UNDERGROUND SEASONAL THERMAL ENERGY STORAGE FOR SMALL-SCALE BUILDINGS

A Design Example

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

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Sy Nguyen-Ky

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Ohjaaja(t) Anssi Knuutila, Katariina Penttilä

TIIVISTELMÄ

Rakennusten lämmitys muodostaa suurimman osan energian kokonaiskulutuksesta etenkin lauhkean vyöhykkeen pohjoisemmassa osassa. Yksi ratkaisu energiatehokkuuden parantamiseen on aurinkoenergiajärjestelmän käyttäminen. Aurinkoenergialla yleinen hyötysuhde on edelleen suhteellisen alhainen energian tarjonnan ja kysynnän välisen eron vuoksi. Tämän ongelman ratkaisemiseksi opinnäytetyössä tutkitaan maanalaista lämpöenergian kausivarastointia (USTES) aurinkojärjestelmiin. Tavoitteena on varastoida aurinkoenergia kesällä myöhempää lämmityskauden käyttöä varten. Opinnäytetyön tavoitteena on selvittää laskennallisen simuloinnin avulla, kuinka käytännöllistä on toteuttaa pienimuotoista kausivarastointia korkeilla leveysalueilla.

Opinnäytetyössä perehdytään USTESin tulevaisuudennäkymiin, sovellettavuuteen pienrakennuksissa ja suunnittelutyökalujen mahdollisuuksiin. Esimerkkikohteena esitellään 35 neliömetrin laboratoriorakennuksen USTES-malli ja simulointitulokset lämpöpumppujärjestelmän kanssa. Tehtyjen simulointikokeiden perusteella järjestelmän suorituskyky analysoitiin verrattuna tapauksiin ilman USTESia. Lämmitystarve väheni jopa 36%, ja sähkön lisälämmitystarve noin viidesosan. Tulokset osoittivat, että alueella, jolla on pitkä ja kylmä talvi, USTES-konseptilla on paljon potentiaalia parantaa aurinkoenergiajärjestelmän kokonaishyötysuhdetta ja pienentää rakennuksen ostoenergian tarvetta.

Avainsanat energiatehokkuus, IDA ICE, rakennuksen energiasimulointi, rakennuksen energiatekniikka, STES

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ABSTRACT

This thesis raises the topic of energy efficiency in buildings and the urge for novel measures in small-scale and residential buildings to improve the energy efficiency level. Heating in buildings accounts for the greatest share of their total energy consumption, especially in cold climate regions. As a solution, solar energy system has been widely used. However, the overall efficiency is still relatively low due to the discrepancy between the energy supply and demand. To deal with this problem, the underground seasonal thermal energy storage (USTES) has been studied to couple with the solar systems, aiming at storing solar energy during summertime for later use in the heating season. The purpose of the thesis was to investigate the feasibility to practice small-scale USTES in a high latitude region, with the assistance of simulation software in the preliminary design stage.

The thesis depicts an outlook across the concepts of USTES, its applications in small-scale buildings and the design tools for USTES. As an illustration, an USTES design example was presented and simulated. A 35 m^2 laboratorial building coupled with an USTES and heat pump (HP) system was designed and modelled. Simulation attempts were made to analyse the performance of the system compared to the cases without the USTES.

The results of the simulations show that, up to 36% of the heating load and around one-fifth of electricity for top-up heating were reduced. The results prove that, even in a country with a prolonged and freezing winter as Finland, USTES applications are still highly potential in improving the energy efficiency of the solar energy system and consequently increasing the amount of energy savings.

Keywords building energy simulation, IDA ICE, energy efficiency, energy technology in buildings, STES

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LIST OF ABBREVIATIONS

AHU	Air handling unit
ASHP	Air-source heat pump
ASHRAE	American Society for Heating Refrigerating and Air-Conditioning Engineers
ATES	Aquifer thermal energy storage
BPS	Building performance simulation
BTES	Borehole thermal energy storage
CEN	European Committee for Standardisation
COP	Coefficient of performance
DHW	Domestic hot water
EC	European Commission
EPBD	Energy Performance of Buildings Directive
EPV	Energy performance value
EU	European Union
GHG	Greenhouse gas
HDD	Heating degree days
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
HX	Heat exchanger
IEA	International Energy Agency
nZEB	Near-zero-energy-building
PTES	Pit thermal energy storage
PV	Photovoltaic

SCOP	Seasonal coefficient of performance
SF	Solar fraction
SPF	Seasonal performance factor
TES	Thermal energy storage
TTES	Tank thermal energy storage
USTES	Underground seasonal thermal energy storage
YMa	[Ympäristöministerion asetus] Decree of the Ministry of the Environment (of Finland)

1 INTRODUCTION

1.1 Background

The world’s population is growing, though at a slower pace than before, still it is expected to add two more billion in 2050, from the current 7.7 billion. The trend is predicted not to witness a downturn until its peak in 2100 at around 11 billion. (United Nations, 2019) Population growth not only brings additional challenges to many socio-economical aspects but also hinders the sustainable use and preservation of natural resources. Heavy dependence on fossil fuel is the main cause of greenhouse gas (GHG) emissions and global warming, also being a problem most governments are coping with.

Furthermore, one other urgent issue raised from a rapid population growth is the need for housing. Housing, nowadays, as usually referred to construction or building sector, is pushed hard to discover more efficient approaches to fulfil the demand. Upon buildings, people have been increasingly aware of the connections amongst indoor climate, occupant comfort, wellbeing, and productivity. In other words, they want the buildings to serve with a more diverse functionality. Higher performance of buildings means a higher amount of energy the buildings consume. In Europe, the building sector is the single largest energy consumer with approximately 40% of energy consumption and 36% of CO_2 emissions. At present, more than one-third of the EU’s buildings are over 50 years old and almost three-fourths of the stock is energy inefficient. (European Commission, 2019a) Renovating the old is a must; besides, new building stock is expected to be built in abundance. For these reasons, a sustainable building design with high energy efficiency and integration of renewable sources is a potential decent means to minimise the substantial proportion of energy consumption from buildings. The introduction of renewable energy into buildings has existed for quite a long time, but its widespread use has just started to be noticeable recently. Buildings consume energy for three main categories: space heating, space cooling, and water heating, according to the International Energy Agency (IEA). In Finland, during 2010-2017, heating energy in residential buildings accounted for around 83%, making it the largest consumer from the sector (Official Statistics of Finland, 2018). Hence, improving the energy efficiency of heating systems as well as implementing hybrid energy systems into the operation of buildings can mitigate the excess consumption of heating energy.

Heat, apart from solar and geothermal heat, can be produced from all other renewable sources through the intermediate form of electricity. Intrinsically, heat is abundant when people do not need it, and vice versa; i.e. summer is hot, and winter is cold. The idea of storing heat when it is excessive for later use in the other season has been thought of since the beginning of the 1980s. Since then, the term “underground seasonal thermal energy storage” (USTES) was coined as a new topic, which has been constantly researched and developed in many countries with a cold and prolonged winter. USTESs at large-scale applications have been observed; however, at small-scale, the amount of study is still modest and unpopular.

1.2 Aim of study and thesis outline

The thesis aims at introducing the concepts of USTES as a potential constituent of a heating plant with solar energy. The study also investigates fundamental aspects to select the right USTES system and design a suitable one, particularly for small-scale buildings. In addition, the thesis also demonstrates a showcase of an USTES design to see how feasible and efficient it is to build one under the Finnish climate.

The thesis will first introduce the previous and current energy efficiency directives in buildings and the importance of research on energy-efficient systems. After that, USTES concepts, their status, and basic knowledge of heating in buildings will be discussed. The next chapter will present two main USTES configurations and the main factors affecting the design and construction of USTES applicable for small-scale buildings. Finally, a design example will be presented to evaluate the feasibility of such a concept in the context of the Finnish climate. Some performance indices were also calculated based on the simulation results and were compared to other similar previous research work in other countries such as USA (Alaska), Denmark, and Greece.

1.3 Scope of study

The thesis consists of literature reviews from both books and scientific articles, and an USTES design example. The modelling and simulation skill of the author was accumulated from work experience and self-study at HAMK Tech Research Unit, Häme University of Applied Sciences. The descriptions of the modelling processes will not include the definitions or the working mechanisms of built-in objects in the simulation software, e.g. heat exchanger, decoupler, stratification tank, top-up ideal boiler, etc. The results of the simulation will mainly focus on the energy perspective, with heating energy as the key matter of interest. This USTES design and simulation work do not represent the opinions of all the stakeholders that should take part in this project, neither correspond to any requirements from the building owner.

2 ENERGY EFFICIENCY IN BUILDINGS

2.1 Energy efficiency directives and energy technology in buildings

In Europe, since 2012, the Energy Performance of Buildings Directive (EPBD) 2010/31/EU has been in force, usually referred to as ‘recast EPBD’ (Figure 1). The EPBD has helped raise a positive trend regarding the promotion and boost of buildings’ energy performance amongst the building markets within the Member States. Recently, it has been partly amended by the revised EPBD 2018/844/EU, which introduces new objectives and promotes the impact of energy efficiency (EE) of buildings in the clean energy transmission progress and other economic sectors in general. (European Commission, 2019b) Along with those, the Energy Efficiency Directive 2012/27/EU, amended by the Directive 2018/2002 EU, has been made valid, targeting at 32.5% energy efficiency in 2030, compared to the 1990 levels (previously the target was to reach 20% energy efficiency in 2020). A revision note for an upwards target will probably be released by 2023 (European Commission, 2019c). Several practical support initiatives have been established to help the EU Member States properly implement these directives. They are called as ‘the energy performance of buildings standards’ (EPB standards), managed by the European Committee for Standardisation (CEN). (European Commission, 2019b)

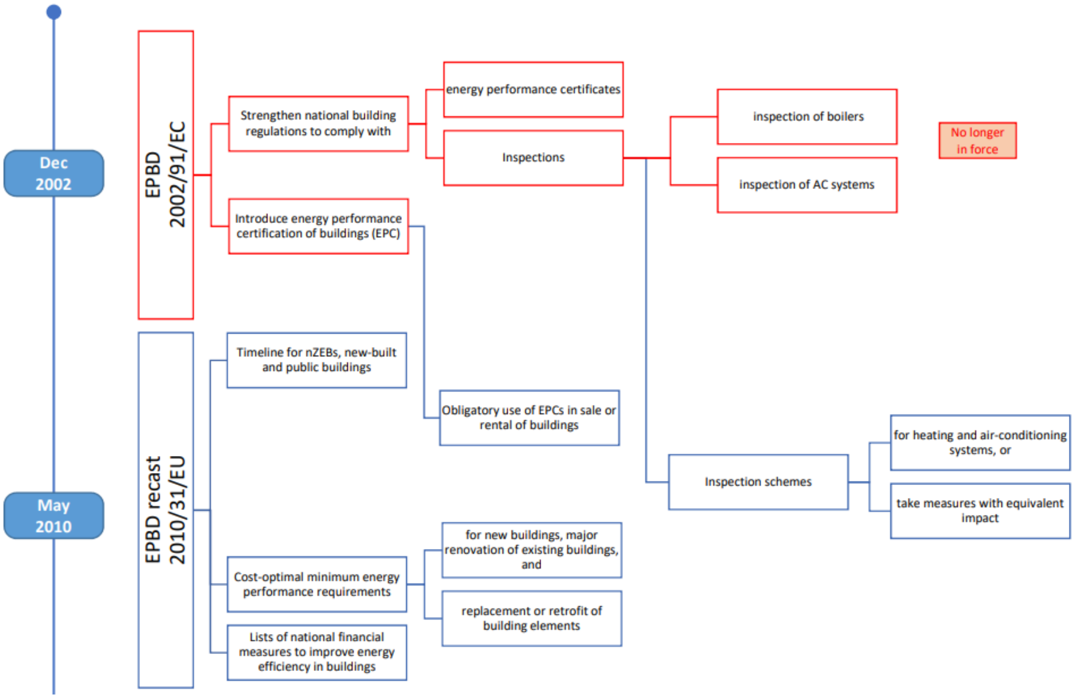

Figure 1. Schematic chart of the core content of EPBD 2010/31/EU.

As mentioned above, building stock accounts for around 40% of the total energy consumption. To concentrate to work on this prominent consumer is a wise approach to contribute to reach the said targets. Amongst newly built buildings, the term near-zero-energy-buildings (nZEBs) was introduced in EPBD 2010/31/EU. nZEBs are categorised as buildings, which require a minimal amount of energy produced by sources other than nearby or in-situ renewable ones. (European Commission, 2013) nZEBs also focus on improving the organisation of its energy systems, building elements, and, automation and controlling. It is regulated that all new buildings shall be nZEBs by 31 December 2020 and the same applies to all new public buildings (owned and occupied by public authorities) after 31 December 2018. Energy-wise criteria are put on top from the planning, designing, constructing, and operating of the buildings. Many state-of-the-art technologies as well as innovative design tools have been presented lately so as to timely adapt the trend and serve the increasing need of fulfilling new regulations.

Generally, the HVAC system plays a vital role in the performance of a building, both in terms of energy and indoor conditions. 'HVAC' stands for heating, ventilation, and air-conditioning; it sometimes also implicitly includes automation. HVAC is essentially meant to provide thermal comfort and good indoor air climate for the occupants. It is also the uppermost energy consumer in the building, especially in regions where heating or cooling need extends over a prolonged period of the year, such as in Finland with a cold and extended winter. This is proven by the fact that 80% of the total energy consumption of residential buildings in this country was used for heating purposes in 2017 (Official Statistics of Finland, 2018). Improvement in energy efficiency of HVAC components as well as development of innovative energy systems in buildings have been witnessed in recent times. Heat recovery in air handling unit (AHU) or HPs are the most known examples. However, from a building level point of view, the energy system is also a significant factor in satisfying the heating demand other than the building envelope, and consequently, the overall performance of the building. Renewable energy sources at a local level usage have been in practice increasingly commonly. Solar and geothermal energy are the two most popular and familiar sources that an independent, off-grid energy system can harness. A hybrid energy system, sometimes also called a combi- or integrated energy system, was invented as a means to lessen the energy cost, but more importantly, to increase the level of energy efficiency of the households. (Figure 2) Such systems not only minimise the dependence on fossil fuel energy, but also contribute towards the GHG reduction.

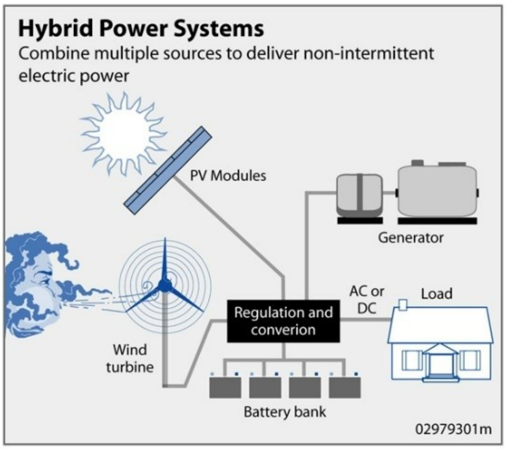

Figure 2. An illustration of a hybrid power system for building with the exploitation of solar and wind energy on-site (U.S. Department of Energy, n.d.)

2.2 USTES concepts and current status of USTES

In the previous part, the hybrid energy system was introduced as a novel solution to contribute to an increasing use of renewable energy sources and a more stable energy security. With solar energy, the yield depends heavily on solar radiation, i.e. an intermittent source. In high latitude regions where there are little shining hours in the winter, the problem arises because winter is the time when the heating need heightens, and vice versa in summer (Figure 3). To solve the mismatch between the demand and supply, USTES has been studied as an important matter in heating plants with solar energy involved to fix the stochastic nature of the heat source.

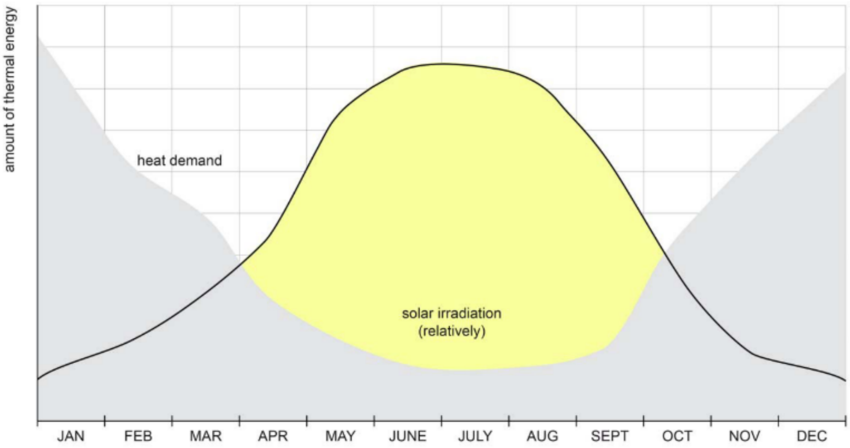

Figure 3. A relative depiction of the mismatch between heat demand and solar irradiation in high latitude regions (reprinted from IEA, 2015)

The idea of USTES is simple: to capture the surplus heat, transfer it into a thermal storing medium, and to discharge it when the demand comes.

Heat sources can be from any of the renewables, but apparently solar energy is the most widely used. The theoretical idea dated back in the 1950s, but not until the 1970s that it was truly realised in Sweden during the energy-crisis period (Hesaraki, Holmberg, & Haghighat, 2015). Upon today's context, the main purposes of USTES are better described as:

- reduction of GHGs, consequently mitigation of pollution,
- improvement of energy system performance reliability,
- heightening of energy efficiency level,
- betterment of initial investment and maintenance cost. (Janiszewski et al., 2016)

USTES' heat-storing media may vary, from solid, liquid, gas, a combination of two amongst them, or, also thermochemical. There are several ways of categorising USTES, in which thermal-storing-form-based is the most popular one as depicted in Figure 4. Sensible heat is stored based on the change of temperature of the media without changing its physical phase. Latent heat storage makes use of the phase changing heat the media absorbs or emits when it witnesses a change of phase (in this case, the media is often referred to as phase-changing material – PCM). Thermochemical heat is the heat charged and discharge based on a chemical reaction. Latent heat and thermochemical heat storages will not be discussed within the scope of this thesis due to its current limitation in previous research and the complexity of the overall systems. The second way to classify USTES is based on its system configuration methodology. Four most typical method-based types of USTES, which were discussed by A. Hesaraki et al. in 2015, Janiszewski et al. in 2016, and later by R. McKenna et al. in 2019, are borehole thermal energy storage (BTES), the aquifer thermal energy storage (ATES), tank thermal energy storage (TTES), and pit thermal energy storage (PTES). (Figure 5) Each type has its own range of thermal capacity, choice of storing media[1], soil compatibility as well as initial investment. Many research papers have shown that these concepts are only suitable for large-scale projects, for example, to serve a community of heating users, due to its overall efficiency and prohibitive cost. They are, as a rule of thumb, only mentioned as a matter of research with a system volume of over 1000 m^3 (IEA, 2015). Such projects have been constructed throughout a wide range of countries, as in Sweden, Germany, Denmark, France, the Netherlands, Turkey, China, the United States, Canada and Korea (Hailu, Hayes, & Masteller, 2017).

