the research team did feel some degree of overheating in several visits when conducting measures.

The house owners did not show the usual EEM implementation barriers reported by ([21], [23]), though a budget was not proposed to them yet at the time of the writing of this document. Other EEMs that are amongst the most common, like the window replacement or attic insulation enhancement, reported by [15], were deemed to not be appropriate as their parameters were already above average.

Table 15 summarizes the benefits of the proposals. In total a 35.6% financial saving can be achieved over the 2023 baseline bills, with the added non-energy benefits such as more sustainability, energy independency and better comfort, yet the initial investment is still to be reckoned with.

TABLE 15. SUMMARY OF THE FINANCIAL BENEFITS OF THE PROPOSED MEASURES.

Measure	Initial Cost (SEK)	Running Cost (SEK/year)	Savings (SEK/year)
Solar PV panels	70 000	0	7 523
MHVR system	21 599	2706[20]	1 704
Temperature reduction	0	0	1 378
Final figure			7898

5.5 Energy class considerations

For a house that was initially believed to have robust insulation and solid space heating sources, different energy use indicators were rather subpar. While the documents label the house with an "E" energy efficiency certificate, Boverket now stablishes that all new buildings must at least meet a "C" grade, that is, EP is > 75% - ≤ 100% of the requirement for a new building [63].

Without any green energy alternatives, the house is far from reaching NZEB status too as:

$$\text{Energy use} = \frac{29.85\ \text{MWh/year}}{143.2\ \text{m}^2} = 208.45\ \frac{\text{kWh}}{\text{m}^2\cdot\text{year}} \gg 60\ \frac{\text{kWh}}{\text{m}^2\cdot\text{year}}$$

If the comparison was to be made with the otherwise defined and calculated EP_{pet} = 106.1 kWh/m^2·year, the objective of 60 kWh/m^2·year although closer would still not be met.

[20] Product of the additional electric 1100 kWh/year to be supplied and the established 2.46 SEK/kWh price for the energy carrier. Though it might seem the running cost outweighs the saving, thus proving inviable, the solar PV surplus could be redirected instead of sold (as electricity sell price is usually a only a third of that purchased).

6 Conclusions

6.1 Study Results

Performing an energy audit in a detached house located in Gävle, Sweden, has provided valuable insights into the energy balance of the dwelling, emphasizing the importance of the architectural design of the building, indoor climate systems and the occupant behavior in the improvement of energy efficiency.

Multiple visits and measurements were conducted at the semi-detached house to perform the energy balance of the dwelling by encompassing airflow assessments, IR images and temperature, relative humidity and CO_2 concentration measures. Additionally, the software IDA-ICE was used to compare the calculations and ensure accuracy during the process. Nevertheless, discrepancies between empirical calculations and IDA-ICE simulations showed limitations in the software accuracy, so empirical data was prioritized for the conclusions and were the ones considered in implementing the cost-saving measures.

When analyzing the energy balance, it was observed that most of the energy entering the dwelling was mainly to district heating and through the solar gains across windows, providing a 93% of the total energy entering the building. However, despite the advantages provided from district heating, the dwelling challenges persists in addressing transmission losses, particularly through the windows. These losses constitute a 42% of the total energy waste and despite efforts to enhance insulation, it was established that replacing the current walls and windows would necessitate a very high initial investment for their returns, and that the existing ones were already rather proficient. Thus, the exploration of other solutions was required to meet energy efficiency standards by addressing a portion of the current demand through the adoption of more sustainable technologies.

Regarding the installation of PV panels, results showed a substantial long-term profitability despite the considerable initial investment of 70 000 SEK. Additionally, it also positions the houseowners to capitalize the excess of energy and it offers an independent energy source that offers reliability, durability, and savings up to 7 523 SEK/year. Another measure to take advantage from the solar energy are thermal collectors. Although they offer environmental benefits and improve energy security, their installation presents financial challenges due to a too high payback period and modest yearly savings, that makes this measure not viable economically.

As well, the integration of the mechanical ventilation heat recovery (MHVR) system offers moderate savings in district heating and aligns with existing infrastructure. However, its economic appeal may be limited due to a payback period of over 12 years. Despite this, it contributes to environmental sustainability and complements other proposed measures. Installing a MVHR system will also help to improve the air quality, since despite CO_2 concentrations are within established limits, concentrations exceeding 1 000 ppm are observed in some areas of the house throughout the day.

Also, during the analysis of the energy balance, it was observed how past behavioral changes by homeowners contributed to a significant reduction in hot water and electricity demand, highlighting the importance of the occupant's performances in energy conservation. For this reason, it was decided to implement a behavioral measure that reduced the indoor temperature by 2 ºC since the temperature inside the house was high and above the recommended 22 ºC. This way, without any initial investment, a 10% decrease in heating energy demand was obtained, which led to significant yearly savings.

To conclude, the total energy purchase in the reference building could be lowered by 1 735.8 kWh/year of electricity (since 1 100 kWh/year of the PV energy would be invested in moving the new MHVR, and a 41% share is inevitable to be sold due to lack of storage) and 4 017.4 kWh of space heating, resulting in an overall 26.15% energy reduction over the 2023 use. There is, however, some level of uncertainty in these results due to abnormally high uncontrolled losses that could not be fully elucidated. Overall, this result, although it pertains to a detached dwelling in Gävle suggests measures and raises awareness among homeowners of similar buildings and underscores the potential for enhancing energy efficiency through the adoption of affordable measures.

6.2 Outlook

Although the study achieved some noticeable energy savings with sustainable alternatives, there remains a rather high degree of uncertainty in some of the estimations. While price sources for energy carriers and installations were compared between sources, figures like those are bound to experiment changes in the future, either by inflation rates going up or technological advancements lowering costs.

On-site metering techniques ought to be further developed too. The impossibility that existed in this study to measure thermal bridges, air leaks and natural ventilation should be asserted with alternatives like closer IR camera measuring, gas tracing and localized long period airflow sampling, respectively. Without these figures properly defined, the discrepancies there may exist between empirical calculations and software results are daunting to discuss as the error source is broad (considering that software models add simulation error both in human and algorithm error forms too).

Additionally, it would be interesting to consider other common energy efficiency measures like the incorporation of an exhaust air heat pump for redirecting exhaust air heat to the domestic hot water demand. As it currently stands, the financial perks of the MHVR were lower than expected so no further research was made for the ventilation system measures. Further system designing and new EEM interrelation could, however, shift this perspective.

In short, more rigorous data collecting and handling may allow to explore other alternatives such as more sophisticated thermal collectors and heat-pump systems. Yet, this work serves as a foundation for further research in the field towards improving energy efficiency in the residential sector to proficiency levels that will comply with new sustainable building policies.

6.3 Perspectives

This thesis has been developed in the framework of an Energy Systems Master program that contains syllabuses aimed at providing students with sustainable technological resources. In this field, there exists the need for improving domestic energy systems since buildings, once erected, do not follow new innovations as sharply as other systems. The proposed renovations and energy auditing process for the semi-detached house in Gävle are based on the state-of-art of residential energy efficiency measures, making this work a reference for future similar investigations.

The discussion of exploiting solar energy, recovering exhausted heat and tuning in temperature and ventilation parameters are ultimately aimed at reducing the primary energy within a house, thus reducing the overall carbon footprint. The development towards NZEB in the residential sector is bound to accompany other standards for a more sustainable society.

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Appendix A: Energy balance development

Transmission energy losses

Power

In setting the thermal parameters for the house, it has been established an indoor temperature of 24° C for the living spaces. With a design temperature found in the DUT_1 map located in Appendix G given by Prof. Forsberg, a value of -22 °C for a light building is chosen. These temperature standards correspond to the outside conditions of Gävle.

In addition, by examining the house blueprints, the floor areas of every portion of the house have been measured. Likewise, the U-values have been computed utilizing the techniques explained in Appendix C. Therefore, for calculating the maximum total power needed, equation 5 has been used:

$$T_i = 24\ °C; \quad DUT = -22\ °C\ ; \quad \sum U_i \cdot A_i = 119.879\ \frac{W}{K}$$
$$Q_{transmission} = 119.879 \cdot \big(24 - (-22)\big) = 5\ 514.417\ W$$

Energy

Energy is calculated by means of the following formula:

$$E_{transmission} = \left(\sum U_i \cdot A_i\right) \cdot h$$

For the calculation of the degree hours (h), an indoor temperature of 24 °C has been considered. Bearing in mind this data, the $T_{balance}$ is assumed to be 18° C. The hours below this temperature taken from the SMHI data are 7 846 h, hence, by means of the next formula multiplying each hour with each respective difference between indoor and outdoor temperature, the degree hours are calculated:

$$h = \sum_{i=1}^{Tout_i < T_{balance}} \left(| T_{out_i} - T_{balance} | \cdot 1\ hour \right) = 105\ 564\ °C{\cdot}h$$

Appendix Table 1. Summary of the heat and energy parameters for different transmission surfaces.

