Master Level Thesis

Energy Efficient Built Environment

No.20, Jun 2020

Energy performance simulation of different ventilation systems in Sweden and corresponding compliance in the LEED Residential Rating System

HÖGSKOLAN DALARNA

MASTER THESIS

Master thesis 15 credits, 2020
Energy Efficient Built Environment

Author:
Patrick Boyle

Supervisors:
Jingchun Shen

Examiner:
Csilla Gál

Course Code: EG3020

Examination date: 2020-06-17

Dalarna University
Energy Engineering

Abstract

The importance of energy efficiency in the operation of the built environment is becoming increasingly important. Energy use in the building sector has exceeded both transportation and industry, while within buildings heating, ventilation, and air conditioning has the greatest share. In light of the recent pandemic forcing governments to issue quarantines and stay-at-home orders people are spending even more time indoors, this further emphasizes the importance of proper ventilation and the impacts on energy use.

The purpose of this research was to perform a case study of a low environmental impact demonstration house to compare the energy performance of various ventilation strategies. The ventilation strategies varied by overall airflow rate, control strategy, and the presence of heat recovery.

Performance was evaluated by establishing a model in IDA ICE, an equation-based modeling tool for the simulation of indoor thermal climate and energy use. The results showed energy savings due to demand-control with a reduction of 12.5%. Results also showed similar savings with a heat recovery system, indicating that any savings in heat loss due to heat recovery is at the expense of increased auxiliary energy. In this particular case, the benefit of upgrading to a heat recovery system from simple demand control set up is not readily apparent.

Results also demonstrated trends and possible complications useful to future research plans that aim to measure real world ventilation performance, including how differences in the number and location of sensors impact the efficacy of the demand-controlled systems.

A secondary aim was to observe how a newly constructed, low environmental impact home built in Sweden performs according the residential LEED energy budget. The results demonstrated that constructing a house using low impact materials with low embodied energy does not have to negatively impact energy performance, scoring extremely well in the Energy and Atmosphere category of a widely used sustainable building rating system.

Contents

Abbreviations

Abbreviation	Description
BBR	Boverkets Byggregler
Btu	British Thermal Unit
CO_2	Carbon Dioxide
DCV	Demand-controlled Ventilation
HDD	Heating Degree Days
HERS	Home Energy Rating System
HVAC	Heating, Ventilation, and Air Conditioning
IDA ICE	IDA Indoor Climate and Environment
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
USGBC	United States Green Building Council
VOC	Volatile Organic Compounds
Wh	Watt-hour

Nomenclature

Symbol	**Description**	**Unit**
RH	Relative humidity	%

1 Introduction

1.1 Background

The importance of energy efficiency in the operation of the built environment becomes clear when looking at a few simple trends in energy use. Historically, over the last few decades, total global energy use has increased every year, with an average annual increase of about 2% [1]. On a planet of finite boundaries and dwindling resources perpetual growth of this magnitude is, by definition, unsustainable. Of this total energy the building sector has increased its share in recent years, exceeding both transportation and industry, and with the amount of time spent indoors and desired comfort levels increasing there is reason to believe this share will continue to rise. Looking even further it can be seen that heating, ventilation, and air conditioning (HVAC) systems consume the greatest energy within the building industry [1].

It goes without saying that reducing energy consumption in HVAC systems is of utmost importance and increasing energy efficiency of ventilation is an important step in this reduction. Both the type of ventilation system (e.g. natural vs. mechanical, with heat recovery vs. without) and the control strategy (e.g. fixed exhaust vs. demand-controlled) have large impacts on the energy use of a building. The applicability and efficacy of different control strategies can vary from country to country based on climate conditions as well as local building regulations. Proper energy performance simulation can begin to shed light on the impacts of these systems.

With an abundance of cheap fossil fuel energy and public resistance to progressive building regulations economics and government intervention alone are not enough to sufficiently reduce energy consumption. One measurement of a buildings energy efficiency and overall environmental impact that is becoming increasingly popular is third party sustainable building rating systems. Many countries are adopting independent rating systems in order to provide a benchmark greater than that of the current regulations. Not only do these systems give a framework for measuring the sustainability of a project, they also act as a market transformation tool giving designers and developers a way of communicating to the public, and to contractors and suppliers, of their environmentally conscious intentions.

The most commonly used rating system in North America, and quickly becoming adopted worldwide, is Leadership in Energy and Environmental Design (LEED). LEED was first introduced in 1998 by the U.S. Green Building Council (USGBC) and has released several editions to date, operating today under the fourth version (v4) [4]. The USGBC is a nonprofit organization financed entirely by members and member organizations. The original intentions of the organization focused on rating systems but has since expanded its reach to education, professional credentials, community engagement, and advocacy campaigns.

The LEED rating system attempts to be as inclusive as possible by separating the system into 5 categories, including building design, interior design, building operation and maintenance, homes, and neighborhood development. These categories are further broken down into 21 different rating systems depending on the type of project, such as school, retail, healthcare, etc. Each rating system however has the same general framework consisting of prerequisites and credits in five basic categories: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Material and Resources, and Indoor Environmental Quality. There are two additional categories, Innovation and Regional Priority, which vary project to project. After meeting prerequisite requirements and earning credits in each of the categories the total number of points is calculated and one of four possible rating levels, Certified, Silver, Gold, or Platinum, is awarded [4].

1.2 Aims and Objectives

The aim of this study is two-fold, to perform a case study of the ventilation system in a single-family house in Sweden and to evaluate the house itself using an accepted sustainable building rating system. The overall aim of the study is to compare the following ventilation systems using a dynamic building performance and energy simulation software:

- Fixed mechanical extraction ventilation
- Occupancy-controlled ventilation
- Demand-controlled ventilation (DCV)
- DCV with heat recovery

More specifically, to fulfill this aim the objectives of the research are to simulate the energy performance of the different ventilation systems, then to fulfill a secondary aim, verify each systems ability to satisfy the annual energy use requirement according to the LEED energy budget, and to compare the systems using the subsequent LEED energy credits. By using LEED energy credits as a basis for comparison a secondary objective can be fulfilled: to observe how the energy performance of a newly constructed, low environmental impact, ‘sustainable’ home built in Sweden compares to the typical reference home in the LEED Residential Single Family Home rating system [13].

2 Literature Review

2.1 Dalarnas Villa

The house in question in this study, named Dalarnas Villa, was built by the insurance company Dalarnas Försäkringsbolag with the help of Dalarna University and local vocational training schools. Dalarnas Villa, seen in Figure 2.1 was built with the intention of being a demonstration house to research fire, burglary, and water damage as well as sustainable construction with low environmental impact [18]. The house is a two-story single-family home with three bedrooms and two bathrooms, plus a detached two car garage. It is located in a rural subdivision on the outskirts of Borlänge in central Sweden.

Figure 1.1. Dalarnas Villa During Winter [19]

Dalarnas Villa has already been the subject of several other reports. The most relevant to this study is the master's thesis by Ahmad and Garman [2] which analyzed one of the target ventilation systems that will be the focus of this study, yet from an indoor air quality point of view rather than energy. The purpose of the study was to determine the overall performance of the demand-controlled ventilation (DCV) compared to fixed exhaust ventilation with the required ventilation rates according to Swedish regulations. Indoor air quality was monitored over a period of 24 hours among a total of 5 different ventilation modes. Three modes were operated with fixed ventilation rates of 0.35 $l/s{\cdot}m^2$ from all zones, 0.35 $l/s{\cdot}m^2$ from wet rooms only, and 0.47 $l/s{\cdot}m^2$ from all zones. One mode operated with two stepped rates triggered by occupation status (0.13 or 0.47 $l/s{\cdot}m^2$). A final mode operated with varying airflow rates based on carbon dioxide (CO_2), humidity, and volatile organic compounds (VOCs) levels (ranging from 0.14 to 0.47 $l/s{\cdot}m^2$). The CO_2 levels were measured by air monitors throughout the house as well as sensors integrated with the air handling unit. Using CO_2 readings, the study determined that the demand-control ventilation maintained indoor air quality comparable to the fixed ventilation yet with about 33% less air volume exchanged, representing a 33% heat loss reduction over the test period.