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[1] System-configuration-method-based USTESs are mostly sensible heat storage, because of its current economical suitability to store heat over seasons (IEA, 2015).

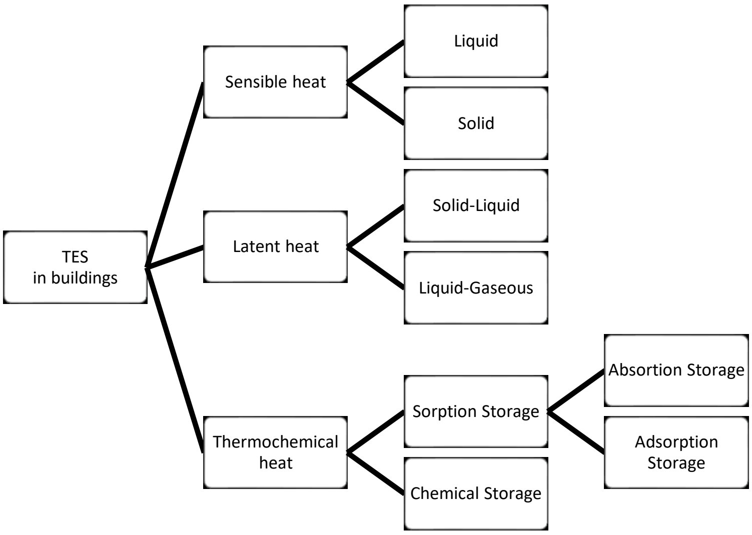

Figure 4. Classification of TES systems based on thermal storing media (adapted from Heier, Bales, & Martin, 2015; Jradi et al., 2017)

Large-scale USTES systems have been reported to have a different level of energy efficiency, as high as up to 99% of solar fraction[2] (SF) in heating energy in the Drake Landing Solar Community (DLSC) in Okotoks, Canada, or, as low as 26% of SF in the Kerava Solar Village (KSV) project in Kerava, Finland (Hesaraki et al., 2015). The DLSC is said to have the best result in the world and 'record in its climatic region' with a higher heat demand although it is located at a lower latitude compared to that of southern coastal part of Finland (Janiszewski et al., 2016). The KSV, however, was described to have an excellent efficiency of 85% of the storage system, but the dimensioning of the tank size and the residential village was not appropriate. These two examples demonstrate that proper design of the storage components holds a pivotal importance in the effectiveness of a large-scale USTES project. In Finland, as evaluated by Janiszewski et al. (2016) based on seven criteria of USTES method for large-scale level, BTES was the most suitable type of USTES for the Finnish context with its simplicity in construction, cost-effectiveness, small-scale feasibility, and suitability in the Finnish geological condition.

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[2] Solar fraction $= \frac{\text{Solar thermal energy used for heating [kWh/a]}}{\text{Total heating demand [kWh/a]}}$ (Marx, 2015)

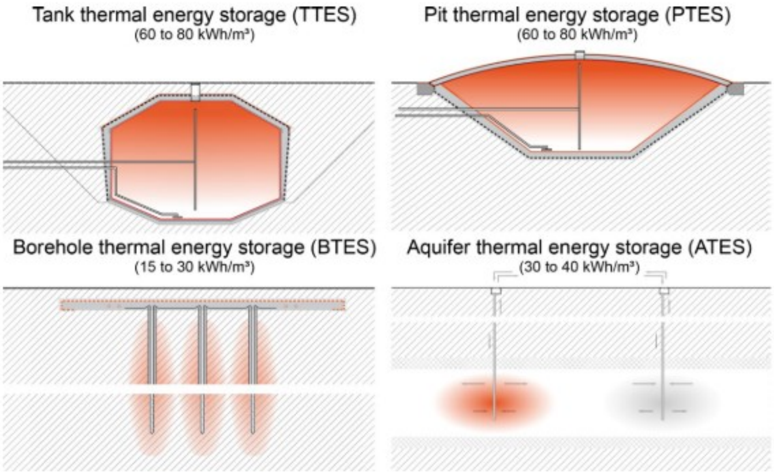

Figure 5. Four main large-scale USTES systems (reprinted from IEA, 2015)

Small-scale USTES, nevertheless, has not been a frequent matter of research, at least not until recent times when many researchers suggest that it is time to downsize the power grid. In 2017, 57.6% of the EU-28 population lives in detached and semi-detached houses. This figure for Finland is significantly at 80.9%. (Eurostat, 2017) Those abovementioned values have reminded that it is important to pay more attention to the detached house sector, which holds the dominant share in Finland and many other European countries as shown in Figure 6. Apparently, no research about small-scale USTES for residential buildings in Finland has been reported.

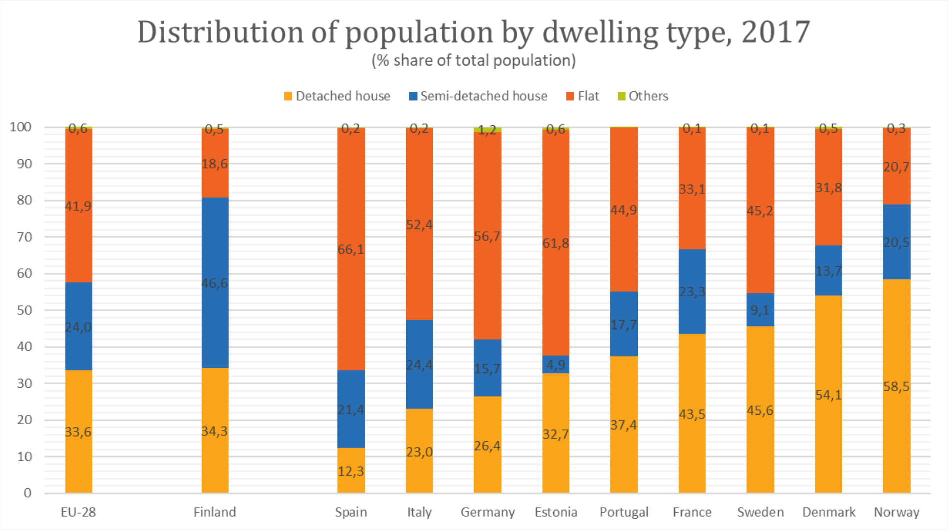

Figure 6. Detached and semi-detached housings in Finland, compared to EU-28 average and other MSs (data from Eurostat, 2017).

Outside of Finland, several USTES designed proposals were conducted by researchers from countries such as Greece, and Denmark. An experiment of an USTES proved optimistic monitored results in Alaska, USA, where the winter lasts long with freezing temperatures. Yet, ASHRAE (the American

Society for Heating Refrigerating and Air-Conditioning Engineers) noted for engineers that 'active solar system is not suitable in climates with long periods of freezing temperatures', and stressed that each solar thermal system should be individually engineered (Hailu et al., 2017). The case was a Net Zero Energy home with heated floor area of 54 m^2 and a sand bed USTES of 36.75 m^3 made of sand and pit run as heat-storing media. In a Net Zero Energy home design, electricity is fed to the utility grid during summer and supplied back from it during the other season. A hundred per cent heat yield from evacuated solar tubes (total absorber area 2 x 3.6 m^2) was transmitted to the USTES right under the garage and storage space floor – the lower floor. After over one year of monitoring, the group of authors concluded that (a) the USTES designed helped reduce the heating load of the garage by 41.5% under Alaska cold and prolonged winter, and, (b) the omnipresent materials as sand and pit run can be a cost-wise choice for such a system (Hailu, Hayes, & Masteller, 2019). In addition, a summary of two selected small-scale USTESs is shown in Table 1. It is noticeable that different USTES system configurations in different climate location have different approach in the designing and the system performance assessment.

Table 1. Details of the USTES system proposals in previous research (Antoniadis & Martinopoulos, 2017; Jradi et al., 2017)

Location	**Floor area**	**Solar energy system**	**USTES volume, media**	**Results**	**Simulation tool**
Thessaloniki, Greece	120 m^2	30 m^2 of flat plate solar collector aperture	TTES, 36 m^3, water	SF reached 52.3% for space heating, 100% for DHW	TRNSYS
Odense, Denmark	225 m^2	30 kW peak capacity PV panel coupled with an ASHP	UTES, 900 m^3, soil	PV-ASHP system energetic efficiency[3] was 22.2%, when surplus electricity was used to run the ASHP to charge the UTES	MATLAB R2015a

The National building code and simulation tools are also of importance in the engineering of a USTES. Currently, there is no mentioning of USTES in the Finnish National Building Codes. However, the latest building codes on

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[3] $\text{Energetic efficiency} = \frac{\text{Total electricity and heating energy demand satisfied by the system}}{\text{Total amount of energy incident on the solar PV system}}$, in this case the PV stand-alone system got an overall energetic efficiency of only 5.88% (Jradi et al., 2017).

energy efficiency YMa 1010/2017 (published 27th December 2017) has been formally amended with the new introduction of EPV (Energy Performance Value) for each building class. All new buildings are supposed to abide by this EPV requirements. There are also exceptions for cases when the EPV does not apply, then, the use of district heating or HP must be used as a heating source, and the annual efficiency of heat recovery from return air must reach at least 70%. (Ympäristöministeriö, 2017) Integrated design with renewable energy systems are promoted in any case. To achieve this new level of energy efficiency, USTES for small-scale building would be a good solution in the context that the Finnish building stock will witness an increasing need for housing in the future, meanwhile being obligated to meet the said requirements of energy efficiency.

2.3 **Knowledgebase: energy in buildings**

2.3.1 Heating in buildings

In a cold climate region, heating is one of the most important design criteria for any building project. The fundamental purpose of heating is to provide indoor thermal comfort for the occupants. Heating sources vary from wood, oil, natural gas, of which heat is made usable through a boiler or a fireplace, to electricity or district heating network through radiators or floor heating. Solar gain is also considered a passive heating source for buildings; yet, it is non-controllable and above all it is not always available during heating season. Proper heating design nowadays requires more than just to satisfy the occupants' thermal comfort, but also to be energy efficient. In addition, heating demand in buildings also includes the heat for domestic hot water (DHW) production. In general, heating in buildings is usually categorised into:

- Space heating
- Heating for ventilating air
- Heating of DHW

In Finland, from 2010 to 2017, space heating in residential buildings amounted up to 68% of energy consumption, while DHW production took a share of 15% (Official Statistics of Finland, 2018). Space heating and heating for ventilation keep the indoor temperature at a stable and comfortable thermal level for occupants, i.e. usually at 21^{o}C in most buildings. Heating for DHW, although it accounts for a minor proportion of the total heating consumption, requires a higher end-used temperature grade of 55 to 58^{o}C. The higher the needed temperature grade is, the larger waste heat will occur. High temperature output also requires specific devices to produce, e.g. HP or electrical resistor. The difference in the final heating purpose leads to the complexity in the design of the energy system of the buildings.

The building envelope plays a significant role in retaining the heat indoor. As other materials, heat is transferred in and out of the building elements through a combination of conduction, convection, and radiation mechanisms. Conduction and convection heat transfer through the building envelope account for most of the share in the total heat loss of a building, which will be discussed later in the next part. In this aspect, buildings in a cold climate region are traditionally designed in a way that the ratio of the total envelope area to its volume is kept minimal. The more compact the shape of the building is, the less heat loss it will have; consequently, the less energy the building will demand to run. Also, it is advisable to avoid the unnecessary design of details such as dormers or roof windows, which are not recommended as they are highly thermal-bridge-prone. In the present time, heating energy-efficient building design should follow these generalised criteria:

- Minimisation of heat losses
- High solar gain utilisation
- Use of heat recovery in ventilation and space heating system

2.3.2 Overall heat losses of buildings

Indoor thermal comfort generally leads to a difference in internal and environmental temperatures. As a consequence, heat flow through the building envelope is inevitable. The heat supplied will partly cover the amount of heat losses, which consists of four fundamental contributors according to Pinterić (2017), as in Figure 7 (the dashed line denotes the building envelope):

- Direct thermal losses, i.e. heat transfer between heated space and outdoor environment, including thermal bridges;
- Thermal losses through ground;
- Thermal losses through ventilation, and
- Thermal losses through unheated space, i.e. crawl space, cold basement.

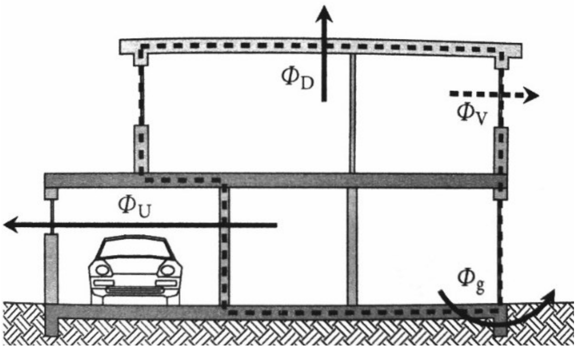

Figure 7. Thermal losses of building (reprinted from Pinterić, 2017).

Hence, the overall thermal loss flow rate of a building is a sum of the four contributors above:

$$\Phi_{total} = \Phi_D + \Phi_G + \Phi_V + \Phi_U, [W]\ (1)$$

A transmission heat transfer coefficient H, $[\mathrm{W/K}]$, is usually introduced as a ratio between the heat flow rate and the temperature difference between two heat transfer environments:

$$\Phi_{\mathrm{total}} = \mathrm{H}_{\mathrm{total}}(\theta_i - \theta_e), [W]\ (2)$$

The National Building Codes of Finland has detailed instructions on how to calculate the approximate total heat loss of a building. It is slightly different in the definition of contributors from the one above: heat losses include heat loss through building envelope, heat loss through thermal bridges and heat loss through building ventilation. U-values [W/(m^2·K)], or thermal transmittance of building components, are also advised not to exceed the maximum values as said in the YMa 1010/2017 (Ympäristöministeriö, 2017). In building performance simulation software, heat loss will be calculated effortlessly with a high accuracy by transient heat transfer calculation, with the correct input of boundary conditions such as the weather, the building envelope information, and heating setpoints. Heat loss through building envelope is the dominant source of the total heat loss in buildings, as seen in Figure 8. Precise heat loss calculation is the first step towards the accurate dimensioning of the generated power of the heating system. Thus, to mitigate the overall heat loss of buildings from the design stage is to step forward a more energy-efficient building generation in the future.

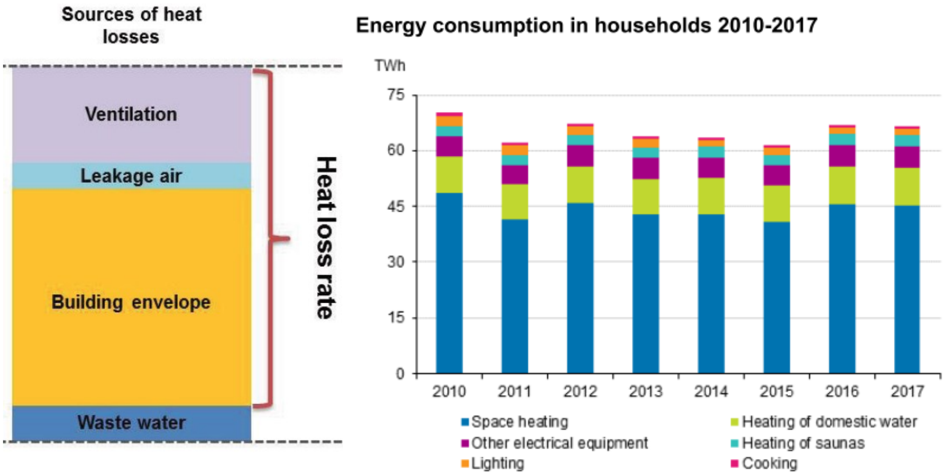

Figure 8. Sources and shares of heat losses vs energy consumption in households in Finland, 2010 – 2017 (adapted from Official Statistics of Finland, 2018; Vihola, Sorri, Heljo, & Kero, 2015)

2.3.3 HPs and USTES with HPs

To compensate for the heat loss and to achieve the heating demand for thermal comfort purpose without consuming excessive energy, HP is one of the best choices. In principle, HPs deliver more useful energy than the required power to run it, which makes it a perfect device to utilise free energy and act as a bridge between heat and electricity with a benefit. HP sales in Finland in 2018 was reported to shoot up by 22% with an investment of more than half a billion euros. This was explained by the fact that people were more aware of the effects of climate change, the profitability of extracting renewable energy sources and the HPs' bidirectional working features[4]. Nowadays, the Finnish HP market has witnessed a more vivid growth for the last two decades, possibly due to its wide availability in size, heat source choice, and improved convenience in installing and maintenance (Figure 9, the vertical axis denotes the number of HPs currently in use). (The Finnish Heat Pump Association SULPU, 2019)

Traditionally, a mere active solar heating system cannot supply all the heating demand of a building. This type of system barely exists nowadays because it produces heat which can only be used in that instance. Solar heat that cannot be stored nor transferred into other types of energy will eventually end up wasted. The same applies for PV panels, with electricity instead. Hence, the SF of such systems is very low, and it is usually used as a secondary source of heating, usually electric heating or district heating as the primary one. A solution for this issue, also to increase the usable solar energy captured, is to use a solar system in combination with an HP and a USTES. This kind of system is said to be feasible also for small- and medium-scale (Chwieduk, 2012). The USTES' temperature is not always high enough for direct final use, i.e. 58°C for DHW. When the temperature grade of the heat source is below the required output temperature, an HP will be employed to shift up the low-grade temperature to the high and ready-to-use one. Such systems have a variety of tailored configurations and modes of operation, depending on the climate conditions as well as the local common practice of engineering.

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[4] Basically, a HP can supply both cooling and heating need when swapping the evaporator and condenser sides.