	Area (m^2)	U ($\frac{W}{m^2K}$)	U · A ($\frac{W}{K}$)	Q (W)	Energy (kWh)
External walls	164.200	0.297	48.767	2243.300	5148.111
Windows	34.440	1.250	43.050	1980.300	4544.556
Roof	117.000	0.090	10.530	484.380	1111.595
Wood floor	63.514	0.176	11.178	514.209	1180.050
Tiles floor	18.583	0.178	3.308	152.158	349.184
Door	2.100	1.450	3.045	140.070	321.444
Total			**119.879**	**5514.417**	**12654.940**

Ventilation energy losses

Power

By using Equation 10, power from ventilation losses is obtained. While maintaining an indoor temperature (T_{in}) of 24 °C, the outdoor temperature ($T_{avg.out}$) is determined using the DUT_{20} map, which provides the outdoor design temperature for light buildings in specific locations. For Gävle, the obtained value for $T_{avg.out}$ is -22°C.

$$P_{vent.\ loss\ (kW)} = v \cdot \rho_{air} \cdot c_{air} \cdot (T_{in} - T_{avg.\ out})$$

Being:

- ρ_{air}: 1.204 kg/m3
- c_{air}: 1.006 kJ/kgK
- T_{in}: 24°C
- $T_{avg.out:}$ -22°C

Energy

Energy is calculated with the same concept of degree-hours from the transmission losses section:

$$E_{vent.\ loss\ (kWh)} = v \cdot \rho_{air} \cdot c_{air} \cdot h$$

The amount of degree hours is the same as calculated for the energy associated to transmission losses (h = 105 564 °C·h).

APPENDIX TABLE 2. SUMMARY OF THE VENTILATION LOSS FIGURES OF POWER AND ENERGY FOR BOTH FLOW REGULATIONS.

Ventilation out calculations								
Room	Low flow (l/s)	Low flow (m3/s)	High flow (l/s)	High flow (m3/s)	Heat power out Low (kW)	Heat power out High (kW)	Energy low (kWh/year)	Energy High (kWh/year)
Upper Bathroom	5.100	0.005	10.400	0.010	0.284	0.557	652.098	1329.769
Lower Bathroom	4.300	0.004	8.800	0.009	0.223	0.501	549.808	1125.189
Laundry room	3.500	0.004	8.200	0.008	0.223	0.446	447.518	1048.471
Dressing room	1.640	0.002	3.280	0.003	0.111	0.167	209.694	419.389
Sauna	-	0.007	-	0.015	0.390	0.836	835.518	1863.849
Kitchen exhaust	38.000	0.038	82.700	0.083	2.117	4.624	462.566	1006.691[21]

Total	3.349	7.132	3157.204	6793.357

[21] The kitchen exhaust air is calculated with the knowledge that the owners activate it for 30 minutes/day in 335 days of the year, rather than with the figure of degree hours that would overrepresent this number.

Hot tap water

Water consumption data is derived from the water usage invoices supplied by the homeowners. Hence, the quantity of hot water can be determined using Equation 13.

$$q_{\text{hot-water}}\left(\frac{m^3}{\text{year}}\right) \cong \frac{q_{\text{total-water}}}{3}$$

Equation 14 is employed to calculate the energy consumed for heating up tap water. This formula is required to calculate the energy used especially to heat water for different household requirements:

$$E_{\text{hot-water}}\left(\frac{\text{kWh}}{\text{year}}\right) = \frac{q_{\text{hot-water}} \cdot \rho_{\text{water}} \cdot c_{\text{water}} \cdot \Delta T}{3\,600}$$

- ρ_{water}: 1 000 kg/m^3.
- c_{water}: 4.18 kJ/kgK.
- ΔT: Water is heated from 5 °C to 55 °C, hence 50 °C of difference.

APPENDIX TABLE 3. WATER CONSUMPTION IN THE LAST YEARS AND THE ASSOCIATED HEAT ENERGY TO WARM IT UP FROM 5°C TO 55°C.

Tap hot water calculations			
Year	Total m^3	Warm m^3	Heat energy (kWh/year)
2018	89.000	29.667	1722.315
2019	80.000	26.667	1548.148
2020	81.000	27.000	1567.500
2021	82.000	27.333	1586.852
2022	74.000	24.667	1432.037
2023	73.000	24.333	**1412.685**

Internal gains

<u>Energy gains from people</u>

APPENDIX TABLE 4. SUMMARY OF THE FIGURES FOR CALCULATING THE INTERNAL ENERGY GAINS FROM THE DWELLERS.

Internal Gains (People)	
Number of people	2
Generation internal (W)	80[22]
Hours at home (h/day)	14[23]
Days	244[24]

[22] SBEVY reference
[23] SBEVY reference
[24] Days between mid-September until mid-May.

By means of the Equation 15, the energy obtained by internal gains of people is calculated:

$$E_{people} = 2\ \text{people} \cdot \frac{80\ \text{W}}{\text{people}} \cdot \frac{14\text{h}}{\text{day}} \cdot \frac{244\ \text{days}}{1\ \text{year}} \cdot \frac{1\text{kW}}{1000\text{W}} = \mathbf{546.560}\ \frac{\mathbf{kWh}}{\mathbf{year}}$$

<u>Energy gains from appliances</u>

According to SVEBY, approximately 70% of the electricity consumed by appliances is converted into heat [39]. From the electricity bills, it is determined that the annual electricity use amounts to 3 117.5 kWh. Excluding the days between mid-May and mid-September since they are considered to be sufficiently warm, this data provides an insight into the energy usage patterns and the corresponding heat generation within the audited house.

APPENDIX TABLE 5. SUMMARY OF THE FIGURES FOR CALCULATING THE INTERNAL ENERGY GAINS BY HOUSEHOLD APPLIANCES.

Internal Gains (Appliances)	
Electricity Use (kWh)	3117.5
Conversion to heat (%)	70[25]
Days	244[26]

$$E_{appliances} = \frac{3\,117.5\ \text{kWh}}{\text{year}} \cdot \frac{244\ \text{days}}{365\ \text{days}} \cdot 0.7 = \mathbf{1\,458.819}\ \frac{\mathbf{kWh}}{\mathbf{year}}$$

[25] SVEBY reference

[26] Days between mid-September until mid-May.

Solar calculation

The house to be audited consists of three façades facing different orientations. Each façade features windows with special glass, all with an r value of 0.60 obtained from building plan documents in 2006 (the owners claimed no window changes ever since construction). It is worth noting that the west-facing wall lacks windows, as it is the attached façade. The calculation process takes into consideration varying levels of cloudiness specific to each month. Furthermore, all the necessary parameters, including the values of c*, r, and irradiance (I*), are obtained from the tables provided in Appendix G. It is important to mention that the values had linearly interpolated, particularly for the irradiance, as the windows are oriented at angles in-between those listed in the tables.

Appendix Table 6. Irradiance values for different months of the year and different orientations. for a latitude of 60° (approximately Gävle's), interpolated from appendix figure 9.

Month	North Wall I* $\left(\frac{Wh}{m^2 day}\right)$			East Wall I* $\left(\frac{Wh}{m^2 day}\right)$			South Wall I* $\left(\frac{Wh}{m^2 day}\right)$		
	-150°	-120°	-132°	-60°	-30°	-42°	30°	60°	48°
January	130	160	148	1440	2360	1992	2360	1440	1808
February	370	640	532	2900	4280	3728	4280	2900	3452
March	900	1720	1392	4520	5740	5252	5740	4520	5008
April	1990	3320	2788	5850	6370	6162	6370	5850	6058
May	3050	4460	3896	6150	5980	6048	5980	6150	6082
June	3870	5230	4686	6350	5820	6032	5820	6350	6138
July	3510	4910	4350	6280	5820	6004	5890	6280	6124
August	2380	3720	3184	5850	6070	5982	6070	5850	5938
September	1230	2200	1812	4820	5760	5384	5760	4820	5196
October	530	1010	818	3570	4860	4344	4960	3570	4126
November	200	270	242	1910	3040	2588	3040	1910	2362
December	80	90	86	1060	1770	1486	1770	1060	1344

The input energy obtained from solar is calculated using Equation 17 for each direction with its corresponding set of areas and irradiances:

$$\mathrm{E_{solar}} = \mathrm{r} \cdot c^{*} \cdot \mathrm{I}^{*} \cdot \mathrm{A} \cdot d^{*}$$

APPENDIX TABLE 7. FIGURES FOR THE CALCULATION OF SOLAR ENERGY THROUGH WINDOWS IN DIFFERENT ORIENTATIONS AND MONTHS OF A YEAR.