There are several studies with a similar objective, analyzing the relationship between energy savings and varying operating conditions when implementing demand-controlled ventilation. Pollet et al. [6] aimed to compare the indoor air quality and energy consumption of two different demand-controlled ventilation modes to fixed mechanical extract ventilation, mechanical extract ventilation with heat recovery, and natural ventilation. The ventilation strategies were simulated using Contam, a program mainly used for indoor air quality and ventilation analysis. The case study, a two-story detached single-family home of about 160 m^2, was very comparable to Dalarnas Villa. Three locations were used for climate data in Pollet's study, one in Belgium and two in the United Kingdom, and ventilation rates were determined according to Belgian and British standards, respectively. Results showed the demand-controlled ventilation required about half the total energy when compared to traditional mechanical extraction, reducing both heat losses and auxiliary energy, and roughly the same total energy as the ventilation with heat recovery. The study went further to compare the costs of ventilation systems, but results depend on local energy rates.

Research by Nielsen and Drivsholm [7] analyzed a simple modification adding demand-controlled ventilation to an existing air handling unit. Measurements were taken in the air handling unit to assess indoor air quality compared to the original fixed mechanical extraction ventilation. The demand-controlled mode consisted of two ventilation rates, a high of 0.35 $l/s \cdot m^2$ and a low of 0.1 $l/s \cdot m^2$, based on Danish regulations and EN minimums for unoccupied offices buildings. High and low rates were controlled by a series of different threshold differences in CO_2 and humidity between the outdoor air and the exhaust air. The optimum threshold value determined that the lower rates could operate 37% of the time without any significant reductions in indoor air quality, implying a 35% reduction in fan energy use.

Another study using Dalarnas Villa as a subject was the life cycle assessment (LCA) performed by Petrovic et al. [3] analyzing global warming potential and primary energy of a typical wooden single-family house in Sweden. The main conclusion of the study was that based on a 100-year lifespan the total emissions of the house are 6 kg CO2e/m2 /year, and that this relatively low impact is due to the use of wood based materials when compared to non-wood based materials. More interesting in relation to this study were the resulting shares of the different processes, or stages. While it was mentioned in the introduction of this report that the operation of buildings comprises a large share of the energy use in the building sector the LCA found that the energy during the in-use stage was responsible for a relatively low impact (21% of total emissions). This is mainly due to the Swedish electricity mix relying on lower carbon emitting energy sources, such as waste heat, and the fact the heat source was a ground source heat pump with a large coefficient of performance.

In terms of the building model the majority of the properties were gathered from the LCA study for further energy simulation in IDA ICE. Basic geometry and layout used for the model of Dalarnas Villa were pulled from the building plans and specifications from the designer Fiskarhedenvillan, which were originally compiled for the LCA.

2.2 LEED

There has been debate concerning the efficacy of sustainable building rating systems; studies have been conducted comparing different systems, their applicability to different types of projects in different locales, their effect on occupant satisfaction, and (of most concern to this report) their effect on energy usage.

Guy, Mancini, and Birt [5] conducted one such study focusing particularly on LEED certified buildings and their energy savings. When looking at actual measured energy use the study found in general LEED-certified buildings used less energy per square foot than similar conventional buildings (18-39%) yet a substantial number of certified buildings (28-35%) used more energy than similar conventional buildings. Since the study used measured data it also compared energy use to the rating level (Certified, Silver, Gold, or Platinum) and to the number of credits in the energy category, both determined prior to the building's completion. Interestingly the analysis found no correlation between the rating level or energy credits and the measured energy use, implying that the system, as a whole, contributes to energy use reductions but with some issues in consistency and credit allocation.

3 Materials and Methods

3.1 Energy Performance Simulation

Energy simulation was conducted using the IDA Indoor Climate and Energy (IDA ICE). The IDA simulation technology was originally developed in the 1980s at the Swedish Institute of Applied Mathematics. In the 1995 the private software company EQUA Simulation was founded in Stockholm where the IDA technology was further developed into IDA ICE to be released in 1998 [9]. IDA ICE is an equation-based modelling tool for the simulation of indoor thermal climate and energy use.

The study methodology is as follows:

1. Establishing the basic building geometry and material properties based on the information from the LCA study by Petrovic et al. [3].
2. Refining the building model with the help of additional building plans from Fiskarhedenvillan originally compiled for the LCA. Screenshots of the floor plan and 3D model from IDA ICE can be seen in Figure 3.1.
3. Collecting glazing and door geometries from site-specific plans (see Appendix A) and setting envelope materials taken from the Fiskarhedenvillan typical envelope detail (see Appendix B), with some modifications. Here, the original aim of building Dalarnas Villa and the subsequent LCA studies [3] was to minimize the environmental impact of the building by reducing energy use as well as using low impact building materials. Blown-in cellulose fiber insulation in the external walls and roof and wood wool insulation in the internal walls were used in place of typical rock wool. Material properties of both alternative materials were found in a study by Hurtado et al. [8].
4. Inputting default values in IDA ICE for all other common materials throughout the house. The model building data resulting from these values and other defaults in IDA ICE can be seen in Figure 3.2.
5. Assuming all relevant user input data based on recommendations from the Sveby guidebook [10]. All relevant input data can be found in Table 3.3.
6. Uploading the climate data file containing historical climate data from the Sveby guidebook [10].
7. Altering the air handling unit in the baseline model to represent the 4 main control strategies (7 total models including variants). The ventilation control types are described in Table 3.1.