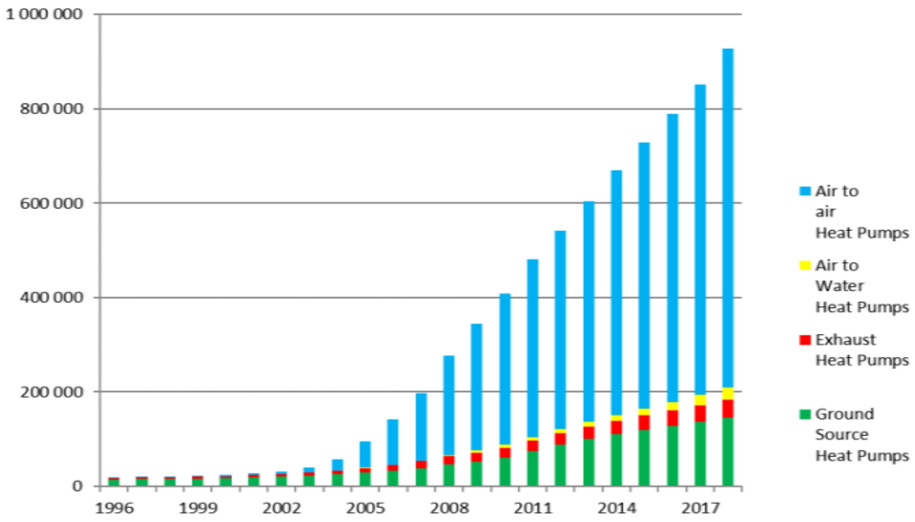

Figure 9. Share of HP sales in Finnish market from 1996 to 2018 (The Finnish Heat Pump Association SULPU, 2019).

2.3.4 Building performance simulation and its practice in the thesis

Simulation is generally the imitation of a process or a status of an entity within a certain given environment. Simulation in the present context most likely refers to a computational model of various simultaneous processes. Computational calculation was a milestone in the development of engineering design. Historically, the application of computer programming in building performance was first introduced in the 1970s, which has constantly been advanced both conceptually and technically. Simple, steady-state methods can be replaced now by dynamic ones with a shorter calculation time. Simulation has helped piloting an idea more easily in terms of saving resources and time. Building performance simulation (BPS), however, relies on an extensive range of disciplines from which the input is gathered. Nonetheless, over time, the capability of manipulating the sets of environmental and intrinsic parameters has been developed and enhanced continually. This turns BPS into an effective tool to predict, assess, and verify new building designs. (Nguyen-Ky & Nguyen, 2019) Therefore, to make use of BPS tools is a wise practice to test novel, innovative design especially in a time when the ground for energy efficiency in buildings is more competitively and productively demanding.

BPS tools were initially developed for research purposes. For the past two decades, it has broadened the range of users with their practical applications and widespread popularity. Engineers and designers have been more conscious of BPS' potential to facilitate their work effectively, meanwhile incorporating multi-disciplinary criteria for a comprehensive design. Why bother using a lengthy spreadsheet with limited variables and mathematical operation if BPS offers much more with faster and more accurate output? That is why BPS tools were commercialised, and nowadays many BPS tools lean more and more to general end-users with a graphical user interface (GUI). BPS tool market has been evolved rapidly in recent times with a high level of localisation. For instance, in the European countries, it is more common to use DesignBuilder, IES VE, ESP-r, IDA ICE, while in the case of North America it is most likely to be EnergyPlus. TRNSYS, however, is widely used across many regions due to its flexible compatibility with other components developed in other tools such as MATLAB or VBA.

IDA ICE (IDA Indoor Climate and Energy) is a simulation tool from EQUA Simulation AB. The IDA modular simulation environment was originally developed by the Division of Building Services Engineering, KTH and the Swedish Institute of Applied Mathematics, ITM in the late 1980s. The product was later developed for end-users and was made commercially available in 1998. (EQUA Simulation AB, n.d.-b) IDA ICE has been validated and certified with a variety of tests from different standards, e.g. ASHRAE 140, 2014, CEN Standard EN 13791, CEN Standard EN 15255 and 15265,2007, and IEA SHC Task 34 (EQUA Simulation AB, n.d.-d). This BPS tool has been used in numerous studies, such as in Häkämies et al. (2015) or in Simson, Arumägi, Kuusk, & Kurnitski (2019). The use of IDA ICE is more popular in the Nordic and Baltic countries because of its origin, common practice of engineering and good adaptability to the local languages and requirements (in climate data, standards, special systems, special reports, product and material data) (EQUA Simulation AB, n.d.-c). Finnish localisation is also well compiled with frequent update according to changes in the National Building Codes and report templates. With IDA ICE by and large, the highlighted reasons which made the author choose it as the working tool in this thesis are (a) the combination of GUI in general model level and user-defined parameterized objects in advanced model level, (b) transparent mathematical models allowing modellers to inspect every parameter and algorithm underlaid, (c) tailorable energy plant (ESBO) with a diverse library of HVAC components, process and logical controlling objects. The simulation work was performed in IDA ICE 4.8 SP 1, the latest at the time of conducting this thesis.

3 USTES FOR SMALL-SCALE BUILDINGS AND SIMULATION TOOLS

3.1 Thermodynamics of USTES

In any system, the internal energy is the energy contained within the system, microscopically speaking. In thermodynamics, there is no measure to quantify the internal energy of the system, but only the change of it, symbolically denoted as ΔU [J]. An increase in the internal energy of a system can be caused by an introduction of matter, by heat added, or by doing work on the system. The first law of thermodynamics states that, in a closed system, the change in the internal energy is equal to the amount of heat added to the system Q [J], minus the amount of work W [J] done by the system to its surroundings, as shown in equation (3).

$$\Delta U = Q - W \text{ (3)}$$

Since no external work is done on the system at all, the change of internal energy of the enclosed system will equal to the heat transferred to the system. Subsequently, the change in internal energy of the system will depend only on the heat added or removed from the system:

$$\Delta U = Q \text{ (4)}$$

The effect on the matter (or USTES medium) is its change in temperature, as a result. With this thermodynamically reasoning, the sensible USTES stores energy based on the increase in enthalpy of the USTES material. The amount of heat stored can finally be obtained by the integral in equation (5).

$$Q = m \int_{T_i}^{T_f} c_p(T)\, dT \text{ (5)}$$

where Q [J] is the energy stored, m [kg] is the mass of the USTES medium, c_p [J/(kg·K)] is the specific heat capacity, T_i and T_f [°C] are the initial and final temperature of the material during the heat transfer process. Note that the specific heat capacity of any material is a function of its temperature. In practice, this is replaced by a value at a certain temperature for simplicity since the variation is small in most materials.

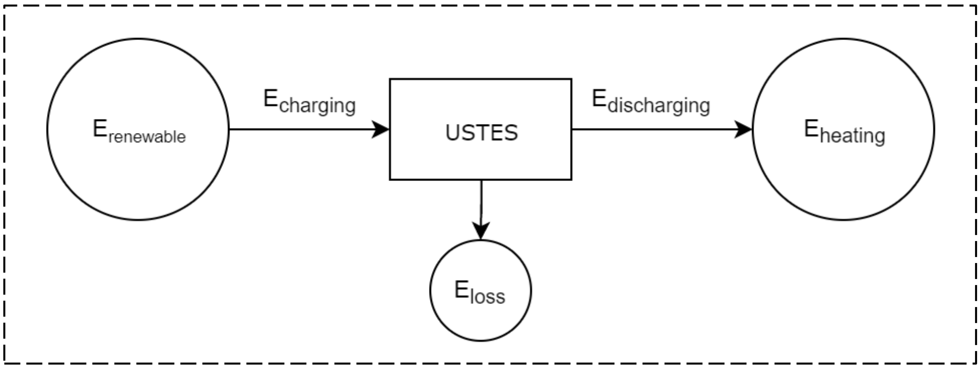

Figure 10. Energy transfer to and from the USTES.

The energy transfer (herein heat) processes through the USTES is shown in the chart in Figure 10. The charging energy is collected or produced from renewable sources and stored in the USTES. It will be discharged for heating supply and partly be wasted due to heat loss to its surroundings and the distribution systems.

3.2 USTES thermal properties

Designing a suitable USTES-HP depends on many factors. As said, USTES system should be individually engineered due to its complexity in terms of localisation and available technology. However, there are certain traits that any USTES should have in common. Following is a list of the most influencing factors that USTES designers should pay more attention to:

– Heat storing medium: The heat-storing medium decides many thermal properties of the USTES. Thermal conductivity λ [W/(m·K)], density ρ [kg/m^3], and specific heat capacity c_p [J/(kg·K)] are some of the important properties of the medium that affect the efficiency of the design. Working temperature range should also be considered, especially if the medium is liquid. A simple quick math of maximum storage capacity estimation can be done by using formula (6).

$$Q_{max} = V\rho c_p(\theta_{max} - \theta_{min}), \quad (6)$$

where Q_{max} is the maximum heat storage capacity, V [m^3] is the volume of the USTES, θ_{max} [°C] and θ_{min} [°C] is the temperature of the USTES when it is fully charged, and fully discharged, respectively. Generally, solids have a lower heat capacity than liquids, and it is slower to exchange heat in solids[5], i.e. solid medium always needs an intermediate fluid to transfer heat for final use; however, liquids have a narrower range of working temperature due to their boiling and

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[5] In fact, heat diffuses in solids through conduction (microscopically) faster than in liquids due to higher λ, but in liquids, heat transfer within themselves in most cases is also due to convection, i.e. uneven in density between their layers cause macroscopic moments in their body. Thus, the combined effect in the case of liquids is more intense than in solids.

freezing points, and ultimately, liquids need a watertight and proper structurally designed USTES envelope. For example, if a house needs annually 22 MWh of heating energy and it has a 300 m^3 USTES made of concrete with maximum and minimum operational temperatures respectively 75^{o}C and 20^{o}C, knowing the density of concrete is 2100 kg/m^3 and specific heat capacity of it is 1.1 kJ/(kg·K), then the maximum storage capacity will be around 10.59 MWh, according to the formula (6). Assume that the efficiency of the USTES discharging process is 50%, then the useful heat that can be extracted from it still amounts up to almost a quarter of the total heating demand (24%). In Table 2, different common materials for USTES and their thermal properties are compiled.

Table 2. Common materials for sensible USTES (modified from Jradi et al., 2017)

Material	**Type**	**λ [W/(m·K)] @ 20^{o}C**	**ρ [kg/m^3]**	**c_p [J/(kg·K)]**
Brick	Solid	1.20	1600	840
Concrete	Solid	0.9÷1.3	2000÷2250	1130
Granite	Solid	2.90	2650	900
Sandstone	Solid	1.83	2200	712
Water	Liquid	0.58	1000	4190

- Maximum USTES temperature: As mentioned above, the significant difference between USTES temperature and its surroundings leads to a high thermal loss rate. A lower USTES medium temperature also increases the efficiency of solar collectors due to a lower return temperature. However, this designed maximum temperature should at least cover the target fraction of heating demand satisfied by the USTES. In most USTES in small-scale buildings, USTES is often placed right underneath the building’s floor to make use of the heat loss from USTES to the upper space. Too high USTES temperature without proper insulation in the floor structure may cause unwanted discomfort during its operation. Small-scale USTES, in most cases, has a volume constraint; hence, the maximum temperature is usually designed as high so as to increase the maximum stored heat capacity of the USTES.

- USTES volume to collector area ratio: It is obvious that an increased collector area will capture more solar energy; thus, increasing the temperature of USTES. This is favourable for the HP in the heating season. In other words, COP of the HP will also be improved. USTES volume in small-scale projects is generally restricted due to cost constraints and the goal of USTES in small-scale buildings is to cover a fraction of the heating demand. Therefore, it is reasonable to dimension the collector area based on the USTES volume. Oversizing the collector area will lead to a decrease in the overall system efficiency and also a waste of resources. Hesaraki et al. (2015) compiled a list of USTES projects across a large number of reports in many European countries, Canada, and China. They built statistical models based on the data collected and found the correlation amongst the COP of HP, SF, and the ratio of USTES volume to collector area (Figure 11). Although most of those cases gathered in the study were of medium- to large-scale USTESs, the conclusion revealed an important characteristic of the USTES properties.

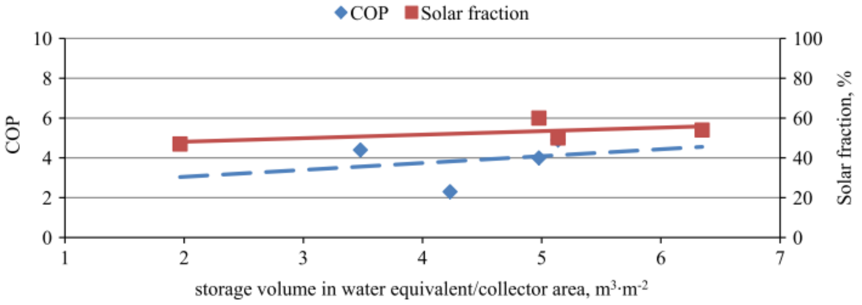

Figure 11. Correlation amongst COP, SF, HP's COP and storage volume[6] to collector area ratio (Hesaraki et al., 2015).

3.3 Common USTES configurations for small-scale buildings

As mentioned above, literature reviews show that the majority of USTES system research has been done for a community scale. Limited applications for residential buildings were reported, usually only active solar thermal system to mainly cover the DHW production and a minimal fraction of space heating with a diurnal water thermal storage. It is even rarer in the case of extremely cold, sparsely populated countries like Finland. However, several USTES-HP system concepts, which were designed and evaluated by both numerical simulations and actual experiments in Turkey, Sweden, Denmark and Alaska, have suggested that it is also highly possible to apply into small-scale buildings (Hesaraki et al., 2015). One of the most highlighted features of USTES designs for small-scale buildings is that the USTES is placed right under the floor of the buildings to make use or reduce the heat loss from the USTES. A research of Janiszewski et al. (2016) about the feasibility of USTES of solar heat in Finland, BTES was the method which is most suitable for small-scale systems. BTES was concluded to have high overall evaluated rating in terms of cost efficiency and small-scale feasibility. Additionally, it was assessed to have high ratings in the simplicity of obtaining sufficient storage volume, in the adaptability to the Finnish ground conditions, and the reliability of storage system over long-term performance. A rendered

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[6] Equivalent water volume conversion was performed due to the different USTES media used in different projects.

3D-model with cross-section view is shown in Figure 12 as an example of a BTES in a small building with a shed.

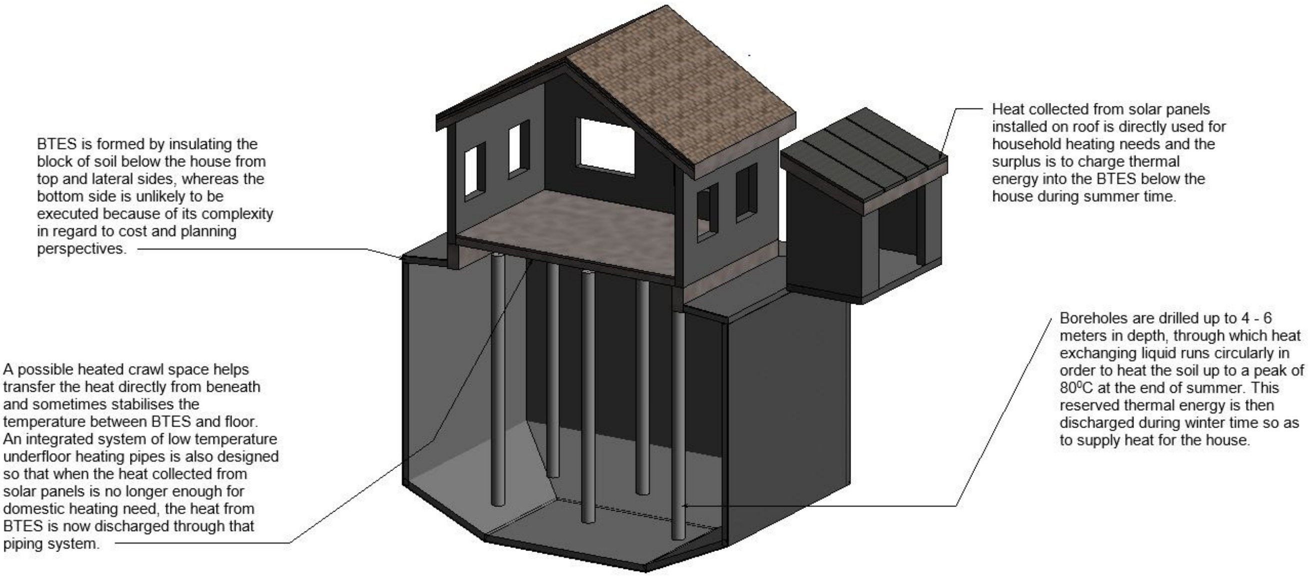

Figure 12. A close-up of an example small-scale BTES.

In this part, two most common configurations will be presented. They are respectively USTES-HP with solar collector, and USTES-ASHP with PV panel. Notice that the position of the storage system is just a demonstration of a schematic system, in reality, it should be placed right under the buildings.

3.3.1 USTES-HP with solar collector

In this configuration, a hundred per cent of solar heat collected will be used to charge the USTES. To minimise heat loss and increase the efficiency of the collector, usually a heat exchanger and a solar heating tank will be employed to regulate the charging temperature to the USTES. The HP will extract the heat to satisfy the heating demand until the USTES temperature reaches a low limit (i.e. frost limit). In case the temperature of the USTES is high enough for the heating system, the HP will not be in use, and direct heat from USTES is extracted for both DHW production and space heating. However, high USTES temperature design is not recommended due to the increasing heat loss when the temperature difference between the USTES and the surrounding soil increases. Figure 13 depicts a schematic arrangement of the system with the highlight that the USTES is placed in the middle of the system series.