				-132º(N)			-42º (E)			48º (S)			138º(W)		
Month	Days	c*	r	I* $\left(\frac{Wh}{m^2 day}\right)$	A (m^2)	E_{solar} (Wh)	I* $\left(\frac{Wh}{m^2 day}\right)$	A (m^2)	E_{solar} (Wh)	I* $\left(\frac{Wh}{m^2 day}\right)$	A (m^2)	E_{solar} (Wh)	I* $\left(\frac{Wh}{m^2 day}\right)$	A (m^2)	E_{solar} (Wh)
January	31	0.45	0.6	148	6.19	7668	1992	10.95	182570	1808	17.3	261800	160	0	0
February	28	0.49	0.6	532	6.19	27109	3728	10.95	336043	3452	17.3	491612	640	0	0
March	31	0.58	0.6	1392	6.19	92955	5252	10.95	620411	5008	17.3	934655	1720	0	0
April	30	0.58	0.6	2788	6.19	180171	6162	10.95	704428	6058	17.3	1094147	3320	0	0
May	15.5	0.63	0.6	3896	6.19	141297	6048	10.95	388016	6082	17.3	616476	4460	0	0
June	0	0.61	0.6	4686	6.19	0	6032	10.95	0	6138	17.3	0	5230	0	0
July	0	0.61	0.6	4350	6.19	0	6004	10.95	0	6124	17.3	0	4910	0	0
August	0	0.59	0.6	3184	6.19	0	5982	10.95	0	5938	17.3	0	3720	0	0
September	15	0.58	0.6	1812	6.19	58549	5384	10.95	307744	5196	17.3	469230	2200	0	0
October	31	0.51	0.6	818	6.19	48032	4344	10.95	451219	4126	17.3	677109	1010	0	0
November	30	0.42	0.6	242	6.19	11325	2588	10.95	214240	2362	17.3	308921	270	0	0
December	31	0.43	0.6	86	6.19	4258	1486	10.95	130141	1344	17.3	185963	90	0	0
TOTAL (Wh/year)				**571362**			**3334812**			**5039913**			**0**		
				8946087											

Heat balance

The heat balance for the year 2023, is obtained by means of Equation 1.

$$E_{in} = E_{out}$$

However, as it can be observed in Equation 2, it is required to identify the amount of energy obtained space heating to complete the total energy input of the dwelling. This data was acquired from the district heating bills provided from the owners and it was the mean value of the 2020-2023 years.

$$E_{space\ heating} = 18\ 883.5\ \frac{kWh}{year}$$

Once this value is obtained, the total energy input can be calculated:

$$E_{in} = E_{space\ heating} + E_{solar} + E_{people} + E_{appliances} = 18.89 + 8.95 + 0.55 + 1.46 = 29.85\ \frac{MWh}{year}$$

The total energy outflow, as governed by Equation 3, should be equal to the total energy inflow, as indicated by Equation 1. Hence, the term corresponding to natural ventilation can be obtained by solving the following equation:

$$E_{out} = E_{transmission} + E_{mech.\ ventilation} + E_{uncontrolled\ losses} + E_{hot\ water} = 29.85\ \frac{MWh}{year}$$

$$E_{out=}\ 12.65 + 3.16 + 1.41 + E_{uncontrolled\ losses} = 29.85\,\frac{MWh}{year}$$

$$E_{uncontrolled\ losses} = 12.61\,\frac{MWh}{year}$$

Normal year correction

From the data acquired from SMHI, the number of degree days of 2023 was calculated: $S_{actual} = 4\ 567.14$ degree days.

Using the data from 1996 to 2023 and by calculating the difference between 17 °C and the average value of the outdoor temperature per day, the number of degree days for a normal year is obtained: $S_{normal} = 4\ 326.53$ degree days.

Hence, the energy index can be calculated:

$$\text{Energy index} = \frac{S_{normal}}{S_{actual}} = \frac{4\ 326.53}{4\ 567.14} = 0.947$$

Only ventilation and transmission calculations are subjected to the outer temperature, therefore, the correction must be applied for both of them to obtain the energy balance for a normal year:

$$E_{N transmission} = 0.947 \cdot 12\ 654.95 = 11\ 984.23\ \frac{kWh}{year}$$

$$E_{N ventilation} = 0.947 \cdot 3\ 157.20 = 2\ 989.87\ \frac{kWh}{year}$$

Therefore, the heating demand of the dwelling for a normal year is:

$$E_{N space\ heating} + 8.95 + 0.55 + 1.46 = 11.98 + 2.99 + 12.61 + 1.41$$

$$E_{N space\ heating} = \mathbf{18.03}\,\frac{\mathbf{MWh}}{\mathbf{year}}$$

Appendix B: U-values calculations

Formulas

The thermal transmittance value, also known as the U-value, represents the inverse of the thermal resistance (R). Thermal resistance is calculated as the ratio between the thickness (d) of the material and its thermal conductivity (λ).

$$R = \frac{d}{\lambda} \quad ; \quad R_{tot} = \sum R \quad ; \quad U = \frac{1}{R_{tot}}$$

Walls

For the purposes of this investigation, the thermal conductivity of air is set at 0.056 W/(m·K). This decision is based on the supposition that there is enough air circulation within the structure due to the current air gap, which improves heat transfer. As a result, the selected value for thermal conductivity is greater than twice that which would normally be assigned if it were assumed that the air is still. It is also important to remember that R_{si} and R_{se} are thermal resistances that take into consideration convection and account for the inner and outer surface conditions, respectively[27]. The current study values for these characteristics were selected to represent common circumstances that arise during building construction (seen in Appendix Table 8).

Appendix Table 8. Summary of the heat transmission parameters for the wall insulation materials.

	Material	d(m)	λ (W/(m·K))	R (m^2·K/W)
Internal walls	Gypsum	0.013	0.220	0.059
	Wooden beams (Reglar600)	0.100	0.041	2.439
	Gypsum	0.013	0.220	0.059
External walls	Concrete seal	0.010	1.000	0.010
	Cellular concrete (LBTG400.100)	0.350	0.110	3.182
Inner convection	Rsi	-	-	0.130
Outer convection	Rse	-	-	0.040

$$R_{walls} = 0.010 + 3.182 + 0.130 + 0.04 = 3.362 \ \frac{m^2K}{W}$$

$$U_{walls} = \frac{1}{3.362} = 0.297 \ \frac{W}{m^2K}$$

[27] These resistances do not belong to any physical material. Rather, they are equivalences to somehow account for the complex convection-radiation heat transfer mechanism that occur in the surfaces of materials.

Roof

In the case of the ceiling, it is imperative to account the significant impact of radiation exchange with the sky, which results in an approximate 15% increase in heat loss. This phenomenon arises from the transfer of thermal energy between the ceiling surface and the cooler sky above, contributing to a higher overall heat dissipation rate. This consideration is only taken into account for the ceiling since walls are not facing the sky, but rather other surfaces like other walls, which are not as cold. Consequently, a correction factor of 1.15 must be taking into account for the final result.

APPENDIX TABLE 9. SUMMARY OF THE HEAT TRANSMISSION PARAMETERS FOR THE ROOF INSULATION MATERIALS.

Material	d(m)	λ (W/(m·K))	R (m^2·K/W)
Wood planks (Trä-14)	0.020	0.140	0.143
Mineral Wool	0.350	0.036	9.722
Air	0.150	0.056	2.679
Gypsum	0.013	0.220	0.059
Rsi	-	-	0.130
Rse	-	-	0.040

$$R_{roof} = 0.143 + 9.722 + 2.679 + 0.059 + 0.130 + 0.040 = 12.775 \ \frac{m^2K}{W}$$

$$U_{roof} = \frac{1}{12.775} = 0.078 \ \frac{W}{m^2K}$$

$$U_{roof} = 0.078 \cdot 1.15 = 0.090 \ \frac{W}{m^2K}$$

Wood floor

APPENDIX TABLE 10. SUMMARY OF THE HEAT TRANSMISSION PARAMETERS FOR THE WOODEN FLOOR INSULATION MATERIALS.

Material	d(m)	λ (W/(m·K))	R (m^2·K/W)
Wood planks (Trä-14)	0.020	0.140	0.143
Wooden beams (Reglar600)	0.200	0.041	4.878
Styrofoam insulation	0.020	0.036	0.556
Wood planks (Trä-14)	0.014	0.140	0.100

$$R_{wood\ floor} = 0.143 + 4.878 + 0.556 + 0.100 = 5.677 \ \frac{m^2K}{W}$$

$$U_{\text{wood floor}} = \frac{1}{5.677} = 0.176\ \frac{W}{m^2K}$$

Floor Tiles (Hall, Bathroom, Laundry)

Appendix Table 11. Summary of the heat transmission parameters for the tiles floor insulation materials.

Material	d(m)	λ (W/(m·K))	R (m^2·K/W)
Fiber coat	0.200	0.036	5.556
Concrete	0.050	1.700	0.029
Concrete	0.050	1.700	0.029
Klinker	0.010	3.500	0.003

$$R_{\text{tiles floor}} = 5.556 + 0.029 + 0.029 + 0.003 = 5.617\ \frac{m^2K}{W}$$

$$U_{\text{roof}} = \frac{1}{5.617} = 0.178\ \frac{W}{m^2K}$$

Appendix C: Time constant calculations

Recalling Equation 26, the value of $C_{internal}$ is calculated in an Excel spreadsheet with the following chart. The volume is calculated as the product of thicknesses and areas.

Appendix Table 12. Summary of the thermal mass parameters for the building envelope materials.

<table>
<tr><th>Surface Type</th><th>Material</th><th>Thickness (m)</th><th>Density (kg/m³)</th><th>Cp (J/kgK)</th><th>Area (m²)</th><th>Thermal mass (J/K)</th><th>Total C_{internal} (J/K)</th></tr>
<tr><td rowspan="4">Wood Floor</td><td>Wood planks (Trä-14)</td><td>0.020</td><td>500</td><td>2300</td><td rowspan="4">63.51</td><td rowspan="4">3118220</td><td rowspan="17">44265575</td></tr>
<tr><td>Wooden beams (Reglar600)</td><td>0.200</td><td>55</td><td>845</td></tr>
<tr><td>Styrofoam insulation</td><td>0.020</td><td>25</td><td>1400</td></tr>
<tr><td>Wood planks (Trä-14)</td><td>0.014</td><td>500</td><td>2300</td></tr>
<tr><td rowspan="4">Floor tiles</td><td>Styrofoam insulation</td><td>0.200</td><td>25</td><td>1400</td><td rowspan="4">18.58</td><td rowspan="4">4301965</td></tr>
<tr><td>Concrete</td><td>0.050</td><td>2300</td><td>800</td></tr>
<tr><td>Concrete</td><td>0.050</td><td>2300</td><td>800</td></tr>
<tr><td>Floor tiles</td><td>0.010</td><td>2700</td><td>1500</td></tr>
<tr><td rowspan="5">Walls</td><td>Gypsum</td><td>0.013</td><td>900</td><td>1100</td><td rowspan="5">164.20</td><td rowspan="5">31491508</td></tr>
<tr><td>Wooden beams (Reglar600)</td><td>0.100</td><td>55</td><td>845</td></tr>
<tr><td>Gypsum</td><td>0.013</td><td>900</td><td>1100</td></tr>
<tr><td>Concrete seal</td><td>0.0100</td><td>1800</td><td>800</td></tr>
<tr><td>Cellular concrete (LBTG400.100)</td><td>0.350</td><td>400</td><td>1050</td></tr>
<tr><td rowspan="4">Roof</td><td>Wood planks (Trä-14)</td><td>0.020</td><td>500</td><td>2300</td><td rowspan="4">117.00</td><td rowspan="4">5353883</td></tr>
<tr><td>Mineral Wool</td><td>0.350</td><td>37</td><td>840</td></tr>
<tr><td>Air</td><td>0.150</td><td>1.204</td><td>1006</td></tr>
<tr><td>Gypsum</td><td>0.013</td><td>900</td><td>1000</td></tr>
</table>

Substituting the final value in Equation 25:

$$\tau_b = \frac{C_{internal}}{H_t + H_v} = \frac{44\,265\,575\,\frac{\mathrm{J}}{\mathrm{K}}}{(98.86 + 71.55)\,\frac{W}{K}} = 259\,753.91\ s \rightarrow 3.006\ \approx 3\ days$$

The value of H_t is calculated with Equation 4, regarding only the U*A products with the figures obtained in the previous Appendix C. H_v is calculated with Equation 8, not accounting for heat recovery and air leakage terms.

Appendix D: Calculations for decreasing 2 ºC the indoor temperature.

For the behavior measure of decreasing 2 °C the inner temperature, the degree hours have been reduced since the $T_{balance}$ is equal to 16 °C and the hours below $T_{balance}$ is 7 198 h. Multiplying each with the respective temperature difference:

$$h = \sum_{i=1}^{T_{out_i} < T_{balance}} (\,|\, T_{out_i} - T_{balance} \,|\, \cdot 1\; hour) = 90\,466\ °C{\cdot}h$$

This value will affect significantly both ventilation and transmission losses.

Ventilation

Appendix Table 13. Summary of the ventilation loss figures of power and energy for both flow regulations at indoor temperature of 22 °C.

Ventilation out calculations (22°C)								
Room	Low flow (l/s)	Low flow (m3/s)	High flow (l/s)	High flow (m3/s)	Heat power out Low (kW)	Heat power out High (kW)	Energy low (kWh/year)	Energy High (kWh/year)
Upper Bathroom	5.100	0.005	10.400	0.010	0.272	0.533	558.833	1139.582
Lower Bathroom	4.300	0.004	8.800	0.009	0.213	0.480	471.173	964.262
Laundry room	3.500	0.004	8.200	0.008	0.213	0.426	383.513	898.517
Dressing room	1.640	0.002	3.280	0.003	0.107	0.160	179.703	359.407
Sauna	-	0.007	-	0.015	0.390	0.799	716.021	1597.277
Kitchen exhaust	38.000	0.038	82.700	0.083	2.025	4.423	462.566	1006.691

Total	**3.220**	**6.822**	**2771.810**	**5965.734**

Transmission

Appendix Table 14. Summary of the heat and energy parameters for different transmission surfaces for indoor temperature of 22 °C.

	Area (m^2)	**U ($\frac{W}{m^2K}$)**	**U · A ($\frac{W}{K}$)**	**Q (W)**	**Energy (kWh)**
External walls	164.200	0.169	48.767	2145.766	4411.816
Windows	34.440	1.250	43.050	1894.200	3894.583
Roof	117.000	0.090	10.530	463.320	952.612
Wood floor	63.514	0.176	11.178	491.852	1011.277
Tiles floor	18.583	0.178	3.308	145.542	299.243
Door	2.100	1.450	3.045	133.980	275.470
Total			**119.879**	**5274.660**	**10845.001**

The losses per ventilation and transmission will be reduced at 2 771.81 kWh/year and 10 845.00 kWh/year respectively. After applying the normal year correction, the values for transmission and ventilation are the following:

$$E_{Ntransmission} = 0.947 \cdot 10\,845.00 = 10\,270.21\ \frac{kWh}{year}$$

$$E_{Nventilation} = 0.947 \cdot 2\,771.81 = 2\,624.90\ \frac{kWh}{year}$$

Therefore, the energy balance for a normal year after this measure is the following:

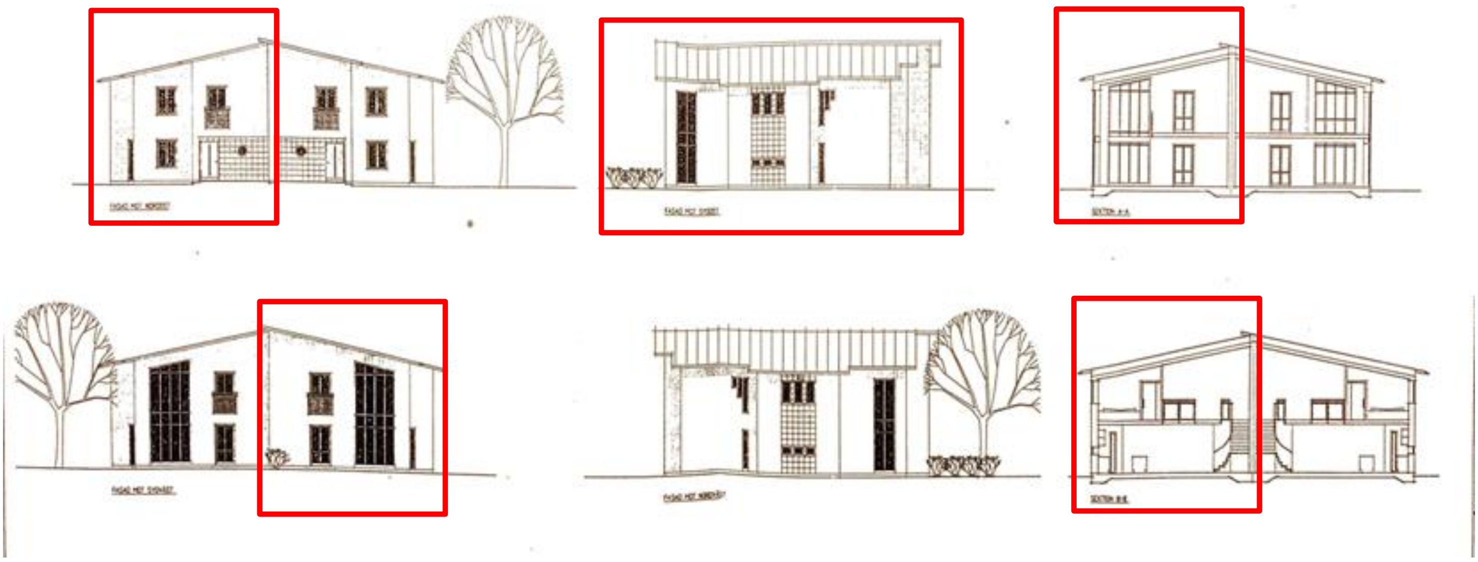
$$E_{in} = E_{Nspace\ heating} + E_{solar} + E_{people} + E_{appliances} = 18.03 + 8.95 + 0.55 + 1.46 = 28.99\ \frac{MWh}{year}$$

$$E_{out} = E_{Ntransmission} + E_{Nventilation} + E_{uncontrolled\ losses} + E_{hot\ water} = 28.99\ \frac{MWh}{year}$$