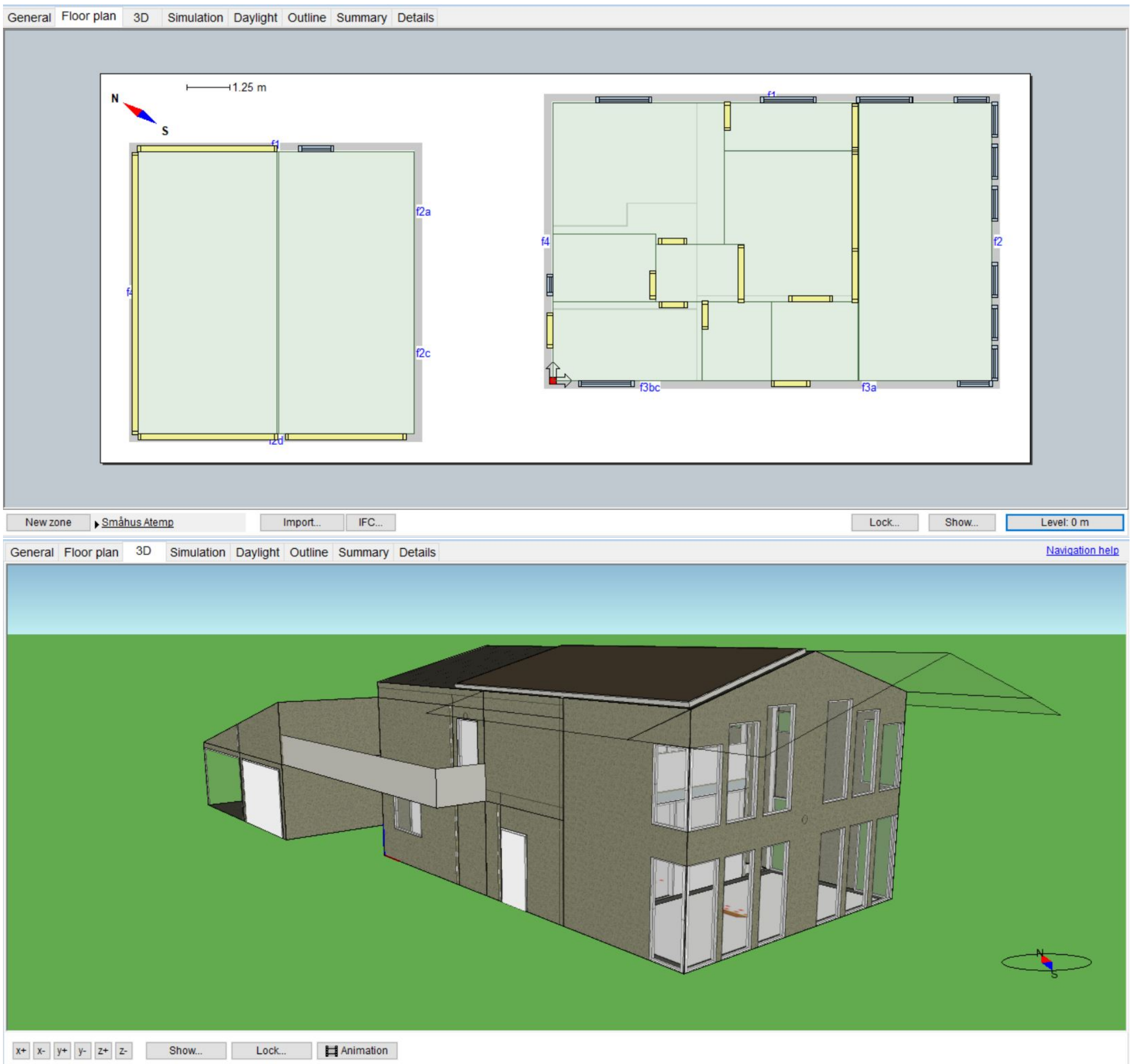


Figure 3.1 Floor Plan and 3D model in IDA ICE.

Input data Report

Building	
Model floor area	150.4 m^2
Model volume	863.0 m^3
Model ground area	176.5 m^2
Model envelope area	731.3 m^2
Window/Envelope	7.2 %
Average U-value	0.2785 W/(m^2 K)
Envelope area per Volume	0.8474 m^2/m^3

Figure 2. IDA ICE Building Data

Table 3.1. Variant Type Description

Variant Type	Description
Type 1A	*Fixed exhaust ventilation* with the baseline rate according to BBR requirement through extraction from all zones.
Type 1B	*Fixed exhaust ventilation* with baseline rate according to BBR requirement through extraction from wet rooms only (kitchen and bathrooms)
Type 1C	*Fixed exhaust ventilation* at rate of 130% of BBR requirement with extraction from all zones.
Type 2	*Occupancy controlled ventilation* (exhaust only) with rates of 100% of BBR requirement when occupied and 30% of BBR requirement as a background rate during unoccupied period
Type 3A	*Demand-controlled ventilation* (exhaust only) with high and low rates (30%/100% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide (CO_2) in dry rooms and relative humidity (RH) in wet rooms
Type 3B	*Demand-controlled ventilation* (exhaust only) with high and low rates (30%/130% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide (CO_2) in dry rooms and relative humidity (RH) in wet rooms.
Type 4A	*Demand-controlled ventilation* (supply and return) and heat recovery with high and low rates (30%/100% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide (CO_2) in dry rooms and relative humidity (RH) in wet rooms. All dry zones set to a single sensor.

The baseline ventilation rate was chosen according to the BBR requirement for a minimum flowrate of 0.35 l/(s·m2) of floor area. The lower overall airflow rate for zones that are unoccupied (Type 2) or below CO_2 thresholds (Types 3 and 4) was chosen according to the BBR minimum for unoccupied dwellings when operating under demand-control. A summary of the variant parameters can be found in Table 3.2. Thresholds for all demand-controlled scenarios were 950 ppm for CO_2 and 45% for relative humidity. Control strategies and their respective ventilation rates followed the scenarios in previous studies on Dalarnas Villa by Ahmad and Garman [2] as closely as possible. This was done in order for future studies and measurements to be compared to simulation results. Future studies will be discussed further in the conclusion of this report.

Table 3.2. Ventilation Variant Parameters

Variant Type	Extraction Rate, l/(s·m2)	Control Strategy	Extraction Location
1A	0.35	Fixed	All zones
1B	0.35	Fixed	Kitchen and bathrooms
1C	0.455	Fixed	All zones
2	0.105/0.35	Occupancy	All zones
3A	0.105/0.35 0.35/0.455	Demand (CO2/RH)	All zones
3B	0.105/0.455 0.35/0.455	Demand (CO2/RH)	All zones
4A	0.105/0.35 0.35/0.455	Demand (CO2/RH)	All zones
4B	0.105/0.35 0.35/0.455	Demand (CO2/RH)	All zones

An additional difference between the control strategies of Types 3A/3B and Type 4A is the location of the sensor. In practice, the demand-controlled exhaust ventilation uses individual sensors in the exhaust of each zone while the heat recovery system has only one sensor in the air handling unit taking measurements from the aggregate exhaust from all zones. Without standard settings in IDA ICE for aggregating the exhaust of all zones the heat recovery system sensor was simulated by keeping all doors open and every dry room control set to the measurements of the living room (the largest zone by volume within the house) while keeping wet rooms on individual sensors. This caused some complications, so an additional variant, Type 4B, was run with sensors identical to Types 3A/3B and with the doors closed. The complication and effects of this difference will be discussed further in the conclusion.

The majority of the input data regarding the behavioral and operational assumptions were taken from the Brukarindata Bostäder (user housing data) report published by the Sveby program (standardization and verification of energy performance for construction costs) [10]. The series of Sveby input guidebooks were specially developed in order to establish standard inputs for the simulating and calculating of energy performance in accordance with the Swedish buildings regulations Boverkets Byggregler (BBR). The Sveby guidebooks compile and summarize data from studies across Sweden analyzing inhabitant behavior to establish a standard user and their effect on energy and water usage. The input data from these publications plus the information from the LCA [3] can be found below in Table 3.3. In addition to the ground source heat pump (specifications of which were gathered from the LCA study) a wood stove is located in the living room. Top-up heat in the form of district heating was provided when necessary.

Table 3.3 Input Parameters

Input	Value	Unit	Reference
Air Tightness (q50)	0.18	$l/(s \cdot m^2)$	Petrovic [3]
Time Constant	62	hours	Petrovic [3]
Indoor Temperature	21	°C	Sveby [10]
Occupants	3.5	persons	Petrovic [3]
Occupancy	14	hrs/day/person	Sveby [10]
Internal Gains (occupancy)	80	W/person	Sveby [10]
Household Electricity	30	$kWh/m^2/year$	Sveby [10]
Domestic Hot Water	20	$kWh/m^2/year$	Sveby [10]
Conditioned Floor Area (A_{temp})	150.4	m^2	Petrovic [3]
Building Envelope (A_{om})	446.5	m^2	Petrovic [3]
Ground Source Heat Pump	5.3	kW	Petrovic [3]
COP, 0/35°C	4.62	-	Petrovic [3]
COP, 0/45°C	3.44	-	Petrovic [3]
COP, 0/55°C	2.64	-	Petrovic [3]

3.2 LEED Rating

As a single-family home of 1 to 3 stories Dalarnas Villa falls under the rating system LEED v4.1 Residential Single Family Homes [13]. When comparing the energy performance of several simulations the most relevant category in the system would be the Energy and Atmosphere (EA) category. Ignoring the category prerequisites (minimum requirements deemed only pass or fail), the only category with available credits that pertains to simulation is a credit called Annual Energy Use. Other credits in the EA category are achieved by specifying certain components (i.e. energy meters or refrigerants with low global warming and ozone depletion potential) or only occur after design is complete (i.e. educating the homeowner or building commissioning to confirm HVAC efficiency) [13].

