Master's thesis

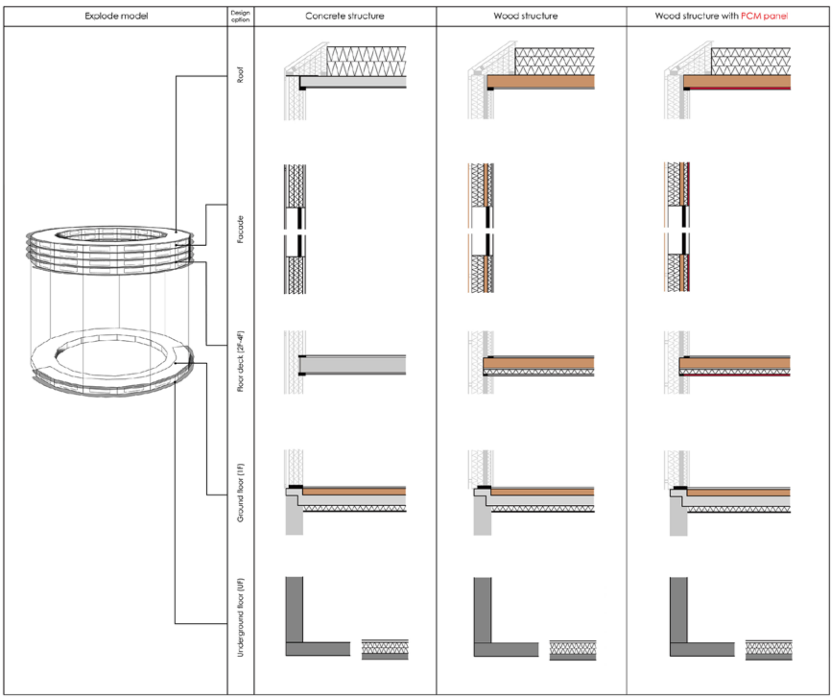
NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Meng-Shen Kan

An alternative structure with PCM-based building component: A case study of OEN project in Oslo

Master's thesis in Sustainable Architecture
Supervisor: Tommy Kleiven
Co-Supervisor: Luca Finocchiaro

June 2020



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Abstract

Statistical data of Norway shows in the next thirty years, market of near zero energy buildings will be rapidly growing. This requires more participation in building industry to carry out design complying with lower energy or passive house energy standards. This research aims to convert a heavy weight structure to a light weight structure driven by lowering the environment impact. A holistic approach is conducted to assess the total environment impact of both embodied emissions and operational heating energy consumption with the introduction of PCM-based building component as additional thermal mass. Study finds that changing concrete structure to light weight wood structure results in increase in heating load, while incorporating PCM panel as additional thermal mass in light weight wood structure reduces heating demand compared to design option without PCM panel. This demonstrates the possibility of improving current static design in a passive standard building of Nordic context. Results of environment impact study based on the context setting of this research show that converting concrete structure to wood structure reduce embodied emissions by 43%. Among proposed design options, wood structure is the recommended alternative solution with the lowest carbon emissions from total lifecycle perspective. Wood structure with PCM panel as additional thermal mass is even though not the least carbon emission design option, it can be a relatively competitive solution if one takes into account reducing both embodied emission as well as operational energy demand as future energy price is expected to increase. The holistic approach driven by lowering environment impact of design choices is deemed vital in response to building market's trend in compliance with future policies and energy goals.

Keywords: cold climate, passive house energy standard, phase change material, environment impact study, carbon emission, life cycle perspective

Acknowledgement

I’m very thankful to everyone who is part of my great journey of master study in Norway, especially guidance and patience from my supervisor Tommy and Luca as well as the teaching team in the master program who kindly share their expertise and knowledge in shaping our prominent future of sustainability.

I’d like to thank also my fellow classmates Farnoosh, Lina, Raj, Matteo, Émilie, Henriette, Vegard, Kirsty, Cecilia, Laura, Markus, Alessandro, Massimiliano, Emilie, Emiliya, Anna, Lena during this amazing two-year adventure in the brightness and darkness of Norway.

Special thanks to Kriss Jin for proofreading, and Taiwanese Ministry of Education who granted scholarship sponsoring my academic work and life as student abroad.

Finally, my utmost gratitude to my parents Wen-Hua and Li-Fang, sister Ji-Ping and brother Mu-Shun who give me the unconditional love and support in my whole life.

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1. INTRODUCTION

Mitigating global climate change and greenhouse gas reduction has leveled up as joint effort from country leaders since 1990s. The EU completes its '20-20-20' climate and energy policy effective between 2009 to 2020. Monitoring over the years shows it is a challenging, ambitious yet essential measures set within the EU regimes to move towards a sustainable future according to European Environment Agency (EEA) report (2019).

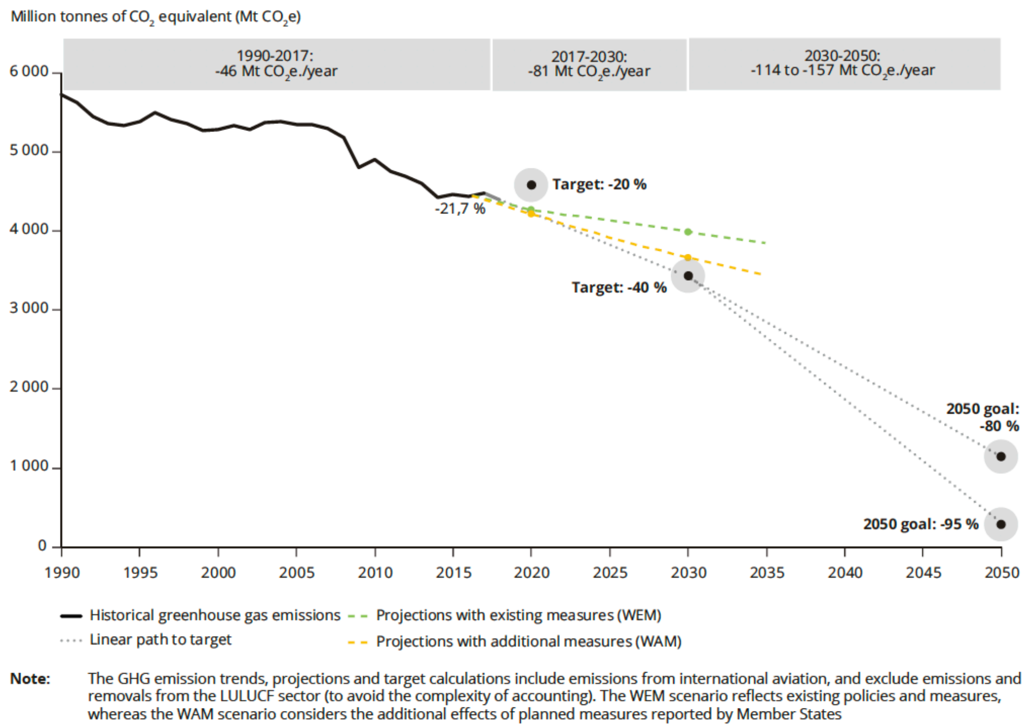


Figure 1-1 Greenhouse gas emission trends, projections and targets in the EU (EEA, 2019)

Update EU-wide target and policy are set effective from 2021 to 2030 (European Council, 2014), the new 2030 climate and energy frameworks are as follows:

- ✓ At least 40% cut down in greenhouse gas emissions (from 1990 levels)
- ✓ At least 32% share for renewable energy
- ✓ At least 32.5% improvement in energy efficiency

The long term goal is to be climate-neutral by 2050 – the world's first climate-neutral continent carrying out commitment under the Paris Agreement. Norway is not a member of EU but one of the member countries of the EEA. The Norwegian government agrees and shares a number of environmental commitments of 2030 policy in line with EU members either under international conventions or by direct participation. *"For the Effort Sharing legislation period from 2021 to 2030, Norway has stated that it intends to fully participate in the reduction effort for the Effort Sharing sectors."- EEA (2017).* The challenging ambition requires broad participation from both public and private sectors imposing actions driven by environment consciousness.

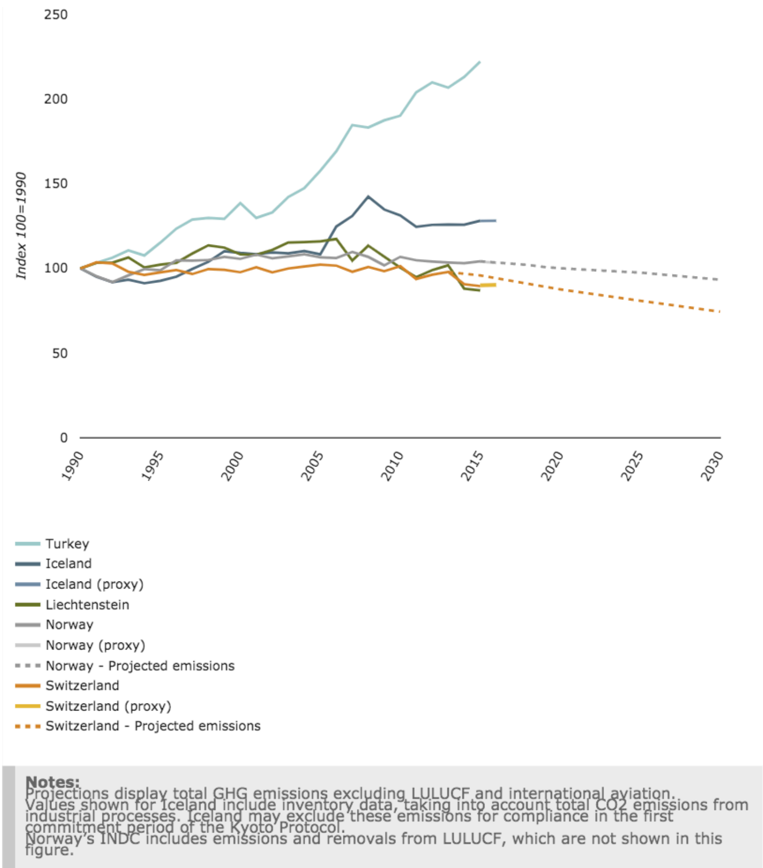


Figure 1-2 Total GHG emission trends and projections in Iceland, Liechtenstein, Norway, Switzerland and Turkey, 1990-2030 (EEA, 2017)

1.1 Zero emission ambition in building industry

Energy use in buildings accounts for approximately 40% of total stationary energy consumption in Norway (Nordiska ministerrådet et al., 2009). Based on United Nation's sustainable gole13 by 2030: "Take urgent action to combat climate change and its impacts" (United Nations, 2016), Norwegian building industry sets legislative measures including NS 3720 greenhouse gas calculations to map out and improve building industry's climatic footprint. NS 3700/3701 are set as passive house and low-energy building design guideline for non-residential and residential buildings to reduce energy consumption and greenhouse gas emissions (Standard Norge, 2013). ZEBRA2020 project monitors market uptake of near zero energy buildings (nZEBs) across Europe and provides data as well as recommendations on how to reach nZEB standard. As one of the participant countries, statistical data of Norway shows in the next thirty years, market of nZEB will be rapidly growing, see Figure 1-3 and Figure 1-4. This requires more participation in building industry to carry out design complying with lower energy or passive house energy standards.

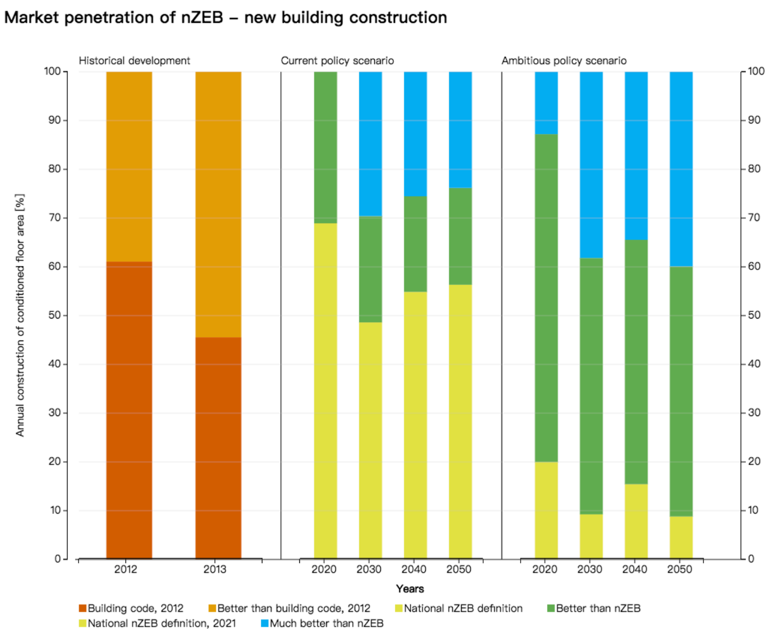


Figure 1-3 New building construction market projection in Norway (ZEBRA2020, n.d.)

For new-built and existing buildings, NS-EN 15978:2011 provides guidelines of sustainability of construction works - assessment of environmental performance of buildings to evaluate the environmental performance from a life cycle perspective. The ZEB ambition level versus lifecycle phases is shown in Figure 1-5. Realization of a ZEB project is done by setting one of these goals as target that guides all design choices and construction activities throughout building's life cycle. Several pilot projects have been designed and built in Norway with participation from both research institutes and industry partners.

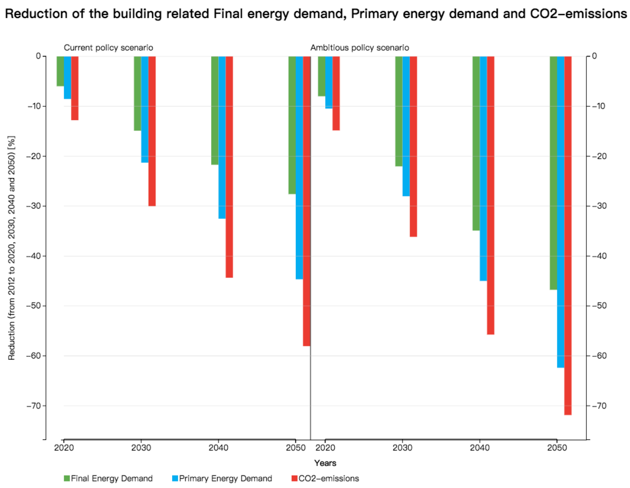


Figure 1-4 Reduction of building related energy demand (ZEBRA2020, n.d.)

	Product stage			Construction process stage		Use stage								End-of-life				Benefits and loads beyond the system boundaries			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6		B7	C1	C2	C3	C4	D1	D2	D3	D4
Levels of ZEB	Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use (space heating)	Operational energy use (appliances)	Operational water use	Deconstruction demolition	Transport	Water processing	Disposal	Reuse	Recovery	Recycling	Exported energy / potential
ZEB–O–EQ		–		–				–			–	✓	–	–			–			–	–
ZEB–O		–		–				–			✓	✓	–	–			–			–	–
ZEB–OM		✓		–				–			✓	✓	–	–			–			–	–
ZEB–COM		✓		✓				–			✓	✓	–	–			–			–	–
ZEB–COME		✓		✓				–			✓	✓	–	✓			–			–	–
ZEB–COMPLETE		✓		✓				–			✓	✓	–	✓			–			✓	–

Figure 1-5 ZEB ambition level versus lifecycle phases (Lobaccaro, G. et al., 2018)

1.2 OEN Project at Ammerud

One of Norway's largest property developers invests on a new residential apartment block housing 150 units at Ammerud, the OEN project. The project is situated at Ammerud in the outskirt of Oslo by 20-minute of public transportation.

Figure 1-6 Perspective view of OEN project

The area has its architectural uniqueness featuring Le Corbusier style housing blocks. Nowadays, the area hosts diverse nationalities and ethnicities. The surrounding of the site has mass coverage of green area. Provisions of public function are well sufficient that makes this project a desired choice for family looking for new property to move in.

Although there are quite some advantages on a surrounding scale, Ammerud lacks the type of common space that brings people together and promotes shared activities. One of the key drivers to land on this circular geometry is to encourage common activities in the central courtyard of the building. Designed by passive house energy standard and set ZEB ambition level as ZEB-O, it is expected to be Norway's first 'energy positive' apartments (Nikel, 2019). The ambition will be realized by solar panel coverage on the rooftop (Figure 1-6) so that self-sufficient energy production is made possible from the building itself to the user demand from the residential units. What is interesting as motivation of this research is the selection of structure system. The building is now designed with concrete-based supporting system. There are several reasons for this decision: the compact thermal mass, maintenance free, acoustic insulation and good performance of air-tightness etc. The foundation is built upon rock earth, and floor deck is suspended floor system (plattendekke) supporting by walls, forming structural bone of the building. Balcony is designed by cantilever concrete slab. When associate building design positioned as a ZEB project, the embodied emission of design choice is one of the key issues that requires further assessment, which is of interest in this research.