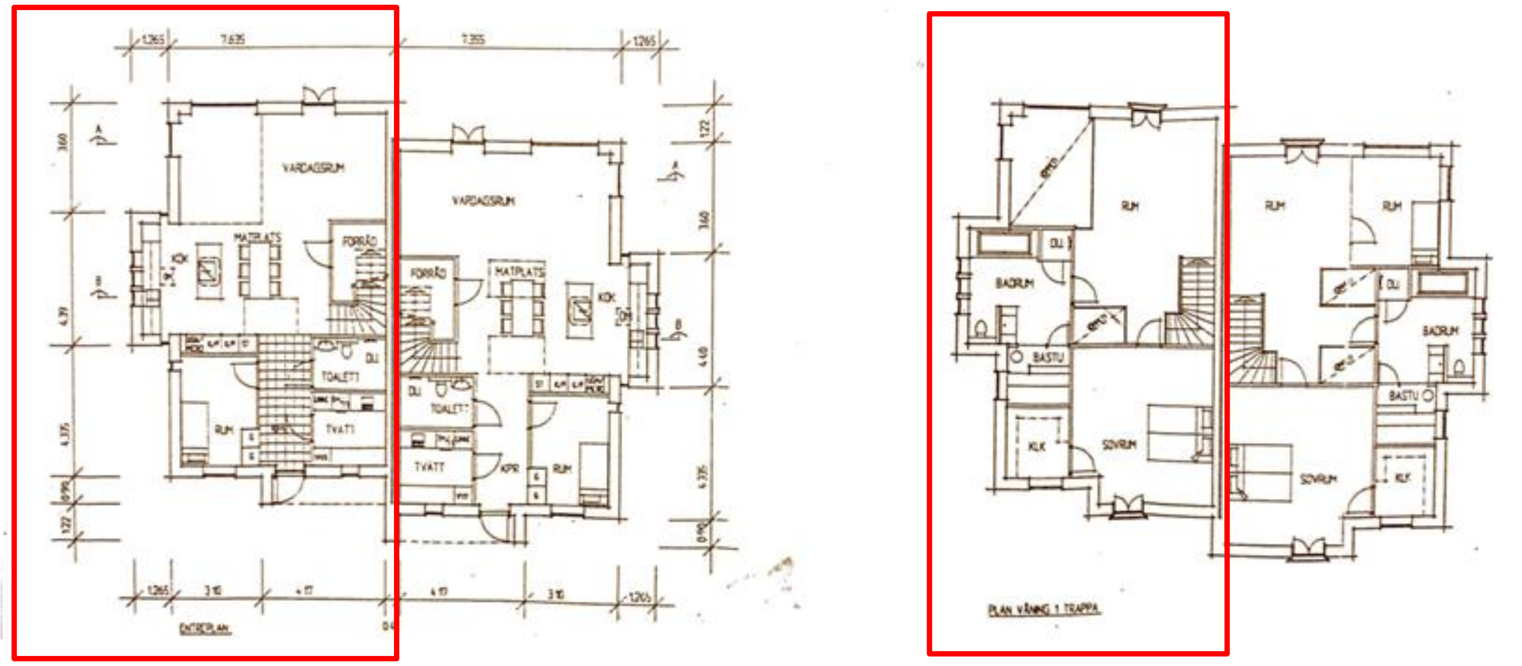
$$E_{out} = 10.27 + 2.62 + 1.41 + E_{uncontrolled\ losses} = 28.99\ \frac{MWh}{year}$$

$$E_{uncontrolled\ losses} = 14.69\ \frac{MWh}{year}$$

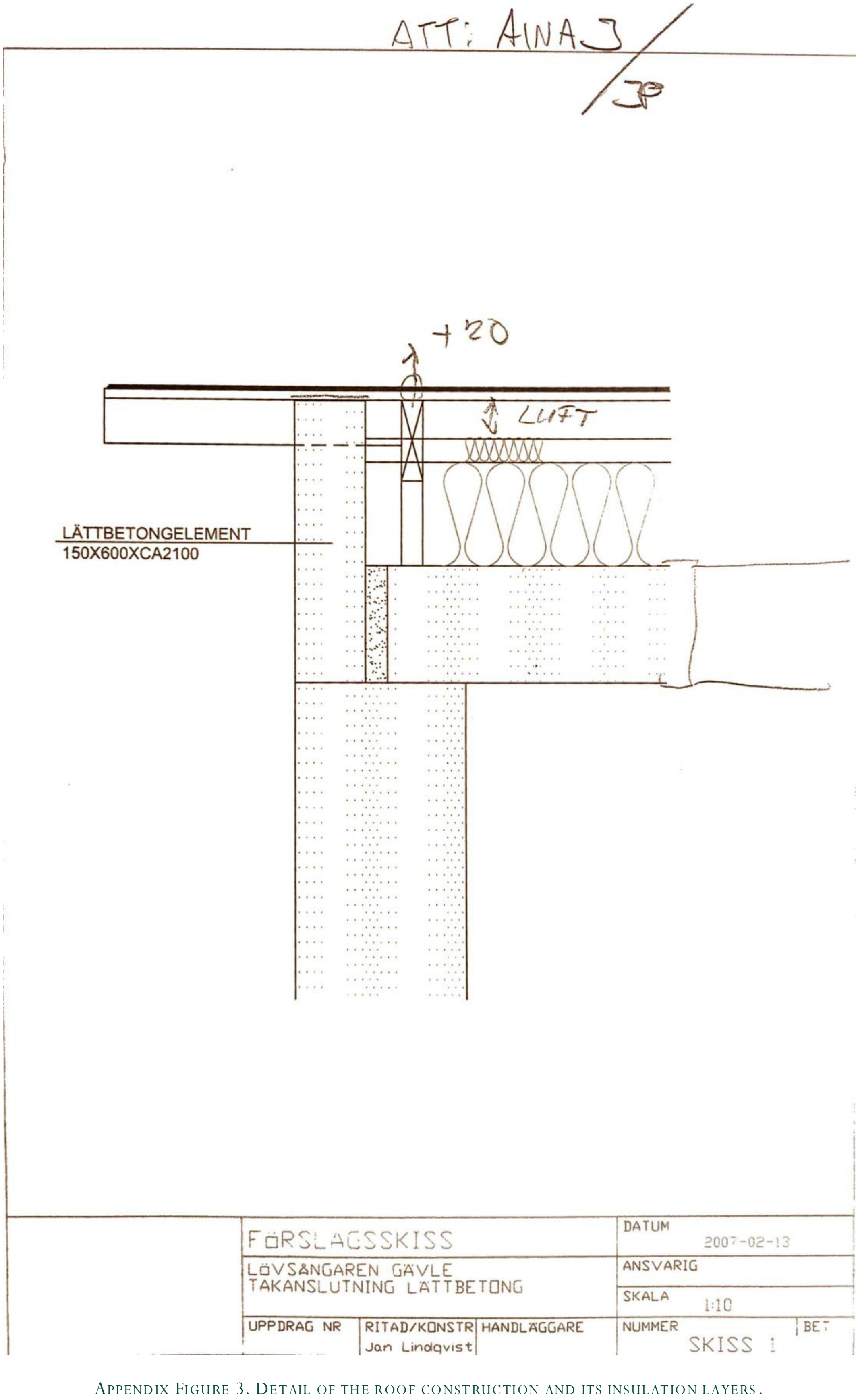
Appendix E: Blueprints for the study house



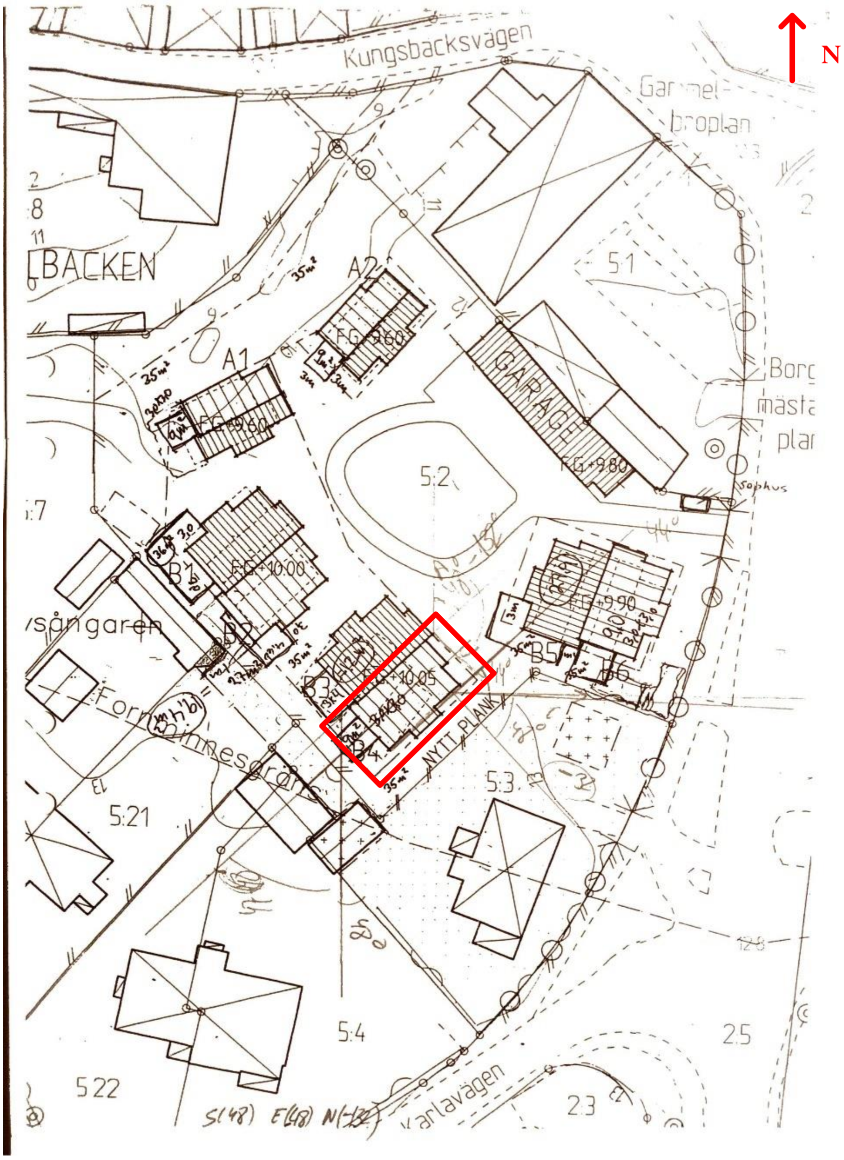
Appendix Figure 1. Front, side (East), back and sections views of the building. The red squares indicate which part is the semi-detached space of the study.