The Annual Energy Use credit is awarded one of two ways: according to the LEED energy budget or according to the Home Energy Rating System (HERS) Index. To calculate credits according to the LEED energy budget a comparable reference home is created under ENERGY STAR for Homes, HERS Index Target Procedure for National Program Requirements. The reference home is created based on the size and number of bedrooms in the designed house plus additional given criteria regarding insulation, glazing, etc. From this reference home an energy budget is calculated in MBtu/year. The energy performance of the designed house can then be simulated and credits are awarded for the percent reduction in annual energy use compared to the reference home (exact credit scale can be seen in Appendix C). To calculate credits according to the HERS Index an ENERGY STAR HERS Index Target is given. A HERS Index rating is calculated for the designed home using an accredited raters software (currently only three available) and then compared to the target, achieving credits for number of points below the target [13].

The original intention in utilizing the LEED rating system was a secondary aim somewhat independent of the first: to see if ranking the variants by energy use would coincide with ranking by rating, or in other words compare energy credits achieved with the simulated energy performance, which, according to previous studies, have shown some inconsistency. After further research and subsequent attempts, it was seen that it is not possible to calculate the HERS rating manually, nor was it feasible to use any of the three certified software programs to calculate a rating for a home outside the United States without extensive modifications to the program. Furthermore, it is not possible to import outside climate data in order to have the consistency to compare energy performance results in IDA ICE to HERS ratings. Therefore, option one in the annual energy use category was chosen which simply compares the energy use per unit area to the generated reference home. If the rating is achieved by a percentage reduction compared to the reference home then obviously variants ranked by energy use will be ranked in the same order by LEED rating. The secondary aim instead became to observe how a newly constructed, low environmental impact, “sustainable” home built in Sweden compares to an average newly constructed code compliant home according to LEED.

Upon choosing the LEED energy budget a reference home was generated using Ekotrope RATER (one of the only three certified software programs mentioned above). Ekotrope is a program designed specifically for inspectors and raters to generate HERS Index ratings [14]. The program generates a simple energy consumption target from an equivalent LEED reference home. The reference home is based on the intended designed home’s residence type, conditioned floor area, foundation type, number of bedrooms, and location (for climate zone) plus standard modifications specified by LEED (see Appendix D for a list of standard modifications [13]). As the program is intended for sites within the United States a representative city was determined based on climate zone. According to ASHRAE Climatic Design Conditions 2009/2013/2017 [16] Borlänge has 4698 Heating Degree Days (HDD) at 18.3°C, falling under $4000 < HDD18°C \leq 5000$ ($7200 < HDD65°F \leq 9000$), or climate zone 6A cool-humid in the International Climate Zone Definitions [17]. The 2015 International Energy Conservation Code lists cities in the U.S. that best represent each climate zone [17], citing Burlington, Vermont as the zone 6A representative city. Using the representative city as the site location the generated LEED reference home resulted in an energy budget of 176.6 MBtu/year (51,756 kWh/year) [14].

4 Results and Discussion

4.1 Energy Performance Results

The simulation results are presented below in Table 4.1 and shown graphically in Figures 4.1, 4.2, and 4.3. Total delivered energy includes all sources of heating energy, HVAC auxiliary energy, and household electricity minus onsite PV production, production was calculated in IDA ICE using available radiation according to the climate file and default efficiency assumptions within the software. Delivered heating energy consists of electric heating (ground source heat pump), fuel heating (in the form of a wood stove), plus some additional top-up heating, in this case assumed to be generic district heating for simplicity. HVAC auxiliary refers to the electricity used to run all fans, pumps, etc. related to the HVAC system.

Table 4.1. Energy Performance Simulation Results

Variant Type	Total Delivered Energy, kWh/year	Delivered Heating Energy, kWh/year	HVAC Auxiliary Energy, kWh/year
1A	11733	5156	222.5
1B	10247	3938	47.3
1C	12459	5788	289.9
2	10791	4362	180.3
3A	10269	3937	74.2
3B	10274	3953	69.5
4A	10340	3873	177.5
4B	69.01	3865	195.6