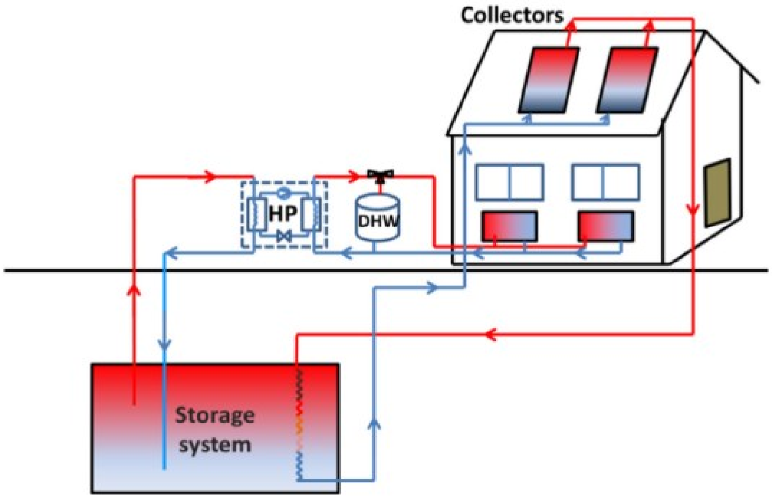

Figure 13. USTES-HP with solar collector (reprinted from Hesaraki et al., 2015)

3.3.2 USTES-ASHP with PV panel

In the former system, collectors, USTES, and HP are put in a series (Figure 14). The heat produced will need to go through the USTES before It arrives at the heating devices. In this configuration, instead of the USTES, the HP is placed in the middle. Generally, the HP will work as the main heat generator for the building. In the summertime, when the heating demand is low and the electricity production from PV panel is excessive, the HP will use the surplus electricity to run the HP to charge the USTES. The addition of another loop (collector – USTES) is optional; however, in this circumstance, it should be noted that the efficiency of solar collectors will decrease considerably when the return temperature to the collector is too high. Also, in the wintertime, the temperature of the collector would barely exceed that of the USTES without the help of an independent heat transfer circuit, which may lead to a further decrease of the overall efficiency of the system. One solution to efficiently use the exergy is to use the low temperature from the collector in low productive time to heat up the air fed to the evaporator side of the HP. The efficiency of the HP increases significantly with a slight increase in the fed air temperature. This would result in a higher COP of HP, and eventually, save the additional electricity amount to run the HP. (Hakkarainen, Tsupari, Hakkarainen, & Ikäheimo, 2015)

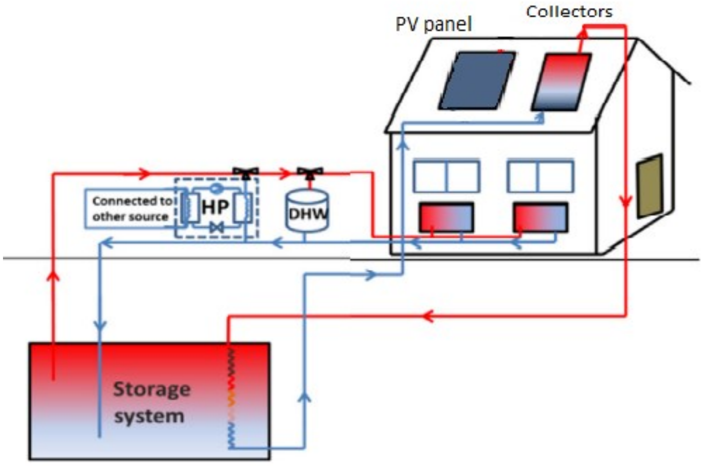

Figure 14. USTES-ASHP with PV panel and an extra loop with solar collector (adapted from Hesaraki et al., 2015).

3.4 Design tools

The study of USTES thermal properties requires a high level of accuracy as to deal with the stochastic nature of solar energy yield and climate conditions. For the simulation of transient thermal processes of thermal energy systems, there are several simulation programmes which were employed in many previous USTES projects. The majority of the written programmes were meant for large-scale USTES, e.g. MINSUN, SOLCHIPS, SmartStore, TRNSYS, EnergyPlus, and Solarthermie-2000. Of the abovementioned tools, except the TRNSYS and EnergyPlus, the rest were either uncommercialised or expired due to the termination of funding.

TRNSYS is a multi-disciplinary graphically based software to simulate transient system, but mostly used for thermal and electrical ones. Like EnergyPlus, TRNSYS also has a kernel (engine) and an extensive library of modules, some of which can be tailored into a model of USTES, most commonly a BTES one. The famous DLSC project in Canada with over 98% of SF was initially modelled in TRNSYS with the module DST in 2006, before it was constructed. (Hesaraki et al., 2015)

IDA ICE, as introduced before, was not specifically written for USTES design. It focuses more on overall building performance, i.e. energy and indoor climate simulation, and is oriented more towards non-expert end-users with many pre-defined parameters and default objects. However, in the latest version of IDA ICE 4.8 SP1, there are several extensions which are available for purchase separately. One of them is the borehole extension, which allows the modelling and predict the performance of large fields of interacting boreholes (EQUA Simulation AB, n.d.-a). The modeller can make use of this extension in combination with the ESBO Plant in the advanced level to fully simulate the behaviour of the USTES as well as the interaction between the USTES and the building. The reasons the author chose this software to perform the simulation work was discussed in section 2.3.4.

That being said, each USTES configuration has its own features and dependencies. The generalisation of any USTES model may need time for more theoretical and experimental research. For now, researchers and USTES designers can choose amongst the tools they are most familiar to, or the ones with available modules whose effects their research targets are pointing towards. It is also possible that new USTES design tools will be either written or developed from the existing simulation engines. It is a matter of the maturity time for design tools of USTES for small-scale buildings. In the author's opinion, TRNSYS is the most suitable software to perform such small-scale USTES' designing, simulating, and assessing tasks.

3.5 System monitoring plan and performance assessment

Like any other energy systems, USTES needs a plan of monitoring and maintenance, as well as performance assessment during the operation stage. Building automation technology nowadays has enabled effortless controlling and measurement. Real-time data processing and integration allow prompt control adjustment and fault detection. Modern IoT sensors and communication protocols development also support the building's energy system metrics collection and surveillance from afar. Thermocouples, flow controllers, energy meters are some of the basic data collectors in such USTES systems, as used in many experiments such as in Hailu et al., (2019).

To evaluate how efficiently a USTES-HP system performs, usually SF and heating pump's SCOP (seasonal coefficient of performance) are calculated. SF tells how many per cent of the total heating demand by the building is satisfied by solar heat collected by the system. Heating demand can approximately be considered as proportional to heating degree day[7] (HDD), which depends on the building's location. Therefore, SF tends to reduce along with the increase of latitude. COP of HP oscillates greatly with respect to the heat source temperature and heating demand. Thus, SCOP, also called seasonal performance factor (SPF) is used instead to measure the overall efficiency of the HP over an entire heating season.

For solar collector systems alone, several research papers had estimated or measured the SF concerned in their work. For example, in Marx (2015), SF was calculated with the simulations of a system of solar collector alone, just to cover the DHW part of the total heat demand. The result was between 14% to 28% in Stockholm with savings from 1 to 2 MWh/a for a

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[7] HDD is a standardisation of the consumption of heating energy in order to compare the energy consumption amongst buildings in different geographical locations. HDD is calculated by adding up the differences of the daily in- and outdoor temperatures of the whole month. Reference Finnish locations' HDD values used within this thesis were taken from the average HDD from the normal period 1981 – 2010. (Finnish Meteorological Institute, n.d.)

120 m^2 residential building. Meanwhile, this SF range is 40% to 84% in the location of Rome with the same system. In a separate study at the location of Adana, Turkey, the range is around 32% to 40% (Yılmaz, 2018). Thus, SF is an informative criterion to evaluate the system, yet, not a comparable value to those of other systems of the same kind in different climate regions. In Hailu et al., (2019), the experiment was monitored for more than one year with a sand bed underneath a garage in Alaska. The authors did not use SF as an evaluation figure, but instead, the reduction in the heating load of the garage. The direct heat loss from beneath partly warmed up the garage, which helped decrease the top-up heat needed. This is also a good indicator in the assessment of USTES' efficiency.

To sum up, USTES' performance can be assessed based on indicators such as SCOP of HP, SF, reduction proportion in heating load, and savings of the total electricity consumption. Essentially, the first two values are for comparison amongst other solar energy systems with or without USTES, while the last one is generally for checking with the requirements of the building codes (the EPV).

4 DESIGN EXAMPLE

4.1 Case description

At the time of conducting this thesis, HAMK Tech Research Unit was planning to build a laboratory to be placed in Valkeakoski Campus. The lab's total heated floor area is 35 m^2 and was structurally designed with a timber frame. The classified purpose of use of the building will be for office use. Four rooms will be shared for laboratorial and working space. The primary heating source in the building is electricity, with solar heat coming as secondary. Although not included in the total energy consumption later at the end of the case simulated results, some of the electricity to the building will be fed from an already existing PV panel production nearby. HAMK Tech engineers and HAMK Construction Engineering Degree Programme's teachers will be responsible for all the structural and architectural design work of this building. The construction work was supposed to start in winter 2019 and continue until spring 2020.

Valkeakoski City is approximately 30 km away to the south-southeast of Tampere. Thus, the weather data used in the simulation will be taken as of Tampere City. The coldest day during winter may have a temperature as low as $-30^{o}C$. The campus as a whole is located in the Matinmäki part, which is in the north-western suburb of the Valkeakoski City. However, the concerned lab building is surrounded by the multi-storey buildings of the campus. Thus, for the calculation of the wind profile and pressure coefficients, urban profile will be selected. In Finland, although at a high latitude, solar irradiation annual yield is only 20% lower than that of Northern Italy. The irradiation data is already included in the reference weather file under hourly data point measurements. The estimated annual irradiation for Valkeakoski location is around 950 ÷ 1000 $kWh/(m^2 \cdot a)$ (Hakkarainen et al., 2015).

City	HDD
Helsinki	3878
Turku	4021
Tampere	4424
Pori	4161
Jyväskylä	4832
Vaasa	4469

Figure 15. Valkeakoski City on the map of Finland and the HDD of major Finnish cities during 1981 – 2010 in increasing latitude order. (Finnish Meteorological Institute, n.d.)

According to the latest Finnish National Building Codes on Energy Efficiency YMa 1010/2017, buildings under 50 m^2 of total floor area will not be concerned, unless it is part of buildings with over 50 m^2 of total floor area. However, the structural design of the building elements in the example case (i.e. external walls, floor, roof, doors, and windows) was made sure that their U-values were no greater than the reference values specified in the heat loss calculation chapter. Structural and site drawings of the lab building are shown in Appendix 1. The goal of the case design is to design a USTES-HP system with solar collectors to be implemented in the lab's energy system. The design feasibility will take into account both technical and economic aspects. The results of three simulation attempts will be discussed and compared amongst three different design models.

4.2 Delimitation of the design work

The design of this USTES-HP system with solar collectors will focus mainly on technical configuration. Although the capital resource for this lab building project is limited, cost calculation will not be performed in detail. However, in the selection as well as the dimensioning of the system's components, cost-effectiveness is still one of the important constraints. This design case does not aim at building the lab to be an nZEB, only to show how the application of an USTES-HP system would improve the solar energy utilisation and the overall energy consumption in a building. Thus, the compliance of it with nZEB requirements will not be performed.

As mentioned above, the weather data of Tampere City was used instead of the exact location where the lab building was planned to be placed. The climate file format is IWEC2, which stands for International Weather for Energy Calculation version 2.0. IWEC2 weather data format contains average values of observations on an interval basis of at least four times per day for at least 12 years of records up to 25 years, depending on locations. (White Box Technologies, n.d.) This is a common weather data file format, which is used by ASHRAE and many other energy simulation tools, including IDA ICE. Climate conditions vary stochastically from year to year, possibly with considerable amplitude. Therefore, simulated results should only be considered a close estimation of the actual behaviour of the system.

Since the lab building was still under planning and designing stage, no information on the equipment load was provided. Laboratorial work might also include testing machinery and instruments which would consume a significant amount of electricity, as well as emit heat into the space. This irregular thermal load will not be included in the simulated model; instead, the reference values from YMa 1010/2017 for office buildings will be taken as input. Some input whose details were not available at the time of constructing this model were also left as default in IDA ICE. Yet, some of them were not so realistic as those of present products, e.g. heat recovery unit’s efficiency was set at 55%, meanwhile, in fact, a new, modern unit can get from 60% up to 90%. Nonetheless, these input values always put the simulation results to be on the safer side, which is a customary practice in general preliminary design.

Lastly, the case design was done mainly together with literature research work, while the author’s modelling skill was not at a highly proficient level. Repeatedly, the number of research for application of STES-HP with solar heat collectors in residential/small-scale buildings was significantly limited, not to mention in regions with extreme climate as in Finland. A complete design of such a system is complicated and requires collective expertise for example from automation controlling, geological surveying, and HVAC engineering, etc. Within a limited timeframe, the author was not capable of obtaining such extended knowledge for those. Hence, in many circumstances, the trivial details were omitted, or in many cases, roughly estimated, and many pre-set parameters in the simulation software remained unchanged.

4.3 Preliminary design and construction of simulation model

Orientation and site shading

The lab building (B) was planned to be placed at the rear of a parking lot to the east of the HAMK-A building, right next to an already-built shed (A), as in Figure 16. In the surroundings, there were no shading objects such as trees or buildings that could shadow the lab’s windows or solar collectors.

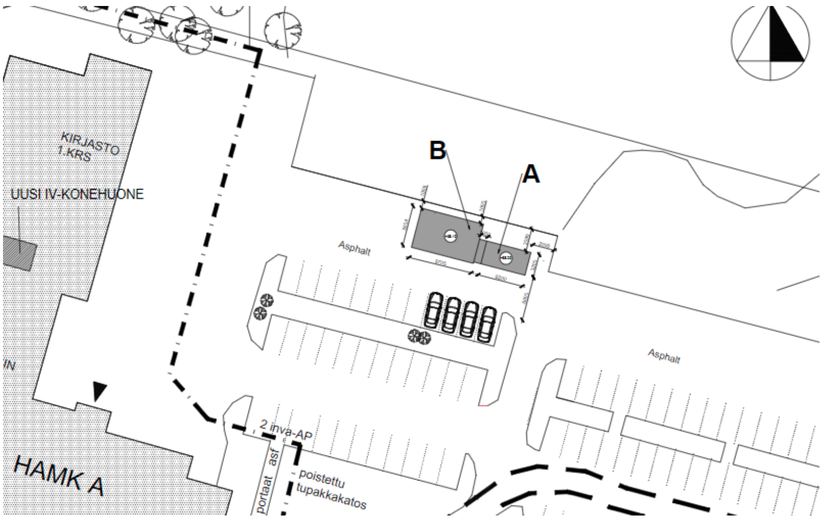


Figure 16. Site orientation and shading

Geometry and structural components:

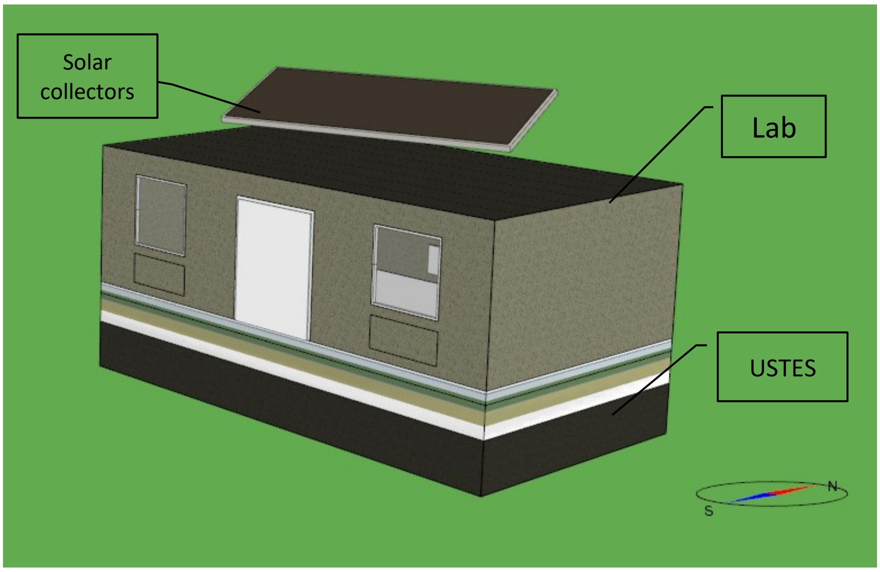


Figure 17. The 3D model of the lab building with USTES underneath and solar collectors on the roof

As seen in Figure 17 above, the laboratory was designed as a rectangular box (floor inner dimensions 4.534 x 7.934 m^2, floor top to ceiling 2.379 m). The wall, roof and floor construction layer material descriptions can be found in Appendix 1/1-3. A cross-section view on the USTES' structural and piping layers are also shown in Appendix 1/4. Table 2 below summarises the U-values and areas of those, and of door and windows of the lab building:

Table 3. Lab building component summarised descriptions

Components	Area [m²]	U-value [W/(K·m²)]
External walls US1	48.94	0.13
Roof YP1	35.97	0.09
Floor AP1	35.97	0.10
Door O16x20	3.18	1.00
Windows 12x12	7.2	1.00

Ventilation airflow and water radiators

An AHU with HR ($\eta = 55\%$) provides a constant supply and return airflow of 2 $dm^3/(s \cdot m^2)$ at 19°C during scheduled time 06 – 19, Monday to Friday, for the whole building. A heating design calculation was run to size the water radiator power, i.e. 2250 W for the whole building. However, it will be divided into four rooms of equal size and it has five windows in total. Thus, the preliminary design for heating devices was five water radiators of 500 W underneath each window. The water radiators will be run by a low-temperature heating flow, i.e. 45°C in supply and 25-35°C in return. The heating setpoint is set at constant 21°C. The building has no active cooling devices. The curve for heating water temperature is shown in Figure 18 below.

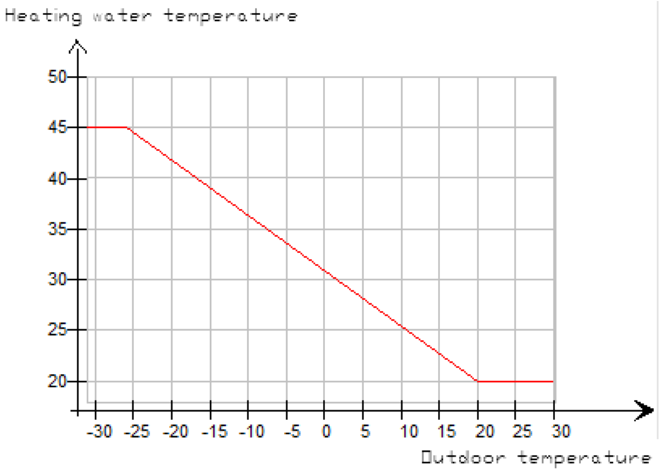


Figure 18. Heating water temperature as a function of outdoor temperature.

Ground temperature model and other concerned inputs

Heat loss to the ground calculation: Calculation of the ground temperature adjacent to the building components underground (i.e. basement walls and slabs) will follow the ground model ISO 13370:2007, which is integrated into the simulation software. This model will calculate the heat resistance at the outermost layer based on the specified geometry of the building. Ground temperature calculation by this model showed a strong agreement with WUFI, which is a dynamic thermal simulation tool with a high level of accuracy (Walter & Antre-Er, 2016). Other input data is presented in Table 4.

Table 4. Other IDA ICE input summary

Input	Profile/Value	Unit
Wind profile	Urban	-
Pressure coefficient	AIVC Exposed	-
Thermal bridge	3.813	W/K
Infiltration	0.1333	$m^3/(h\cdot m^2)$ ext. surf.
DHW*	6	$kWh/(m^2\cdot a)$
Occupant**	4	Adult of 1.2 MET
Lighting**	10	W/m^2
Equipment**	12	W/m^2

*according to YMa 1010/2017

**active schedule 07 – 18, Mon – Fri, with usage factor 0.65 according to YMa 1010/2017

Heating system design

The schematic heating energy flows are depicted in the process chart in Figure 19. E [J] stands for energy (heat) and W [J] for input power from electricity. Other system components will be described as follows.