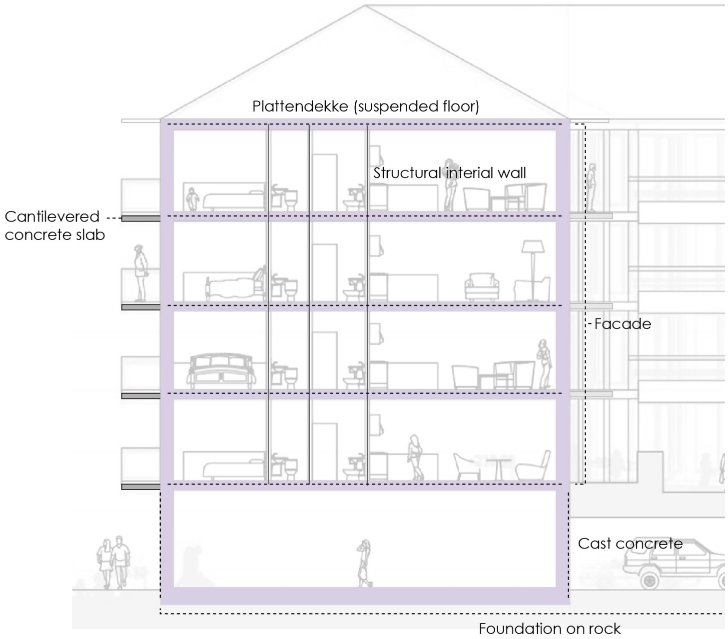
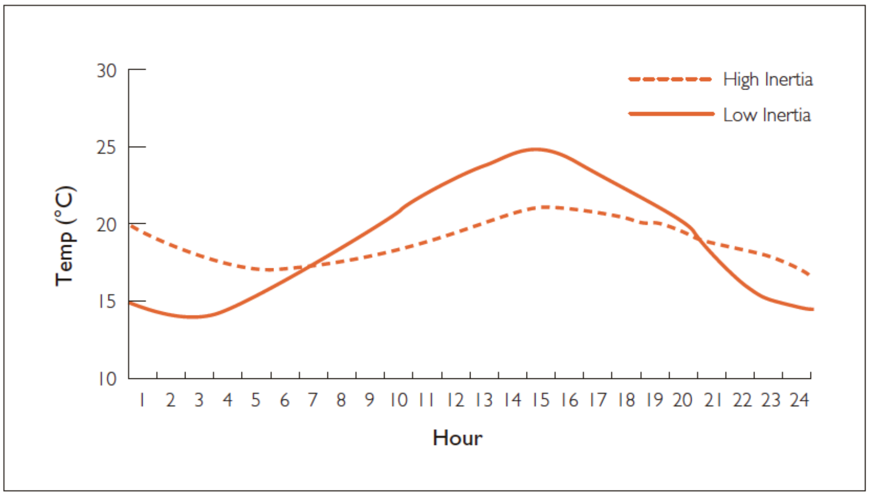


Figure 1-7 Structure of the building

1.3 Thermal mass of building

Building designed by passive energy standard refers to a continuous, very well-insulated thermal envelope which minimizes heat loss. The design often comes with high thermal mass materials like concrete and bricks with high density that are effective in absorbing and storing heat energy, consequently large amount of heat energy is needed to change the temperature of high density materials. In contrast, timber is the most common lightweight building materials with lower thermal mass.

Thermal mass of building functions by absorbing solar heat at daytime and radiating it at night, modulating the indoor temperature of a building, providing "inertia" against temperature fluctuation. Thermal inertia refers to "*the degree of slowness with which the temperature of a body approaches that of its surroundings and which is dependent upon its absorptivity, its specific heat, its thermal conductivity, its dimensions, and other factors*" (Merriam-Webster, n.d.). In cold climate like Norway, a heavy envelope structure with high thermal inertia delays peak load, averaging out diurnal extreme. This increases comfort and reduces operational energy cost. One of the main reasons choosing concrete as main structure in OEN project is also because of its high thermal inertia characteristic.



Internal temperatures on a hot day in buildings of high and low thermal inertia.Thermal mass can help in both hot and cold climates

Figure 1-8 Thermal inertia (Brophy and Lewis, 2011)

1.4 PCM application in building component

Phase change material (PCM) refer to material able to reversibly change their state in response to external influences are classified as phase change material (Ritter, 2017). The advanced technology has been widely applied in building techniques, including compound material in building envelopes and in internal construction components. "It can be utilized for many different purposes to reduce air conditioning energy demand, perform thermal peak load shaving and shifting, control local temperature of building envelope components, or improve of overall system durability" (Kośny, J., 2015). It is a latent heat storage material using chemical bonds to store and release heat. The heat transfer happens when phase changes from one state to another, also called the charging and discharging state of material.

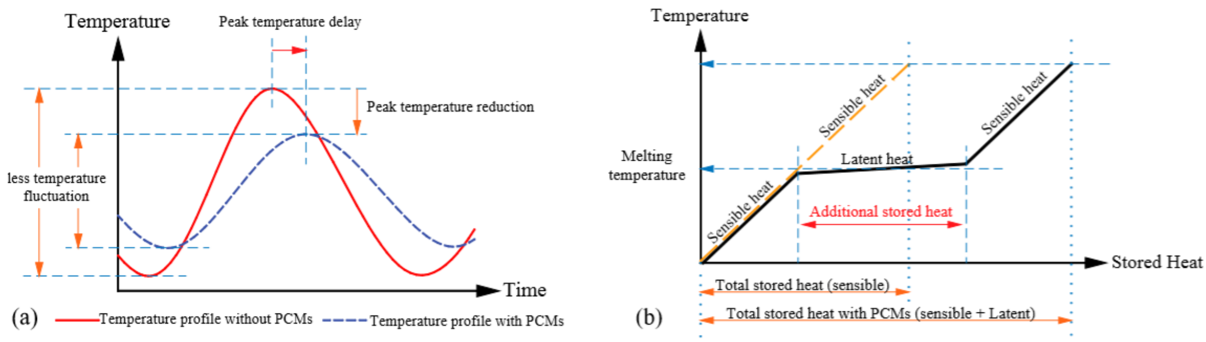


Figure 1-9 (a) PCMs application in regulating building's indoor temperature and (b) Storage capacity of materials with latent heat compared to sensible heat only (Zeyad Amin Al-Absi, et al., 2020)

PCM can be categorized into organic, inorganic and eutectic. For building application, organic PCMs do not suffer from phase segregation and crystallize with little or no super-cooling, they have many qualities which make them suited for building implementation (Delgado, J.M.P.Q. et al., 2018).

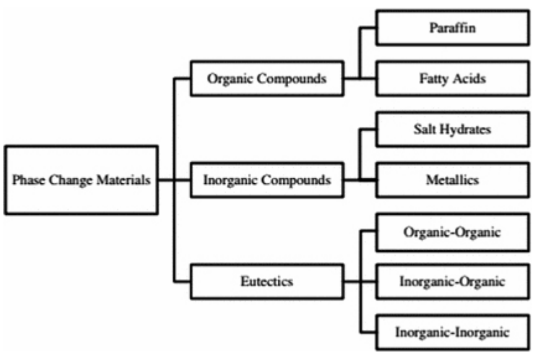


Figure 1-10 Different type of PCMs (Delgado, J.M.P.Q. et al., 2018)

In Norway, several PCM materials applied in building component have been carried out to explore its potential and possibilities. Cao, Bui and Kjøniksen (2019) develop a numerical model to evaluate performance of multilayer walls with PCM for a single family house in Oslo. The study finds energy results are significantly improved by integrating microencapsulated phase change material (MPCM) into geopolymer concrete (GPC) and by adding PCM to multilayer wall, see Figure 1-11. Scenario with thick PCM layer and thin insulating layer results in an annual energy reduction up to 32% in summer, and 23% in winter. It is also notice that even though increasing thickness and reducing thermal conductivity of insulation layer decrease energy consumption, PCM's heat storage capacity is much less effective.

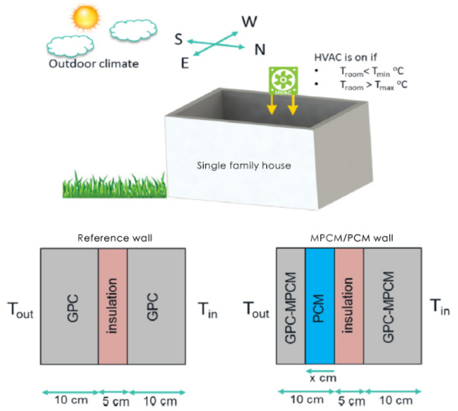


Figure 1-11 PCM study by Cao, V.D. et al. (2019)

Cao, S. et al. (2010) examine performance with and without PCM wall board in a well-insulated wall in a guarded hot box by recording the temperature, heat flux, air velocity, and electrical power during testing. Study finds significant attenuation effect of mean air and interior surface temperature with PCM layer. Change of air temperature in the metering box slows down due to the phase change process of PCM layer. It is also observed that temperature difference between the air in metering box and surface temperature of wall with PCM layer is larger than the case without it, especially during the heating period.

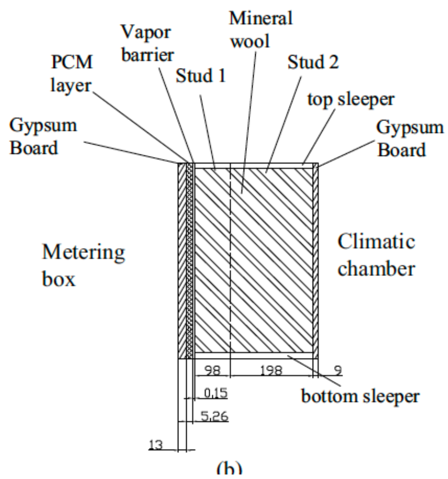


Figure 1-12 Hot box experiment by Cao, S. et al. (2010)

Study by Cao, Bui and Kjøniksen (2019) indicates that PCM's heat storage capacity is more effective in lighter construction. Thermal inertia of light weight construction (e.g., a wood or steel frame buildings, lightweight masonry buildings) is possible to be modified with the introduction of PCM material as additional thermal mass (Kośny, J., 2015, p.14)

1.5 Research purpose

The structure choice of OEN project using heavy weight concrete material is expected to result in large amount of emissions brought by the heavy structure. It is worth exploring alternative solution of using light weight structure that can reduce embodied emissions while maintain the required energy performance. Also in Norway, advanced technology of PCM is one of the prospect solutions to realize ambitious sustainability goals. Higher energy prices at peak demand will speed up the introduction of PCM-based solutions in Norway (Sevault A., 2018). This research is motivated by the design choice of OEN project and the potential of PCM material, aiming to:

- Propose alternative light weight structure with lower embodied emission.
- Evaluate the potential of using PCM-based building component as extra thermal mass on light weight structure.
- Conduct environment impact study from life cycle perspective and make suggestion on design option with the least carbon emissions.

2. METHODOLOGY

To solve research questions, a workflow including several working packages is logically structured for connecting all the essential information. This chapter introduces how information is collected in each stage, see Figure 2-1 research workflow. The following bulletins provide an overview of where relevant academic and design information are sourced from, what software is chosen to aid in modeling design option, and how necessary building data is collected along with research progress.

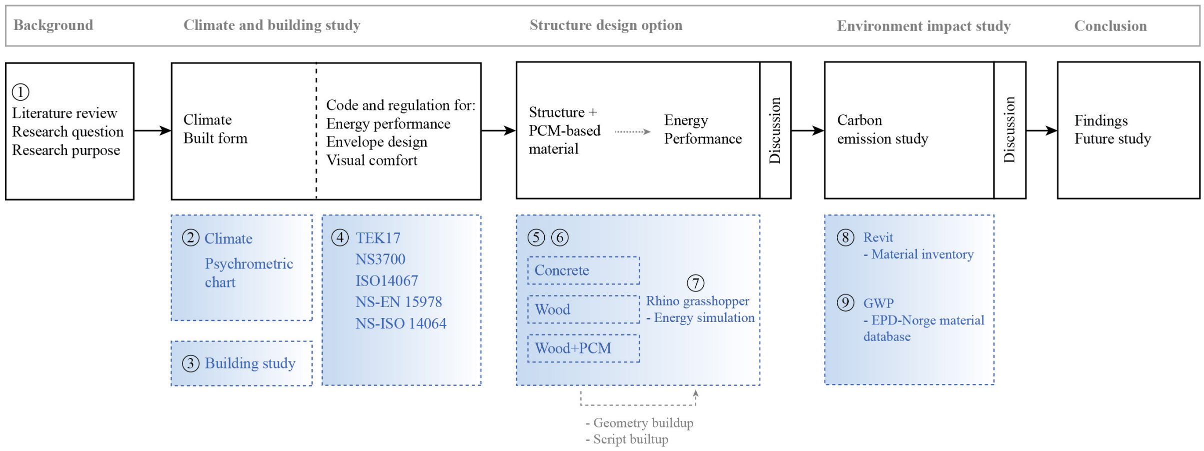


Figure 2-1 Research workflow

①Literature review

The broad research background comes from online resource of either official website or report publication regarding the environment protocol, joint goals under the European and Nordic context. Academic search engine ScienceDirect, a leading source as scientific database, is mostly used to sort out relevant studies related to the application of PCM-based material, energy simulation and environment impact assessment.

②Climate study

Site weather data is analyzed by Rhino5 grasshopper Ladybug plug-in. The climate and weather data retrieved from EnergyPlus website in EnergyPlus weather (.epw) format is imported to Rhino grasshopper Ladybug plug-in to visually present weather data in diagrams for further analysis at customized condition.

③Building study

Architectural floorplans, vision rendering and energy design concept of case study building are kindly provided by developer (owner), architect and energy consultant. All building information is shared under approval by the owner. The project is under design stage by the time developing this research, some of the necessary details are built up based on reasonable assumptions.

④Code and regulation

There are several applicable regulations which is fundamental and deemed vital for a building at this ambition level. These are set as design parameter and boundaries to ensure the energy performance complying with passive standard and maintaining good indoor comfort level. Byggteknisk forskrift (TEK17) is the applicable technical standard by the time developing this research and is sourced from official website of Direktoratet for Byggkvalitet in Norway. Other regulations and guidelines practiced in Norway source from standard.no, which hosts comprehensive standardized details of various design disciplines.

⑤Reference project

Design and construction detail reference to as-built reports published by The Research Centre on Zero Emission Building, as well as database of Norske arkitekters landsforbund. These two source websites are great knowledge base as lessons and experience sharing to architects and engineers in sustainable building industry of Nordic context.

⑥ Material information from supplier

Thermal property and installation of PCM-based material is given by supplier of the product. Previous studies using similar PCM-based material is also referenced for purpose of the study.

⑦Energy simulation software

Rhino5 grasshopper plug-in and Honeybee are used for building up modeling environment for energy simulation. The visual scripting interfaces are user-friendly and it support comprehensive study in all aspects of energy-related design. The thermodynamic modeling is run by EnergyPlus/OpenStudio engine. The results are visually presented and understandable by users from beginner to advanced levels (Ladybug Tools LLC, 2017).

⑧Autodesk Revit 2018

Revit is a powerful tool hosting key building information which can be accessed from its data base from component to system level. It is chosen as to retrieve material dimension (area, volume, unit weight etc.) for further environment impact study. Furthermore, the 3D visualization tool gives perspective of different structure design options proposed at this research.

⑨Carbon emission quantification

EPD-Norge database comprises verified documentation for environmental performance of building materials throughout its lifecycle. The environment impact is quantified by multiplying material's quantity and its global warming potential (GWP), resulting in the equivalent carbon emission amount of designated building material. Total carbon emission amount is further compiled in Microsoft Excel for generating diagrams and charts.

3. BUILDING STUDY

The OEN project is under design stage at the time being of this research. The owner, designer and energy consultant share up-to-date building information for giving an overview of the project and a better understanding of design choices they have made for the building. This chapter introduces from outdoor climate scale, to examination of various built forms, and zoom in to building design program in detail. These are the guidelines regarded as basis for developing design options.

3.1 Climate

Oslo is situated at latitude 59°N and longitude 10°E in Scandinavia. The Köppen climate classification lists Oslo as climate "Dfb", warm summer continental climate. The annual average dry bulb temperature is 6.5°C. Summer (June-August) is mild and comfortable. Winter (November to March) is long freezing and mostly cloudy. Oslo has an average relative humidity of 74%. The most humid month occurs in January, and the least humid month in May.