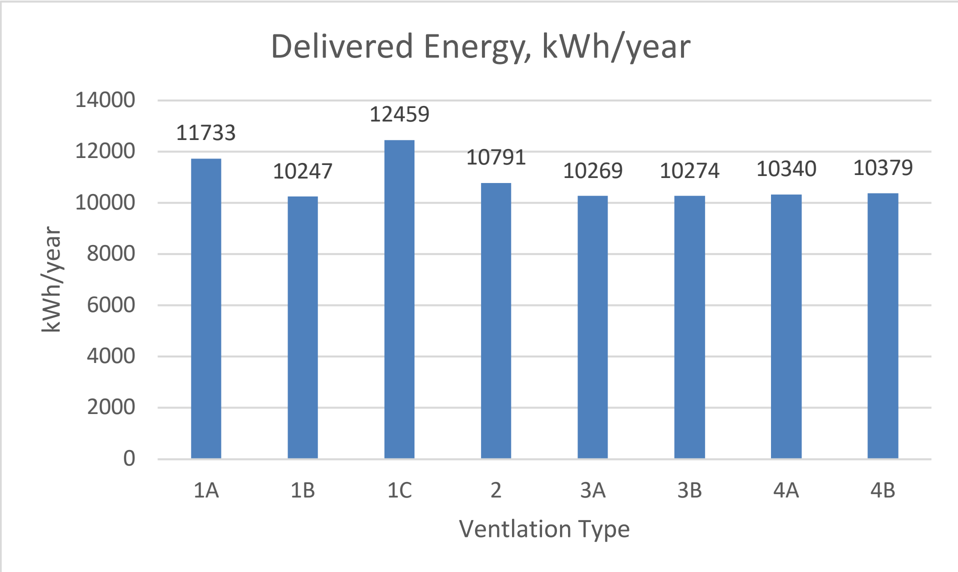


Figure 4.1. Total Delivered Energy Results

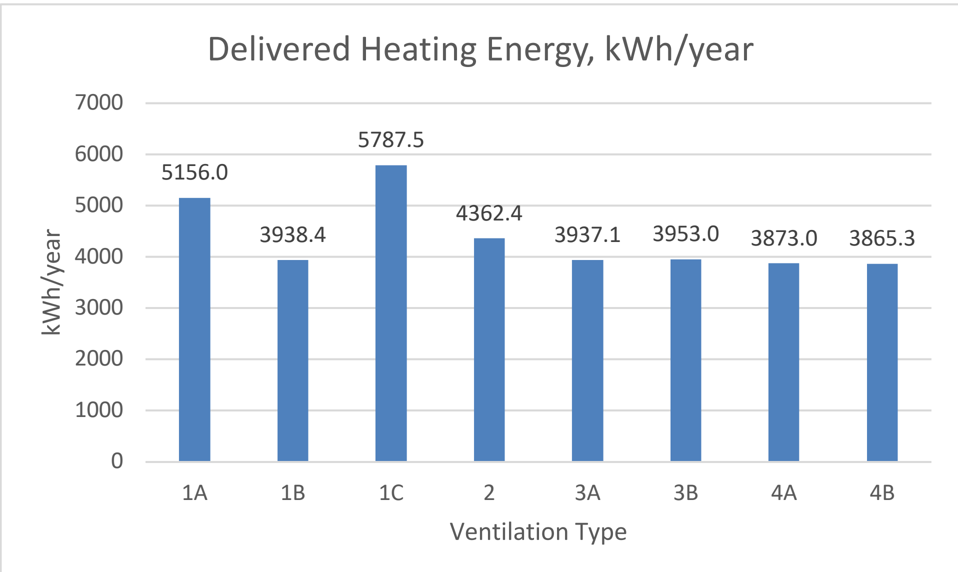


Figure 4.2. Heating Demand Results

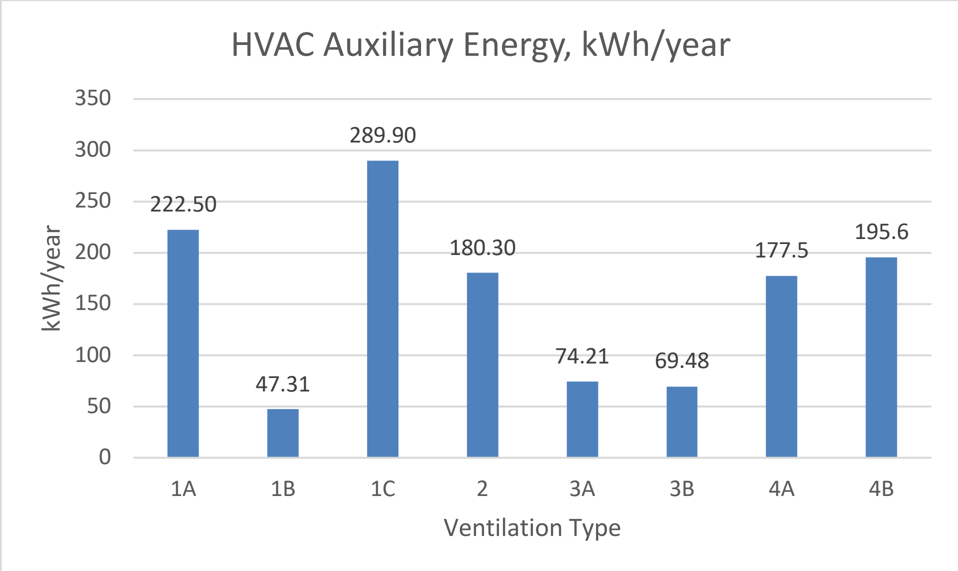


Figure 4.3. HVAC Auxiliary Energy Results

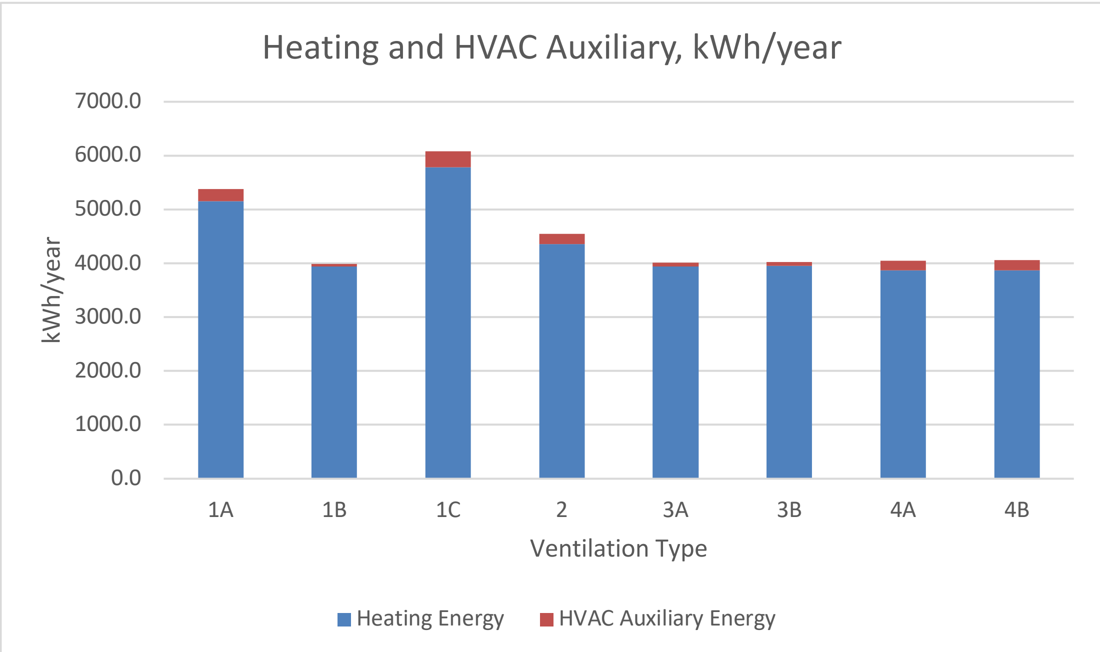


Figure 4.4. Heating and Auxiliary Energy Stacked

It can be seen in Table 2 that Type 1B, with extraction from only the kitchen and bathrooms, consumes the least overall energy, but according to previous research (Ahmad and Garman [2]) this comes at a cost of diminishing indoor air quality. More notably though, Type 3A (DCV with BBR baseline rate) consumed 12.5% less energy than Type 1A (fixed with BBR baseline rate) presumably with no compromise in indoor air quality [2]. Type 2, 3B, 4A, and 4B all achieved similar energy savings; tradeoffs between variants will be discussed in more detail below.

As mentioned above the most notable observation is that Type 3A shows significant savings over a fixed extraction system at standard BBR rates with a reduction of 12.5%. This reduction is not as substantial as in any of the previous studies found in the literature review, it is believed this is due to the very standardized occupancy schedule specified in the Sveby guidebook [10]. For consistent modelling occupancy was distributed throughout the house and set on a standard schedule of 14 hours/day/person. In a real-world scenario occupancy would vary more throughout the day and the entire year, and occupants would concentrate differently than assumed in models. With the ability of demand-control to react to these variations not included during simulation it is possible energy savings would be greater in practice. Future research with long term observations could verify actual savings.

Type 3B, a DCV system with a ramped rate at 130% of BBR standards, performed no better than Type 3A, implying that the decreased ventilation time did not compensate for the increased power of the higher rate.

An issue that arose with Type 4A was that with all doors open and all dry rooms set to sensors in the main living room the CO_2 threshold was never reached and all dry rooms remained in the lower setting the entire time, well below BBR requirements. Even after switching all zones back to individual sensors, as in Type 3A /3B, the dry rooms still remained under threshold levels. With the ideal mixing in the model this indicates adequate indoor air quality in the living room but it cannot be assumed that this would be the case in practice, especially in the smaller rooms. Again, for consistent modeling occupancy was distributed throughout the house, air quality could vary even more in actual practice due to more sporadic and consolidated occupancy found in a real-world scenario. Future research on Dalarnas Villa will have to determine whether one whole house sensor can deliver consistent air quality to all zones of the house.