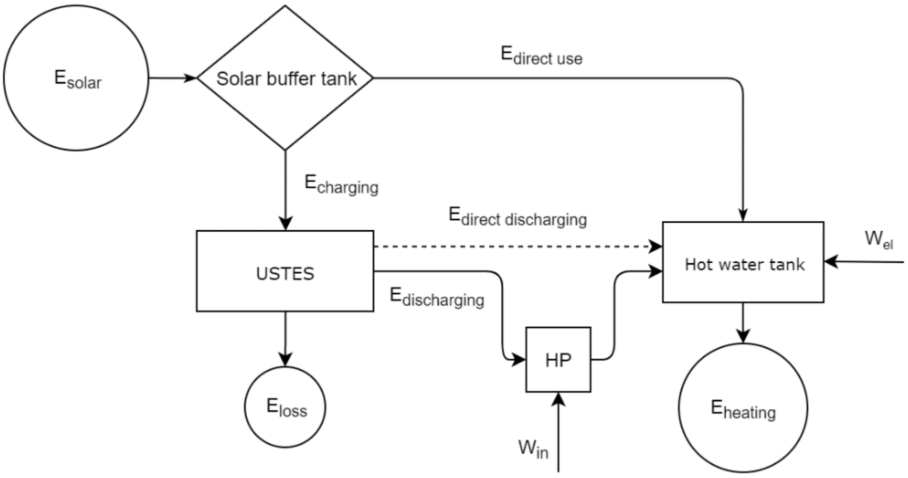


Figure 19. Energy flow in the USTES design example.

Solar collectors

The total aperture area of solar collectors is 9.9 m^2. Five flat plate collector panels will be installed at a 41^o slope facing to the right south on the roof of the building. The heat production of solar collectors is decided by the inlet fluid temperature to the collector and the ambient temperature, as shown in formula (7). Thus, a spiral heat exchanger is installed inside the solar tank to get the low fluid inlet temperature into the collector, help increase the collector efficiency even in freezing days. Low temperature loop also minimises the heat loss to the environment during circulating. The chosen aperture area 1.98 m^2 solar collector panel has the manufactured value as 0.88, 4.0 and 0.005 for η, a and b, respectively. IDA ICE will extract location-dependent values from the weather file.

$$q_C = A_C \times E_C \times \eta \times \left[1 - a \times \left(\frac{T_{in}-T_{amb}}{L}\right) + b \times \left(\frac{T_{in}-T_{amb}}{L}\right)^2\right] \tag{7}$$

where q_C [kWh] is the average amount of heat produced, E_C [kWh/m^2] is the average amount of solar energy received by 1 m^2 of collector area, T_{in} and T_{amb} [^{o}C] are the heat transferring fluid inlet temperature into the collector and the ambient temperature, respectively, η [dimensionless] is the efficiency of the collector, specified by the manufacturer, a and b are the test-determined coefficients, and finally L [dimensionless] is the average monthly value of atmosphere lucidity. (Hesaraki et al., 2015)

Water tanks and HP

There will be two water tanks in use: a solar tank and hot water tank. An HP is employed to shift the low-grade temperature heat from the USTES to the hot water tank when in need. A 2-kW resistor is equipped inside the hot water tank as a top-up heating source if the heat generated does not suffice. Figure 20 shows a simplified piping plan of the whole system. Solar tank and hot water tank sizes are both 500 L. The HP heating capacity is 4 kW at rated conditions.

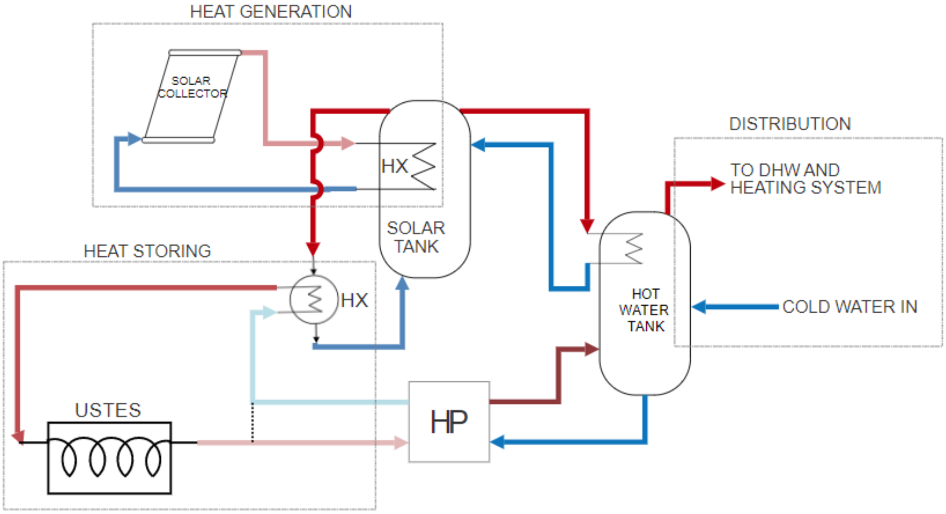


Figure 20. Schematic looping of the USTES-HP with solar collector heating system.

Fluid loops

Glycol-water solution will be the heat transfer liquid in both the solar collector loop and USTES-HP loop. When the liquid in the collector surpasses 5^{o}C in difference between inlet and outlet, a pump will pass it through a heat exchanger located inside the solar tank to store. The heat will be passed constantly to the hot water tank whenever it asks for heat. Otherwise, the heat will be transferred to the USTES loop through another crossflow heat exchanger by a pump. In the heating season when heat in the solar tank is insufficient, the HP will be turned on to extract the heat from the USTES. The dashed line in the schematic diagram represents an option of a pipeline to bypass the HP. This is unnecessary in a small-size piping system because the distribution heat loss and pump power are trivial.

USTES structural design and piping layers

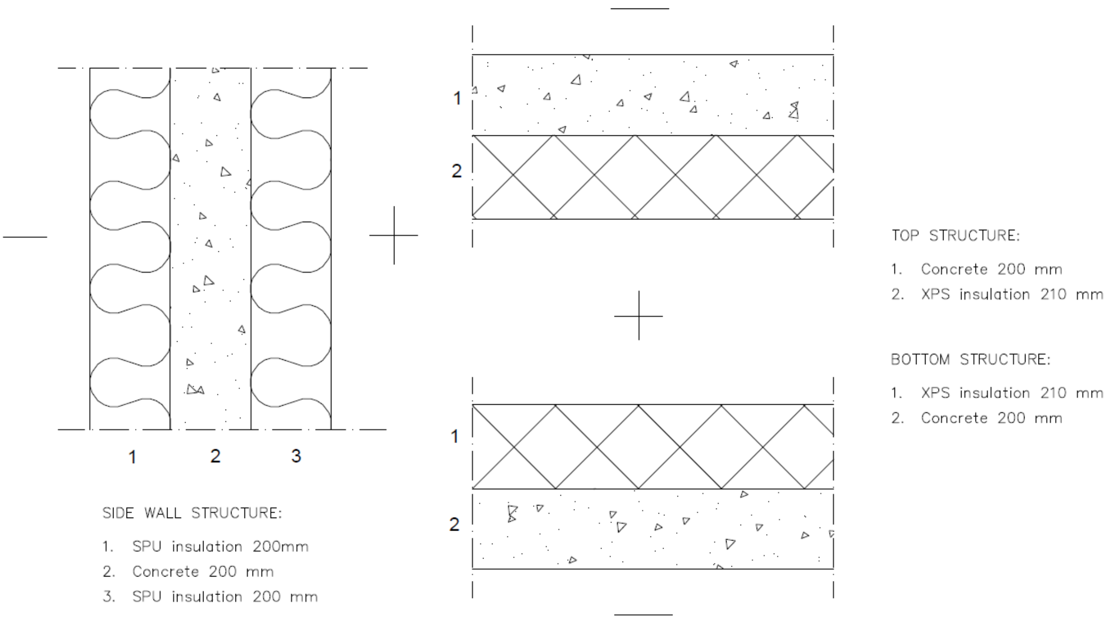


Figure 21. USTES' structural drawings.

The lab building floor is in direct thermal connection with the 200 mm concrete slab on top of the USTES, whose cross-section can be seen in Figure 21 above. The USTES medium was chosen to be compact sand with a total thickness of 2 m. At the bottom, there are two layers of EPS insulation board, 100 mm each. The walls of the USTES are insulated with 200 mm thick polyurethane insulation on both side of a 200 mm thick poured concrete. Information on thermal properties of the USTES medium is shown in Table 5. Three layers of 30 m cross-linked polyethylene (PEX) DN40 pipe will be installed at the depths of 0.4 m, 0.9 m and 1.4 m from the lower surface of the USTES top slab.

Table 5. Thermal properties of wet compact sand (Hailu et al., 2019)

Properties	Value	Unit
Density	2015	kg/m^3
Thermal conductivity	1.41	$W/(m^2 \cdot K)$
Specific heat capacity	980	$J/(kg \cdot K)$
Water mass content	16%	-

Model construction in IDA ICE

USTES model

Major components of the USTES represented by objects in IDA ICE schematic mathematical model were BDFWALL wall, HCFLOOR floor heating piping layer, TQNODE thermal node and TQGROUND ground temperature calculator. The arrangement and connection between the objects are shown in Figure 22. With this model, the heat flux at the uppermost surface of the USTES will distribute into its top and four sidewalls, since BDFWALL is a 1-D heat transfer through a flat, indefinite solid wall model. Liquid loop into USTES and back to the technical plant is marked at the X sign on the lower left-hand side.

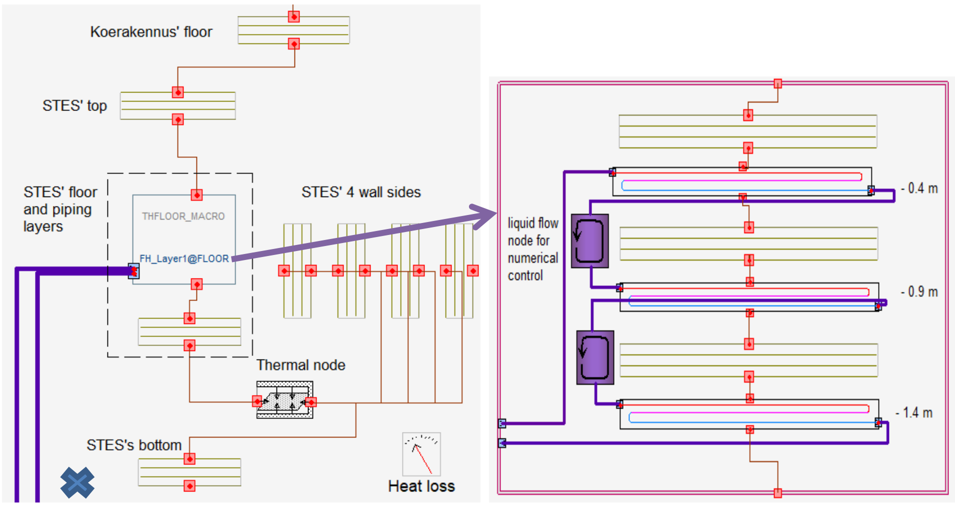


Figure 22. USTES in IDA ICE schematic model

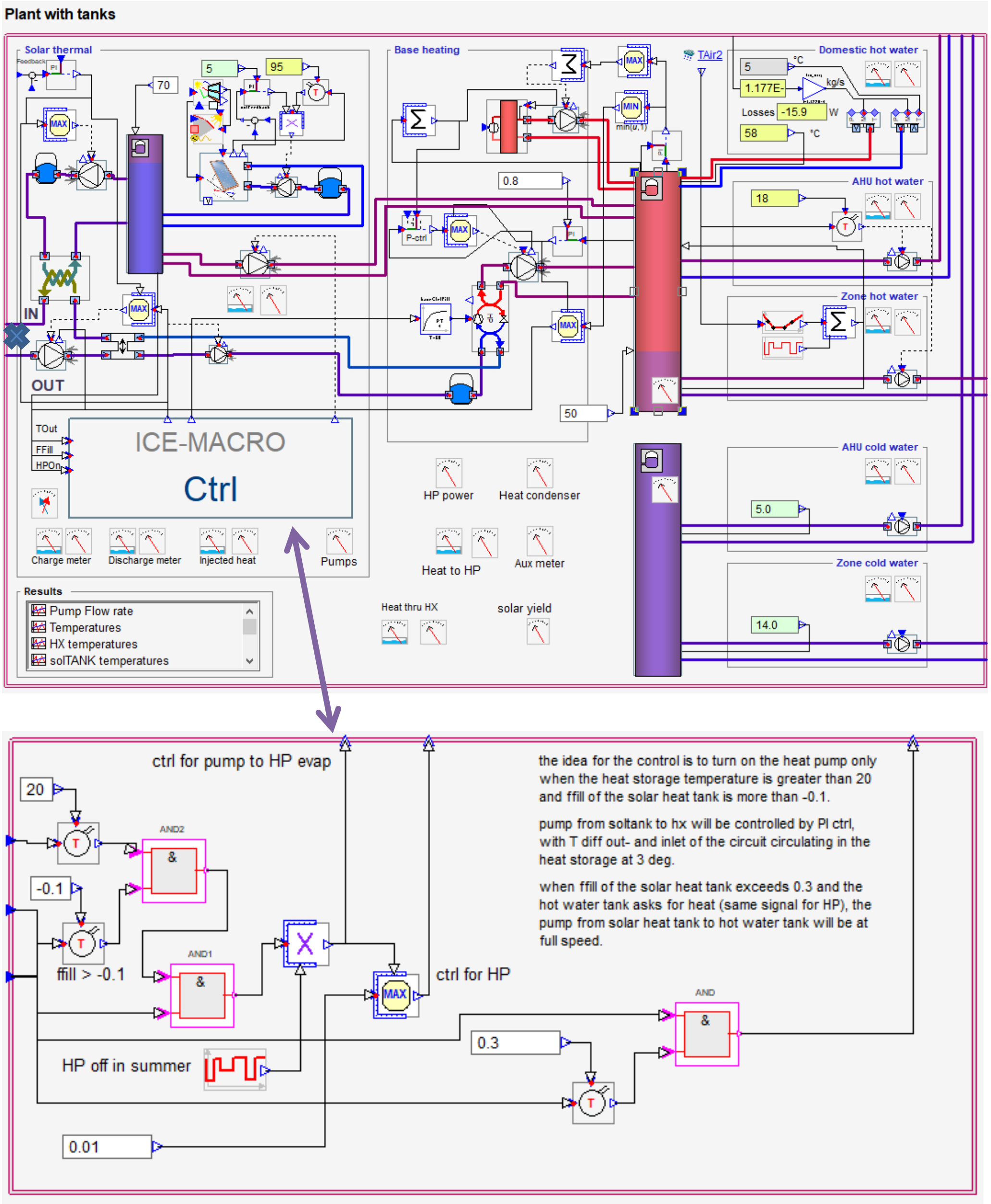
Technical plant and controls

Initially, the technical plant was built based on the ESBO plant of IDA ICE. That is the reason the cold tank and other cooling system related objects are presented. However, they will not have any impact on the result since the building does not have any cooling devices. The resistor inside the hot water tank was modelled as a separate electric boiler, just for an easier control parameter adjustment in IDA ICE.

The setpoint temperature for DHW, which was originally 55°C, was increased to 58°C. To evaluate the heat collection degree of the solar heating system, the author chose a quantity called FFILL of tanks. The control logic for the HP and many pumps, including the pump to charge the USTES depends on it. The FFILL is calculated as shown in formula (8).

$$FFILL = \sum_{i=1}^{n} \frac{T_i - T_{amb}}{n \times max\{0.1; T_{setmax} - T_{amb}\}} \quad (8)$$

where n is the number of stratification layer of the ideal tank model, usually 5; T_i[°C] is the temperature of layer i; T_{amb}[°C] is the ambient temperature. Generally, FFILL represents a factor describing the degree of heat charge to the tank with respect to the outdoor temperature and the maximum setpoint temperature of the water in the tank, e.g. hot water tank 58°C and solar tank 70°C. An FFILL of 1.00 is reached when the temperature from the top layer to the bottom layer of the tank is all equal to the maximum setpoint of the tank, meaning tank fully charged. Likewise, FFILL is 0 when the temperature from the top layer to the bottom layer of the tank is all equal to the outdoor temperature. Hot water tank for DHW and space heating is usually kept at an FFILL of 0.8, so that in case there is DHW heat demand, the production will be timely delivered.



the idea for the control is to turn on the heat pump only when the heat storage temperature is greater than 20 and ffill of the solar heat tank is more than -0.1.

pump from soltank to hx will be controlled by PI ctrl, with T diff out- and inlet of the circuit circulating in the heat storage at 3 deg.

when ffill of the solar heat tank exceeds 0.3 and the hot water tank asks for heat (same signal for HP), the pump from solar heat tank to hot water tank will be at full speed.

Figure 23. Technical plant of the heating plant in IDA ICE schematic model

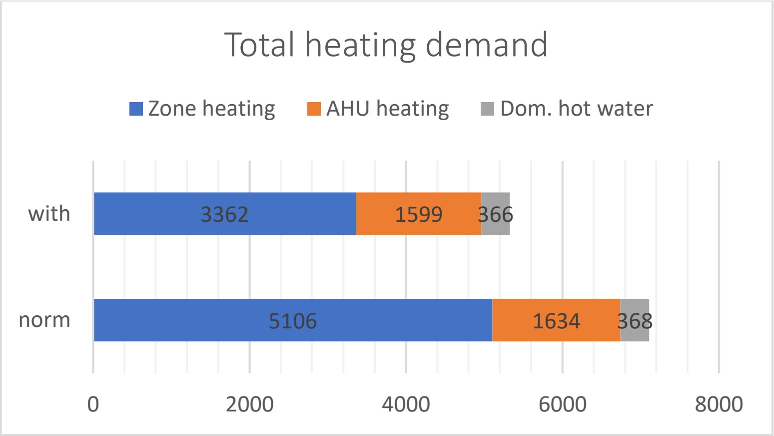
The HP is scheduled not to work from 15th April to 31st October, while the heat yield from the solar collector is usually still sufficient for the heating need. The temperature of the USTES is kept not below 20°C all the time so as to mitigate the heat loss of the lab building through the ground floor. A description of the control logic for pumps and HP is shown in the lower part of the schematic plan of the plant. Notice the X mark, where the fluid loop continues to the USTES in Figure 23. Many flow and energy meters were used to calculate the energy yielded and distributed throughout the plant.