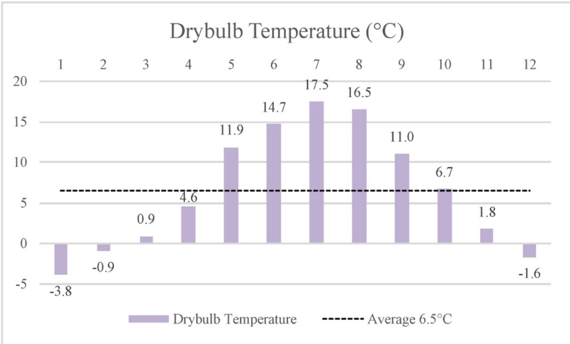


Figure 3-1 Dry bulb temperature

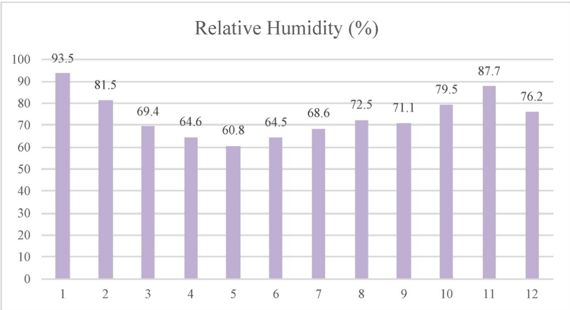


Figure 3-2 Relative humidity

Annual global horizontal irradiance (GHI) is 1198.8 kWh/m^2, converted to an average of 3.28 kWh/m^2/day. This value is important reference to photovoltaic (PV) installation, especially in summer when long sunlight hours makes PV production effective in the Nordic climate, making it promising of using solar energy to realize zero or plus-energy level building. Precipitation data (Weather-Atlas, n.d.) shows there is significant amount of rainfall in a year. Annual rainfall is 763 mm with lowest in February, highest in August and September with an average of 90mm. Heavy rainfall causes serious flood in several areas in recent years. Dominant frequent wind comes from north and south direction. Hourly average wind direction is predominant from south in summer and north in winter.

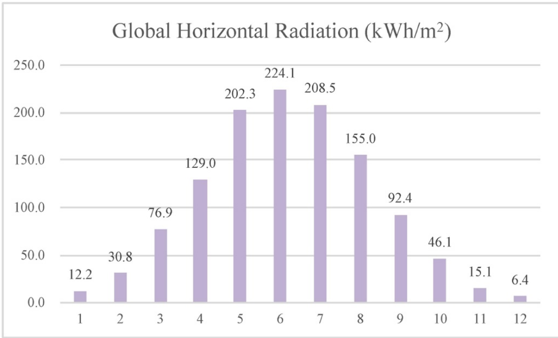


Figure 3-3 Global horizontal radiation

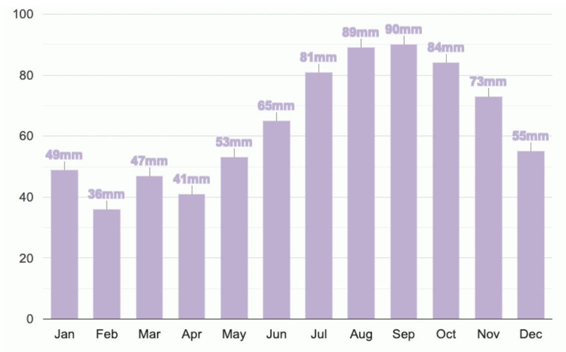


Figure 3-4 Precipitation

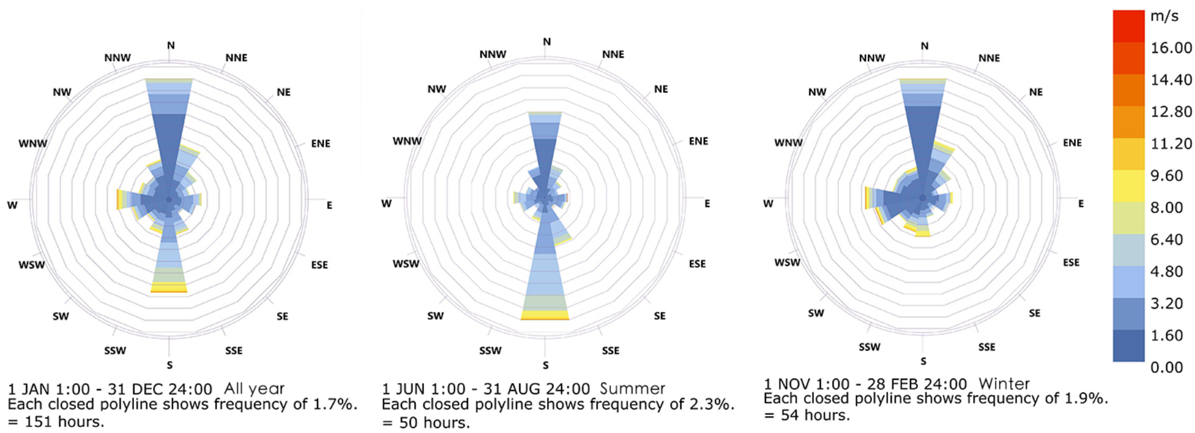


Figure 3-5 Wind rose

In Norway, most of the time in a year is cold and relatively dry. Psychrometric chart shows without implementing thermal control strategies, most of the time it is below comfort zone with comfort hour accounting for only 2.4% of the time in a year. For project designed driven by sustainability and passive house energy standard, a very well-insulated building envelope blocking air infiltration while keeping indoor heat gain as much as possible is an essential strategy. Thermal mass as passive strategy improves indoor comfort hours to 76.5%. Total comfort hours are fulfilled with heating and humidification control throughout the year.

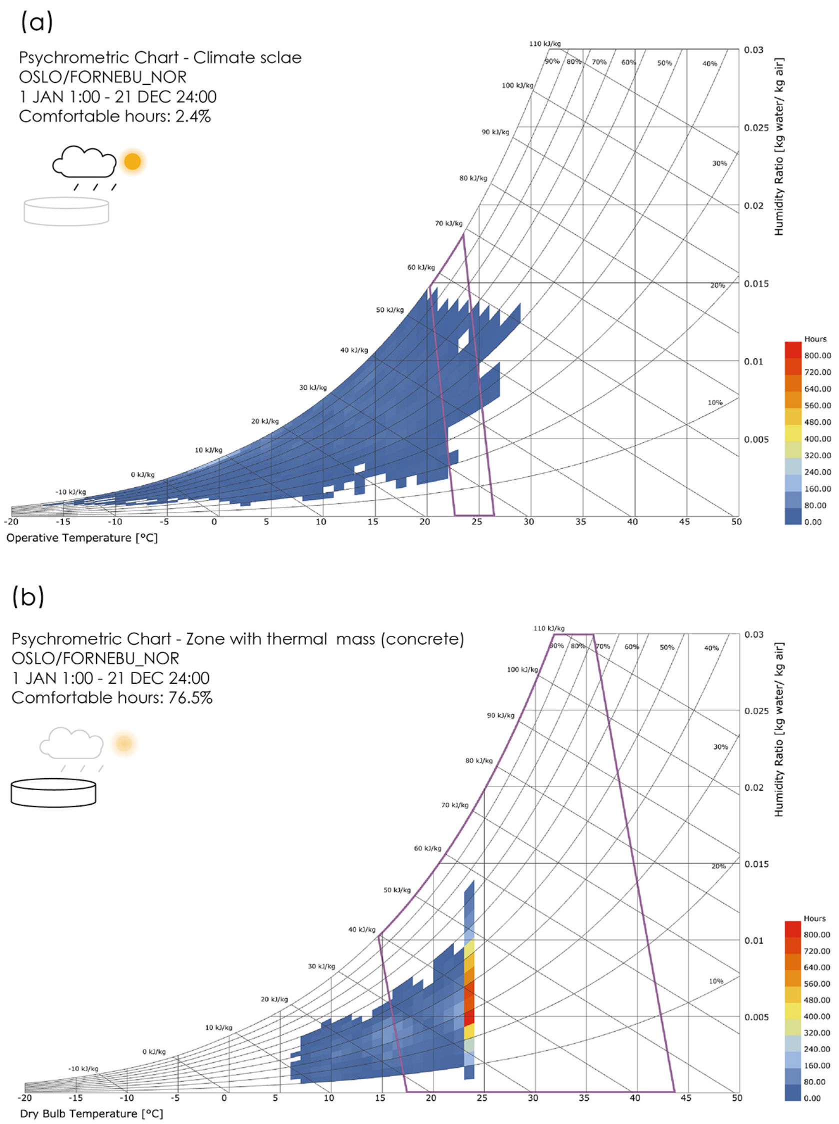


Figure 3-6 Psychrometric chart: (a) Climate scale (b) Thermal mass as passive strategy

3.2 Built form

One of the important factors landing on the circular shape is daylight accessibility. This relates to the harvest of solar energy and quality of daylight environment at both indoor and outdoor spaces of OEN project.

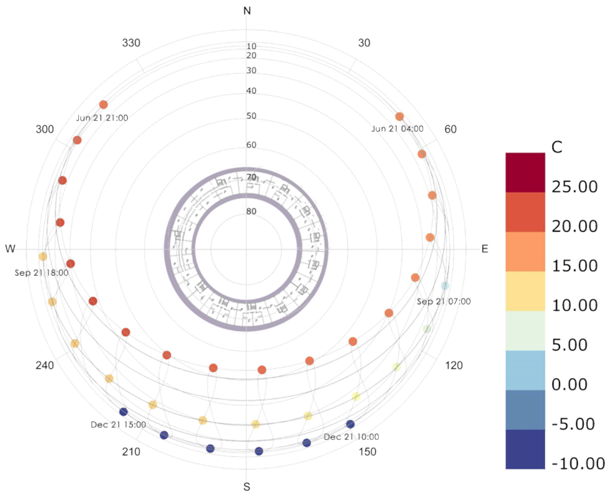


Figure 3-7 Sun path diagram 1

Sun path shows sun orbits around the south side of the site. Summer sun is high with relatively long daylight hours, in contrast winter is long dark day due to the low sun location. This indicates that south and west façade will need proper shading design to prevent glare and overheating problem.

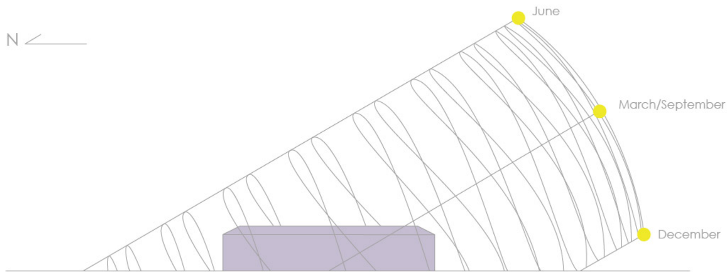


Figure 3-8 Sun path diagram 2

Various built forms with same floor area are tested to examine solar accessibility and shading effect. Compared to other built forms, circular shape has the most solar accessibility by looking at the average radiation amount, this can be explained by less shading effect of this geometry and volume. Despite of having less roof surface area than square geometry for solar harvesting, circular shape is the chosen built form by considering solar accessibility, daylight and the most decisive factor: space quality designer seeks to create for the inhabitants, the idea of embracing social activities as part of the neighborhood concept in the central courtyard.

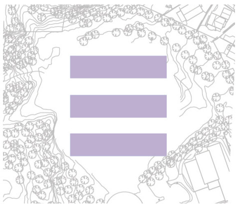
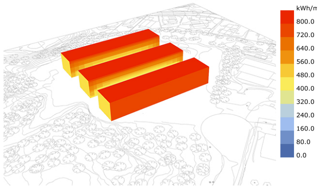
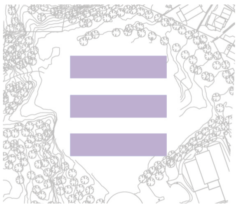
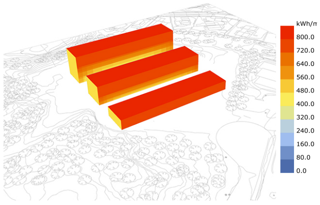
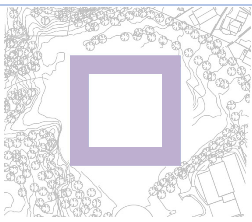
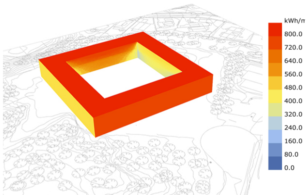
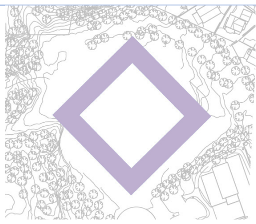
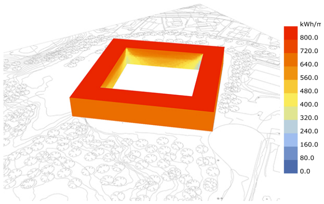
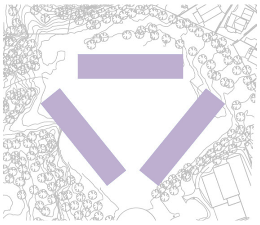
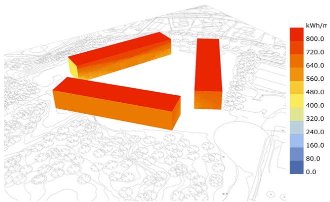
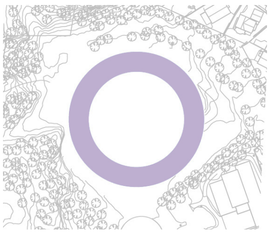
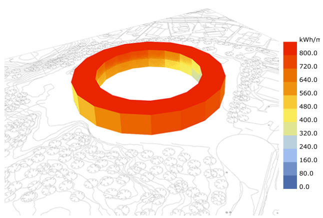
Form	Plan	Solar radiation	Total amount
Barcode (444)			549 kWh/m2 Roof surface area=3,393m^2
Barcode (246)			560 kWh/m2 Roof surface area=3,393m^2
Square			577 kWh/m2 Roof surface area=3,380m^2
Rhomb			578 kWh/m2 Roof surface area=3,380m^2
Triangle			582 kWh/m2 Roof surface area=3,393m^2
Circular			613 kWh/m2 Roof surface area=3,275m^2
*From January to December *Same floor area (≈13,450m^2)			

Table 3-1 Solar radiation of various built forms

3.3 Building design

This section introduces building's architectural design and regulation-based energy design schemes for the building. Below shows general design information:

Name of building	OEN
Context	Suburban
Building use	Residential
Heated floor area (m^2)	11,145
Total floor area (m^2)	13,450
Storey	4 storeys above ground and a basement storey
Number of housing unit	150 units ranging from $60m^2$-$90m^2$
Demand reduction strategies	Thermal insulation, air tightness, built form, solar shading, demand control
Renewable energy technology	Natural ventilation, passive solar heating, daylighting, PV on roof top
Efficient energy conversion	Ground source heat pump

Table 3-2 General design information of OEN project

- **Architectural design**

The building appearance features a circular shape, creating a central courtyard for landscaping and housing public activities.

The leading architect expresses that the team concern themselves with giving residents a pleasant place to live. "*The advantage of the circular shape is that everyone will get sun and views, with balconies facing the common area*" he says.

Figure 3-9 Perspective view of central courtyard

Floorplans from the basement (UF) to above ground floors are shown in Figure 3-10. The center grey part on the UF is the foundation of detention pond located right at the center of the courtyard which functions as part of the landscape design, grey water treatment, as well as flood control system when heavy rainfall occurs.

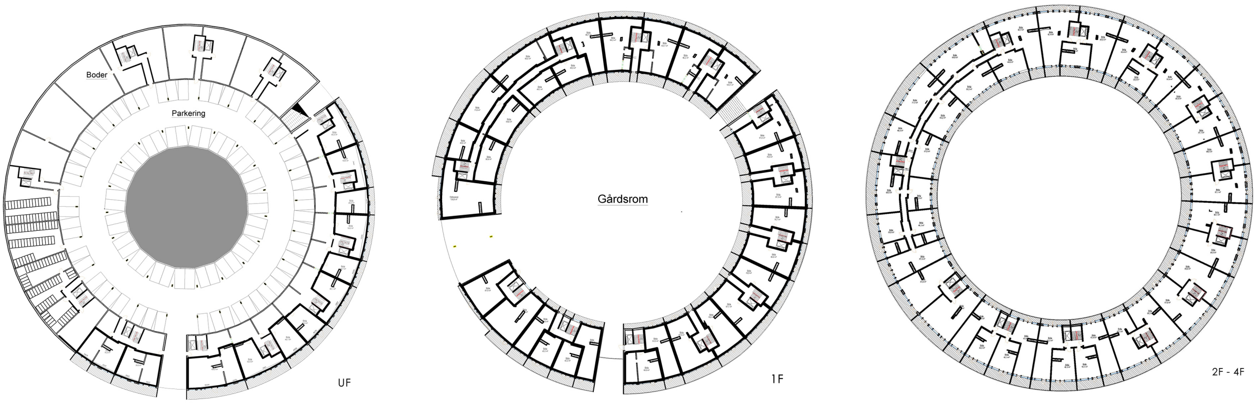


Figure 3-10 Floorplan (UF - 4F)

Looking at the apartment solution, most of the units have view to both courtyard and to the nature around. The idea is to bring the common area (e.g. living room) to the inner ring where living area has view to the central courtyard, while private bedrooms at the outer ring with view to the nature. The apartments vary in configuration from one to three bedrooms. The majority will be sized around 70 square meters.

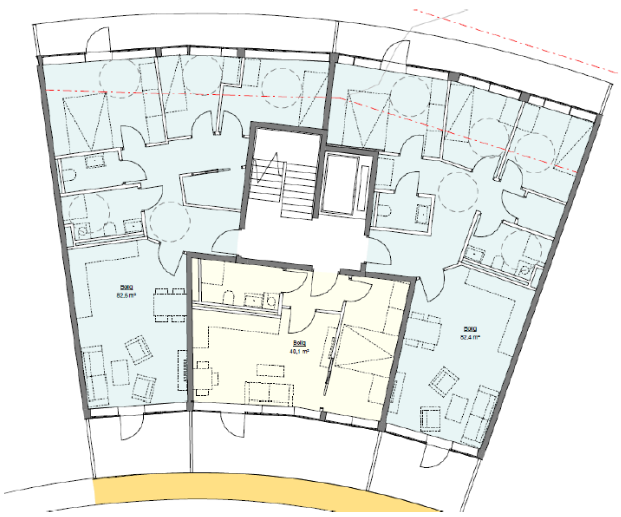


Figure 3-11 Example of apartment solution

The design of balcony is driven by both provision of shading device and internal accessibility. Section 3.2 shows the most effective way to reduce direct solar heat gains is by adding shading devices on south and west facade. When simulating overheating hours of indoor area, contour of percentage over 20% defines the geometry of balcony.

Figure 3-13 shows the balcony width varies from 1meter to 2 meters, wider at units demanding more shading. As balcony designed as private property, building's accessibility is designed with vertical access option as not to disturb private ownership and the aspiring view for residents.

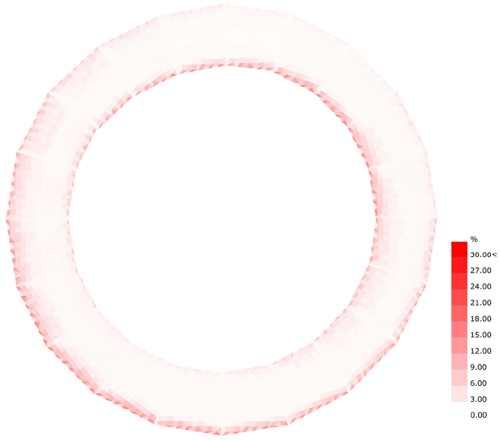


Figure 3-12 Percentage of overheating hours in summer (without balcony)

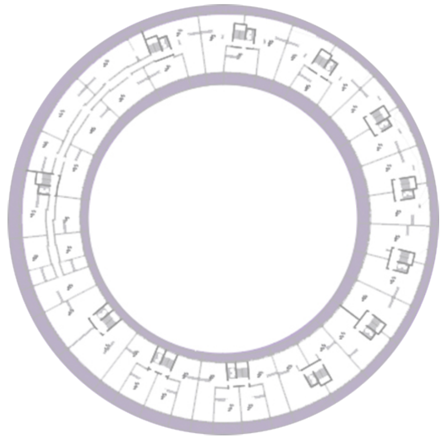


Figure 3-13 Balcony geometry

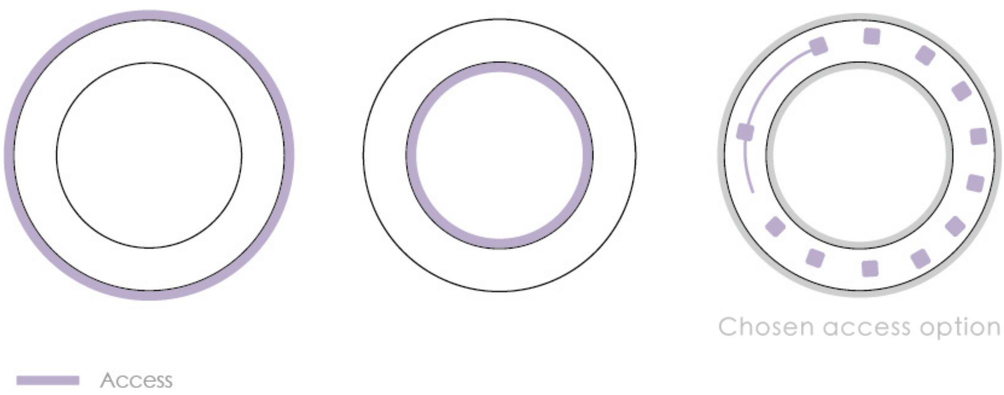


Figure 3-14 Different access options

- **Energy related design**

Two important applicable regulations related to energy design of the building includes TEK17 technical standard and NS 3700. Key design criteria and parameters are sorted out in Table 3-3. Design with these guidelines on a static level helps to reduce operational energy demand and realize the ambitious energy goal of the project.

Standard	Criteria	Value
TEK17	Proportion of window and door area	≤ 25% of heated gross internal area
	Energy requirement	Block of flats ≤ 95 kWh/m^2.year
	Energy supply solution	Buildings with a heated gross internal area of more than 1,000 m2 shall: a) have multi-source heating systems; and b) be adapted for use of low-temperature heating solutions.
NS3700:2013	Specific space cooling demand	No mechanical cooling allowed
	Airtightness test	≤ 0.43 $W/(m^2.K)$
	Specific fan power (SFP) for ventilation fans	≤ 1.5 $kW/(m^3/s)$
	Heat recovery efficiency	≥ 80%
	Specific space heating demand	≤ 15 kWh/m^2.year (Annual average temperature at site over 6.3°C)
	U-value	
	Roof	0.08-0.09 $W/(m^2.K)$
	Outer wall	0.10-0.12 $W/(m^2.K)$
	Foundation	0.08 $W/(m^2.K)$
	Windows and doors	≤ 0.80 $W/(m^2.K)$

Table 3-3 Key design parameter from applicable regulations

In cold climate like Norway, glazing area should be carefully determined to provide adequate level of indoor visual comfort while avoid large amount of heat loss. TEK17's light and views clause specifies "*Rooms for continuous occupancy shall have adequate access to daylight and window that provides a satisfactory view.*" The average daylight factor in the room must be at least 2.0%. In determining the window to wall ratio, daylight simulation shows most of the areas reach required daylight factor at window to wall ration of 50%, see Figure 3-15.

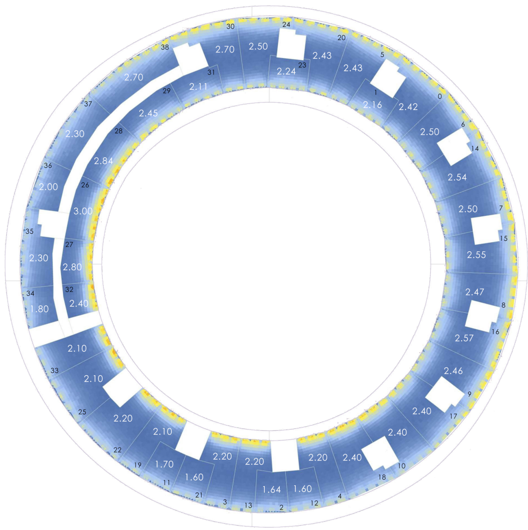


Figure 3-15 Daylight factor simulation (50% window to wall ratio)

The proportion of window and door area 1,694m^2 ≤ 2,786m^2 (25% heated gross internal floor area = 11,145m^2). The window to wall ratio also addresses to designer's vision to provide appealing view towards the courtyard and the nature.

The first design idea of photovoltaic (PV) system is to have building-integrated photovoltaics (BIPV). This is later changed to independent roof top PV considering the power covert efficiency and maintenance. PV covered on the roof top is dimension by 2m*0.6m per panel. It is supported by aluminum rack and aligned in gable shape with peak at 3.5 meters above flat roof. This decision is to allow ventilation underneath the PV system, as well as provide sufficient height for maintenance work considering it will be the main energy source, maintaining system's up and running at all times is very important.

4. DESIGN OPTION

Based on previous understanding of the project from climate, building design and regulation perspectives, key design context is set up for proposing alternative structure type (hereinafter is referred to as “design option”) as well as setting up energy simulation. Thermal envelope of the building encloses all the apartment units needed for thermal control to keep indoor temperature at comfort state, see Figure 4-1.

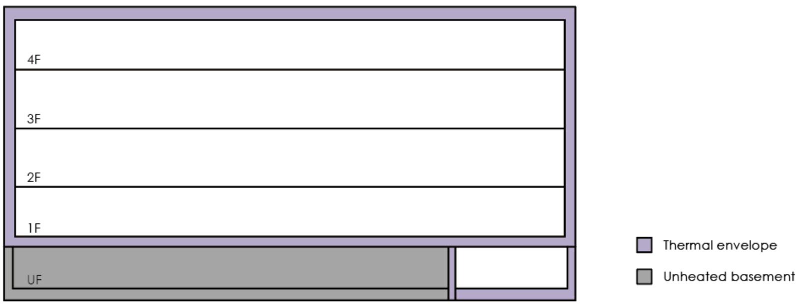


Figure 4-1 Thermal envelope

The building elements focused here are structures of building envelope and floor deck, interior supporting partitions are considered identical in all design options. To make design option aligned with present practices and building techniques, three pilot projects are referenced as to decide construction detail of building element:

- Powerhouse Kjørbo (Sørensen et al., 2017) at Sandvika: Two office buildings built at early 1980s are renovated to achieve high energy-efficiency goal. The original concrete structure is kept, while building envelope is upgraded according to passive house energy standard.
- Moholt50/50 (Lolli and Kjendseth Wiik, 2019) at Moholt: A student housing project built by massive wood structure (cross laminated timber, CLT). Completed in 2017, the project is designed according to passive house energy standard, key design driver is to lower the

CO_2 production compared to traditional construction practice.

- Husabøryggen at Hundvåg (Husabøryggen bofellesskap rapport, n.d.): Completed in 2013, the project is built with passive house energy standard with loadbearing structure in extensive use of CLT panels.

The first section presents design options specifying construction details assigned to energy model. The second part introduces modeling environment setup, energy simulation result and findings. The chapter is summarized by zooming in to room unit's scale as to explain simulation result and land on finalizing design options for further environment impact study.

Key design parameter	Value
Total floor area	13,450 m^2
Heated floor area	11,145 m^2
Window to wall ratio	0.50
Building envelope U-value [W/(m^2.K)]	
Roof	0.08-0.09
Wall	0.12
Window	0.80
Ground floor	0.08

Table 4-1 Key design parameter

4.1 Structure of envelope and floor deck

Three proposed design options are concrete, massive wood and massive wood with PCM panel at designated envelope and floor deck assemblies. The choice of heavy weight concrete structure follows what has been originally proposed in OEN project. Besides high thermal mass, concrete withstands wind and moisture, making it less susceptible to deterioration. Due to its high-density, concrete has advantages over lightweight materials with respect to acoustic performance. Based on its thermal and physical properties, it is commonly recognized as an economical-effective solution.

In Norway, wood structure has been widely used for long history and nowadays possibilities have been broadly explored as robust structure component. Many significant projects structured by massive wood have been carried out across the country. The concept of sustainability often associates with wood by the appraisal of its classic appearance as well as its low impact towards the environment. It is light, easier to fabricate and install which can perform as good as concrete and steel in structural performance. For OEN project, comparisons between using concrete and wood structure is listed in Table 4-2.

Factor	Concrete structure	Wood structure
Material thermal mass	High	Low
Durability (Water/wind resistance)	Durable	Susceptible
Fire resistance	Non-combustible	Combustible
Acoustic proof	Effective	Less effective
Maintenance	Low	High
Cost	Expensive	Less expensive
Built schedule	Longer	Shorter
Other	Susceptible to efflorescence	Structural depreciation

Table 4-2 Comparison between concrete and wood structure in OEN project

The coverage of PCM is to enclose the building volume as additional thermal mass. Design option with PCM is a type of PCM panel that is embedded within opaque layer of façade wall and floor deck assemblies in either ceiling or flooring layer of wood structure. In cold climate like Norway, the effective method is to add PCM panel where exposes to the greatest heat. For design option with PCM panel, it is placed at the inner layer of assemblies to keep the indoor heat from escaping, stabilizing indoor temperatures. Construction detail and assigned material is shown in Figure 4-2. Consider the structural load bearing performance, the basement floor (UF) is identical for all design options.

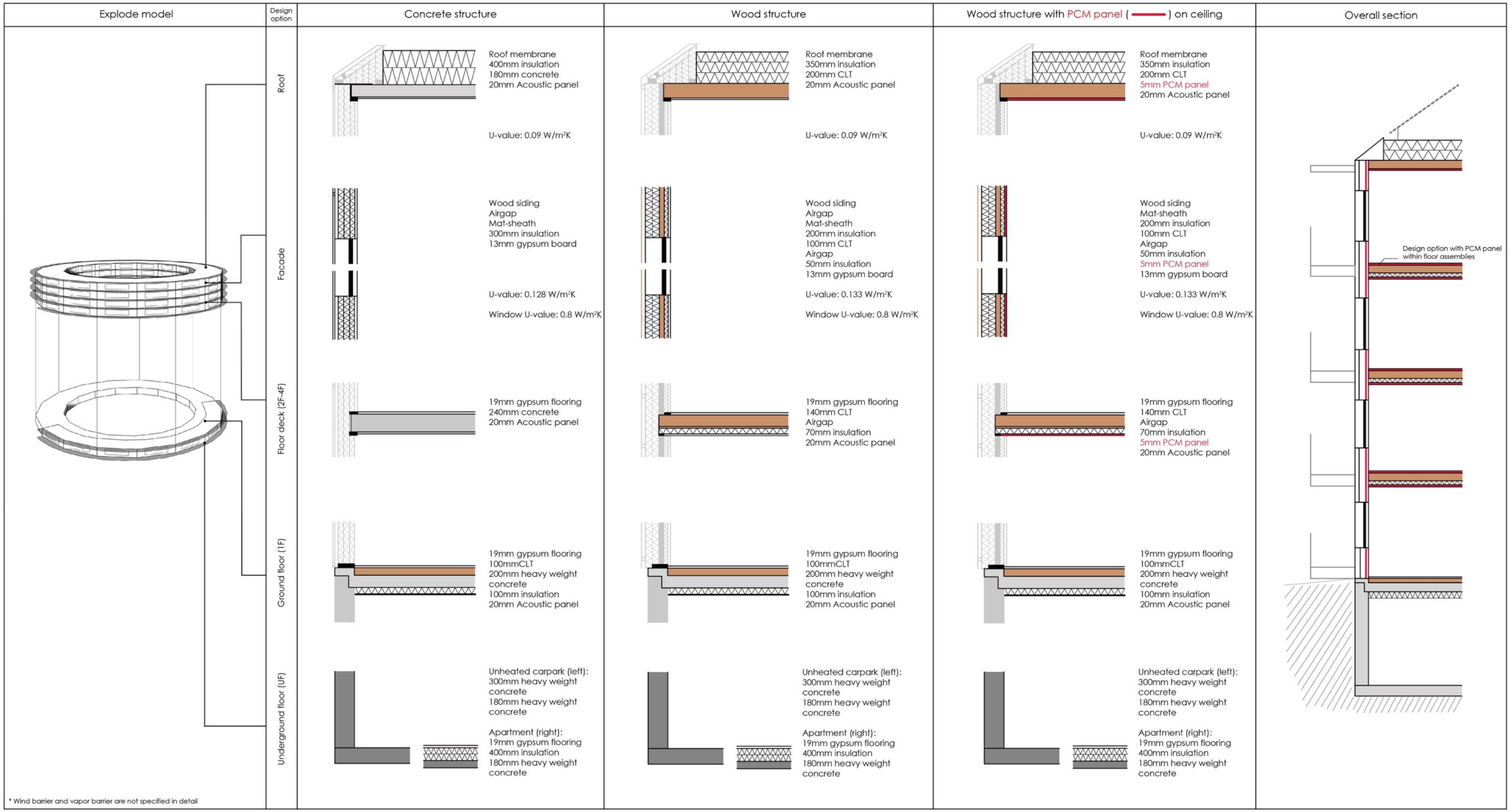


Figure 4-2 Construction detail of design option

4.2 Energy Model setup

EnergyPlus engine follows basic heat balance principles in almost all aspects of the program by conduction transfer function (CTF) transformation. The restriction lies on the fact that in most cases building surface constructions are set with constant properties. To model the heat transfer property of PCM panel with varying conductivity, a conduction finite difference (CondFD) solution algorithm is introduced in EnergyPlus, which complements CTF solution algorithm with the ability to simulate phase change materials or variable thermal conductivity. Simulation result compared with real measured data are validated in previous studies on opaque wall assemblies by the National Renewable Energy Laboratory (Tabares-Velasco et al., 2012). Overall simulation script is shown as follows:

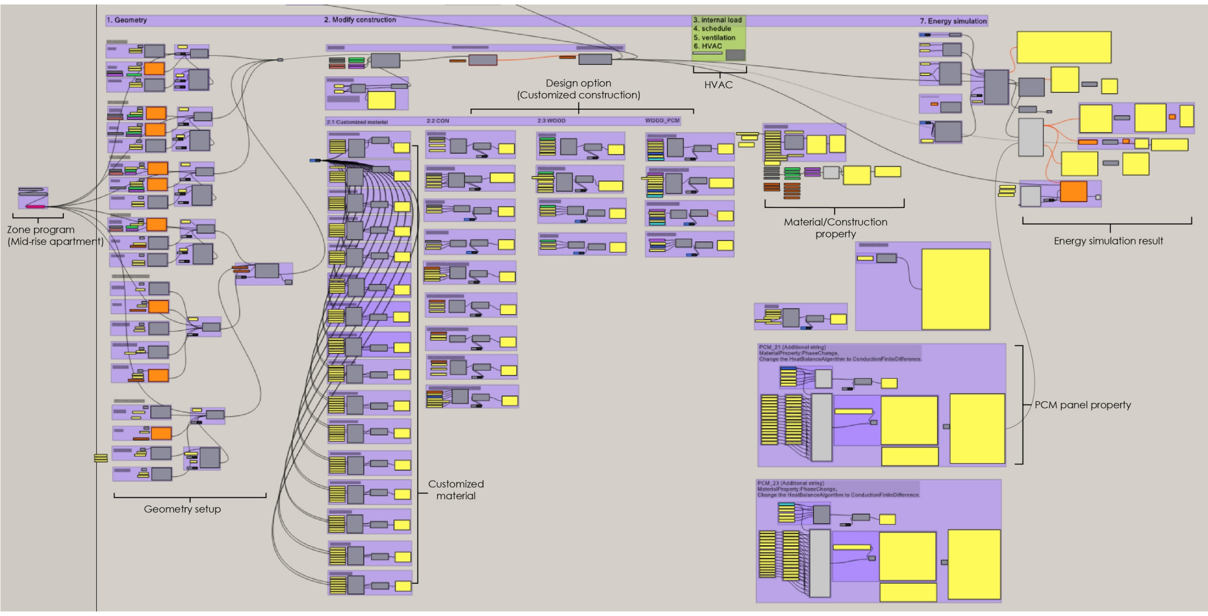


Figure 4-3 Grasshopper script

The model comprises of 6 zones divided by storey and heated/unheated zone on the UF. Boundary condition is set based on corresponding site surroundings.

The study focuses on the envelope and floor deck and runs by whole building energy perspective as to find out heating demand.

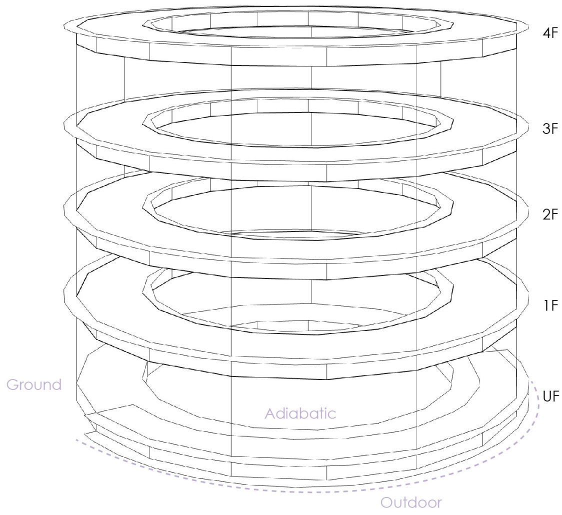


Figure 4-4 Zoning and boundary condition

Energy simulation schedules of occupancy, lighting, equipment, and HVAC (heating, ventilation, and air conditioning) are based on the default setting of a mid-rise apartment in EnergyPlus library. Heating set point is 21.5 °C. Air control is calculated by ideal air load as to simulate nominal heating load of all design options.

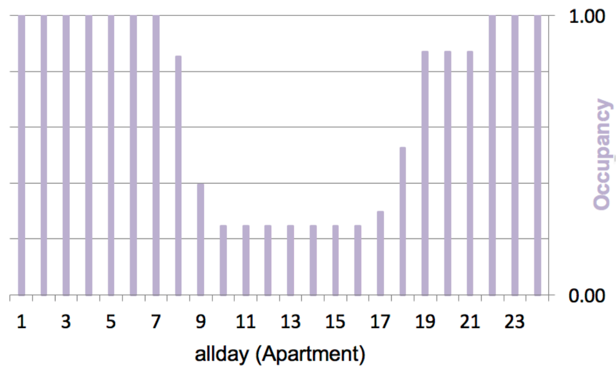


Figure 4-5 Occupancy schedule

The PCM material property in EnergyPlus requires at least 16 sets of temperature versus enthalpy data. These data is provided by supplier as well as referenced from early study (Cao et al, 2010, pp. 15–26).

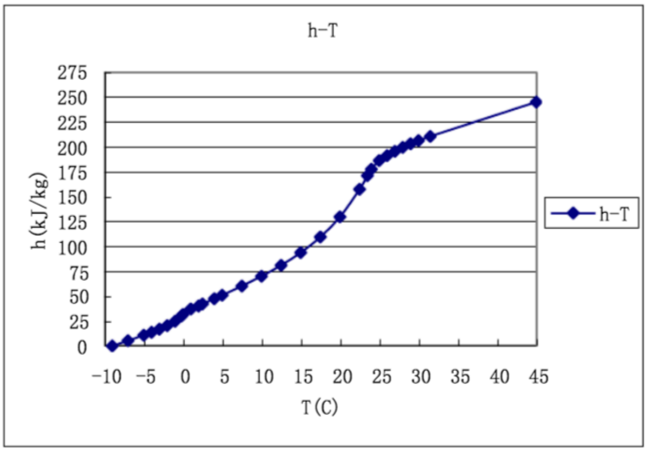


Figure 4-6 Corresponding h(T) curve of PCM panel (Cao et al, 2010)

Thermal and physical properties of PCM panel (DuPont, 2012) used in this study can be found in Table 4-3.

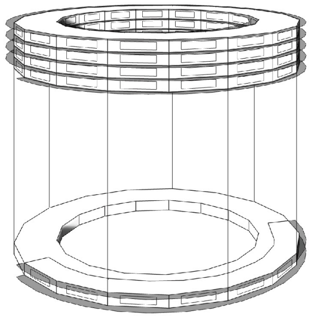
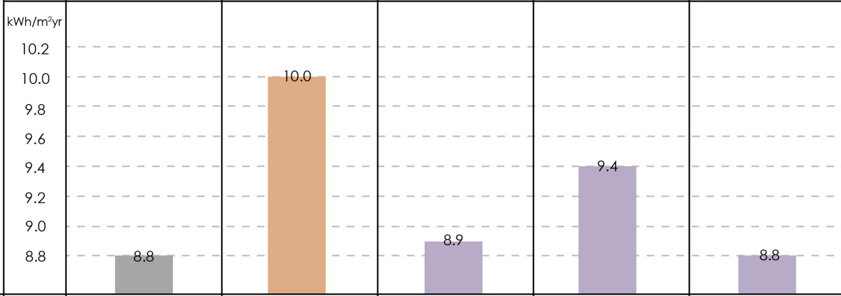
Installation picture	Material property	
	Thickness	5mm
	Area weight	4.5 kg/m^2
	L*W	1200mm*1000mm
	Paraffin loading	60% microencapsulated paraffin within a copolymer
	Melting point	21.7 °C
	Conductivity	0.18 W/(m.K) - Solid 0.14 W/(m.K) - Liquid
	Density	855 kg/m^3
	Specific heat	2500 J/kg.K
	Latent heat storage capacity	> 70 kJ/kg (0°C - 30°C)
	Total heat storage capacity	~ 140 kJ/kg (0°C - 30°C)

Table 4-3 Material property of PCM panel

4.3 Energy simulation

Whole building energy simulation is carried out to look at the energy performance of design options. In design option with PCM panel, more than one scenarios are simulated as to find out what is the optimal location for installation. In total there are 5 design options: Concrete structure (CON), wood structure (WOOD), wood structure with PCM panel within ceiling assemblies (WOOD_CEI), flooring assemblies (WOOD_FL) and both ceiling and flooring assemblies (WOOD_CEI+FL). All design options have PCM panel on facade layer to enclose the building as additional thermal mass.

Simulation results from 1F to 4F are sorted out to compare the energy performance between different design options. The basement floor is excluded in the comparative study as it is with constant setting, plus the different geometries and boundary conditions (adjacent to unheated storage and carpark) from the floor above the ground. Figure 4-7 shows simulation results by storey and energy consumption difference (±%) compared with concrete structure. For a building designed by passive house energy standard, no mechanical cooling is allowed, hence heating load is the focus in comparing simulated results.

Explode model	Design option	CON	WOOD	WOOD_CEI	WOOD_FL	WOOD_CEI+FL
	Graph					
	4F	31101.7	33898.9(+9.0%)	32448.0	32991.0	32185.0
	3F	15999.0	19694.2(+23.1%)	17098.6	18199.3	16746.1
	2F	16933.4	20347.3(+20.2%)	17951.3	18970.8	17635.0
	1F	24451.9	27069.1(+10.7%)	22323.0	25114.6	22290.7
						
Total nominal heating load (1F-4F)	kWh	88486.0	101009.4	89821.0	95275.8	88856.9
Difference (%) compared with CON design option	%	-	+14.1%	+1.5%	+7.7%	+0.4%

Note1: PCM panel within facade assemblies applies to all PCM design options
Note2: Same occupancy, lighting, equipment and HVAC schedules applie to all design options
Note3: UF setting remains constant

Figure 4-7 Total nominal heating demand (1F-4F)

Findings:

1. In proposed design option, change concrete structure to wood structurer results in higher heating demand (+14.1% compared with concrete structure).
2. Adding PCM panel on wood structure results in less heating demand compared to wood structure without PCM panel.
3. PCM panel installed at different building component results in different heating demand. PCM panel embedded within ceiling assemblies results in less heating demand than PCM panel at flooring assemblies.

Another PCM material with melting temperature at 23.0°C is also tested, and result shows melting temperature at 21.7°C performs much better in reducing heating demand on wood structure.

4.4 Discussion

The zone energy simulation results are further examined by zooming in room unit scale to find out reasons for why heat demand is reduced. Four locations at 2F are chosen as representative units. Each room has opening towards the central courtyard.

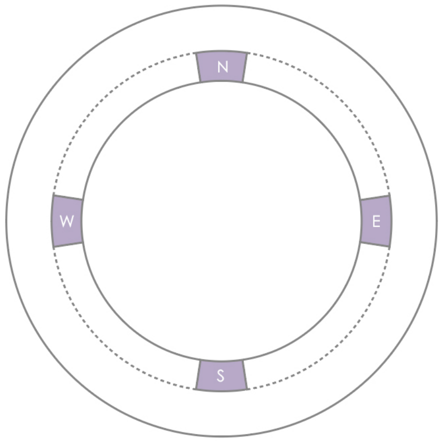


Figure 4-8 Representative unit

When room temperature goes above PCM panel's melting temperature, the PCM panel absorbs excess heat, and the absorbed heat is then released in the overnight hours when temperature drops down. The temperature setbacks require less heating. The charging and discharging cycle of PCM panel helps to modulate the indoor temperature in an effective way.

1. **In proposed design option, change concrete structure to wood structurer results in higher heating demand (+14.1%) compared with concrete structure).**

   Concrete structure is with high thermal inertia which consequently results in smaller temperature change in a diurnal cycle. For building designed by passive standard, the choice of concrete structure type is a comparably high thermal inertia design option than wood. Wood structure of 2F and 3F, compared to UF and 4F which still have heavy-insulated enclosure, are enclosed by relatively lighter structure, resulting in increasing heating load by +20.2% and +23.1% separately compared to concrete structure. The indoor operative temperature is shown in Table 4-4. During shoulder season, temperature of concrete structure doesn't fluctuate as much as wood structure, especially between 00:00-09:00 when wood structure displays relatively low indoor temperature when ambient temperature drops down. This shows why heating load is much demanding in wood structure. Also, north and west representative units have bigger operative temperature difference between two structures than east and south counterpart. This is due to north unit's glazing towards south, and less shading effect brought by the balcony in west room that expose structure to more solar gain. While in winter, except the temperature of north unit fluctuates significantly in wood structure due to solar gain at noon, the two structures at all other units display quite comparable results.

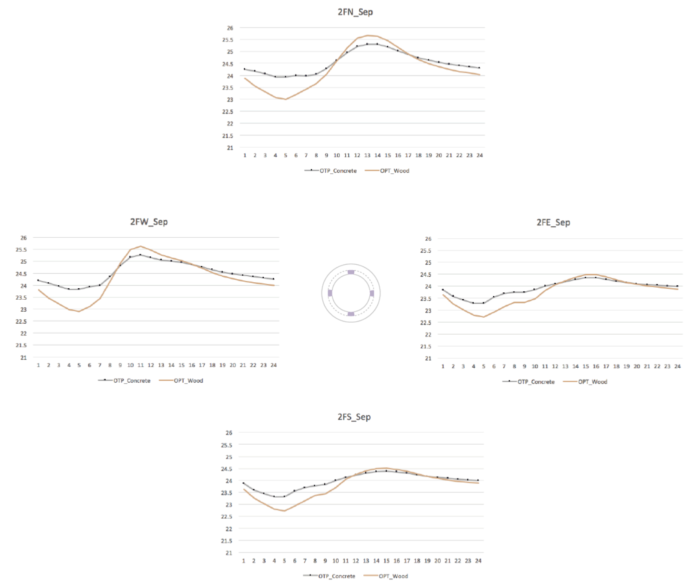
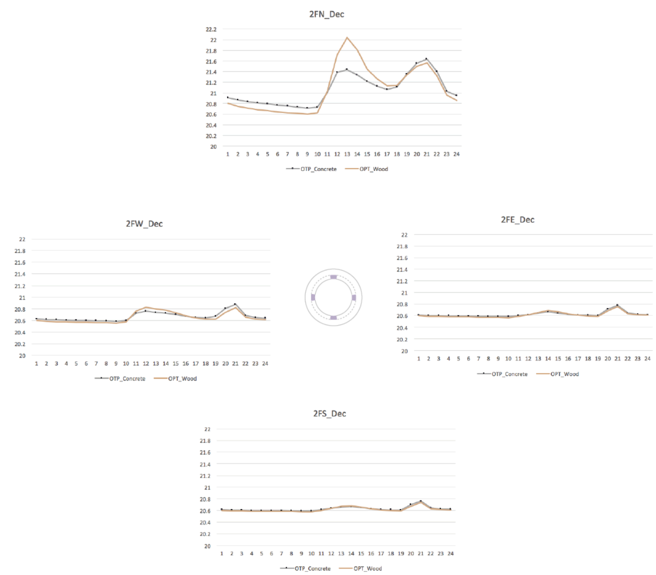
Season	Indoor operative temperature
Shoulder season (21 Sep.)	
Winter (21 Dec.)	

Table 4-4 Operative temperature of concrete and wood structure during heating season

2. **Adding PCM panel on wood structure results in less heating demand compared to wood structure without PCM panel.**

PCM is characterized by its ability to modulate the fluctuating indoor temperature. As mentioned earlier, when change structure from concrete to wood, it becomes lighter structure which exposes PCM panel to bigger temperature difference, stimulating PCM panel's transition state (charging and discharging), further modulating the indoor temperature in wood structure. PCM panel as additional thermal mass reduces 11% of heating demand than design option without PCM panel.

Indoor operative temperature with and without PCM panel on wood structure is shown in Table 4-5. Result shows that structure with PCM works better in shoulder season due to ambient temperature that allows PCM to store heat at daytime, and release during the night time. In winter, the average low ambient temperature makes PCM less efficient in modulating the indoor temperature. It is observed again that north and west representative units have relative higher operative temperature (+0.5°C) than east and south counterpart. This is again due to north unit's glazing towards south, and less shading effect brought by the balcony in west room that expose structure to more solar gain.

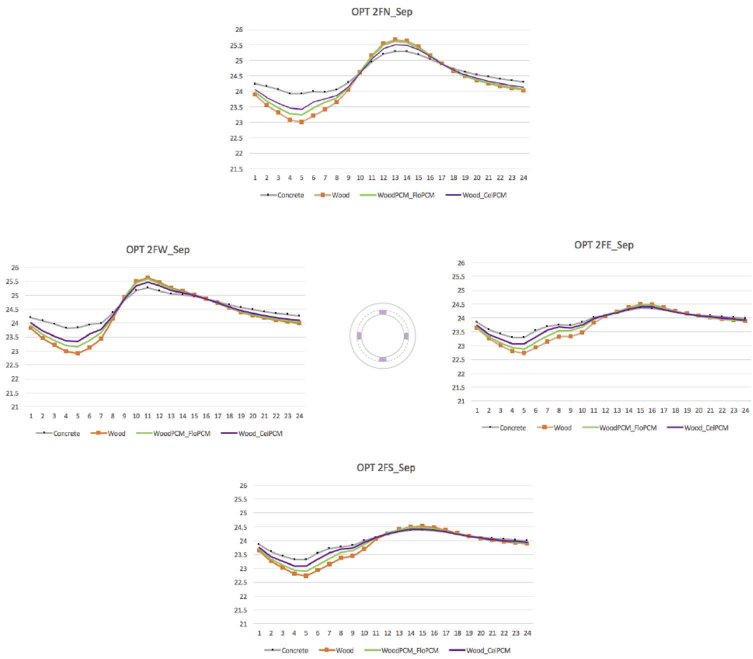
Season	Indoor operative temperature
Shoulder season (21 Sep.)	
Winter (21 Dec.)	

Table 4-5 Operative temperature of design options during heating season

3. **PCM panel installed at different building component results in different heating demand. PCM panel embedded within ceiling assemblies results in less heating demand than PCM panel at flooring assemblies**.

Surface temperature of ceiling and floor deck can be affected from dynamic solar gain, internal heat gain and conduction heat from adjacent zone, to heat transfer between material layers.

Even though floor temperature is affected by solar heat gain during daytime which display higher instant surface temperature, PCM_FL option doesn't perform as good as PCM_CEI option, see Table 4-6.

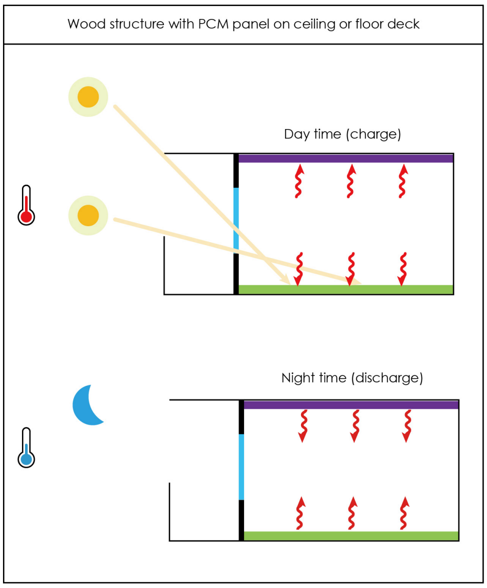


Figure 4-9 Indoor temperature modulated by PCM panel

Different material of ceiling and flooring assemblies is assumed to be one of the reasons where PCM panel at WOOD_CEI option exposes to lighter adjacent material. It is also observed that ceiling temperature at night time is slightly lower, which indicates PCM panel at WOOD_CEI option has more potential of discharging heat than WOOD_FL. We can summarize by saying that PCM panel installed on ceiling option is more effective in capturing and releasing total heat gain than WOOD_FL. Furthermore, furniture coverage is not included in WOOD_FL energy simulation. With furniture covered on top of the floor, in real case it would be even less effective.

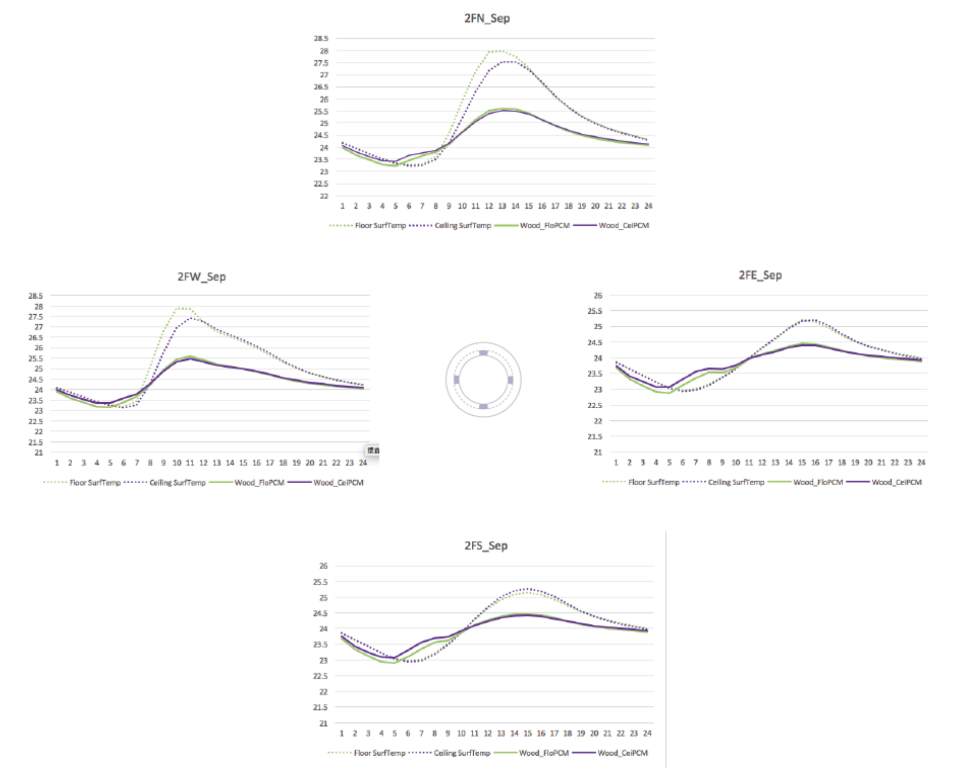
Season	• Surface temperature without PCM panel (dashed line) • Indoor operative temperature of WOOD_CEI versus WOOD _FL
Shoulder season (21 Sep.)	

Table 4-6 Surface temperature without PCM panel and indoor operative temperature with PCM panel

Among all design options, WOOD_CEI+FL has the least heating load that performs almost as good as concrete structure. However, adding on both ceiling and flooring assemblies doesn't show significant reduction on heating demand compared to WOOD_CEI. It is not a good choice consider doubling the use of material, therefore WOOD_CEI is selected as design option with PCM. During summer, PCM panel helps in reducing peaking temperature during summer daytime, indoor comfort is expected to increase with the help of also natural ventilation in the building. Based on results and findings, it can be summarized that PCM panel installed within ceiling assemblies is the finalized design option with PCM. Total heating load of three design options: Concrete structure (CON), wood structure (WOOD) and wood structure with PCM panel on ceilings (WOOD_CEI) are shown in Figure 4-10. Results will be integrated in environment impact study in the next chapter.

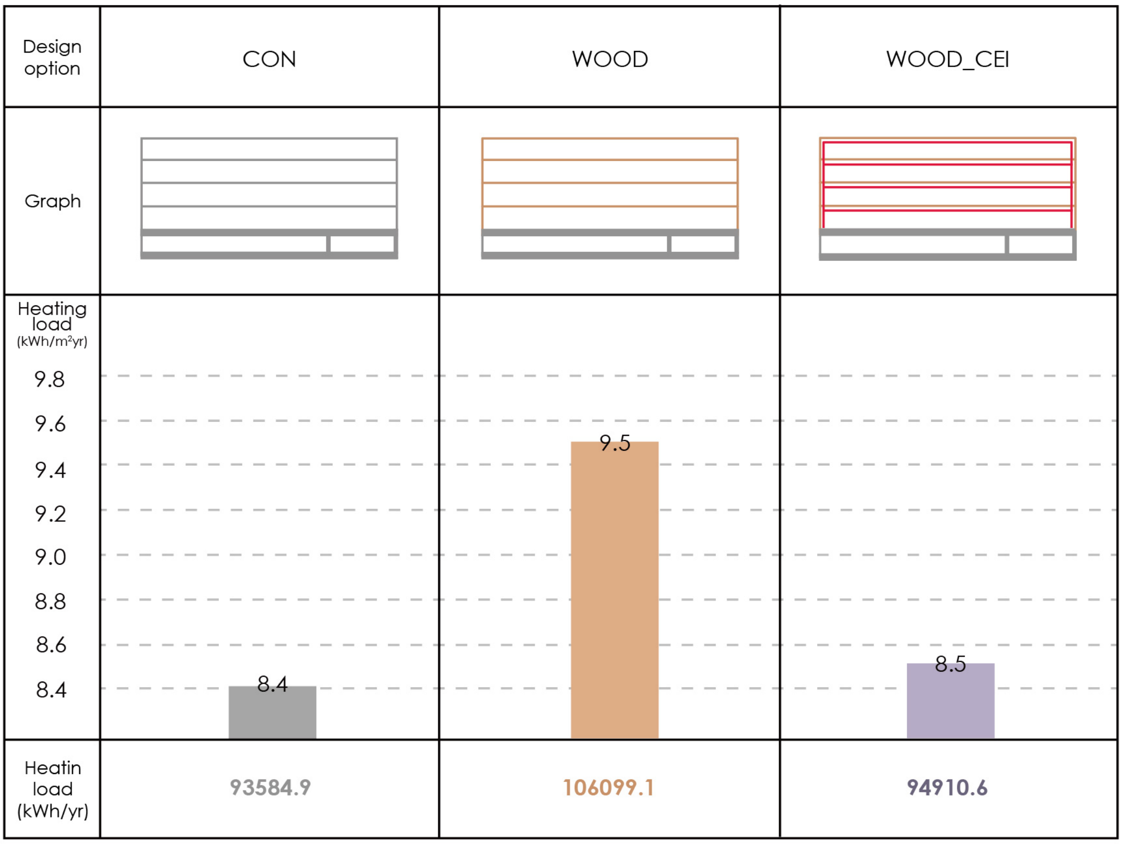


Figure 4-10 Annual heating demand of final design options

5. ENVIRONMENT IMPACT STUDY

Change from concrete to wood structure is driven by lower embodied emission. Though adding PCM panel as additional thermal mass reduces heating load, it should be examined by integrated approach to look at the environment impact brought by both material's embodied emission and operational energy use. The calculation follows process specified under clause 6 of NS 3720:2018. System boundary framed for environment assessment is A1-A3 (product stage) and heating load of B6 (operational energy use) with a reference lifecycle of 60 years.

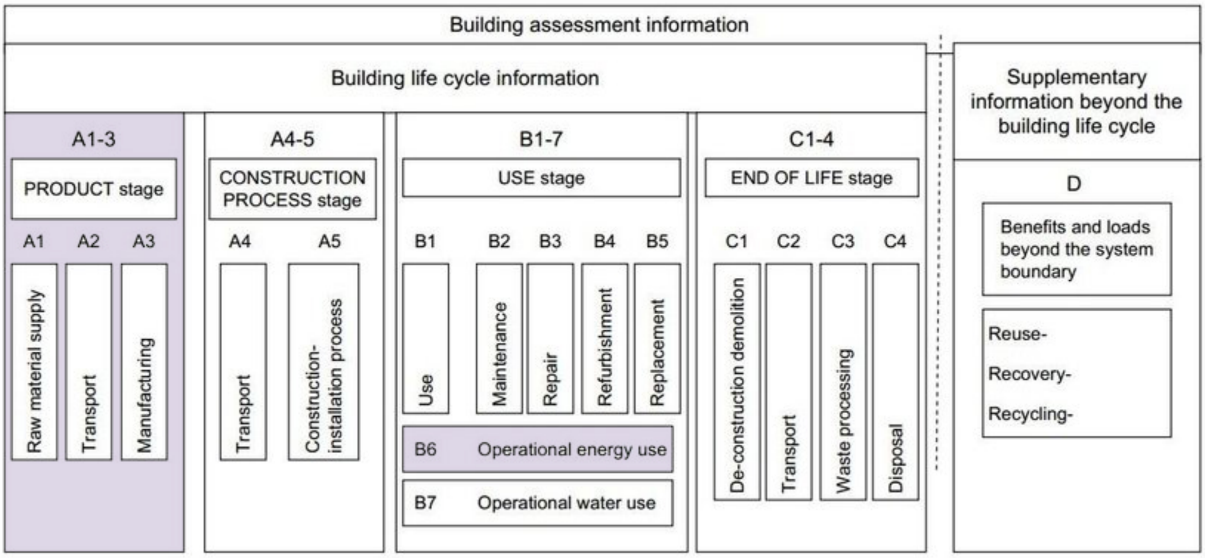


Figure 5-1 System boundary (NS-EN 15978:2011)

5.1 Building model

Model built up in Revit are structures of building envelope and floor deck. Original design with balcony in concrete structure is also changed to wood structure. The following building components are assumed identical in all three design options, hence not included in the Revit building model:

- Interior structural wall

- Interior light partition
- Elevator
- Parking area at the center of UF storey

Material property and layers are assigned to model according to construction detail shown in section 4.1. Below shows building model in Revit.

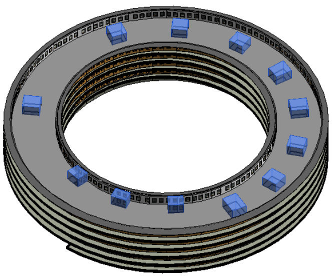
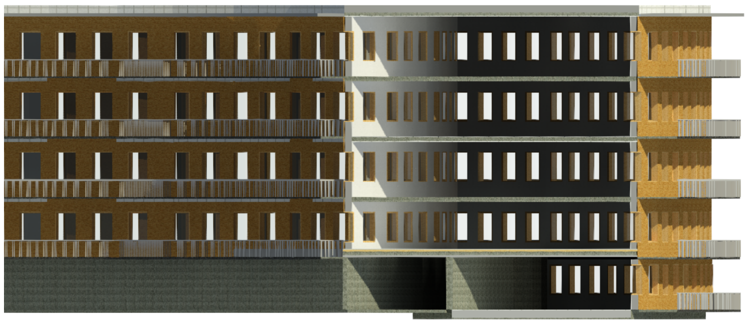
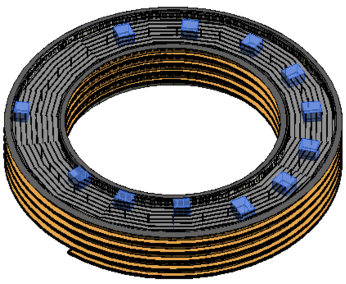
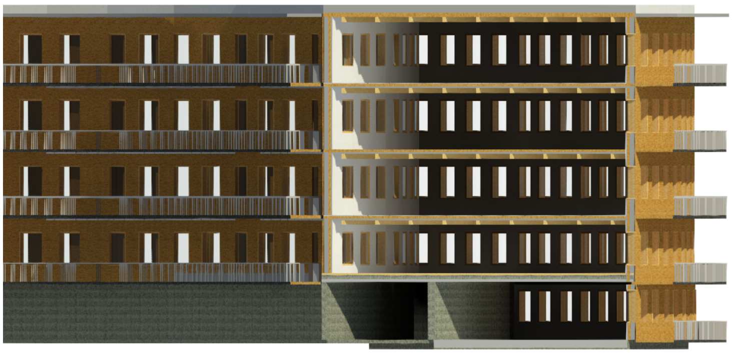
3D perspective	Section
Concrete structure	
	
Wood structure	
	

Table 5-1 Building model in Revit

5.2 Material inventory

Material dimension accessed from Revit in applicable functional unit of material is converted to equivalent carbon emission amount. All materials match as close as possible in terms of both function and appearance, see APPENDIX A for reference data sources. For concrete product, the priority is given to material documented as low carbon material. In the boundary and context setting of this research, the embodied emission of concrete structure design option results in carbon emission amount of 2.82 $KgCO_2$-eq/m^2.year.

Building component	Material	Quantity	(A1-A3) Emission factor/Function unit	Embodied GHG (GWP) emission (KgCO2-eq)
Roof	Roof membrane	3340 m^2	5.05 KgCO2-eq/m^2	16867.0
	Insulation(400mm)	44533 m^2	0.55 KgCO2-eq/m^2	24462.2
	Plattendekke(180mm)	12024 m^2	23.05 KgCO2-eq/m^2	277153.2
	Acoustic panel	3340 m^2	3.09 KgCO2-eq/m^2	10320.6
External wall	Wood siding	4589 m^2	7.81 KgCO2-eq/m^2	35840.1
	Mat-sheath	4628 m^2	1.70 KgCO2-eq/m^2	7867.6
	Timber frame	103 m^3	57.70 KgCO2-eq/m^3	5923.9
	Insulation(300mm)	42778 m^2	0.55 KgCO2-eq/m^2	23485.0
	Gypsum board	4587 m^2	1.70 KgCO2-eq/m^2	7797.9
	Window	1010 unit	83.70 KgCO2-eq/unit	84537.0
Floor	Gypsum flooring board	9297 m^2	2.87 KgCO2-eq/m^2	26682.4
	Plattendekke(240mm)	44626 m^2	23.05 KgCO2-eq/m^2	1028620.1
	Acoustic panel	9297 m^2	3.09 KgCO2-eq/m^2	28727.7
Ground floor	Gypsum flooring board	3098 m^2	2.87 KgCO2-eq/m^2	8891.3
	CLT(100mm)	310 m^3	140.00 KgCO2-eq/m^3	43365.0
	Plattendekke(200mm)	12392 m^2	23.05 KgCO2-eq/m^2	285635.6
	Insulation(100mm)	10327 m^2	0.55 KgCO2-eq/m^2	5669.3
UF foundation	Concrete(180mm)	392 m^3	197.52 KgCO2-eq/m^3	77390.3
	Steel reinforcement	22709 kg	0.33 KgCO2-eq/kg	7380.5
UF wall	Concrete(300mm)	919 m^2	74.32 KgCO2-eq/m^2	68314.9
	Concrete(180mm)	108 m^3	197.52 KgCO2-eq/m^3	21292.7
	Steel reinforcement	50645 kg	0.33 KgCO2-eq/kg	16459.8
UF_apartment_ foundation	Gypsum flooring board	999 m^2	2.87 KgCO2-eq/m^2	2867.1
	Insulation(400mm)	13320 m^2	0.55 KgCO2-eq/m^2	7312.7
	Concrete(80mm)	399 m^3	175.00 KgCO2-eq/m^3	69895.0
Balcony	Light concrete	606 tonne	132.92 KgCO2-eq/tonne	80606.3
			Total(CON)	2273365.2
			$KgCO_2$-eq/m^2.yr	2.82

Table 5-2 Quantity and emission factor of construction material (Concrete structure)

See Table 5-3 for material inventory of wood structure with and without PCM. At this stage developing research, there are yet verified carbon emission documentation for similar PCM panel. The unit carbon emission data of similar PCM panel references from Inman and Wiberg (2015, p.50) for its application at one pilot passive house building. In the boundary and context setting of this research, the embodied emission of wood structure design options result in 1.60 $KgCO_2$-eq/m^2.year without PCM panel, and 1.83 $KgCO_2$-eq/m^2.year with PCM panel.

Building component	Material	Quantity	(A1-A3) Emission factor/Function unit	Embodied GHG (GWP) emission (KgCO2-eq)
Roof	Roof membrane	3340 m^2	5.05 KgCO2-eq/m^2	16867.0
	Insulation(350mm)	38967 m^2	0.55 KgCO2-eq/m^2	21392.7
	CLT(200mm)	668 m^3	140.00 KgCO2-eq/m^3	93479.4
	PCM panel (5mm)	13941 kg	2.37 KgCO2-eq/kg	33040.2
	Acoustic panel	3339 m^2	3.09 KgCO2-eq/m^2	10317.5
External wall	Wood siding	4573 m^2	7.81 KgCO2-eq/m^2	35715.1
	Mat-sheath	4613 m^2	1.70 KgCO2-eq/m^2	7842.1
	Timber frame	100 m^3	57.70 KgCO2-eq/m^3	5770.0
	Insulation(200mm+50mm)	34723 m^2	0.55 KgCO2-eq/m^2	19063.1
	CLT(100mm)	453 m^3	140.00 KgCO2-eq/m^3	63452.2
	PCM panel (5mm)	20700 kg	2.37 KgCO2-eq/kg	49059.0
	Gypsum board	4579 m^2	1.70 KgCO2-eq/m^2	7784.3
	Window	1010 unit	83.70 KgCO2-eq/unit	84537.0
Floor	Gypsum flooring board	9297 m^2	2.87 KgCO2-eq/m^2	26682.4
	CLT(140mm)	1301 m^3	140.00 KgCO2-eq/m^3	182200.2
	Insulation(70mm)	21693 m^2	0.55 KgCO2-eq/m^2	11909.5
	PCM panel (5mm)	41823 kg	2.37 KgCO2-eq/kg	99120.5
	Acoustic panel	9297 m^2	3.09 KgCO2-eq/m^2	28727.7
	Glulam beam system	254 m^3	62.00 KgCO2-eq/m^3	15723.2
Ground floor	Gypsum flooring board	3098 m^2	2.87 KgCO2-eq/m^2	8891.3
	CLT(100mm)	310 m^3	140.00 KgCO2-eq/m^3	43365.0
	Plattendekke(200mm)	12392 m^2	23.05 KgCO2-eq/m^2	285635.6
	Insulation(100mm)	10327 m^2	0.55 KgCO2-eq/m^2	5669.3
UF foundation	Concrete(180mm)	392 m^3	197.52 KgCO2-eq/m^3	77390.3
	Steel reinforcement	22709 kg	0.33 KgCO2-eq/kg	7380.5
UF wall	Concrete(300mm)	919 m^2	74.32 KgCO2-eq/m^2	68314.9
	Concrete(180mm)	108 m^3	197.52 KgCO2-eq/m^3	21292.7
	Steel reinforcement	50645 kg	0.33 KgCO2-eq/kg	16459.8
UF_apartment _foundation	Gypsum flooring board	999 m^2	2.87 KgCO2-eq/m^2	2867.1
	Insulation(400mm)	13320 m^2	0.55 KgCO2-eq/m^2	7312.7
	Concrete(80mm)	399 m^3	175.00 KgCO2-eq/m^3	69895.0
Balcony	Timber deck	531 m^3	90.30 KgCO2-eq/m^3	47933.9
			Total (WOOD)	1293871.6
			$KgCO_2$-eq/m^2.yr	1.60
			Total (WOOD_CEI)	1475091.3
			$KgCO_2$-eq/m^2.yr	1.83

Table 5-3 Quantity and emission factor of construction material (Wood structure)

5.3 Carbon emission study

The concrete structure consumes large amount of embodied emission of all three options, especially from plattendekke. Concrete in wood structure is mainly from structure of underground foundation. When change from concrete to wood structure, total carbon emission is reduced by 43% in WOOD option, and 35% in WOOD_CEI option in the boundary and context setting of this research. Concrete-based material alone (concrete, plattendekke, balcony) results in 2.36 $kgCO_2eq/m^2$.year of embodied emission, more than the total emission amount of either WOOD or WOOD_CEI option (1.60 $kgCO_2eq/m^2$.year, 1.83 $kgCO_2eq/m^2$.year, respectively).

PCM panel contributes to 12.3% of total embodied emissions in WOOD_CEI option, increasing total emission by 14% compared to WOOD option, making it the third largest emission source after CLT. The extensive use of PCM panel on building envelope and ceiling results in relatively high embodied emission in

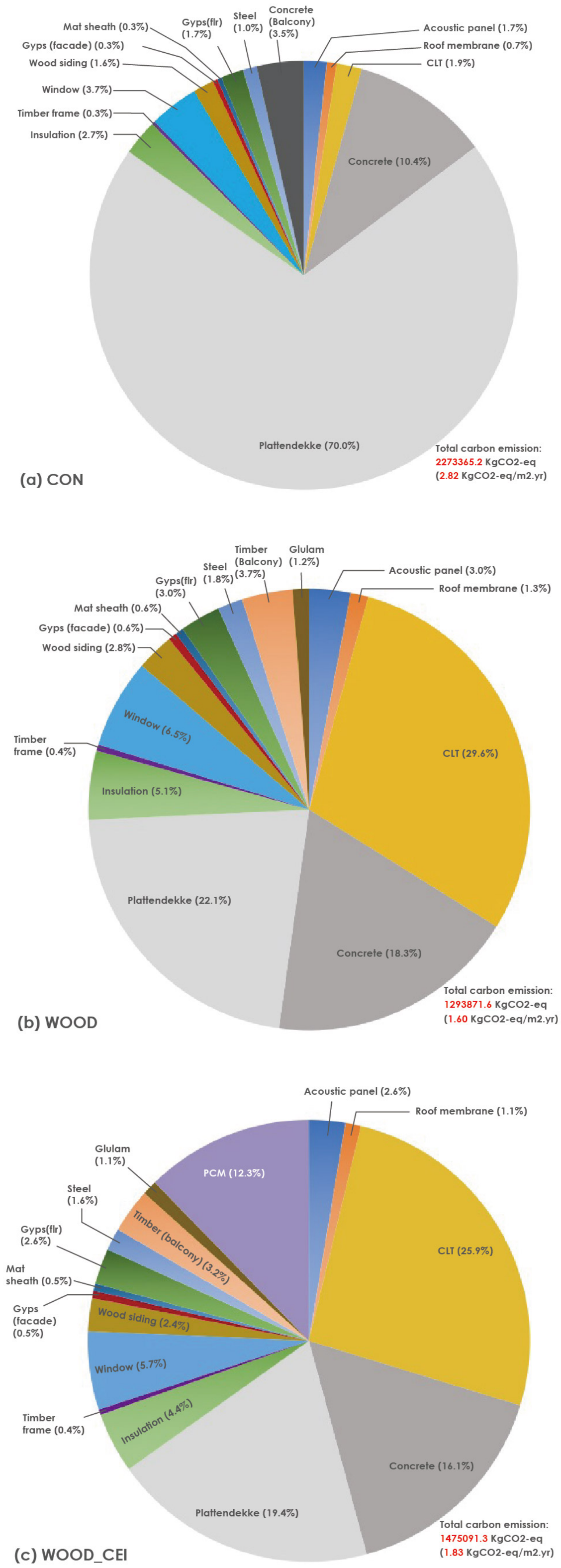


Figure 5-2 Carbon emission result by material

WOOD_CEI option. If emissions are categorized by building component, the largest reduction occurs at floor deck where plattendekke is replaced by CLT from 2F-4F. This results in an average of 70% reduction of carbon emissions. PCM panel embedded in ceilings contributes to 27% emission of floor deck and 19% on roof. WOOD_CEI facade has the biggest emissions compared to CON and WOOD options. This is because in concrete structure there's no load bearing structural on facade, while wood structure has CLT as part of the load bearing system, adding PCM panel results in the highest emission at external wall (facade). For balcony, changing from concrete to wood deck results in 40% reduction of emissions.

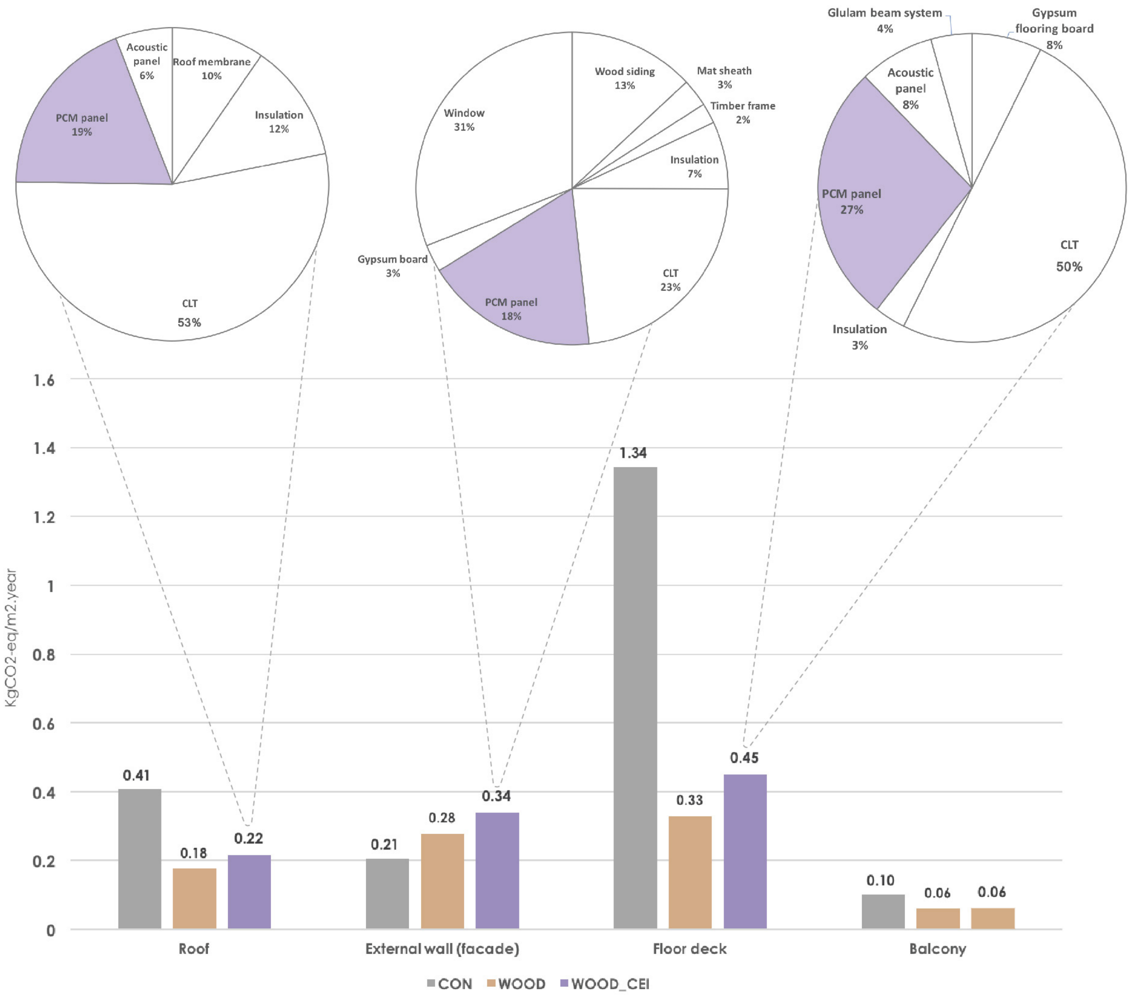


Figure 5-3 Carbon emission result by building component

5.4 Discussion

Carbon emissions study shows great amount of reduction from changing concrete to wood structure due to the low embodied emission of materials. The results are combined with heating consumption in chapter 5, see Figure 5-4. Average carbon emission factor 132 grams CO2 eq/kWh developed by Graabak and Feilberg (2011) is applied for electricity consumption in the context of Norway. Even though CON design option performs the lowest yearly heating consumption, the combined result indicates it is the option with the highest carbon emissions in total mainly due to high embodied emissions from the materials. WOOD option's heating load is 13% higher than CON design option, however the comparable low embodied emissions makes it the least carbon emissions among the three design options. The WOOD_CEI design option even though has heating demand almost as low as CON design option, the embodied emissions of PCM panels results in higher emissions than WOOD design option in total from life cycle perspective.

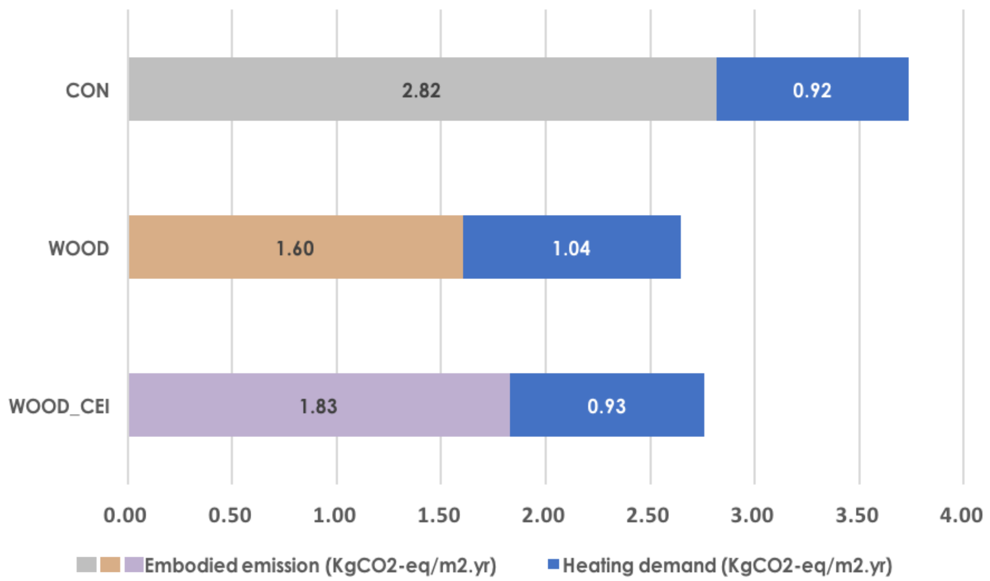


Figure 5-4 Total of embodied emission and operational energy (heating demand)

Carbon emission ratio between materials versus operation heating energy emission are approximately 6:4 for wood structure, and 7:3 for concrete structure. Proposed WOOD design option will be the recommended alternative structure option by considering total carbon emissions based on the context setting of the research. Since PCM panel as additional mass reduces operational heating load, there are also possibilities to level down WOOD_CEI option's total emissions to be on the same emission level as WOOD. One is to reduce embodied emission of PCM panel from 2.37KgCO2-eq/kg to 1.26KgCO2-eq/kg in the manufacturing process, this results in comparable total emissions with WOOD option, see Figure 5-5. In real case, if concrete structure is still finalized as design option, plattendekke is the most important key driver that will make significant impact in reducing embodied carbon emissions.

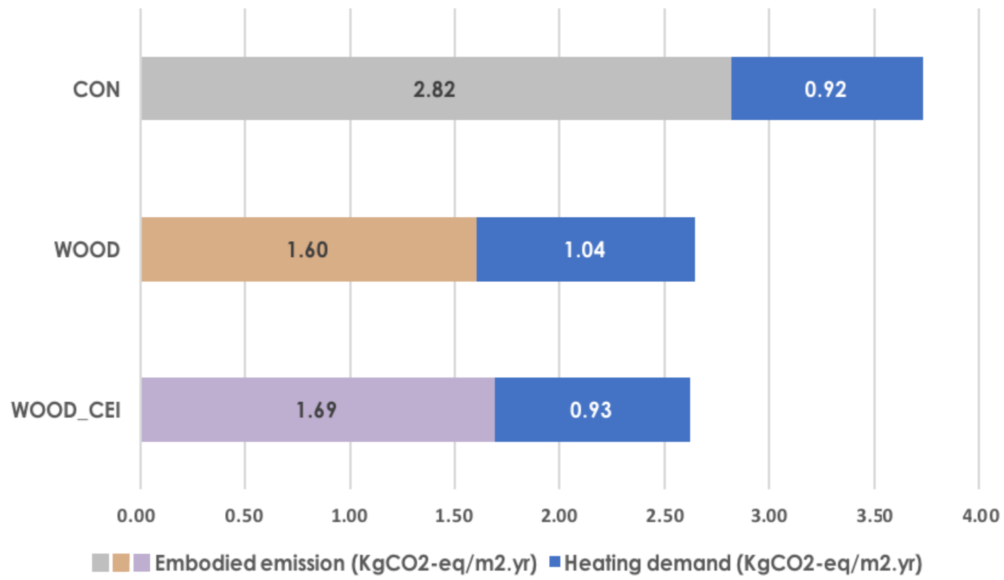


Figure 5-5 Total emission of design option with lower embodied emission PCM panel

Advanced materials such as PCM may be sensitively studied without contributing to large amount of embodied emission. Strategic solution can be looking for PCM material that works more efficiently with technical system to maximize its energy saving potential. The energy simulation sets one storey as one zone, for a building scale like OEN project, the coverage of PCM panel can be further downsized in detail zoning plan, or install at where it is exposed to greater heat source to maximize energy saving performance with the least coverage of PCM material.

6. CONCLUSION

This research converts a heavy weight structure to a light weight structure driven by lowering the environment impact, demonstrating a holistic approach of assessing total environment impact of both embodied emissions and operational heating energy consumption with the introduction of PCM-based building component as additional thermal mass.

Study finds that changing concrete structure to light weight wood structure results in 14% increase in heating load because concrete structure has higher thermal inertia that consequently leads to smaller temperature change in a diurnal cycle. It has been demonstrated that incorporating PCM panel as additional thermal mass works effectively in light weight structure during shoulder season, reducing 11% of heating demand compared to design option without PCM panel. It is observed that PCM panel integrated within ceiling assemblies performs more effective than flooring assemblies in modulating indoor temperature. Units exposed to more solar gain is considered having more potential integrating PCM panel for maintaining indoor comfort. These demonstrate the possibility of improving current static design in a passive standard building of Nordic context.

Results of environment impact study show that converting concrete structure to wood structure on envelope and floor deck in the context set up of this study reduce embodied emissions by 43%. Wood structure is although the design option with the least carbon emissions from lifecycle perspective, wood structure with PCM panel as additional thermal mass can be a relatively competitive solution if one takes into account reducing both embodied emission as well as operational energy demand as future energy price is expected to increase.

There are limitations which is not included in this research that should be aware of. This refers to the acoustic performance, fire resistance performance, maintenance of different design options which are not further elaborated but play important role in decision making process of passive house building designed in light weigh structure. Furthermore, at the time being developing this research, there aren't sufficient manufacturing information on PCM building materials, carbon emission data can be hard to source from when evaluate the actual environment impact of PCM building materials. The life cycle carbon emission amount of PCM material are required for further study on their actual benefits in the Nordic context. Extended future work of this study can be optimization of how PCM material can efficiently function with the technical system, trial of other material with different thermal property, thickness or consider different installation within multilayers taking into account the total performance with other building materials.

Current energy policy scenario sets an ambitious guideline for building industry in Norway. More building projects will endeavor themselves to the investment on nZEB project. The holistic approach driven by lowering environment impact of design choices are deemed vital in response to building market's trend in compliance with future policies and energy goals. The life cycle perspective approach conducted in this research can hopefully be a reference and encourage more participation on building up nZEB projects.

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APPENDIX A: EPD-Norge data source

Concrete structure

Building component	Material	Quantity	Unit	(A1-A3) Emission factor/Function unit		Embodied GHG emission (KgCO2-eq)	Declaration number	Note
Roof	Roof membrane	3340	m²	5.05	KgCO2-eq/m²	16867.0	NEPD-2051-921-EN	1 m² Protan EX 1,6 Roofing membrane
	Insulation(400mm)	44533	m²	0.55	KgCO2-eq/m²	24462.2	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	Plattendekke(180mm)	12024	m²	23.05	KgCO2-eq/m²	277153.2	NEPD-1340-439-NO	Slab-reinforced Plate Cover 50 mm inc. 8 kg reinforcement and 1.66 lm. lattice supports per.m²
	Acoustic panel	3340	m²	3.09	KgCO2-eq/m²	10320.6	NEPD-1258-404-EN	1 m² of installed ceiling tile (15mm)
External wall	Wood siding	4589	m²	7.81	KgCO2-eq/m²	35840.1	NEPD-1866-805-NO	1 m² varmebehandlet og brannimpregnert kledning av furu
	Mat-sheath	4628	m²	1.70	KgCO2-eq/m²	7867.6	NEPD-1263-406-EN	1 m² (9.5mm) of installed sheathing Board
	Timber frame	103	m³	57.70	KgCO2-eq/m³	5923.9	NEPD-1937-857-NO	Produksjon av 1 m³ fingerskjøtt trelast
	Insulation(300mm)	42778	m²	0.55	KgCO2-eq/m²	23485.0	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	Gypsum board	4587	m²	1.70	KgCO2-eq/m²	7797.9	NEPD-1260-406_EN	1 m² of installed standard plasterboard
	Window	1010	unit	83.70	KgCO2-eq/unit	84537.0	NEPD-385-265-NO	Produksjon av 1 vindu med målene 1,23 m x 1,48 m med 3-lags glass og uten/med aluminiumskledning
Floor	Gypsum flooring board	9297	m²	2.87	KgCO2-eq/m²	26682.4	NEPD-2139-966-EN	1 m² of installed gypsum board
	Plattendekke(240mm)	44626	m²	23.05	KgCO2-eq/m²	1028620.1	NEPD-1340-439-NO	Slab-reinforced Plate Cover 50 mm inc. 8 kg reinforcement and 1.66 lm. lattice supports per.m²
	Acoustic panel	9297	m²	3.09	KgCO2-eq/m²	28727.7	NEPD-1258-404-EN	1 m² of installed ceiling tile (15mm)
Ground floor	Gypsum flooring board	3098	m²	2.87	KgCO2-eq/m²	8891.3	NEPD-2139-966-EN	1 m² of installed gypsum board
	CLT(100mm)	310	m³	140.00	KgCO2-eq/m³	43365.0	NEPD-1269-410-EN	1 m³ of cross laminated timber of spruce
	Plattendekke(200mm)	12392	m²	23.05	KgCO2-eq/m²	285635.6	NEPD-1340-439-NO	Slab-reinforced Plate Cover 50 mm inc. 8 kg reinforcement and 1.66 lm. lattice supports per.m²
	Insulation(100mm)	10327	m²	0.55	KgCO2-eq/m²	5669.3	NEPD-2076-937-EN	1m² with a thickness of 30 mm
UF foundation	Concrete(180mm)	392	m³	197.52	KgCO2-eq/m³	77390.3	NEPD-1301-423-NO	1 m³ B30 M60 LAVKARBON A - Konsistens 180 mm.
	Steel reinforcement	22709	kg	0.33	KgCO2-eq/kg	7380.5	NEPD-347-238-EN	Per kg steel
UF wall	Concrete(300mm)	919	m²	74.32	KgCO2-eq/m²	68314.9	NEPD-1930-853-NO	1 m² Kompakt veggelement 250 MM B35 M45 Lavkarbon B
	Concrete(180mm)	108	m³	197.52	KgCO2-eq/m³	21292.7	NEPD-1301-423-NO	1 m³ B30 M60 LAVKARBON A - Konsistens 180 mm.
	Steel reinforcement	50645	kg	0.33	KgCO2-eq/kg	16459.8	NEPD-347-238-EN	Per kg steel
UF_apartment_ foundation	Gypsum flooring board	999	m²	2.87	KgCO2-eq/m²	2867.1	NEPD-2139-966-EN	1 m² of installed gypsum board
	Insulation(400mm)	13320	m²	0.55	KgCO2-eq/m²	7312.7	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	Concrete(80mm)	399	m³	175.00	KgCO2-eq/m³	69895.0	NEPD-1717-700-NO	1 m³ concrete
Balcony	Light concrete	606	tonne	132.92	KgCO2-eq/tonne	80606.3	NEPD-1876-808-NO	1 tonne Balkong lavkarbon
					Total	2273365.2		

Wood structure

Building component	Material	Quantity	Unit	(A1-A3) Emission factor/Function unit		Embodied GHG emission (KgCO2-eq)	Declaration number	Note
Roof	Roof membrane	3340	m²	5.05	KgCO2-eq/m²	16867.0	NEPD-2051-921-EN	1 m² Protan EX 1,6 Roofing membrane
	Insulation(350mm)	38967	m²	0.55	KgCO2-eq/m²	21392.7	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	CLT(200mm)	668	m³	140.00	KgCO2-eq/m³	93479.4	NEPD-1269-410-EN	Manufacturing of 1 m³ of cross laminated timber of spruce
	PCM panel (5mm)	13941	kg	2.37	KgCO2-eq/kg	33040.2	Livinglab emission data	per kg
	Acoustic panel	3339	m²	3.09	KgCO2-eq/m²	10317.5	NEPD-1258-404-EN	Declare unit:1 m² of installed ceiling tile (15mm)
External wall	Wood siding	4573	m²	7.81	KgCO2-eq/m²	35715.1	NEPD-1866-805-NO	1 m² varmebehandlet og brannimpregnert kledning av furu til utvendig bruk, fra vugge-til-grav med en referanselevetid på 60 år.
	Mat-sheath	4613	m²	1.70	KgCO2-eq/m²	7842.1	NEPD-1263-406-EN	1 m² (9.5mm) of installed Gyproc Bris™ – Sheathing Board, with a reference service life of 60 years
	Timber frame	100	m³	57.70	KgCO2-eq/m³	5770.0	NEPD-1937-857-NO	Produksjon av 1 m³ fingerskjøtt trelast av gran, transportert,installert og avfallsbehandlet ved endt levetid.
	Insulation(200mm+50mm)	34723	m²	0.55	KgCO2-eq/m²	19063.1	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	CLT(100mm)	453	m³	140.00	KgCO2-eq/m³	63452.2	NEPD-1269-410-EN	Manufacturing of 1 m³ of cross laminated timber of spruce
	PCM panel (5mm)	20700	kg	2.37	KgCO2-eq/kg	49059.0	Livinglab emission data	per kg
	Gypsum board	4579	m²	1.70	KgCO2-eq/m²	7784.3	NEPD-1260-406_EN	1 m² of installed Gyproc® Normal – 12.5mm StandardPlasterboard, with a reference service life of 60 years
	Window	1010	unit	83.70	KgCO2-eq/unit	84537.0	NEPD-385-265-NO	Produksjon av 1 vindu med målene 1,23 m x 1,48 m med 3-lags glass og uten/med aluminiumskledning
Floor	Gypsum flooring board	9297	m²	2.87	KgCO2-eq/m²	26682.4	NEPD-2139-966-EN	1 m² of installed gypsum board
	CLT(140mm)	1301	m³	140.00	KgCO2-eq/m³	182200.2	NEPD-1269-410-EN	Manufacturing of 1 m³ of cross laminated timber of spruce
	Insulation(70mm)	21693	m²	0.55	KgCO2-eq/m²	11909.5	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	PCM panel (5mm)	41823	kg	2.37	KgCO2-eq/kg	99120.5	Livinglab emission data	per kg
	Acoustic panel	9297	m²	3.09	KgCO2-eq/m²	28727.7	NEPD-1258-404-EN	Declare unit:1 m² of installed ceiling tile (15mm)
	Glulam beam system	254	m³	62.00	KgCO2-eq/m³	15723.2	NEPD-456-318_EN	1 m³ glulam
Ground floor	Gypsum flooring board	3098	m²	2.87	KgCO2-eq/m²	8891.3	NEPD-2139-966-EN	1 m² of installed gypsum board
	CLT(100mm)	310	m³	140.00	KgCO2-eq/m³	43365.0	NEPD-1269-410-EN	Manufacturing of 1 m³ of cross laminated timber of spruce
	Plattendekke(200mm)	12392	m²	23.05	KgCO2-eq/m²	285635.6	NEPD-1340-439-NO	Slab-reinforced Plate Cover 50 mm inc. 8 kg reinforcement and 1.66 lm. lattice supports per.m²
	Insulation(100mm)	10327	m²	0.55	KgCO2-eq/m²	5669.3	NEPD-2076-937-EN	1m² with a thickness of 30 mm
UF foundation	Concrete(180mm)	392	m³	197.52	KgCO2-eq/m³	77390.3	NEPD-1301-423-NO	1 m³ B30 M60 LAVKARBON A - Konsistens 180 mm.
	Steel reinforcement	22709	kg	0.33	KgCO2-eq/kg	7380.5	NEPD-347-238-EN	Per kg steel
UF wall	Concrete(300mm)	919	m²	74.32	KgCO2-eq/m²	68314.9	NEPD-1930-853-NO	1 m² Kompakt veggelement 250 MM B35 M45 Lavkarbon B
	Concrete(180mm)	108	m³	197.52	KgCO2-eq/m³	21292.7	NEPD-1301-423-NO	1 m³ B30 M60 LAVKARBON A - Konsistens 180 mm.
	Steel reinforcement	50645	kg	0.33	KgCO2-eq/kg	16459.8	NEPD-347-238-EN	Per kg steel
UF_apartment _foundation	Gypsum flooring board	999	m²	2.87	KgCO2-eq/m²	2867.1	NEPD-2139-966-EN	1 m² of installed gypsum board
	Insulation(400mm)	13320	m²	0.55	KgCO2-eq/m²	7312.7	NEPD-2076-937-EN	1m² with a thickness of 30 mm
	Concrete(80mm)	399	m³	175.00	KgCO2-eq/m³	69895.0	NEPD-1717-700-NO	1 m³ concrete
Balcony	Timber deck	531	m³	90.30	KgCO2-eq/m³	47933.9	NEPD-2042-902-NO	1 m³ Krysslimt tre
				Total (WOOD)		1293871.6		
				Total (WOOD_CEI)		1475091.3		

Master's thesis

Trondheim, 2020

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