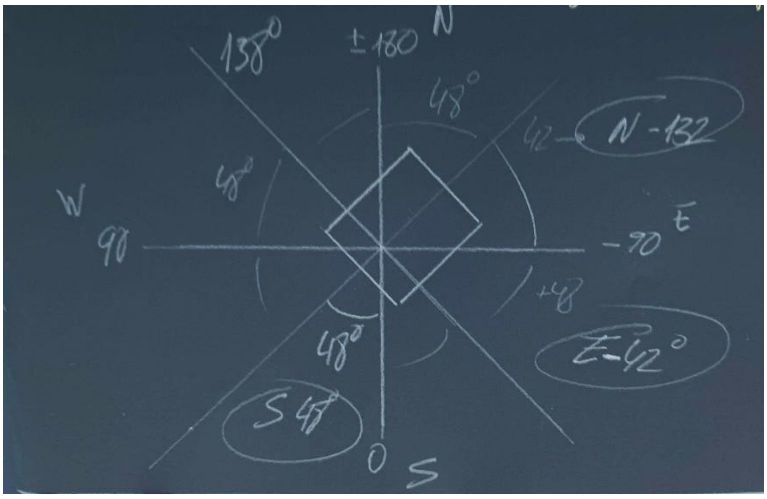
Appendix Figure 2. Floor plan of the building. left figure illustrates the ground floor. Right picture illustrates the second story. The red squares indicate which part is the semi-detached space of the study.



APPENDIX FIGURE 3. DETAIL OF THE ROOF CONSTRUCTION AND ITS INSULATION LAYERS.



Appendix Figure 4. Top view of the Borgmästarplan neighborhood in Gävle. The red square indicates which part is the semi-detached space of the study.



Appendix Figure 5. Orientations of the house deduced from appendix figure 4.

Appendix F: House parameters from building plans

INDATA Clima

Allmänt

Beräkningsdatum	2007-11-02 (13:12:45)
Beräkningsperiod - Dag	1 - 365
Klimatdata	BORLÄNGE
Latitud	60.4 grader
Klimatzon BBR12	NORR
Solreflektion från mark	20.00 %
Vindhastighet	70.00 % av klimatdata
Lufttryck	1000 hPa
Horisontvinkel mot markplan	S:20 SV:20 V:20 NV:20 N:20 NO:20 O:20 SO:20 °
Formfaktor för vindtryck	S:-0.60 SV:0.70 V:0.70 NV:0.70 N:-0.60 NO:-0.60 O:-0.50 SO:-0.60 TAK:0.00
Vridning av byggnad	0 °
Verksamhetstyp	Bostad
Antal lägenheter	2
Ventilationsvolym	0.0 m³
Uppvärmd bruksarea enl SS021052	331.2 m²
Markegenskap Värmeledningstal: Silt, icke dränerad sand ,icke dränerat grus.	2.3 W/m,K

Nota: floor Heating 12-(15)W/m²

Energipriser

Pris-grupp	Vecko-dagar	Dag-nummer	Tid	Värmeför-sörjning kr/kWh	Process-energi kr/kWh	Elför-sörjning kr/kWh	Fjärr-kyla kr/kWh
PRISTYP 1	MÅND-SÖND	1 - 365	0 - 24	0.70	1.00	1.00	1.00

Aktuellt Hus Paredes

Byggdelstyper 1-dimensionella - Katalog

Byggdelstyp	Material Från utsida till insida	Skikt-tjocklek m	Värme-ledningstal W/m²°C	Densitet kg/m³	Värme-kapacitet J/kg°C	U-värde W/m²°C	Delta-U-värde W/m²°C	Luftläck. q50 l/s,m²
Lätt innervägg	GIPSSKIVA	0.013	0.220	900	1100	0.363	0.010	0.80
	REGLAR600	0.100	0.041	55	845			
	GIPSSKIVA	0.013	0.220	900	1100			
Taktyp 1	TRÄ-14	0.020	0.140	500	2300	0.099	0.010	0.80
	MINERALULL36	0.350	0.036	37	840			
	GIPSSKIVA	0.013	0.220	900	1100			
Väggtyp 1	KCBRUK	0.010	1.000	1800	800	0.286	0.010	0.80
	LBTG400.100	0.365	0.110	400	1050			
GOLVVÄRME TRÄ	TRÄ-14	0.020	0.140	500	2300	0.169	0.010	0.80
	REGLAR600	0.200	0.041	55	845			
	CELLPLAST36	0.020	0.036	25	1400			
	VÄRMESKIKT							
	TRÄ-14	0.014	0.140	500	2300			
Golvtyp 2	CELLPLAST36	0.200	0.036	25	1400	0.173	0.010	0.30
	BETONG1.7	0.050	1.700	2300	800			
	VÄRMESKIKT							
	BETONG1.7	0.050	1.700	2300	800			
	KLINKER	0.010	3.500	2700	1500			
Golvtyp 1	CELLPLAST36	0.200	0.036	25	1400	0.170	0.010	0.30
	BETONG1.7	0.050	1.700	2300	800			

x dubble gips

Appendix Figure 6. Page 1 of different construction data from reports in 2006.

Byggdelstyper 1-dimensionella - Katalog

Byggdelstyp	Material Från utsida till insida	Skikt-tjocklek m	Värme-ledningstal W/m²°C	Densitet kg/m³	Värme-kapacitet J/kg°C	U-värde W/m²°C	Delta-U-värde W/m²°C	Luftläck. q50 l/s,m²
	VÄRMESKIKT							
	BETONG1.7	0.050	1.700	2300	800			
	TRÄ-14	0.014	0.140	500	2300			

Byggnadsdelar - Väggar, bjälklag (Paredes y vigas)

Benämning	Byggdelstyp	Orien-tering	Mängd Area m² Längd m	Sol-absorb-tion %	Lägsta nivå m	Högsta nivå m	Angränsande temp °C	Andel av effekt-behov %	U-värde med mark och d-U W/m²°C	Psi-värde W/m°C
	Taktyp 1	TAK	165.6m²	90.0	2.5	2.5		0	0.109	
	Väggtyp 1	SÖDER	71.0m²	70.0	0.0	2.5		0	0.296	
	Väggtyp 1	VÄSTER	71.0m²	70.0	0.0	2.5		0	0.296	
	Väggtyp 1	NORR	71.0m²	70.0	0.0	2.5		0	0.296	
	Väggtyp 1	ÖSTER	71.0m²	70.0	0.0	2.5		0	0.296	
1/2 Bottenplan	Golvtyp 1	PPM 1-6 m	82.8m²	0.0	0.0	2.5		25	0.134	
1/2 Bottenplan	Golvtyp 2	PPM 1-6 m	82.8m²	0.0	0.0	2.5		25	0.135	
	Lätt innervägg	INNER	400.0m²					0		
Övre plan	GOLVVÄRME TRÄ	INNER	165.6m²					50		

Byggnadsdelar - Fönster, dörrar, ventiler (ventanas, puertas y

Benämning	Byggdelstyp	Orien-tering	Area m²	Glas-andel %	Sol-transm. Total %	Sol transm. Direkt %	U-värde W/m²°C	Lägsta nivå m	Högsta nivå m	Luftläck. q50 l/s,m²	Sol-skydd
	Dörr	NORR	4.2	0	0	0	1.45	0.0	2.5	0.80	
	Fönstertyp 1	SÖDER	16.3/2	70	60	50	1.25	0.0	2.5	0.80	
	Fönstertyp 1	VÄSTER	16.3	70	60	50	1.25	0.0	2.5	0.80	
	Fönstertyp 1	NORR	16.3/2	70	60	50	1.25	0.0	2.5	0.80	
	Fönstertyp 1	ÖSTER	16.3	70	60	50	1.25	0.0	2.5	0.80	

Driftdata

Temp max y min.

Driftfalls-benämning	Vecko-dagar	Dag-nummer	Tid	Process-energi W/m²	Process-energi W/lgh	Process-energi varmv. W/m²	Fastig-hets-energi rumsluft W/m²	Person-energi W/m²	Tapp-varm-vatten W/m²	Tapp-varm-vatten W/lgh	Högsta rums-temp °C	Lägsta rums-temp °C
BOST 22	MÅND-SÖND	1 - 365	0 - 24	2.51	251.00	0.00	0.00	1.00	2.05	205.00	29.00	22.00

Ventilationsaggregat

Aggregat-benämning	Tilluft Fläkttryck Pa	Tilluft Verkn.gr %	Frånluft Fläkttryck Pa	Frånluft Verkn.gr %	Verkn.gr återvinning %	Lägsta tilluftstemp °C	Utetemp Driftp. L °C	Flöde Driftp. L %	Utetemp Driftp. H °C	Flöde Driftp. H %
F-vent	0.00	0.00	300.00	50.00	0.00	18.00	-20.0	100	20.0	100

Ventilationsaggregat - Drifttider och flöden

Aggregat-benämning	Vecko-dagar	Tilluft l/s	Frånluft l/s	Startdag-Slutdag	Starttid-Sluttid
F-vent					
	MÅND-SÖND	0.00	110.00	1 - 365	0 - 24

APPENDIX FIGURE 7. PAGE 2 OF DIFFERENT CONSTRUCTION DATA FROM REPORTS IN 2006.

Appendix G: Other relevant charts and data

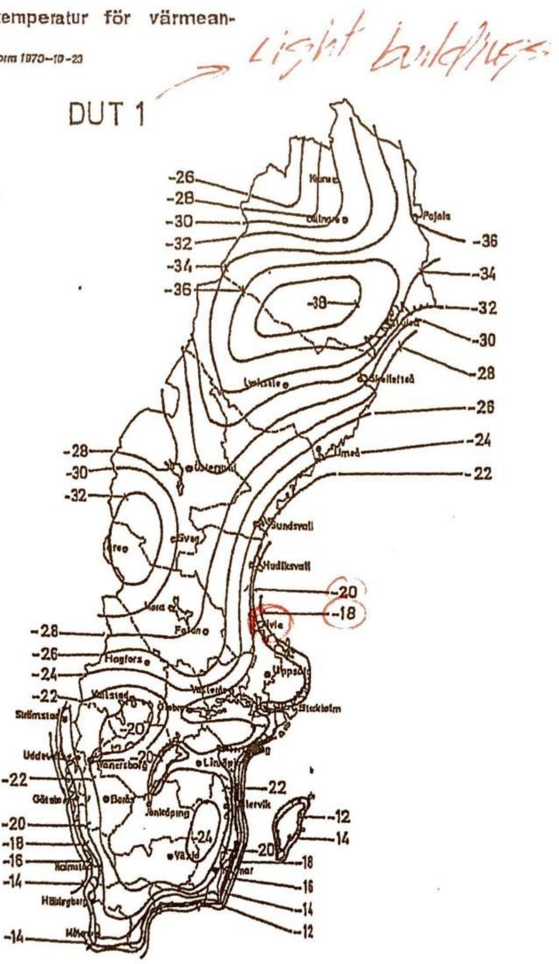
rologi och klimatologi

nperaturer vintertid

/:22

ionerande utetemperatur för värmean-
g, DUT 1 ⑩

6 figur 35:11 c, förslag till norm 1970–10–23



ionerande lägsta utetemperatur

'äkning av maximal erforderlig värmeeffekt an-
den dimensionerande utetemperatur, som erhålls
–1 eller 7:23–1 enligt följande:

byggnad med lätt väggkonstruktion (ytvikt< 100
n²) fastställs den dimensionerande temperaturen
Γ 1) med ledning av 7:22–1.

byggnad med tung väggkonstruktion (ytvikt>100
n²) fastställs den dimensionerande temperaturen
Γ 5) med ledning av 7:23–1.

DUT-värden enligt ovan korrigeras om ifrågava-
byggnad ligger på en plats, som bedöms vara kalla-
akten i genomsnitt.

är uppritad för byggnad med tidskonstanten R =
7:23–1 för byggnad med tidskonstanten R = 80 h.

Vid noggrannare värmebehovsberäkning interpoleras ett DUT-värde, om R ligger mellan 24 h och 80 h.

För byggnad med extremt lätt väggkonstruktion (ned mot 50 kg/m²) används lämpligen värdet DUT 1 minskat med 2° à 4°C beroende på R-värdets storlek.

I nu vanliga flervånings stenhus är tidskonstanten av storleksordningen 160 h hos innerrum och 100 h hos hörnrum (hörnrum har större avkylningsfaktor och därför mindre värmetröghet än innerrum). Vid mineralullsisolerade regelhus med träbjälklag är R av storleksordningen 30 h om inredningens och värmeanläggningens inverkan försummas.

Appendix Figure 8. DUT 1 map for light buildings in Sweden.

II:2.1.2 Dygnssummor den 15:e i varje månad av strålning mot vertikala ytor, Wh/m²dygn 151

Månad	Horisont-avskärmning,°	Vertikala ytans orientering N −180	−150	−120	E −90	−60	−30	S 0	30	60	W 90	120	150
Latitud 60° N													
Januari	0	130	130	160	550	1440	2360	2710.	2360	1440	550	160	130
	10	70	70	70	90	140	180	200	180	140	90	70	70
Februari	0	370	370	640	1550	2900	4280	4880	4280	2900	1550	640	370
	10	340	340	400	1030	2240	3530	4020	3530	2240	.1030	400	340
Mars	0	730	900	1720	3050	4520	5740	6320	5740	4520	3050	1720	900
	10	710	730	1290	2460	3920	5290	5970	5290	3920	2460	1290	730
April	0	1350	1990	3320	4750	5850	6370	6410	6370	5850	4750	3320	1990
	10	1170	1640	2810	4220	5420	6160	6390	6160	5420	4220	2810	1640
Maj	0	2350	3050	4460	5630	6150	5980	5730	5980	6150	5630	4460	3050
	10	1840	2570	3910	5130	5840	5920	5710	5920	5840	5130	3910	2570
Juni	0	3210	3870	5230	6190	6350	5820	5460	5820	6350	6190	5230	3870
	10	2420	3180	4570	5650	6070	5790	5430	5790	6070	5650	4570	3180
Juli	0	2830	3510	4910	5960	6280	5820	5580	5890	6280	5960	4910	3510
	10	2270	3020	4410	5540	6050	5870	5560	5870	6050	5540	4410	3020
Augusti	0	1700	2380	3720	5020	5850	6070	5970	6070	5850	5020	3720	2380
	10	1400	2020	3240	4550	5520	5950	5940	5950	5520	4550	3240	2020
September	0	900	1230	2200	3520	4820	5760	6130	5760	4820	3520	2200	1230
	10	880	1070	1930	3200	4530	5580	6080	5580	4530	3200	1930	1070
Oktober	0	510	530	1010	2110	3570	4960	5620	4960	3570	2110	1010	530
	10	470	480	650	1500	2850	4290	4870	4290	2850	1500	650	480
November	0	200	200	270	840	1910	3040	3480	3040	1910	840	270	200
	10	160	160	160	300	990	1590	1810	1590	990	300	160	160
December	0	80	80	80	350	1060	1770	2030	1770	1060	350	90	80
	10	40	40	50	60	90	120	130	120	90	60	50	40

Appendix Figure 9. Irradiation values for a latitude of 60°.

CALCULATION FACTORS FOR WINDOWS ACCORDING TO CLOUDY DAYS

MONTH	CALCULATION FACTOR
January	0.45
February	0.49
March	0.58
April	0.58
May	0.63
June	0,61
July	0,61
August	0,59
September	0.58
October	0.51
November	0.42
December	0.43

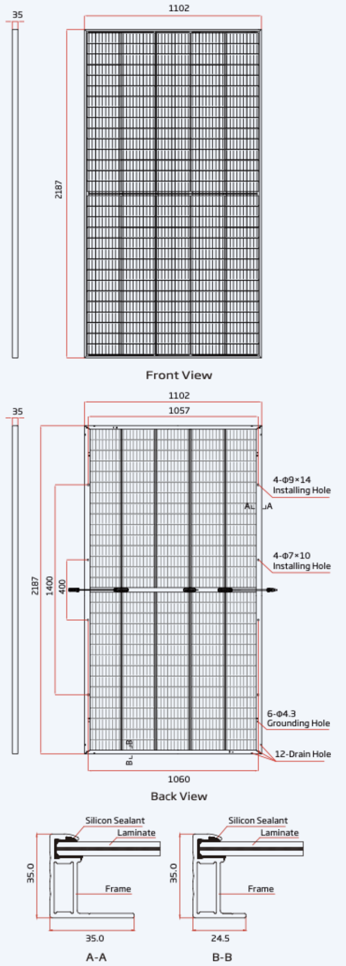
Appendix Figure 10. Cloudy factor for different months employed in the solar gains calculations.

Appendix H: Solar panel specification sheet

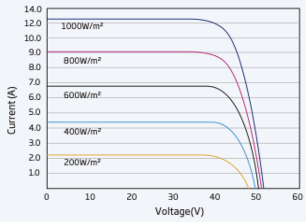
Vertex

BIFACIAL DUAL GLASS MONOCRYSTALLINE MODULE

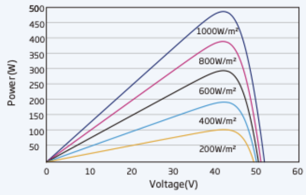
DIMENSIONS OF PV MODULE(mm)



I-V CURVES OF PV MODULE(490 W)



P-V CURVES OF PV MODULE(490W)



ELECTRICAL DATA (STC)

Peak Power Watts-P_{MAX} (Wp)*	480	485	490	495	500
Binning Tolerance-P_{MAX} (W)	0 ~ +5				
Maximum Power Voltage-V_{MPP} (V)	42.2	42.5	42.8	43.1	43.4
Maximum Power Current-I_{MPP} (A)	11.38	11.42	11.45	11.49	11.53
Open Circuit Voltage-V_{OC} (V)	50.7	50.9	51.1	51.3	51.5
Short Circuit Current-I_{SC} (A)	11.97	12.01	12.05	12.09	12.13
Module Efficiency η_m (%)	19.9	20.1	20.3	20.5	20.7

STC: Irradiance 1000W/m², Cell Temperature 25°C, Air Mass AM1.5.
*Measuring tolerance: ±3%.

Electrical characteristics with different power bin (reference to 10% Irradiance ratio)

Total Equivalent power -P_{MAX} (Wp)	514	519	524	530	535
Maximum Power Voltage-V_{MPP} (V)	42.2	42.5	42.8	43.1	43.4
Maximum Power Current-I_{MPP} (A)	12.18	12.22	12.24	12.29	12.34
Open Circuit Voltage-V_{OC} (V)	50.7	50.9	51.1	51.3	51.5
Short Circuit Current-I_{SC} (A)	12.81	12.85	12.89	12.94	12.98
Irradiance ratio (rear/front)	10%				

Power Bifaciality:70±5%.

ELECTRICAL DATA (NOCT)

Maximum Power-P_{MAX} (Wp)	362	366	369	373	377
Maximum Power Voltage-V_{MPP} (V)	38.7	40.0	40.2	40.5	40.7
Maximum Power Current-I_{MPP} (A)	9.11	9.15	9.18	9.22	9.26
Open Circuit Voltage-V_{OC} (V)	47.7	47.9	48.0	48.2	48.4
Short Circuit Current-I_{SC} (A)	9.65	9.68	9.71	9.74	9.78

NOCT: Irradiance at 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s.