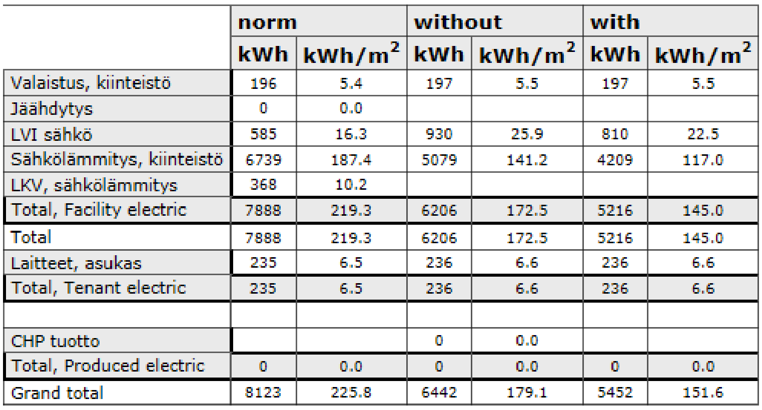
4.4 **Simulation results**

In order to gain a better view on the effect of the USTES, three models with different energy systems were run. The lab building model with correct geometry, structural components and basic loads were run first with a standard electricity-based plant (the “norm” model). Then, the standard plant was replaced by plant with solar collectors but without USTES-HP. The so-called “without” model had only one tank with volume of 1000 L. These two models were created effortlessly, because no changes in the schematic mathematical model in IDA ICE was required. Finally, the “with” model, the main USTES-HP plant, was run. The simulation period is from 1st April to 1st April of the following year without any holidays specified.

4.4.1 Purchased energy and space heating energy

Figure 24 summarises the simulation results from three models. As can be seen, it is obvious that the “with” model achieved the lowest purchased energy thanks to the USTES-HP with a solar collector system. It also helped a reduce the energy purchased by 27.5 kWh/(m^2·a) in comparison to the “without” system, and up to 74.2 kWh/(m^2·a) in comparison to the “norm” one, which was basically a purely electricity-based heating system. The table below the chart displays the broken-down energy consumption both in total and per meter square. In terms of space heating, the USTES-HP system reduced the space heating (the sum of zone heating and AHU heating) of the lab building by 36%. Heating energy stays the same for the “norm” and “without” system. This is explained by the effect of the sand bed right underneath the floor. The heat loss to the ground through the floor is minimised by keeping the USTES sand bed around 20^oC. On the other hand, electricity used for a heating purpose witnessed a cutback of roughly one-fifth, from 141.2 to 117.0 kWh/(m^2·a). A detailed comparative report amongst the simulation results of three cases can be found in Appendix 3.





	norm		without		with	
	kWh	kWh/m²	kWh	kWh/m²	kWh	kWh/m²
Valaistus, kiinteistö	196	5.4	197	5.5	197	5.5
Jäähdytys	0	0.0				
LVI sähkö	585	16.3	930	25.9	810	22.5
Sähkölämmitys, kiinteistö	6739	187.4	5079	141.2	4209	117.0
LKV, sähkölämmitys	368	10.2				
Total, Facility electric	7888	219.3	6206	172.5	5216	145.0
Total	7888	219.3	6206	172.5	5216	145.0
Laitteet, asukas	235	6.5	236	6.6	236	6.6
Total, Tenant electric	235	6.5	236	6.6	236	6.6
CHP tuotto			0	0.0		
Total, Produced electric	0	0.0	0	0.0	0	0.0
Grand total	8123	225.8	6442	179.1	5452	151.6

Figure 24. Energy simulation results of the three models.

4.4.2 Free energy utilisation

With the solar collector system, another concern is how much heat the collectors yield from the Sun annually. This amount of collected heat depends mainly on the heating tank size and the heating demand. Generally, when the heating tank is fully charged and the building does not ask for heat, all the solar heat gain in the collectors will go to waste. As one can see in Figure 25, with a USTES-HP, total annual solar heat yield from collectors surged by up to 65% compared to the ordinary solar collector system, “without”. Continuous distribution of collected solar heat reduces the temperature of the solar tank; consequently, it lowers the inlet fluid temperature to the collector and heightens the collector efficiency. The heat recovered from AHU HR unit also increased slightly due to greater heat deposited in the building from the heat loss of the USTES sand bed through the floor.

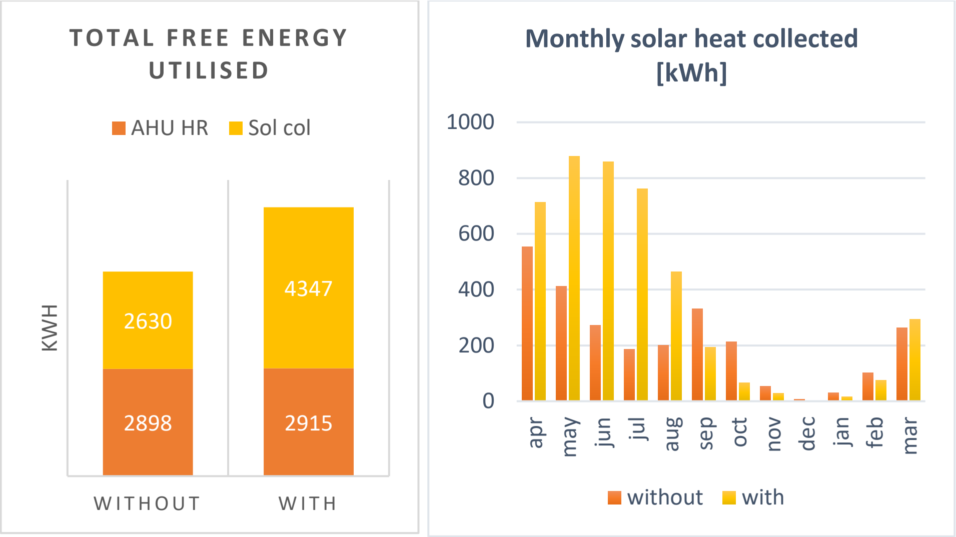
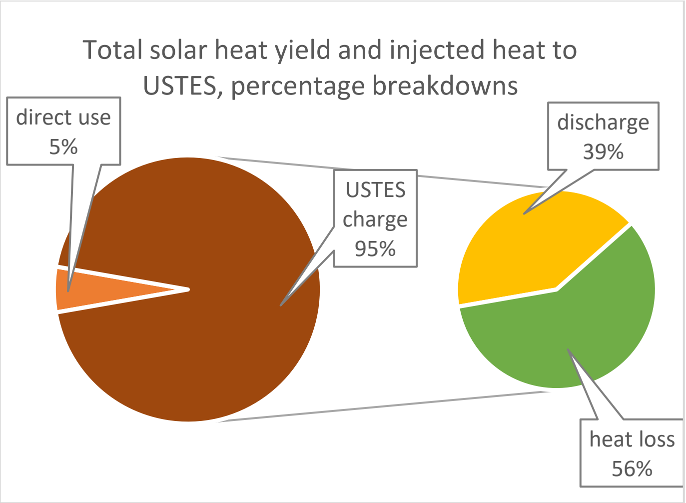


Figure 25. Free energy utilisation and solar heat collected simulation results

4.4.3 Solar heat yield distribution and SCOP of HP

With the USTES-HP system, part of the collected solar heat was transferred directly to the hot water tank. The rest was injected to the USTES sand bed through a heat exchanger to another fluid loop (regard Figure 20 and 23). Then, when the HP worked, it would extract heat from the USTES, and if possible, partly directly from the solar tank, due to the fact that the fluid always had to pass the heat exchanger. The solar heat yield and the USTES heat flow breakdowns are described in Figure 26. In fact, the solar heat supplied to the total heating demand was the sum of direct heat use and the discharge amount. It was calculated that the SF for the USTES-HP with the solar collector system achieved over 36%. Meanwhile, in the “without” system, SF only reached the value of 23.5%. Heat loss accounted for a considerable share of the total, which is inevitable in this small-scale system. However, a small part of the USTES’s heat loss turned to be useful when it transferred upwards to the building’s floor, either reduced the heat loss of the building to the ground or even helped warm up the building.



Unit:	kWh
Collected	4346.2
Charge	4107.0
Direct use	238.6
Discharge	1693.0
Heat loss	2414.6

Figure 26. Solar heat yield distribution in the solar heating system with USTES-HP.

With the simulation result, the maximum COP of the HP during the operation period was recorded at the value of 6.53 at the beginning of November. This is the time when the USTES was freshly charged and the heating demand was still not significant. Under the designed control logics, the HP achieved a SCOP of 4.17 throughout the heating season. A detailed calculation of SF and SCOP can be found in Appendix 2.

4.4.4 USTES thermal behaviour

Figure 27 depicts the temperature of the USTES medium at different depth levels from the top surface of the 2 m deep wet compact sand medium, with the red line representing the ground temperature at the surface between the ground and the lower side of the bottom. The designed USTES system witnessed a very high maximum temperature during the heat capturing season, up to 75°C in the third week of August. This is one of the reasons which caused the high heat loss proportion mentioned in the previous part and the overheating problem in the lab building space in summer. In comparison with the “norm” case, the maximum temperature in the lab building was simulated as 28.3°C, while that in the case with USTES was 31.8°C. Less than 1% of the hours when temperature exceeded 27°C was observed in the “norm” case. That of the “with” case is more than 4%. Detailed reports on the mean air temperature inside the lab building in both cases can be found in Appendix 4. It can also be seen that, from the end of December, the USTES was not extracted anymore to keep itself always above the pre-set minimum operating temperature of 20°C. The lowest temperature in the USTES can be seen at the end of February, when the coldest day of winter typically occurred around two weeks before. According to this maximum and minimum temperatures of the USTES, the calculated capacity of this USTES is 2170.4 kWh. The discharge heat from it was 1693.0 kWh, which is roughly 78% of its capacity.

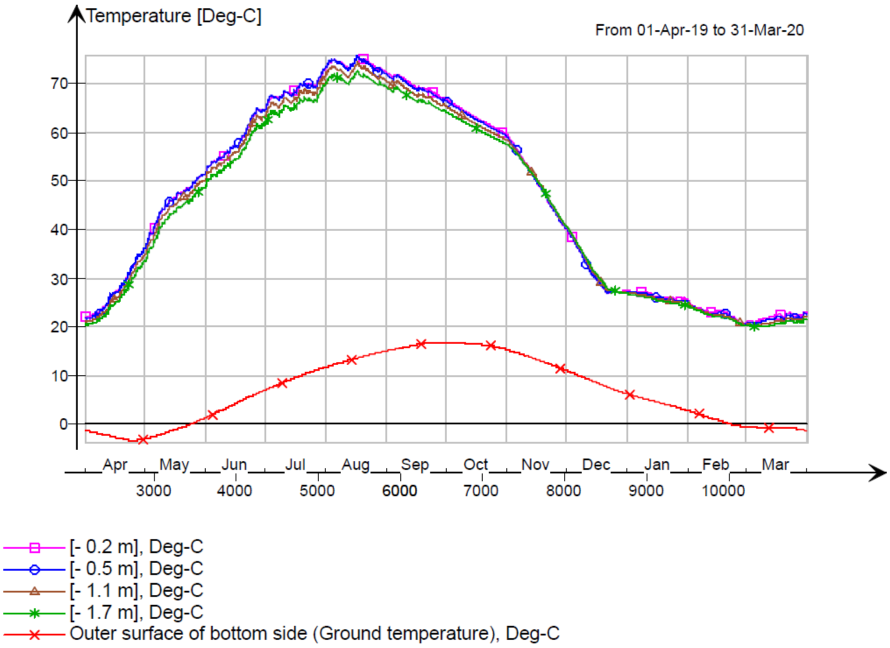


Figure 27. Temperatures of the USTES medium of layers at different depth levels.

4.5 **Discussion**

4.5.1 Shortcomings and proposals for solutions

Building performance simulation, alike any other system simulation, always bears a firm level of uncertainty. Most sensitive or influencing factors are translated or modified into coefficients for the results to take into account. Unimportant ones, otherwise, are omitted. In this thesis, several matters were discovered during the modelling process of the USTES. While some were already solved with approximations or estimations, some were skipped. The most important dismissed subjects in the author's opinion and the proposals for further development are listed below:

- Heat loss: In the USTES-HP model, the sand bed was modelled in a way that the heat loss rate through its four side walls were the same as through its bottom. Additionally, heat loss through thermal bridges was also ignored. Heat loss to the sides modelling is complex and needs a separate calculator to simulate at least in a two-dimensional heat transfer model. An appropriate approximation to include heat loss, in this case, would take time and effort due to the temperature gradient in the ground.
- Waterproofing issue: The chosen USTES medium was wet compact sand, which contains approximately 16 m-% water. Waterproofing layers should be added to the structures adjacent to the sand bed. Despite being underground, the depth of the USTES is still not enough to avoid sub-zero temperature during Finnish winter. Any

unexpected fault or breakdown in the system might cause frost to form, consequently, negatively affect the structure of the building. To prevent this, a preheating system should be planned within the USTES if high water content material is chosen. It must be durable and highly resistant to fluctuating temperature and waterproofing. Thus, a proper design and installation within the USTES should be concerned.

- Overheating in the summer: Due to the high temperature in the USTES during the charging time, up to 75°C at the middle layer of the STES, the surface temperature of the laboratory building was also correspondingly increased, i.e. 32°C. This caused the overheating issue and negatively affected the thermal comfort. PEX pipe running in the STES should not bear fluid temperature higher than 70°C over a prolonged period. Thus, it is wise to redesign the control logic to prevent the USTES temperature surge and provide cooling measures for the laboratory, either passive or active cooling.
- Excavation work: The depth of the designed USTES was set at 2 m. It is necessary to have a ground investigation before doing any excavation work. Digging and removing a considerable amount of soil/rock may cost a lot and here comes the importance of site planning. Not only that, it also requires that the site area is large enough to sustain the open pit surface area, because a minimum slope must be maintained when excavating (maximum 0.5:1 if not stable rock).

4.5.2 Ideas for further progress

The design example only includes the solar collector heating system with an HP. It is also possible that PV panels are added, with/without another loop for an air-to-water HP. In this case, the sizing of the USTES volume and the selection of its medium/media should be made carefully so as to efficiently use the captured energy. Another idea to develop this work is to evaluate the financial viability in this kind of system, and/or to do the cost optimisation analysis. Repeatedly, within the scope of this work, cost-related consideration was not explicitly mentioned, but the practicality of any engineering application should be economically feasible and certain advantages should be achieved.

5 CONCLUSION

In this thesis, the topic of energy efficiency in buildings was presented, together with the introduction of various energy systems that can be applied in buildings to achieve the energy goal from the EC’s directives. USTES concepts and its potential as well as feasibility to be realised in a cold climate region as Finland was also put forward. In addition, a brief discussion about building performance simulation with simulation tools opened an outlook on its role and support in the design and innovation of new energy systems in buildings.

As a showcase for those abovementioned points, an example for a preliminary design of an USTES application in a 35 m^2 laboratory building was presented. Three models were created and simulated to provide an extended view on the effects of the solar collector heating system equipped with USTES-HP in a region with prolonged freezing and dark winter. The structure of the sand bed, which was used as the USTES, is from a cheap and readily available material. The USTES simulation results suggest that such a designed system is one of the viable alternatives to improve the efficiency of solar heating system in cold climate regions. One-fifth of the electricity consumption and 36% heating energy load of the lab building were reduced with the coupling of the sand bed USTES-HP compared to the solar collector system alone. A solar fraction of 36% and a HP’s SCOP of 4.17 were also calculated. Although cost-related calculation was not performed during the course of the example presentation, this simple additional structure underneath the building being used as the USTES and a small extension in the heating system proposed that a minor additional investment in the solar heating system will bring considerable amount of energy savings.

In conclusion, the application of USTES in small-scale and/or residential buildings in Finland is feasible in the author’s opinion, although more accurate research and experiments should be conducted in the near future. USTES is a potential innovation which will help the reduction in conventional energy sources, mitigate GHGs from its production, and enhance energy security. Additionally, this study also demonstrates that the practice of building/building energy system performance simulation can effectively assist the proper design of USTES during concept testing or preliminary design stage.