Due to the complications of Type 4A an additional variant, Type 4B, was modelled with doors closed and sensor settings identical to Type 3A. Both variants with heat recovery performed almost identically to the DSV with BBR baseline rates (Type 3A). Comparing heating energy and HVAC auxiliary energy in Figures 4.2, 4.3, and 4.4 it seems that any saving in heat loss due to heat recovery is at the expense increased auxiliary energy, resulting in energy use similar to Type 3A. In this particular case the benefit of upgrading to a heat recovery system from simple demand control set up is not readily apparent. According to other researchers in Sweden [20] this has been seen recently when calculating energy use for BBR compliance. It seems that modern houses with well-insulated and airtight envelopes, such as Dalarnas Villa, already experience less heat loss than traditional houses and heat recovery does not provide as much benefit. The results from this simulation support these assumptions.

4.2 LEED Rating Results

The total annual delivered energy gathered from the simulations was converted to imperial units, including adjustment factors according to source energy type specified by LEED [13], then compared to the LEED reference home energy use of 176.6 MBtu/year. Percent reduction determines the LEED EA credits for each variant, shown Table 4.2.

Table 4.2. LEED Results

Variant Type	Total Delivered Energy, kWh/year	Total Delivered Energy, MBtu/year*	Reduction from Reference	LEED EA Credits
1A	11734	114.88	35%	27
1B	10248	104.44	41%	29
1C	12458	120.30	32%	26
2	10791	108.53	39%	28
3A	10269	104.49	41%	29
3B	10275	104.61	41%	29
4A	10340	105.81	40%	29
4B	10379	106.32	40%	29

**This figure includes adjustment factors according to source energy type.*

When compared to the LEED reference home energy 176.6 MBtu/year the Dalarnas Villa model performs extremely well regardless of ventilation type. Among all variants the average reduction was 38% when compared to the reference home, achieving on average 28 credits of a maximum 36.

5 Conclusions

5.1 Energy Performance Conclusions

To summarize the conclusions drawn from the discussion, DCV results in savings when compared to traditional fixed exhaust ventilation. The savings of about 12.5% were less than expected; one theory is that the very standardized and evenly distributed occupancy given in user input data publications does not provide as many opportunities for DCV to save energy as would real-world occupancy variations. Also, increasing rates of a DCV system to 130% of BBR requirements did not increase savings, implying that the decreased in ventilation did not overcome the increased power.

When comparing DCV with and without heat recovery it was found that in this particular case heat recovery did not have significant benefit over demand-controlled exhaust ventilation. With a well-insulated, highly airtight house with DCV any incremental savings from heat recovery does not compensate for increase in power and auxiliary energy use, similar to the cost-benefit of simply increasing the ventilation rate above standards.

5.2 LEED Rating Conclusions

Under all LEED rating systems, including v4.1 Residential Single Family Homes, the level of certification is determined according to the following

- Certified: 40 to 49 points
- Silver: 50 to 59 points
- Gold: 60 to 79 points
- Platinum: 80 to 110

Dalarnas Villa achieved on average 28 credits of a maximum 36 in the Annual Energy Use. Annual Energy Use is one opportunity for credits in the EA category, one of eight categories in the system, yet the house already has more than half the credits required to achieve silver.

This supports that constructing a house using low impact materials with low embodied energy (shown previously in the LCA study [3]) does not have to negatively impact energy performance, scoring well in the Energy and Atmosphere category of a widely used sustainable building rating system.

5.3 Future Work

Additional studies surrounding Dalarnas Villa are already under way. Currently a study expanding on the work of Ahmad and Garman [2] is in place, measuring real-world performance of ventilation control strategies over longer periods with aims to observe changes with weather and season. At this time a demand-controlled ventilation system (identical to Type 3A in this study) is in operation with a family of four living in the house to provide real life occupancy behavior. Other ventilation systems and control strategies will be tested as well, including a demand-controlled system with heat recovery.

The current and future research using Dalarnas Villa will provide an excellent opportunity to compare real-world measurements with simulated performance. The measurements can show how much actual occupancy deviates from standard input data, with more movement within the house and variation in schedule throughout days and seasons and could possibly help determine more realistic schedules for simulation. The results of this report will give a solid baseline to compare to when observing whether these variations and determining whether they provide benefits to the performance of demand-control as opposed to traditional fixed systems.

Future work measuring the performance of a heat recovery system with one sensor in the combined exhaust will address issues and answer questions stated in the above conclusions. If the CO_2 in the aggregate exhaust remains below thresholds for the majority of the time will the air quality in the smaller rooms suffer? Will a different threshold create higher air quality without affecting the energy performance? If these issues arise in actual practice additional questions will need to be asked. What has the greatest effect on airflow between zones that causes dilution in the aggregate exhaust, the room layout, openings between rooms, the size ratio of larger rooms to smaller rooms? Continued simulation research parallel to ongoing measurements could provide answers.

References

[1] Pérez-Lombard, L., Ortiz, J., and Pout, C. (2008) 'A review on buildings energy consumption information', *Energy and Buildings,* 40(3), pp. 394-398.

[2] Ahmad, A.J. and Garman, I. (2019) *Monitoring air quality indicators and energy consumption in Dalarnas Villa during operation of a demand-controlled exhaust ventilation system*, Borlänge, Sweden: Dalarna University.

[3] Petrovic, B., Myhren, J.A., Zhang, X., Wallhagen, M., and Eriksson, O. (2019) 'Life cycle assessment of a wooden single-family house in Sweden', *Applied Energy,* 251(113253)

[4] McCombs, H.C. (2015) *LEED Green Associate: Exam Preparation Guide LEED v4 Edition*, Orland Park, Illinois: American Technical Publishers.

[5] Guy N. R., Mancini S., and Birt, B.J. (2009) 'Do LEED-certified buildings save energy? Yes, but…', *Energy and Buildings,* 41(8), pp. 897-905.

[6] Pollet, I; Laverge, J; Losfeld, F; Reeves, M; Vens, A; and Janssens, A (2013) 'Performance of a demand controlled mechanical extract ventilation system for dwellings ', *SDAR* Journal of Sustainable Design & Applied Research,* 1(3), Article 5.

[7] Nielsen, T.R., and Drivsholm, C. (2010) 'Energy efficient demand controlled ventilation in single family houses', *Energy and Buildings,* 42(11), pp. 1995-1998.

[8] Pablo Lopez Hurtado, Antoine Rouilly, Virginie Vandenbossche Maréchal, Christine Raynaud. A review on the properties of cellulose fibre insulation. Building and Environment, Elsevier, 2016, 96, pp.170-177.

[9] EQUA Simulation (2020) *About EQUA -History,* Available at: https://www.equa.se/en/about-us/history (Accessed: 9 May 2020).

[10] Svebyprogrammet (2012) *Brukarindata bostäder,* Stockholm, Sweden: Sveby.

[11] Enertech Group (2016) *CTC GSi 12*, Ljungby, Sweden: Enertech AB.

[12] Boverket (Swedish Housing Agency) (2018) *Boverket´s mandatory provisions and general recommendations, BBR*, Karlskrona, Sweden: Boverket.

[13] Leadership in Energy and Environmental Design (2020) *LEED v4.1 Residential Single Family Homes*, Washington, D.C.: U.S. Green Building Council.

[14] Ekotrope (2020) *Ekotrope Rater - Products,* Available at: https://www.ekotrope.com/ekotrope-rater (Accessed: 22 April 2020).

[15] Leadership in Energy and Environmental Design (2019) *LEED v4 Homes scorecard,* Available at: https://www.usgbc.org/leed (Accessed: 28 May 2020).

[16] American Society of Heating, Refrigerating and Air-Conditioning Engineers (2017) *ASHRAE Climatic Design Conditions 2009/2013/2017,* Available at: http://ashrae-meteo.info/ (Accessed: 8 May 2020).

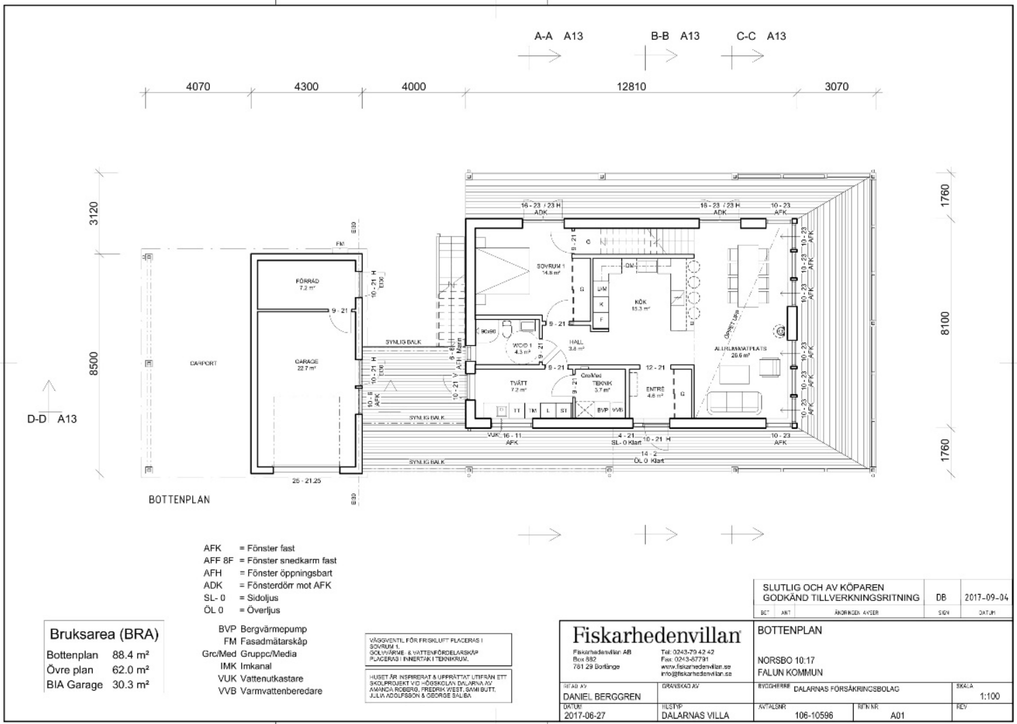
[17] International Code Council (2015) *2015 International Energy Conservation Code*, Washington, D.C.: ICC Publications.

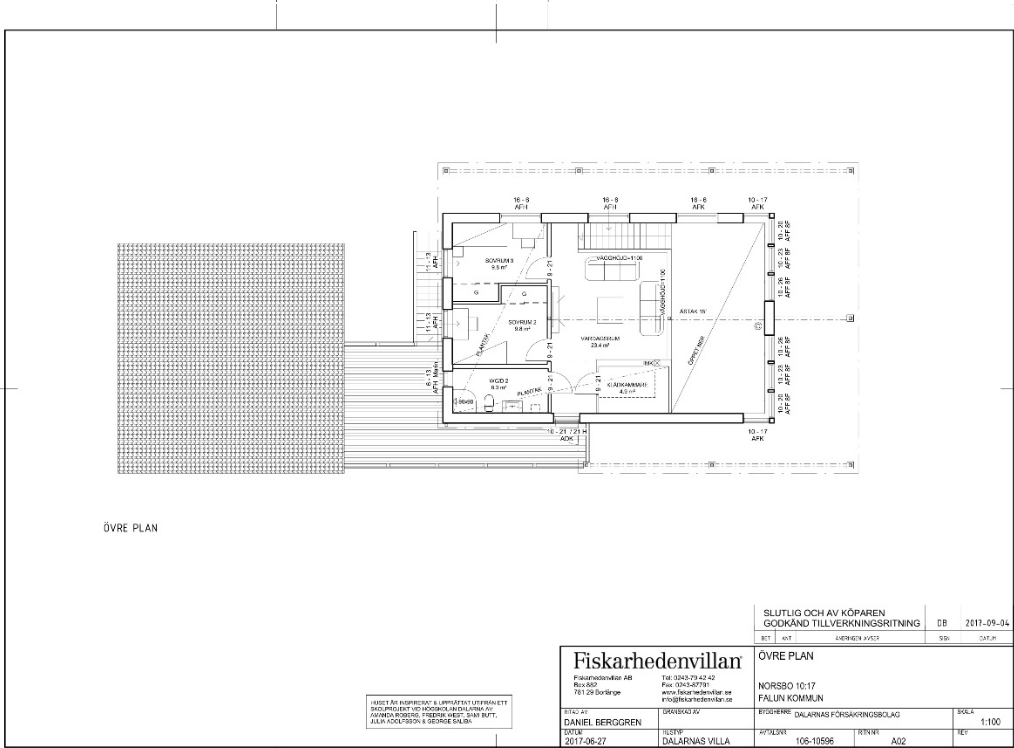
[18] Dalarnas Försäkringsbolag (2019) *Välkommen till Dalarnas Villa,* Available at: https://www.lansforsakringar.se/dalarna/privat/om-oss/hallbarhet--forskning/miljo/dalarnas-villa/ (Accessed: 4 June 2020).

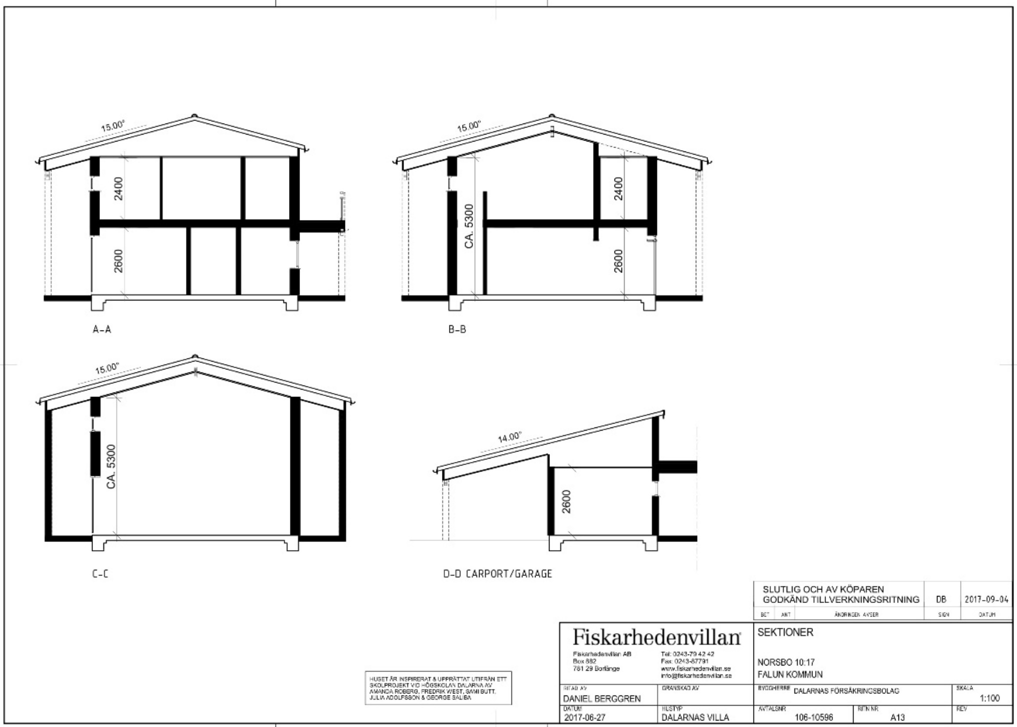
[19] Kontrollbolaget (2019) *Dalarnas Villa Will Change Future Construction Processes,* Available at: https://www.kontrollbolaget.se/dalarnas-villa-ska-forandra-framtida-byggprocesser/ (Accessed: 4 May 2020).

[20] Myhren, Jonn Are. Presentation discussion. June 2020.

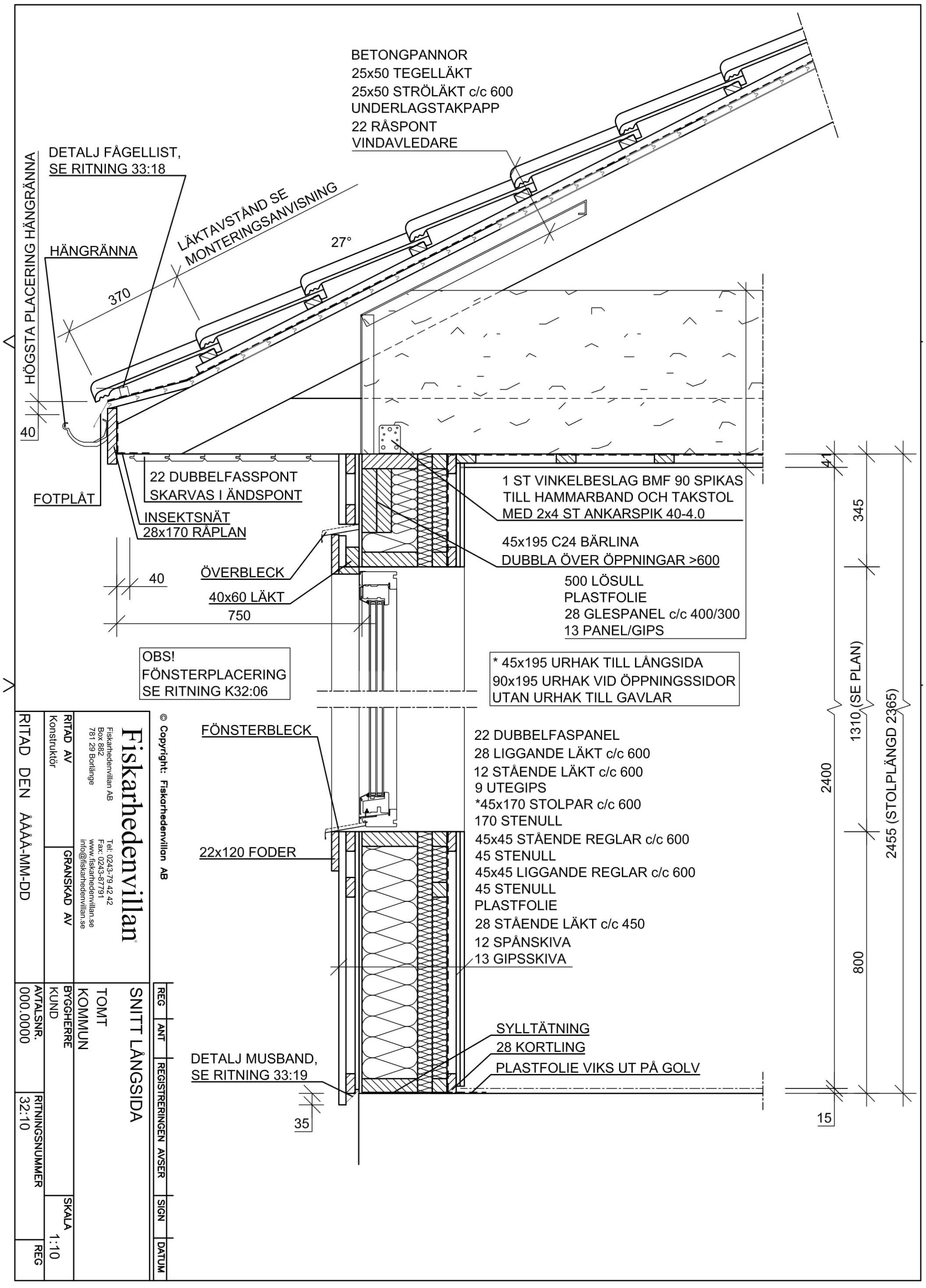
Appendix A: Dalarnas Villa Building Plans






15.00°
2400
2600
A-A
15.00°
CA. 5300
2400
2600
B-B
15.00°
CA. 5300
C-C
14.00°
2600
D-D CARPORT/GARAGE
SLUTLIG OCH AV KÖPAREN GODKÄND TILLVERKNINGSRITNING
DB
2017-09-04
BET
ANT
ÄNDRINGEN AVSER
SIGN
DATUM
HUSET ÄR INSPIRERAT & UPPRÄTTAT UTIFRÅN ETT SKOLPROJEKT VID HÖGSKOLAN DALARNA AV AMANDA ROBERG, FREDRIK WEST, SAMI BUTT, JULIA ADOLFSSON & GEORGE SALIBA
Fiskarhedenvillan
Fiskarhedenvillan AB
Box 882
781 29 Borlänge
Tel: 0243-79 42 42
Fax: 0243-87791
www.fiskarhedenvillan.se
info@fiskarhedenvillan.se
SEKTIONER
NORSBO 10:17
FALUN KOMMUN
RITAD AV
DANIEL BERGGREN
GRANSKAD AV
BYGGHERRE
DALARNAS FÖRSÄKRINGSBOLAG
SKALA
1:100
DATUM
2017-06-27
HUSTYP
DALARNAS VILLA
AVTALSNR
106-10596
RITN NR
A13
REV

Appendix B: Fiskarhedenvillan Typical Envelope Detail



Appendix C: LEED Energy Budget Point Scale

Percentage reduction	Points	Percentage reduction	Points
1%	1	19%	19
2%	2	20%	20
3%	3	21%	21
4%	4	23%	22
5%	5	25%	23
6%	6	27%	24
7%	7	29%	25
8%	8	31%	26
9%	9	33%	27
10%	10	36%	28
11%	11	40%	29
12%	12	45%	30
13%	13	50%	31
14%	14	60%	32
15%	15	70%	33
16%	16	80%	34
17%	17	90%	35
18%	18	100%	36

Appendix D: LEED Energy Budget Reference Home Modifications

Option 1. LEED Energy Budget

Design and construct a building whose modeled annual energy usage is lower than the LEED energy budget. The LEED energy budget is based on the ENERGY STAR for Homes, HERS Index Target Procedure for National Program Requirements, version 3, with the following modifications:

- The size adjustment factor is always 1.
- The building is a slab-on-grade ranch whose floor area is equal to the ENERGY STAR reference home's conditioned floor area.
- There are no floors over unconditioned spaces.
- The gross exterior wall area is as shown in Table 1.
- There are two exterior half-lite doors, unshaded, one on the south wall, one on the west wall.
- Glazing is 15% of the floor area.
- The ceiling is insulated, and its gross area equals the conditioned floor area.
- The storage water heater has an energy factor of 0.59 for gas, 0.92 for electric.
- The thermal distribution system is 100% in the attic, above insulation.
- The LEED energy budget shall be displayed in MBtu/year, and is based on source energy.
- Any major energy users not covered by the energy model, including heated driveways, pools, spas, and heated garages, must be added to the annual energy consumption of the Rated Home.

Table 1. Exterior wall area of LEED reference home, by number of bedrooms

	1	2	3	4	5	6	7	8 or more
Area (square feet)	1,300	1,667	1,957	2,200	2,411	2,600	2,773	+ 150 ft^2 per additional bedroom
Area (square meters)	120	154	181	204	223	241	257	+ 14 square meters per additional bedroom