MECHANICAL DATA

Solar Cells	Monocrystalline
No. of cells	150 cells
Module Dimensions	2187×1102×35 mm (86.10×43.39×1.38 inches)
Weight	30.1 kg (66.4 lb)
Front Glass	2.0 mm (0.08 inches), High Transmission, AR Coated Heat Strengthened Glass
Encapsulant material	POE/EVA
Back Glass	2.0 mm (0.08 inches), Heat Strengthened Glass (White Grid Glass)
Frame	35mm(1.38 inches) Anodized Aluminium Alloy
J-Box	IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm² (0.006 inches²), Portrait: 280/280 mm(11.02/11.02 inches) Landscape: 2000/2000 mm(78.74/78.74 inches)
Connector	MC4 EVO2 / TS4

TEMPERATURE RATINGS

NOCT(Nominal Operating Cell Temperature)	43°C (±2°C)
Temperature Coefficient of P_{MAX}	- 0.34%/°C
Temperature Coefficient of V_{OC}	- 0.25%/°C
Temperature Coefficient of I_{SC}	0.04%/°C

MAXIMUM RATINGS

Operational Temperature	-40~+85°C
Maximum SystemVoltage	1500V DC (IEC)
Max Series Fuse Rating	25A

(Do not connect Fuse in Combiner Box with two or more strings in parallel connection)

WARRANTY

12 year Product Workmanship Warranty
30 year Power Warranty
2% first year degradation
0.45% Annual Power Attenuation

(Please refer to product warranty for details)

PACKAGING CONFIGURATION

Modules per box: 31 pieces
Modules per 40' container: 620 pieces

Appendix Figure 11. TSM-DEG18MC.20 Solar panel specification sheet. Source: TrinaSolar.com.

Appendix I: Inverter specification sheet

DATASHEET

5K-2P-N

Residential Hybrid Inverter

Inverter Model:	Sol-Ark-5K-48-ST
SKU:	5K-2P
Input Data (PV)	
Max. Allowed PV Power (STC)	6,500W
Rated MPPT Operating Voltage Range	175 - 425V
MPPT Voltage Range	150 - 500V
Startup Voltage	125V
Max. Input Voltage [1]	500V
Max. Operating Input Current per MPPT	10A (self-limiting)
No. of MPP Trackers	2
No. of PV Strings per MPPT	2
Max. AC Coupled Input	9,600W
Output Data (AC)	
Nominal AC Voltage	120/240V, 120/208V, 220V
Grid Frequency	50 / 60Hz
Real Power, max continuous	5,000W
Max. Output Current	20.8A
Peak Apparent Power (10s, off-grid)	16,000VA @ 240V
Peak Apparent Power (100ms, off-grid)	25,000VA @ 240V
Max Output Fault Current (100ms)	104A
Max. Grid Passthrough Current	63A
Power Factor Output Range	+/- 0.9 adjustable
Backup Transfer Time	4ms
CEC Efficiency	96.5%
Max Efficiency	97.5%
Design (DC to AC)	Transformerless DC
Stackable	No
Battery Input Data (DC)	
Battery Technologies	Lithium / Lead Acid
Nominal DC Voltage	48V
Operating Voltage Range	43 - 63V
Capacity	50 – 9900Ah
Max. Battery Charge / Discharge Current	120A
Charging Controller	3-Stage with Equalization
Grid to Battery Charging Efficiency	96.0%
External Battery Temperature Sensor (BTS)	Included
Automatic Generator Start (AGS)	2 Wire Start - Integrated
BMS Communication	CANBus & RS485 MODBUS
General Data	
Dimensions (H x W x D)	750 x 450 x 254 mm (29.5 x 17.7 x 10 in)
Weight	35.4 kg / 78 lb.
Enclosure	IP65 / NEMA 3R
Ambient Temperature	-25~55°C, > 45°C Derating
Noise	< 30 dB @ 25°C (77°F)
Idle consumption - No Load	60W
Communication and Monitoring	Wi-Fi & LAN Hardware Included
Standard Warranty	10 Years
Protection and Certifications	
Certifications and Listings	UL1741-2010/2018, IEEE1547a 2003/2014, FCC 15 Class B, UL1741SB, CA Rule 21, HECO Rule 14H
PV DC Disconnect Switch – NEC 240.15	Integrated
Ground Fault Detection – NEC 690.5	Integrated
PV Rapid Shutdown Control – NEC 690.12	Integrated
PV Arc Fault Detection – NEC 690.11	Integrated
PV Input Lightning Protection	Integrated
PV String Input Reverse Polarity Protection	Integrated
AC Output Breaker - 63A	Integrated
250A Battery Breaker / Disconnect	Integrated
Surge Protection	DC Type II / AC Type II

1. See Installation Guide for more details on sizing array strings. The highest input voltage is based on the open-circuit voltage of the array at the minimum design temperature.

Appendix Figure 12. 5K-2P-N inverter specification sheet. Source: SolArk.com.

Appendix J: Monitoring system specification sheet

Product datasheet

Specifications

PowerLogic, Power and energy meter PowerLogic PM5350 with THD, alarming

METSEPM5350

Main

Range	PowerLogic
Product Name	PowerLogic PM5350
Device Short Name	PM5350
Product Or Component Type	Power meter

Complementary

Power Quality Analysis	total demand distortion total harmonic distortion
Device Application	Power monitoring
Type Of Measurement	Current Voltage Frequency Power factor Energy Phase angle Apparent power Active power Reactive power
Supply Voltage	85...265 V AC 45...65 Hz 100...300 V DC
Network Frequency	50 Hz 60 Hz
[In] Rated Current	5 A 1 A
Type Of Network	1P + N 3P + N 3P
Maximum Power Consumption In Va	11.9 VA
Ride-Through Time	100 ms 120 V AC typical 400 ms 230 V AC typical 50 ms 125 V DC typical
Display Type	Monochrome graphic LCD
Display Resolution	6 lines
Sampling Rate	32 samples/cycle
Measurement Current	5…9000 mA
Analogue Input Type	Current 0.05...9 A (impedance <= 0.3 mOhm) Voltage (impedance 10 MOhm)
Measurement Voltage	35…480 V AC 45...65 Hz phase to phase 20…277 V AC phase to neutral
Frequency Measurement Range	45…70 Hz

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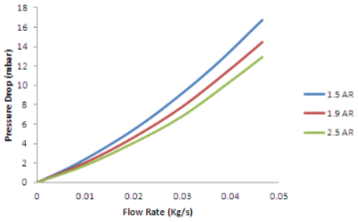
Appendix Figure 13. PM5350 Monitoring system specification sheet. Source: Se.com.

Appendix K: Thermal collector specification sheet

Pressure Drop



AES Solar EST. 1979

	1.5 AR	1.9 AR	2.5 AR
Gross Area	1.5m²	1.9m²	2.5m²
Height	1300mm	1650mm	2150mm
Width	1150mm	1150mm	1150mm
Thickness	70mm		
Aperture Area	1.38m²	1.76m²	2.31m²
Weight	23Kg	28Kg	35Kg
Absorber	Aluminium Fins metallurgically bonded to rhombic copper waterways providing large water to wall contact for maximum heat transfer. Sputter coated selective surface: solar absorption = 96%±2, thermal emission = 7%±2.		
Glazing	Low iron solar glass. 3.2mm thick. Double sided anti reflective surface. Matt/matt textured surface. Tempered according to EN 12150. Solar transmission $95.5\%^{+2}_{-1.5}$		
Frame	Custom designed aluminium extrusion with all round fixing channels and sliding nuts for easy fitting. Coloured RAL 7012 dark grey.		
Insulation	Rigid PIR foam, manufactured with zero ODP. Class O fire rating. Thermal conductivity 0.021W/mK		
Flow & Return Connections	Flow = 15mm copper pipe. Return = AES connection kit including external sensor pocket required – connection is to 15mm copper compression fitting.		
Fluid Content	0.86L	1.03L*	1.29L
Recommended Flow Rate	0.25 – 1 L/min/m²		
Transfer Fluid	Premixed solar antifreeze with inhibitors. (100% Tyfocor antifreeze mixture recommended)		
Max. Working Pressure	10 bar (tested to 15 bar)		
Zero loss Efficiency, η	0.788	0.785*	0.781
Heat loss coefficient	a_1= 5.028, a_2= 0.009	a_1= 4.621*, a_2= 0.014*	a_1= 4.021, a_2= 0.022
Peak Power Output (at irradiance of 1000W/m²)	1.082kW	1.372kW*	1.808kW
Tilt angle range	20° - 90°		
Stagnation Temperature	170.1°C		
Maximum snow loading	≤2.4kN/m²		
Maximum wind loading	≤1.2kN/m²		
Testing	ISO EN 9806 by CENER, Spain. Solar Keymark certification by DIN CERTO, Germany.		
Certification	Solar Keymark - registration number: 011-7S2383 F		
Life expectancy	In excess of 25 years		
Warranty	10 Years		
Applications	Small to large domestic hot water systems, industrial process and swimming pool heating.		

*Interpolated from test data for 1.5 AR and 2.5 AR models

Design | Manufacture | Install | Commission | Service

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Appendix Figure 14. 1.5 AR Solar Collector specification sheet. Source: AESSolar.co.uk.