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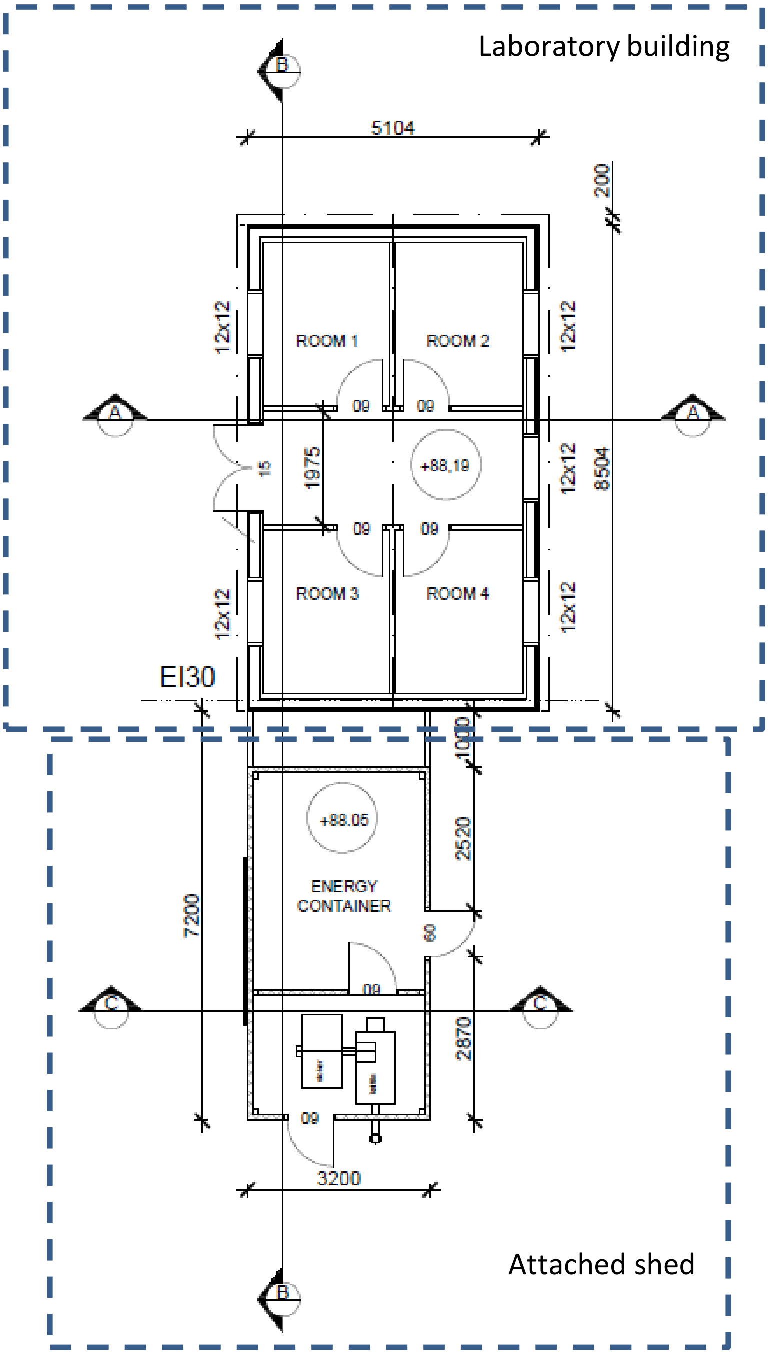
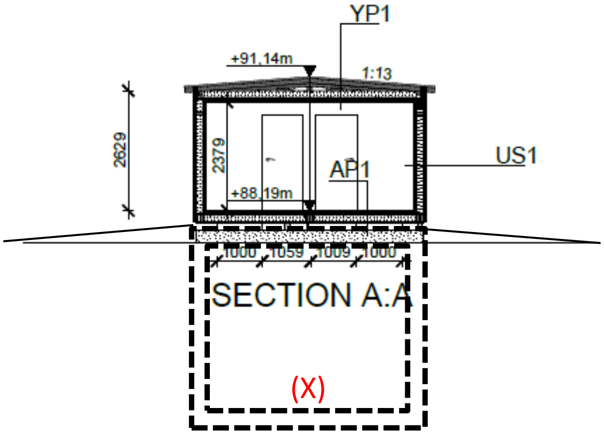
Appendix 1/1

FLOOR PLAN, CROSS-SECTIONS, AND SITE DRAWINGS OF THE LABORATORY BUILDING

Floor plan:



Cross-sections:



YP1 (U) 0.10 W/(m²K)

Self adhesive bitumen and underlay membrane

Plywood 13mm

Ventilation gap 100mm with 100x50mm battens c/c 600mm

Trusses (max. heigh 316mm) c/c 600mm with soft insulation 150mm

Polyurethane insulation panel 50mm

Battens 22x100mm c/c 300mm

Plywood 11mm

US1 (U): 0.13 W/(m²K)

Exterior cladding 21mm

Ventilation gap 22mm

Windshield 9mm

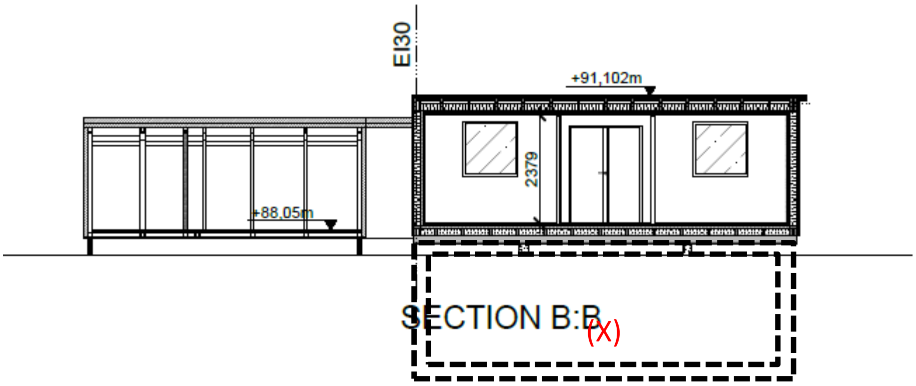
Mineral wool + frame (48x148) 148mm

Polyethylene thermal panel 50mm

Air gap with 22x100 battens 22mm

Plywood 11mm

Fire class: REI 60



AP1 (U): 0.10 W/(m²K)

Plywood 32mm

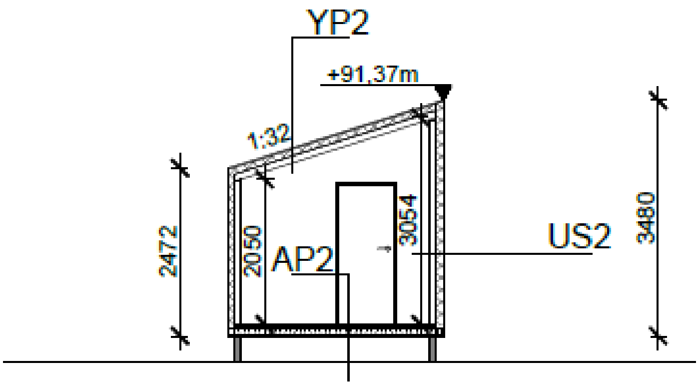
Battens 22x100mm c/c 300mm

Polyurethane insulation panel 50mm

Soft insulation 150mm + frame 150x50mm c/c 600

Plywood 11mm

SECTION C:C



YP2 (U): 0.40 W/(m²K)

RUUKKI Classic C roofing sheet

RUUKKI Sandwich panel SPA 100 E

US2 (U): 0.40 W/(m²K)

RUUKKI Sandwich panel SPA 100 E

RUUKKI Classic C roofing sheet

AP2 (U): 0.16 W/(m²K)

Plywood 20mm

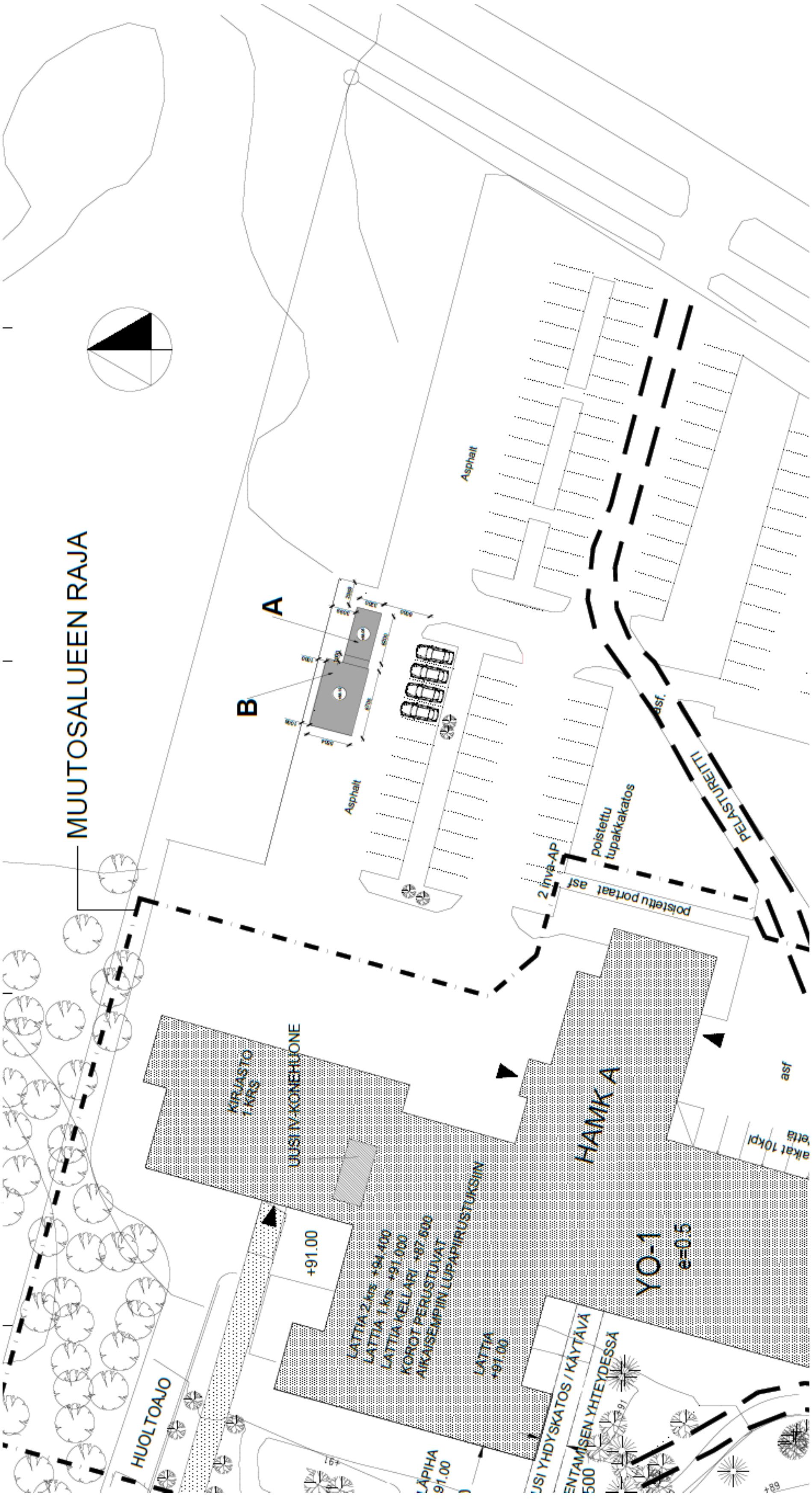
Mineral wool 30mm + steel frame (30x50)

Mineral wool 100mm + steel frame (100x100)

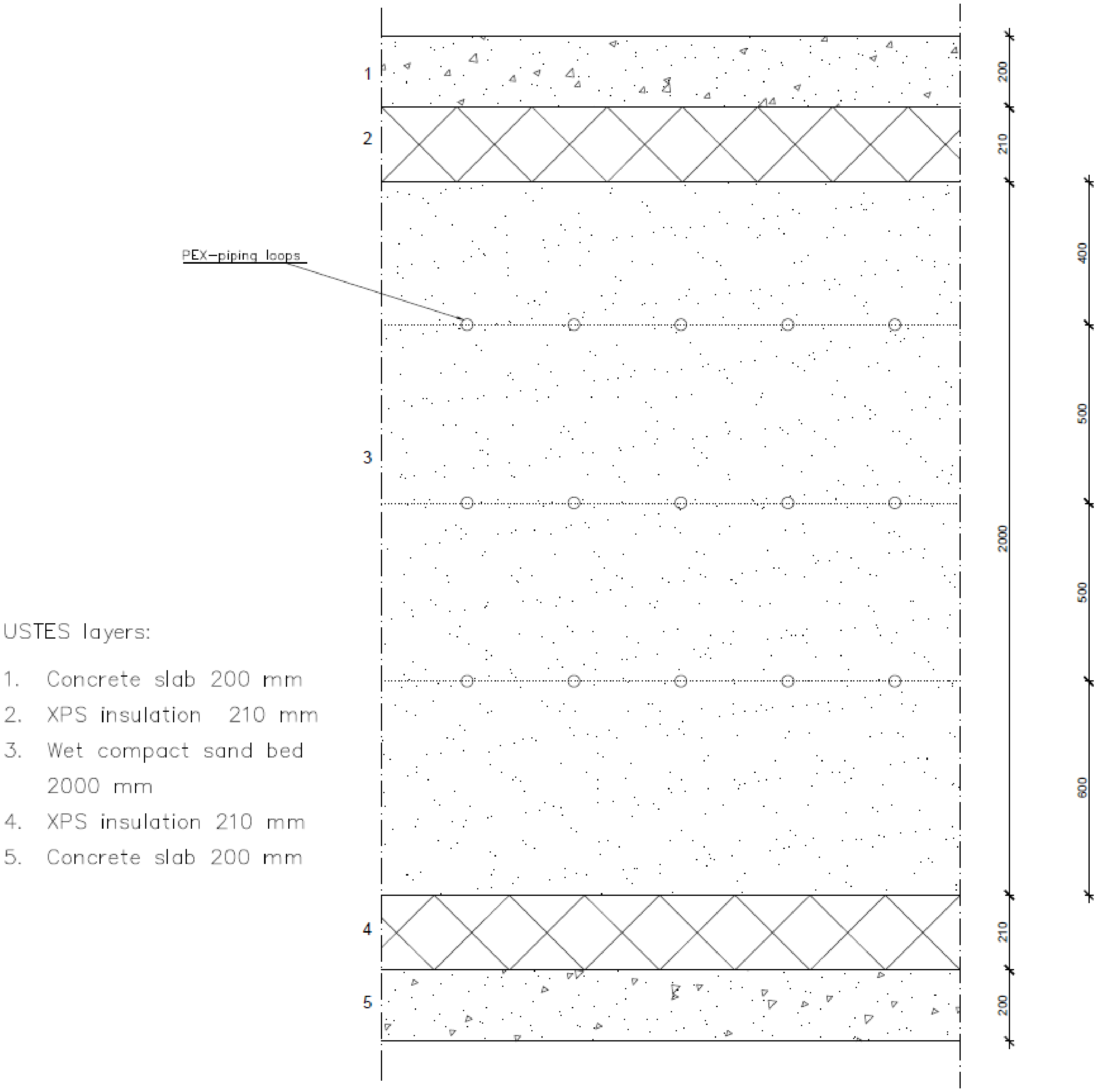
Plywood 20mm

Appendix 1/3

Site plan:



USTES'S layering cross-section view (X):



Appendix 2

CALCULATION OF SOLAR FRACTION AND HP'S SCOP

The solar fraction of a solar collector system is calculated by:

$$\text{Solar fraction} = \frac{\text{Solar thermal energy used for heating [kWh]}}{\text{Total heating demand [kWh]}}$$

Typically, in a building, total heating demand consists of heating in zone (heating devices), for AHU, and for DHW production:

$$\text{Total heating demand} = \text{Zone heating} + \text{AHU heating} + \text{DHW [kWh]}$$

(values found in Appendix 3/4)

$$\begin{aligned} &S\text{olar heat used for heating in case 'with'} \\ &= \text{Direct heat use} + \text{Heat to heat pump's evaporator} \\ &= 238.6 + 1693.0 = 1931.6\ \text{kWh} \end{aligned}$$

Since no changes were made in thermal behaviour of the case "without" and "norm", the share of solar heat in the total heating demand will be equal to the difference between their total supplied energy:

$$\begin{aligned} &\text{Solar heat used for heating in case 'without'} \\ &= \text{Total supplied energy in case 'norm'} \\ &- \text{Total supplied energy in case 'without'} \\ &= 8123.0 - 6442.0 = 1681.0\ \text{kWh} \end{aligned}$$

Case	Solar thermal energy used for heating [kWh]	Total heating demand [kWh]	SF
without	1681.0	7145.3	**23.5%**
with	1931.6	5326.4	**36.3%**

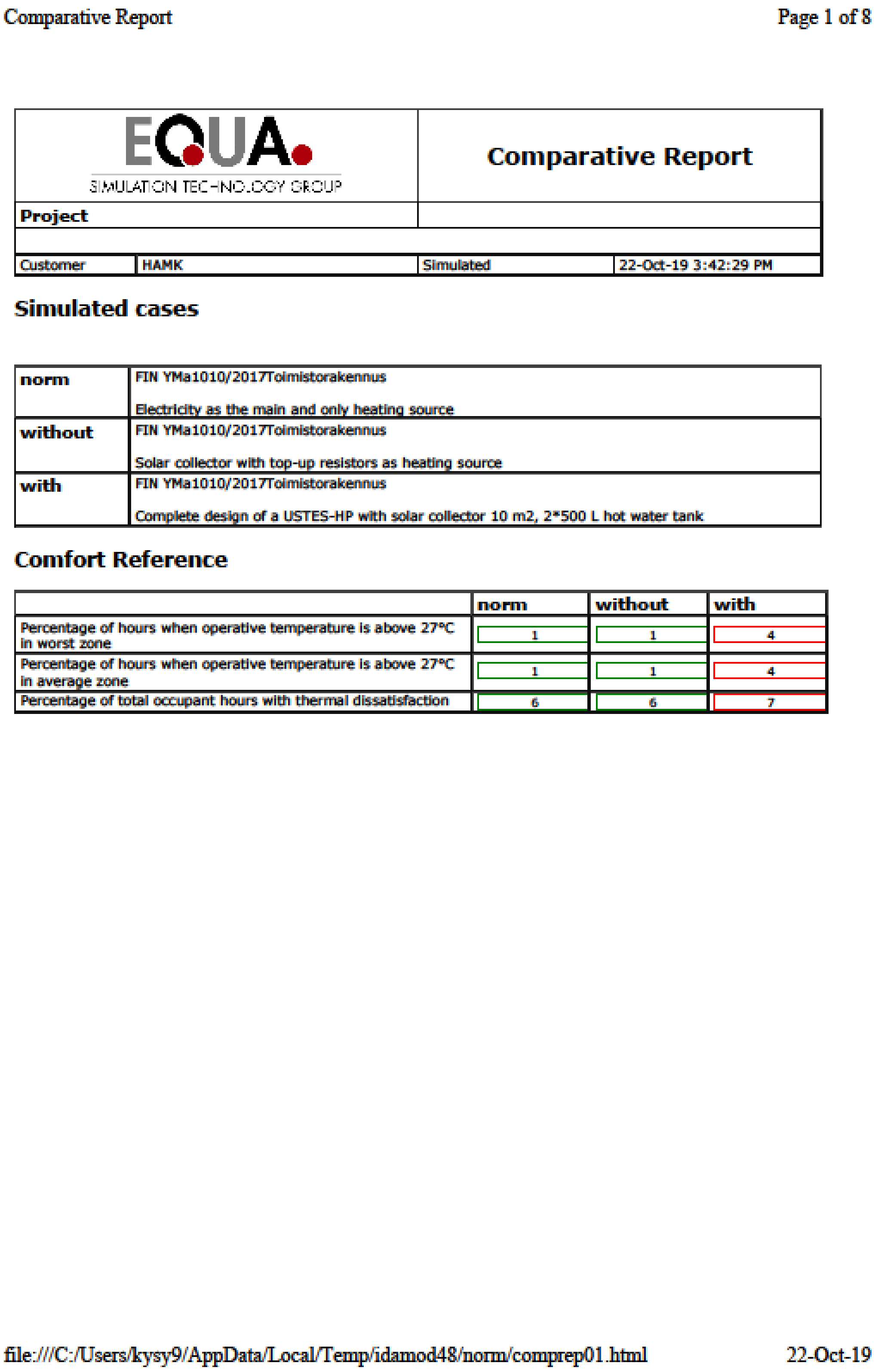
In the case 'with', the SCOP of heat pump is calculated as:

$$\text{SCOP} = \frac{\text{Total heat supplied by HP [kWh]}}{\text{Total electricity the HP consumed [kWh]}} = \frac{2005.0\ \text{KWh}}{480.6\ \text{kWh}} = \mathbf{4.17}$$

Energy meters were used in the maths model of the case 'with', and total heat supplied by the HP was the heat output at the condenser side of it, meanwhile the total heat electricity the HP consumed was read directly from the HP object.

Appendix 3/1

COMPARATIVE REPORT OF THE SIMULATION RESULT
This report was produced by IDA ICE comparative tool.



Comparative Report | Page 1 of 8

EQUA SIMULATION TECHNOLOGY GROUP	**Comparative Report**
Project	

Customer	HAMK	Simulated	22-Oct-19 3:42:29 PM

Simulated cases

norm	FIN YMa1010/2017Toimistorakennus Electricity as the main and only heating source
without	FIN YMa1010/2017Toimistorakennus Solar collector with top-up resistors as heating source
with	FIN YMa1010/2017Toimistorakennus Complete design of a USTES-HP with solar collector 10 m2, 2*500 L hot water tank

Comfort Reference

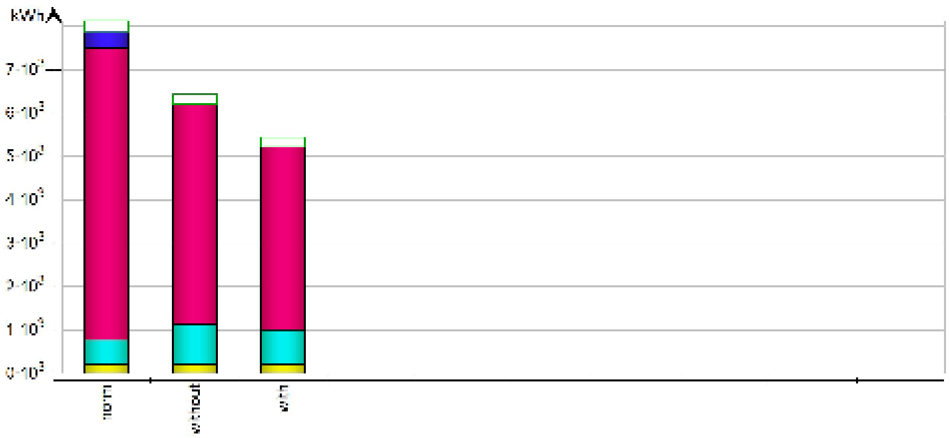
	norm	**without**	**with**
Percentage of hours when operative temperature is above 27°C in worst zone	1	1	4
Percentage of hours when operative temperature is above 27°C in average zone	1	1	4
Percentage of total occupant hours with thermal dissatisfaction	6	6	7

file:///C:/Users/kysy9/AppData/Local/Temp/idamod48/norm/comprep01.html | 22-Oct-19

Supplied Energy

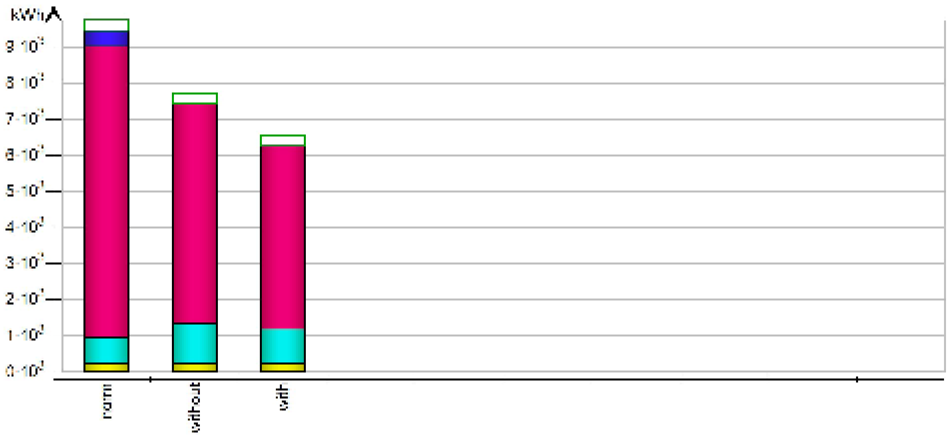
Meter Energy

		norm		without		with	
		kWh	kWh/m²	kWh	kWh/m²	kWh	kWh/m²
🟫	Valaistus, kiinteistö	196	5.4	197	5.5	197	5.5
🟦	Jäähdytys	0	0.0				
🟦	LVI sähkö	585	16.3	930	25.9	810	22.5
🟥	Sähkölämmitys, kiinteistö	6739	187.4	5079	141.2	4209	117.0
🟪	LKV, sähkölämmitys	368	10.2				
	Total, Facility electric	7888	219.3	6206	172.5	5216	145.0
	Total	7888	219.3	6206	172.5	5216	145.0
☐	Laitteet, asukas	235	6.5	236	6.6	236	6.6
	Total, Tenant electric	235	6.5	236	6.6	236	6.6
☐	CHP tuotto			0	0.0		
	Total, Produced electric	0	0.0	0	0.0	0	0.0
	Grand total	8123	225.8	6442	179.1	5452	151.6



Primary Energy

		norm		without		with	
		kWh	kWh/m²	kWh	kWh/m²	kWh	kWh/m²
■	Valaistus, kiinteistö	235	6.5	236	6.6	236	6.6
■	Jäähdytys	0	0.0				
■	LVI sähkö	702	19.5	1116	31.0	972	27.0
■	Sähkölämmitys, kiinteistö	8087	224.8	6095	169.4	5051	140.4
■	LKV, sähkölämmitys	442	12.3				
	Total, Facility electric	9466	263.2	7447	207.0	6259	174.0
	Total	9466	263.2	7447	207.0	6259	174.0
□	Laitteet, asukas	282	7.8	283	7.9	283	7.9
	Total, Tenant electric	282	7.8	283	7.9	283	7.9
□	CHP tuotto			0	0.0		
	Total, Produced electric	0	0.0	0	0.0	0	0.0
	Grand total	9748	271.0	7730	214.9	6542	181.9

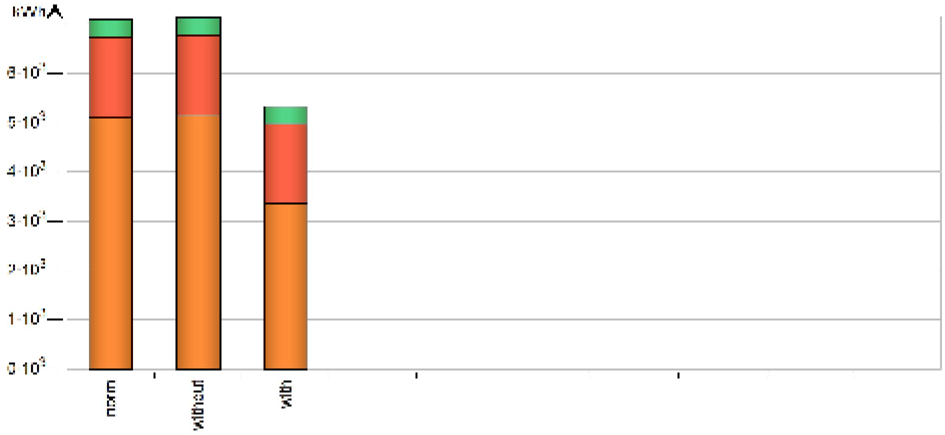


Systems Energy

Used energy

kWh

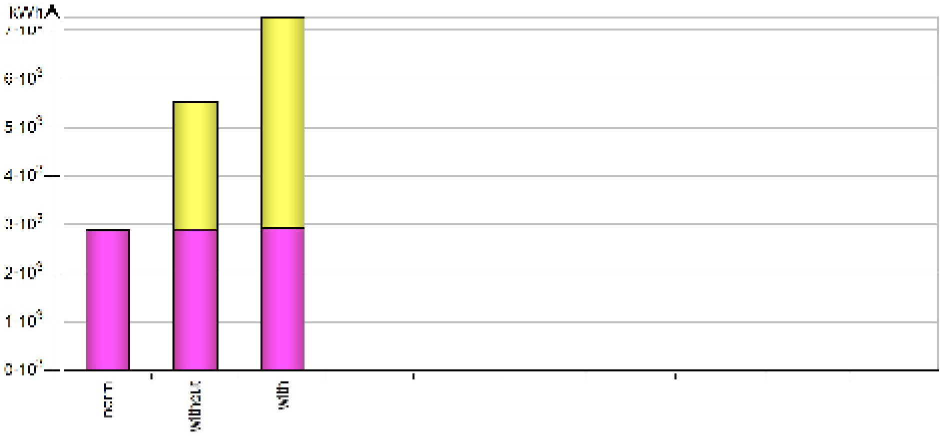
Case	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
	🟧	🟦	🟥	🟪	🟩
norm	5105.9	0.0	1633.6	0.0	368.0
without	5172.0	0.0	1611.8	0.0	361.5
with	3362.3	0.0	1598.5	0.0	365.6



Utilized free energy

kWh

Case	AHU heat recovery	AHU cold recovery	Plant heat recovery	Plant cold recovery	Solar heat	Ground heat	Ground cold	Ambient heat	Ambient cold
	🟪	🟦	🟫	🟩	🟨	🟥	🟦	🟥	🟦
norm	2881.4	-0.4							
without	2898.0	-0.0			2629.7				
with	2915.4	-0.1			4346.8				



Generated electric energy

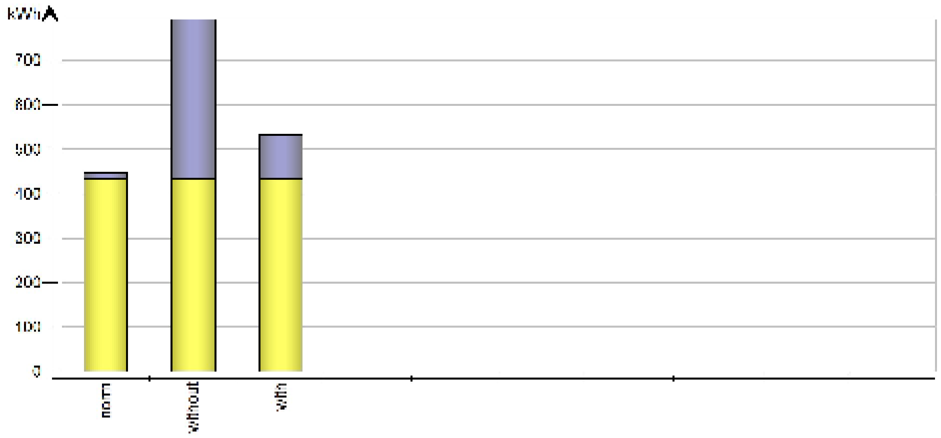
kWh

Case	Solar (PV)	Wind turbine	CHP
	🟫	🟦	🟩
norm			
without			
with			

Auxiliary energy

kWh

Case	Humidi-fication	Fans	Pumps
	🟩	🟨	🟪
norm		433.9	11.8
without		433.8	357.2
with		434.1	97.3

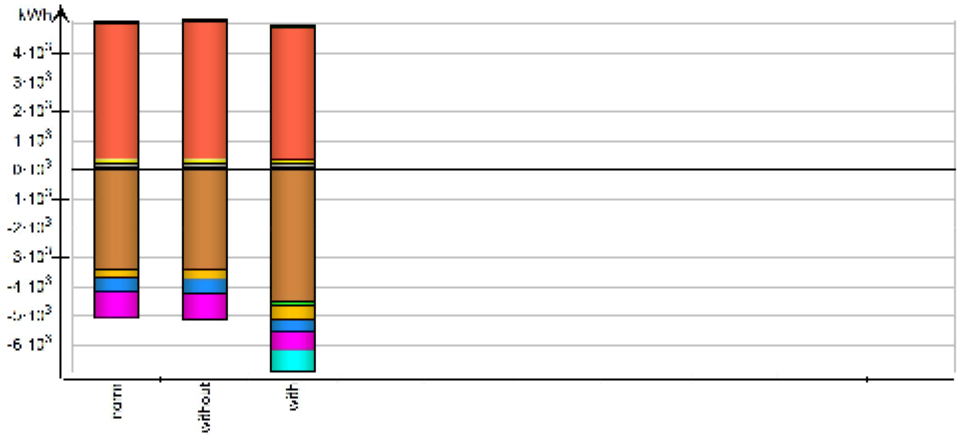


Energy for all zones (sensible only)

During heating

kWh

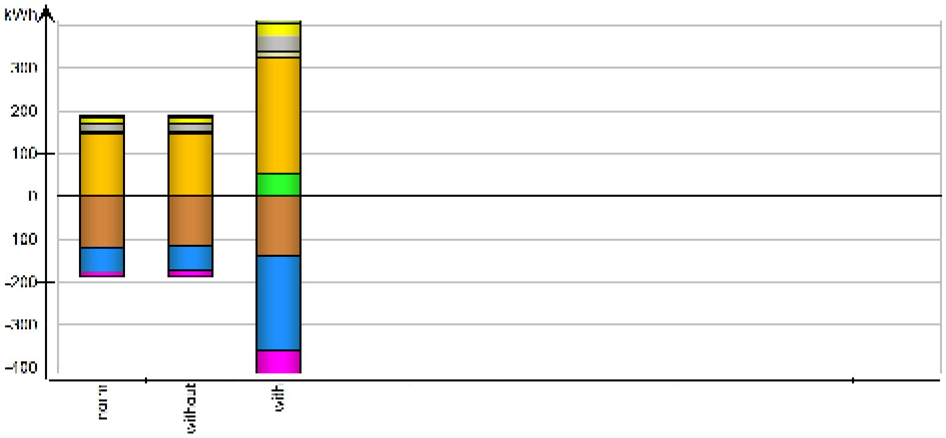
Case	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
	■	■	■	■	■	■	■	■	■	■	■
norm	-3411.1	0.1	-292.5	-475.8	-901.7	71.6	181.7	151.5	4625.0	0.0	47.9
without	-3391.7	0.1	-333.6	-505.3	-903.9	70.9	180.1	150.1	4686.1	0.0	47.4
with	-4519.5	-123.0	-502.8	-409.2	-645.5	58.8	150.4	125.3	4517.8	-714.7	97.1



During cooling

kWh

Case	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
	■	■	■	■	■	■	■	■	■	■	■
norm	-119.8	-0.2	146.3	-54.6	-12.6	7.2	17.3	14.4	0.0	0.0	3.3
without	-116.4	0.0	145.2	-55.6	-14.1	7.0	16.9	14.1	0.0	0.0	3.4
with	-140.2	53.7	269.1	-219.6	-52.4	14.9	36.1	30.1	0.0	0.0	8.8



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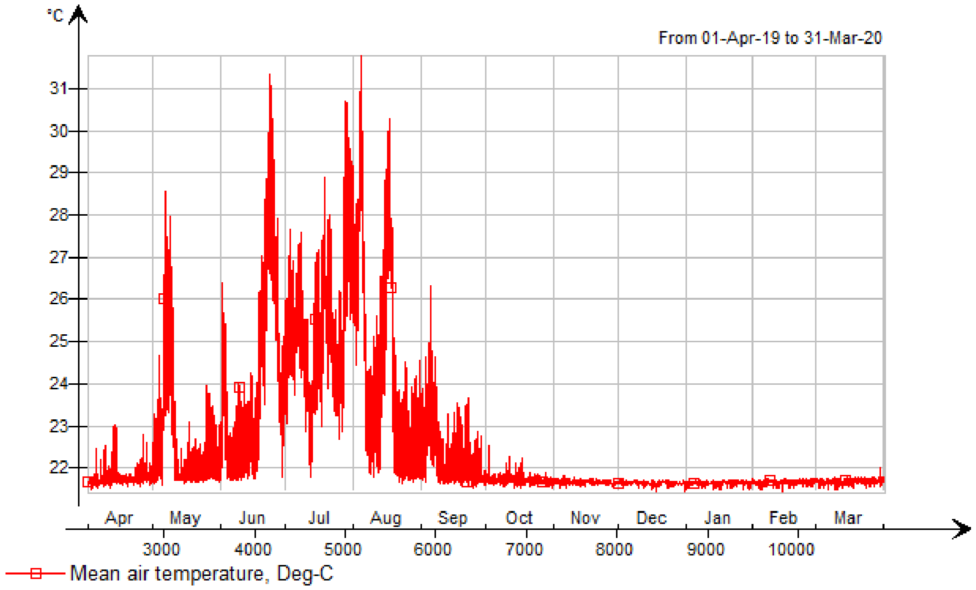
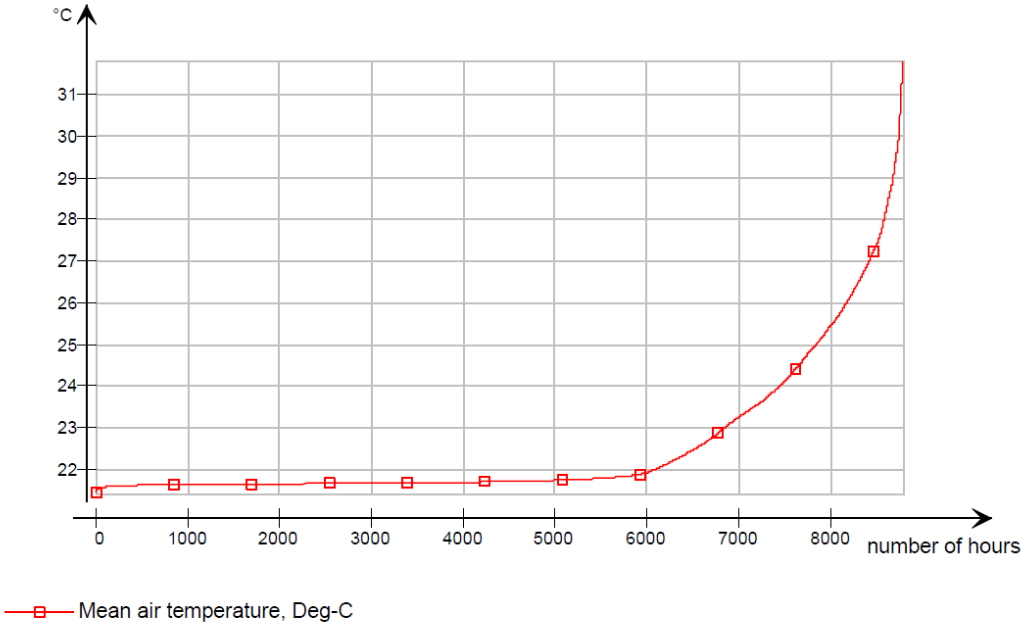
SIMULATION RESULT OF THE MEAN INDOOR AIR TEMPERATURE

The mean air temperature and duration diagrams inside of the lab building are shown below. The diagrams were taken from IDA ICE simulation detailed results.

(a) In “with” case:





(b) In “norm” case: