FLOATING DISTRICT ENERGY PLANNING

Exploring the Impact of Urban Form on Heating and Cooling Energy Demand in a Floating District Using Parametric Modelling

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MSc. Thesis, August 2024
Amsterdam

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COLOPHON

August, 19th 2024

MSc. Metropolitan Analysis, Design & Engineering

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Abstract

The municipality of Amsterdam is exploring the feasibility of a large-scale floating district (FD) designed to be self-sufficient in its energy needs. Creating this new floating urban form presents an opportunity to integrate the complex interactions between energy planning and urban design during the early stages of the FD project. This research aims to contribute to the feasibility exploration of the FD project by examining how urban form and energy planning interact at the urban block scale, focusing specifically on the impact of horizontal and vertical density on the surface water thermal energy system (SWTE).

To achieve this, the study integrates findings from co-creation sessions, desk research, and expert feedback to develop a parametric model using Rhinoceros 3D CAD software with Grasshopper and Ladybug plugins. The model, validated against benchmark values, evaluates six urban form scenarios with varying horizontal and vertical densities. The impact of these urban form parameters on the energy system is assessed, focusing on the simulation of demand reduction, reuse potential and solar production potential.

The results indicate that variations in horizontal density do not affect operational thermal energy demand or reuse potential, despite changes in solar potential on building facades. In contrast, vertical density variations impact the system, with high-rise scenarios (three floors) achieving the optimum regarding KPIs. Model simplifications, such as assuming constant building heights and excluding direct building adjacency, limit representativity. The research also highlights a lack of urban form metrics applicable to new large-scale designs and floating urban forms.

This study highlights the complex interactions between urban form and energy systems, emphasising the need to expand current model functionality. The theoretical framework, workflow, and model developed here provide a foundation for future research to enhance model accuracy and applicability to urban floating development. Conducted as part of a six-month internship at the Amsterdam Municipality Ingenieursbureau in collaboration with the AMS Institute, these findings support decision-making on energy planning and district design, contributing to sustainable urban development and the acceleration of the energy transition.

Keywords: *Energy Planning; Parametric Modelling; Renewable Energy Sources (RES); Urban Form*

Acknowledgements

I want to thank all the people involved in supporting this thesis project. First, I would like to thank my academic supervisors. My first supervisor, Méava Dang, supported this learning process with constructive guidance and positivity, helping me adopt new knowledge and skills in energy planning and parametric modelling. My second supervisor, Fransje Hooimeijer, provided critical feedback and shed light on the topic from her field and open perspective. Both supervisors helped me explore this topic and method with enthusiasm and trust, which I value greatly.

I would also like to thank my municipal supervisor, Mimi Eelman, for including me in the floating district project and providing me with the opportunity to freely explore this new domain of energy planning and floating innovation. Furthermore, many thanks to the CWA team at the Ingenieursbureau for their enthusiasm and encouragement throughout the process, particularly Steven Roerink and Lotte Bruinsel, for taking the time to help me improve my understanding of energy system theory and practice. Finally, I would like to thank everyone who contributed to the research process through their input, feedback, and encouragement: Kyra Koning, the Floating District project team, all co-creation participants, the experts interviewed, the Amsterdam Smart City organisation, and last, all people close to me.

Contents

List of Abbreviations

BAR	Building Area Ratio
BENG	Nearly Energy Neutral Building
CAD	Computer-Aided Design
COP	Coefficient Of Performance
EPW	EnergyPlus Weather (file format)
FD project	Floating District project
FSI	Floor Space Index
GJ	Gigajoules
GSI	Ground Space Index
HVAC	Heating, Ventilation, and Air Conditioning
HP	Heat Pump
KPI	Key Performance Indicator
kWh	Kilowatt-hours
LCZ	Local Climate Zones
LT	Low Temperature
m^2	Square Metres
MWh/m^2	Megawatt Hour per Square Metre
OSR	Open Space Ratio
PV	Photovoltaic
RES	Renewable Energy System
R	Cell Size
R-value	Thermal Heat Resistance
SWTE	Surface Water Thermal Energy

SUI	Smart Urban Isle
TEA	Thermal Energy from Wastewater
TED	Thermal Energy from Drinking Water
TEO	Thermal Energy From Surface Water
TES	Thermal Energy Storage
TKK	Total Chain Cost
U-value	Heat Transfer Rate
WWR	Window-to-Wall Ratio
3D	Three-dimensional

1. Introduction

1.1. Background

The ongoing housing crisis in Amsterdam has raised a growing need for urban expansion, which is challenged by water increasingly pressuring the city's delta environment (Dignum, 2022; Gemeente Amsterdam, 2023; Smits, 2022). The future livability of the Amsterdam Delta region is stressed by the impacts of climate change, being exposed to heavier rainfall, drought, heat, and sea level rise (KNMI, 2023). To turn vulnerability into strength, the municipality of Amsterdam wishes to rethink the role of water in urban planning and establish future resilient housing, aiming to "build on water where possible" (Gemeente Amsterdam, 2023-a, p.53). Through research- and pilot projects the municipality wishes to explore the opportunities of living on the water. One such project is the Floating District (FD) project, exploring the potential realisation of a self-sufficient floating district on Amsterdam waters, with the preliminary target location being the IJmeer waterbody.

The FD project has two main objectives. The first is to develop a mixed-use district that is scalable up to 1.500 floating units, including affordable housing and utilities. The second is for the FD project to be self-sufficient, at least in its energy needs to align with the Paris Agreement goal of carbon neutrality by 2050 (Chantzis et al., 2023; Gemeente Amsterdam, 2020, p.4; Reimann et al., 2023). Therefore, the FD should rely on Renewable Energy Sources (RES). To achieve self-sufficiency, a local balance must be created where the RES supply consistently matches the demand. Only then, a large-scale FD be realised that functions independently from the mainland energy system (Groppi et al., 2021; Jansen, Mohammadi & Bokel, 2021; Pombo et al., 2023).

The energy system is interrelated with the urban form, which affects energy system aspects like RES applications and building energy efficiency. Therefore, the potential to create a scalable and self-sufficient FD depends on its urban design (Wu & Liu, 2023). Since the FD project is in its early-stage design phase, it provides an opportunity to integrate the relationship between the urban form and the energy system into the design process. Therefore, this research will use parametric modelling to conduct an early-stage design exploration of how urban form at the block scale could impact energy planning. This model could assess the effect of urban form on the energy system's potential to reduce operational heating and cooling demand, reuse waste heat, and produce RES locally.

1.2. Problem Statement

Although self-sufficient floating houseboats and arks exist in Amsterdam, knowledge about their large-scale implementation is lacking (Reimann et al., 2023). Research on self-sufficient and scalable energy planning for island-like contexts is limited, with existing studies mainly focusing on retrofitting and optimisation of the existing systems rather than exploring new energy systems (Jansen, Mohammadi & Bokel, 2021; Mimica & Krajačić, 2021). While most research explores the relationship between energy systems and morphology design at the building scale, research on the interconnectedness between urban form, building energy consumption, and renewable energy application at the block scale is lacking (Wu & Liu, 2023). This emphasises the need for design-based research on the energy planning of new large-scale floating development, specifically focusing on how urban form design at the block scale impacts energy planning.

1.3. Research Aim & Research Questions

This research will explore the impact of urban form parameters, specifically horizontal and vertical density, on the thermal energy system of the FD project through parametric modelling. Therefore, the main research question reads:

> ***How do block-scale urban form parameters, specifically horizontal and vertical density, impact the operational thermal energy demand, reuse and production potential of the Floating District (FD) project?***

To answer this research question, four sub-research questions are formulated. These questions comprise the successive phases of the research process and are described below. The objectives of each research phase are specified in their corresponding chapter.

> The first selection phase answers the sub-research question: *What energy system and urban form parameters are relevant when assessing the early-stage floating district energy planning and design?*
>
> The second analysis phase answers the sub-research question: *How do the selected energy system and urban form parameters influence the design and energy planning of the FD?"*
>
> The third modelling phase answers the sub-research question: *How can a parametric energy model be created to assess the impact of different urban form scenarios on the FD energy system?*
>
> The final assessment phase answers the sub-research question: *What model scenarios minimise the trade-offs between urban form and the energy system according to the KPIs?*

1.4. Research Scope

This research focuses on floating districts, defined as a distinctive type of neighbourhood consisting of scalable structures, designed to float on bodies of water and sustain themselves in their energy needs. This study explicitly explores possible early-stage urban design scenarios of floating urban form at the block scale and its impact on the energy planning of a floating district. Therefore, the research does not consider the implementation of these scenarios. This limits the scope of this research to explore the technical potential of energy planning for FD design. This follows the IF Technology (2016) definition of potential energy supply, explaining the concept contains several layers as illustrated in Figure 1 below. First, the basis is the widest scope of **technical potential**, which is then corrected by financial feasibility in the layer of the **economic potential**, followed by the last correction due to social factors included in the **societal potential**, e.g. political or ecological limitations. The latter two scopes are crucial when assessing the implementation of the FD project but are excluded in this early-stage explorative design research.

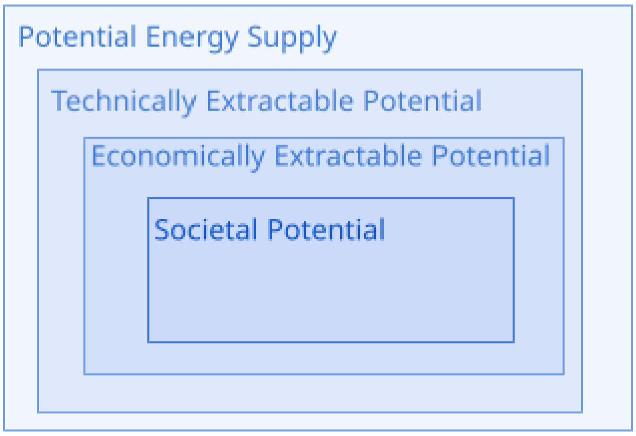


Figure 1: Definitions of Potential, adjusted from IF Technology et al. (2016, p.25)

1.5. Relevance

Scientific Relevance

Research that operationalises energy planning for islands and island-like contexts already exists (Groppi et al., 2021; Pombo et al., 2023). The same applies to parametric modelling methods, which are already widely implemented in energy planning research (Dang, van den Dobbelsteen and Voskuilen, 2024; De Sousa Freitas et al., 2020; Shen, 2018). However, both types of research primarily focus on retrofitting existing energy concepts. This research adds to existing knowledge of energy planning in interaction with floating district early-stage design. This research method can be applied to similar early-stage design studies, specifically for floating developments. Finally, the knowledge gained on the FD project can contribute to accelerating the energy transition as argued by literature outlining that island or island-like case studies are proven to have a catalytic role in energy innovation (Groppi et al., 2021; Jansen, Mohammadi, and Bokel, 2021; Pombo et al., 2023).

Societal Relevance

The results of this study provide insights into the impact of urban form at the block scale on the thermal energy system of the FD. These insights into the scalability of self-sufficient floating urban forms can support future decision-making in the FD and other floating innovation projects. Additionally, these insights establish a foundation to assess further the technical, economic, and societal potential of FD project energy planning. Consequently, this research forms a starting point for exploring how living on water could contribute to the energy transition, urban adaptation to climate change, and urban expansion. In a broader context, by understanding the dynamics of energy planning and urban form in floating districts, this study contributes to the global goal of sustainable urban development (The Global Goals, n.d.).

Practical Relevance

This research is an MSc Thesis project that is conducted in the capacity of a six-month internship at the Ingenieursbureau of Amsterdam Municipality, in collaboration with the Advanced Metropolitan Solutions (AMS) Institute. In addition to supporting the municipal FD project feasibility exploration, this study further contributes to two research programs. First, it explores the possible energy planning, hence the feasibility of the FD project, coordinated by Joke Dufourmont. Second, it contributes to the AMS Institute's High-hanging Fruit research program, coordinated by Maéva Dang.

2. Methodology

This methodology chapter provides the reading guide and the general workflow adopted in this research.

2.1. Reading Guide

This research uses an integrated approach of methods to answer the four sub-research questions that comprise the phases of this research; selection; analysis, modelling, and assessment. A general overview of the phases is provided in this methodology chapter. The specific methods used per research phase are discussed in more detail in the corresponding chapters of each phase. Even though the research phases are explained in the approximate chronological order of completion, it is an iterative process, meaning the steps within the processes can occur in parallel or (partly) overlap. The four phases are briefly described:

Phase 1 - Selection

This phase defines the focus of the research by selecting its key parameters. Through co-creation, a thermal energy system for the FD project is selected, along with the urban form parameters, which are the variable parameters to be assessed for their impact on this energy system.

Phase 2 - Analysis

This phase analyses the FD project context, the selected thermal energy system, and the selected urban form parameters. Through desk research, this phase results in a literature study of these main FD project features. Additionally, Key Performance Indicators (KPIs) are defined, by which the modelling results are assessed in the final phase.

Phase 3 - Modelling

This phase describes the steps taken to create the parametric energy model to assess the impact of the selected urban form parameters on the energy system’s reduction, reuse and production potential. In brief, a baseline model is created encompassing the block-scale morphology and energy system logic of the FD project. To explore the isolated effect of the selected variable urban form parameters, all other energy systems and urban form-related parameters are considered fixed. These are defined based on relevant references. The performance of this baseline model is validated, by recalibrating it until acceptable deviance of less than 10% from relevant benchmark values is achieved. Then, certain model parameters are adjusted to the FD project-specific characteristics, after which the final model is completed.

Phase 4 - Assessment

This final phase assesses the results of the model scenarios by evaluating which scenario minimises trade-offs between the urban form and the energy system according to the KPIs defined in the analysis phase.

2.2. General Workflow Diagram

Figure 2 on the next page visualises the generic workflow of this research. The phasing is based on similar parametric modelling approaches for energy retrofitting by Dang, Cunin and van den Dobbelsteen (2023) as well as Dang, van den Dobbelsteen and Voskuilen (2024). Rather than retrofitting the energy concepts of existing buildings, the method of this research concerns parametric energy modelling for a newly created block scale morphology. This approach aligns with research that proposes a framework for achieving locally balanced RES-based systems at the neighbourhood scale, as well as studies emphasising the importance of assessing the impact of urban form at the block scale on energy systems (Jansen, Mohammadi & Bokel, 2021; Wu & Liu, 2023). The workflow diagram is developed throughout this research according to findings and insights gained during its application to the FD project context.

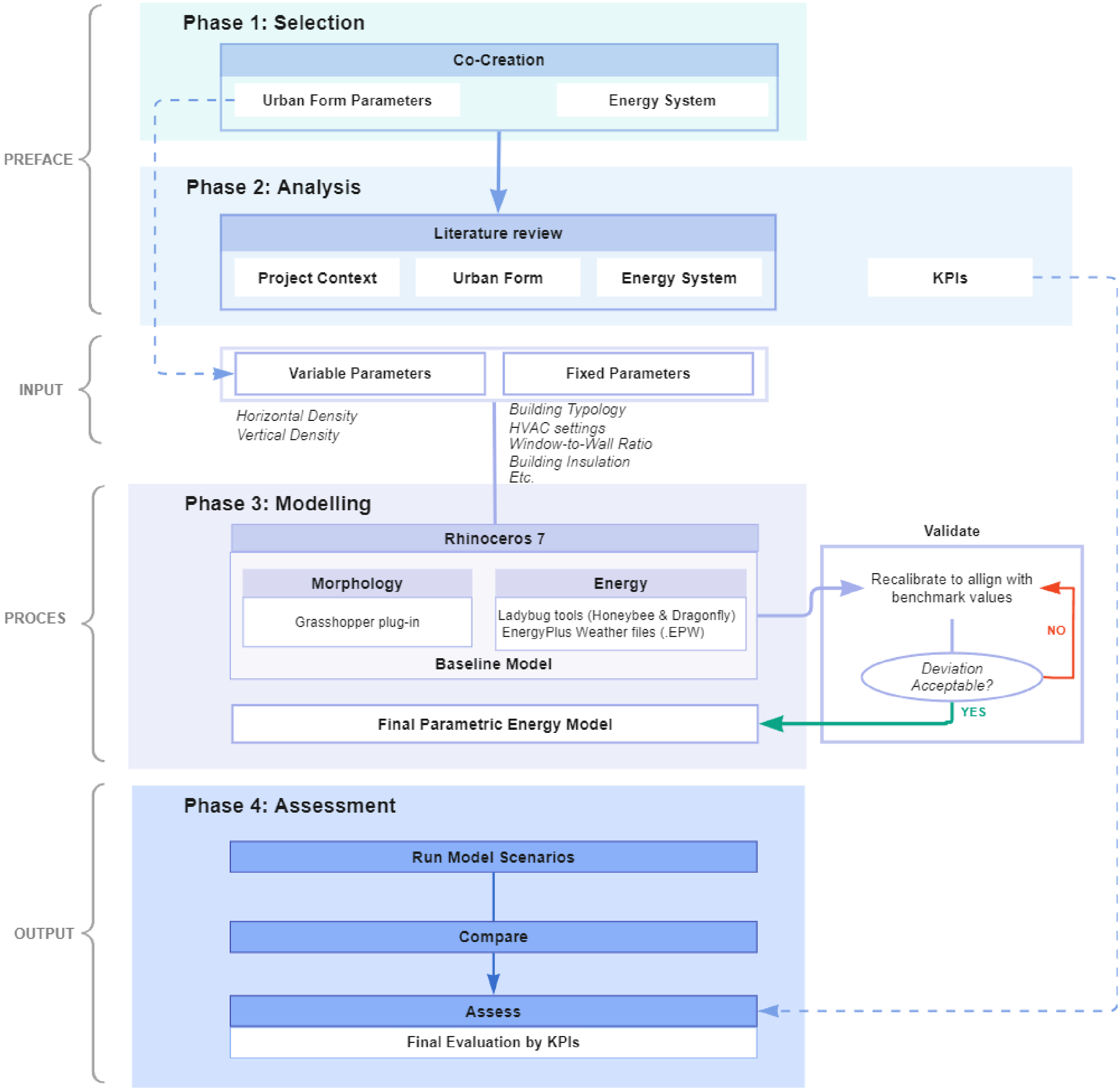


Figure 2: General workflow diagram describing the phasing of the research

3. Phase 1 - Selection

This selection phase aims to set the research focus by identifying which parameters are relevant in assessing early-stage floating district energy planning and urban form design. The objectives of this phase are:

Objective 1.1. Co-create to identify the possible energy system(s) and urban form parameter(s) relevant for assessment in this research
Objective 1.2. Select the energy system to be focused on in this research
Objective 1.3. Select the variable urban form parameter(s) to be assessed in this research

3.1. Method

As this research is an early-stage design exploration, the urban form and energy system parameters are undefined. Co-creation sessions are held to determine which energy system and urban form parameters to assess in this research. The urban form parameters are regarded as the variable parameters of this research, and their impact on the energy system is assessed. This selection is conducted in two co-creation sessions. The interactive co-creation approach facilitates the integration of these diverse expert and non-expert perspectives in energy planning and urban form design of the FD project. A detailed overview of the specific co-creation methods and documented results can be found in Appendix A (co-creation 1) and Appendix B (co-creation 2). Possible limitations of this co-creation method can be found in the Limitations (Chapter 7.4.).

The first co-creation session is held with experts in energy planning, urban design, and floating construction. Participants contributed their expertise to identify the key assumptions and variables relating to energy planning for floating district design. First, participants are split into two groups that co-create the design of a complete energy system for the FD. The designs must ensure the minimum FD requirement for a self-sufficient system that can function year-round. Furthermore, the designs need to account for a certain degree of systemic flexibility: either self-sufficient and fixed in location to allow for using Thermal Energy Storage (TES), or fully flexible and movable, but without using TES.

It is chosen to focus on the design of a complete energy system, rather than already narrowing down the focus to the thermal energy aspect of it. This holistic approach encourages experts to consider the dynamics between the different energy system components and their interactions when designing for optimal reliability. The resulting energy systems are then pitched, after which experts explore possible trade-offs between energy planning and urban form parameters. Based on this discussion, participants summarise the urban form parameters they consider relevant to assess for their impact on the chosen energy system. This first co-creation results in a comprehensive energy system design and identifies which urban form parameters could be relevant to research.

The second co-creation has a broader participant profile with the aim of reflecting on the possible trade-offs between energy planning and urban form as identified by the experts in co-creation 1. Participants discuss these topics in groups and share their reflections in a presentation and discussion. This co-creation primarily serves a reflective purpose, aiming to assess the extent to which the findings of co-creation 1 are validated or challenged from the diverse perspectives of non-experts.

3.2. Results

3.2.1. Co-creation 1

The first co-creation sessions helped define the main assumptions regarding the focus of this study. First, experts designed a comprehensive energy system that met the minimum requirement of ensuring self-sufficiency by creating local balance. Furthermore, experts chose to design an energy system that would allow the FD to flexibly move around. According to the experts, the main challenge regarding a self-sufficient scalable energy system for the FD will likely relate to its electricity demand. In terms of thermal energy, experts expect the demand to be met relatively easily with a heating and cooling system that relies entirely on aquathermia. This closed Surface Water Thermal Energy (SWTE) system, known as the TEO system in Dutch, extracts energy from surface water year-round. Since it does not require a TES system, it allows the FD to move freely, fully utilising its floating nature.

Secondly, the participants identified urban form parameters that possibly impact the operational thermal energy demand. Three parameters are most frequently mentioned: the number of building floors (at most 3 floors), function placement, and building spacing. The impact of these urban form parameters on the selected energy system is regarded by the experts as potentially interesting to assess.

3.3.2. Co-creation 2

In the second co-creation, non-expert participants reflected on the urban form parameters and trade-offs identified in the first co-creation. This reflection focused on four themes: density, flexibility, function placement, and the number of floors. The main findings of this co-creation showed that participants valued conventional urban characteristics such as compactness, multiple-story buildings, and centralised functions. They associated these characteristics with positive socio-economic effects, including social cohesion, facilitation of material waste stream reuse, centralised infrastructure, and diversity. This co-creation provided a societal, non-expert perspective on how the urban form parameters and dilemmas regarding the energy system are perceived.

3.3.3. Selection

More detailed documentation of the co-creation approach and results can be found in Appendix A (co-creation 1) and Appendix B (co-creation 2). However, the main results of the co-creation indicate that a closed SWTE system without TES is suitable for creating a self-sufficient and scalable FD that could be flexibly movable. Additionally, three urban form parameters are of interest to assess for their impact on this SWTE system: the number of building floors, building spacing, and function placement. This study focuses on the two parameters directly related to spatial density: the number of building floors and building spacing. These parameters are further defined as vertical and horizontal density in this research, following the definition by Chen et al. (2020). Both these urban form parameters and the selected energy system will be further analysed in the following chapter.

4. Phase 2 - Analysis

This phase conducts desk research to analyse the selected urban form parameters and energy system. The objectives of this phase are:

Objective 2.1. Analyse the project context through current practice theory, focusing on the relationship between urban form and energy planning-specific to the FD context.
Objective 2.2. Analyse the selected thermal energy system, its supply potential, and its systemic feasibility
Objective 2.3. Analyse the selected urban form parameters
Objective 2.4. Determine the Key Performance Indicators (KPIs)

4.1. Method

In the analysis, desk research is conducted, resulting in a literature review. The literature review comprises three parts, discussing the project context, the selected energy system, and the selected urban form parameters. Subsequently, the interrelation between the key concepts derived from this literature review is summarised in the theoretical framework. Finally, the KPIs are determined.

Data from this desk research is primarily retrieved through academic databases (e.g., Google Scholar) and other knowledge platforms (e.g., openresearch.amsterdam, CBS, STOWA, and Waternet Innovation). By snowballing, references from initial articles are used to find other relevant sources. Furthermore, conversations are held with experts from CE Delft, Royal HaskoningDHV, Waternet, and the Municipality of Amsterdam. These conversations helped enhance the understanding of the literature findings and the experts referred to other relevant references.

4.2. Literature Review

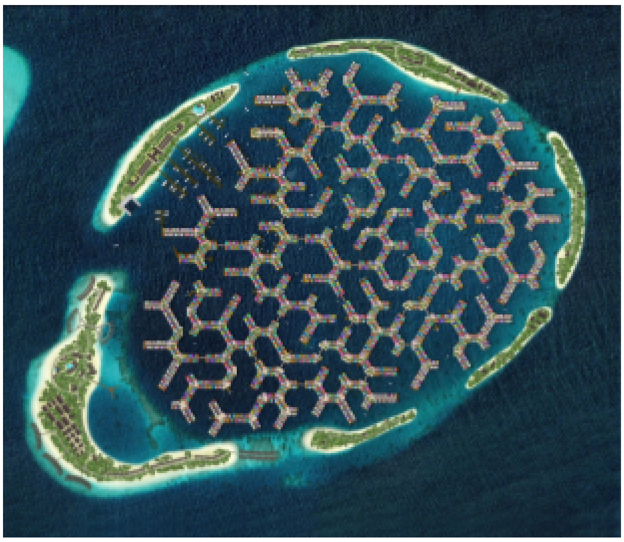
4.2.1. Project context

This section examines the project context through existing practices and theories relating to the FD project. Furthermore, the interaction between urban form and energy planning is analysed, specifically the floating context.

Current Practice of Floating Innovation

Various sustainable floating construction practices exist worldwide. Figures 3, 4, and 5 below outline three examples of newly developed projects of sustainable floating construction and their key features. As floating construction varies significantly in aspects such as scale, design, and level of systemic independence, this limits the extent to which these examples are directly scalable to other contexts. Nonetheless, lessons can be learned from these examples like the Maldives Floating City, which is closely aligned with the FD project in scale. The FD project could benefit from lessons learned from this large-scale implementation of a floating district, particularly regarding the interaction between mixed-use urban forms and energy systems.

As Reinmann et al. (2023) indicate, large-scale implementation of new sustainable floating units lacks in the Dutch context. Therefore, the other two examples focus on single residential and non-residential units. While these single units do not represent the interaction between urban form and energy systems at the relevant scale, they could provide valuable insights into the characteristics of newly built floating designs. This is particularly important as they are located in the Netherlands, meaning their energy systems account for the Dutch context, unlike the larger-scale Maldives example.



Maldives Floating City
Large scale, new-built project on sea.

Year	In process (expected completion 2027)
Location	Indian Ocean (southwest of Sri Lanka)
Scale	5.000 mixed-use buildings
Area	200 ha
Dependency	Self-sufficient
Electricity	Photovoltaic (PV)
Thermal	Deep sea water (cooling)
Ventilation	Sea breeze
Construction	Concrete and polystyrene
Design	WaterstudioNL

Figure 3: Maldives Floating City (n.d.)

The Float

Single family home, new-built project on a historic canal

Year	2021 (finished)
Location	Leiden, NL
Scale	1 building
Area	80 m^2
Dependency	Self-sufficient (all-electric)
Construction	Wood and cork
Design	Studio RAP

Figure 4: Studio RAP (n.d.)

Floating Office Rotterdam (FOR)

Office of the Global Centre on Adaptation, a new-built project on river Meuse.

Year	2020
Location	Rotterdam, NL
Scale	5.000 mixed-use buildings
Area	5.880 m^2
Dependency	Self-sufficient, but connected to grid
Electricity	Photovoltaic (PV)
Thermal	Surface Water Thermal Energy (SWTE)
Ventilation	Outside air + heat recovery
Construction	Wood
Design	Powerhouse Company

Figure 5: Powerhouse Company (n.d.)

Energy Planning for Floating Design

In the existing literature, attention has been dedicated to exploring the current decarbonisation process and the transition to the use of RES. Specifically related to the FD project context, research acknowledges the unique role of islands in accelerating the energy transition. These 'Energy Islands' make great case studies for the feasibility of a complete transition towards RES (Groppi et al., 2021; Pombo et al., 2023). Pombo et al. (2023) outline this is due to the need for independence and self-sufficiency caused by an Island's isolated location, and the high availability of RES, e.g. wind, water and solar energy. Although the concept of floating districts is not a conventional island, it shares the outlined characteristics, making Energy Island literature applicable to the island-like context of this project.

The main challenge of self-sufficient Energy Island is releasing a flexible system that can match energy demand and supply at all times, overcoming the unpredictability of the locally available RES (Groppi et al., 2021; Pombo et al., 2023). A method aiming to operationalise the planning of a flexible self-sufficient energy system at the neighbourhood scale is the Smart Urban Isle (SUI) approach (Jansen, Mohammadi & Bokel, 2021). In SUI theory, an 'isle' is less literal, but rather considered to be an urban area with a smart locally balanced energy system that minimises the need for importing external energy. Flexibility can, according to the SUI approach, be achieved by realising a local balance between demand and supply, e.g. through storage. Only then, the energy system can become scalable to the neighbourhood level. Thus, the flexibility that Energy Islands, like the FD, require to function independently from the mainland can be achieved by creating a so-called locally balanced energy system, as is proposed in the SUI approach. Only then, a project can become scalable.

Energy System and Urban Form

When implementing RES-based systems, it is essential to not only assess the supply stressed by SUI and Energy Island literature but also to consider how to reduce demand and reuse waste-stream energy (Dang, van den Dobbelsteen & Voskuilen, 2024; Jansen, Mohammadi & Bokel, 2021). Urban form impacts these components of the energy system by influencing the potential to reduce demand and reuse waste-stream energy, ultimately affecting the required energy production capacity.

As the RES production potential is addressed in Chapter 4.2.3, this section will elaborate on the reduction and reuse potential. Given that the FD project concerns new design, these effects can be accounted for. Most studies assessing this relationship focus on isolated buildings; however, as Wu and Liu (2023) emphasise in their block scale modelling research, this approach overlooks the surrounding microclimate changes and the influence of adjacent buildings on factors like daylighting, which can significantly alter building energy simulations.

Reduce-potential

Reducing energy demand through the urban form can be achieved by bioclimatic improvements, meaning reducing energy demand through architectural design measures (Jansen, Mohammadi & Bokel, 2021). This can be achieved at the building and the urban block scale (Wu & Liu, 2023). On the building scale, significant improvements in insulation can lead to reduced space heating demands. However, as outside temperatures are projected to increase, cooling demands are expected to rise, emphasising the need for bioclimatic improvements to mitigate the increased cooling demand (CE Delft, 2023).

It is important to analyse how these trends affect floating construction, as building insulation values can differ from those of conventional buildings. The Dutch energy norm NTA 8800 (2024) provides guidelines and calculation methods to assess building energy performance and ensure it aligns with the BENG requirements for newly built construction. Two key metrics from NTA 8800 are important for assessing building insulation:

- R-value: This measures thermal resistance (m²·K/W), where higher values indicate better insulation. It is typically used for facades, floors, and roofs. For roofs, factors like the slope or material properties impact thermal gains and losses. For facades and floors, e.g. the adjacent environment or materials properties impact thermal gains and losses (NTA 8800, 2024).

- U-value: This measures heat transfer rate (W/m²·K), where lower values indicate better insulation. U-values are especially relevant for windows and depend on many factors like glazing type (e.g., single glazing, double glazing, triple glazing), solar heat gain coefficient (SHGC), window frame materials, Window to Wall Ratio (WWR), window orientation and window shading (NTA 8800, 2024; Raji, Tenpierik, & Van Den Dobbelsteen, 2016).

As the FD will be newly built, it has to meet the same standards as conventional buildings, including circularity and insulation norms. An example of a circularity norm is the increased use of wooden constructions in the future of Gemeente Amsterdam. (n.d.-a). Considering insulation, floating buildings will have materials bordering water that have a different R-value than materials bordering outside air. These insulation differences are found by analysing the "The Float" reference case (Appendix C)[1]. The Float reflects the material characteristics relevant to the FD project: a newly built wooden floating home following the BENG norm for new construction. The Float shows that materials exposed to water have lower R-values (3.39 for facades bordering water, 4.01 for the floor) compared to those exposed to air (4.06 for the rear facade, 4.89 for remaining facades), indicating that materials exposed to water are less effective at retaining heat. This lower R-value benefits cooling requirements but may influence heating efficiency. Thus, while The Float still meets BENG requirements, it is important to recognise that the relatively lower insulation values of surfaces boardering water could result in differing heating and cooling demands for floating constructions from conventional buildings.

Furthermore, the HVAC (Heating, Ventilation, and Air Conditioning) system is a key component influencing this heating and cooling demand. The efficiency of the HVAC system is significantly impacted by its operational settings, which include cooling and heating setpoint temperatures and on/off schedules. Setpoints determine when the HVAC system activates to maintain the desired indoor temperatures and on/off schedules are based on occupational patterns, which differ per building typology (NTA 8800, 2024, p.200 -203; TNO, 2021, p.21). Research increasingly acknowledges adopting progressive setpoint temperatures that help to save energy while still maintaining thermal comfort. These studies are based on e.g. seasonal clothing factors or adaptive thermal comfort, i.e.

[1] The Float reference documents with the building details and Energy performance Coefficient (EPC) calculation are provided by the owner of the houseboat and the relevant pages can be found in Appendix C.

occupants' increased tolerance after exposure to a certain temperature over time (Aghniaey & Lawrence, 2018; van Hattum, 2021). Adopting more progressive HVAC system settings can help minimise the thermal energy demand.

At the urban block scale, the energy demand is affected by factors like daylighting, solar potential, and efficient energy utilisation. The latter is discussed in the reuse potential paragraph below. As Wu and Lui (2023) outline, these factors are determined by urban form parameters like floor area ratio, building density, building height, and building spacing. These block-scale urban form parameters thus include horizontal and vertical density, which will be further assessed in the following section, Chapter 4.2.2.

Reuse potential

The FD project concerns a mixed-use district with residential and non-residential building typologies (Reimann et al., 2023). This mixed-use urban form is important for the energy system of the FD project, as this allows for efficient use of energy (Charan et al., 2021; Wu & Liu, 2023). This is due to variations in operational schedules, meaning when one function requires cooling another can require heating. Therefore, the waste heat released in the process of cooling one building can be reused to cover the heating demand of another building, e.g. an office being cooled in the summer while a gym needs hot water for its showers at the same moment. This simultaneous heating and cooling demand can be referred to as thermal overlap (Charan et al., 2021).

4.2.2. Urban Form

This section discusses the two block-scale urban form parameters selected in co-creation with experts (Appendix A). As no urban form metrics specific to the context of floating urban form or newly created urban are found, this research adopts the vertical and horizontal density definition of Chen et al. (2020), who apply a deep learning method to monitor these two morphological dimensions of urban density for existing cities. Chen et al. (2020) measure both densities per group of grid cells. Vertical density is determined by the mean height of buildings within a group. This dimension consists of three classes: high-rise, low rise and not-built-up. Horizontal density refers to the proportion of ground area within a specific group of grid cells that is covered by buildings., i.e. Building Area Ratio (BAR). This dimension consists of four classes: compact, open, sparse, and not built-up. This horizontal and vertical density classification is illustrated in Figure 6 below.

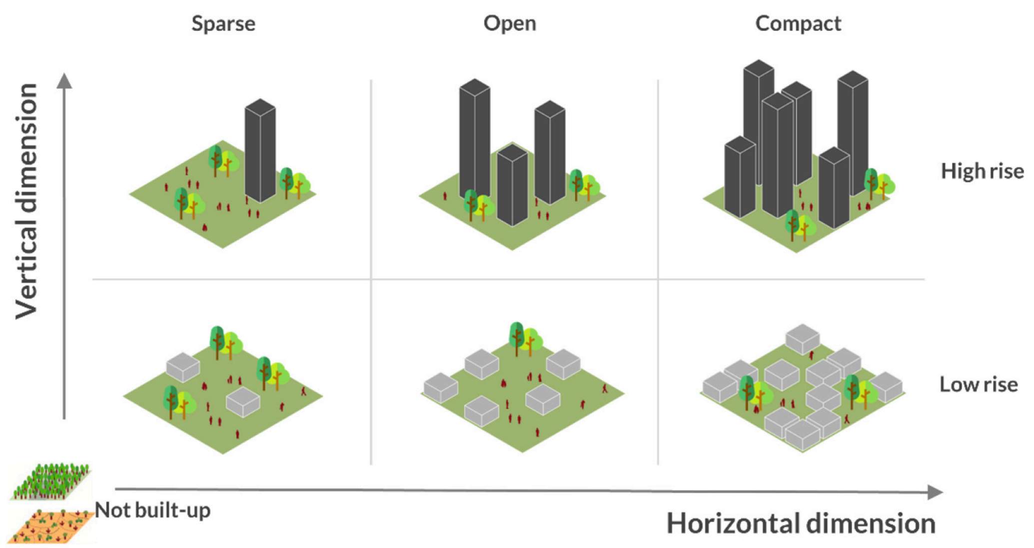


Figure 6: Vertical and horizontal urban density classification of Chen et al. (2020)

This vertical and horizontal density classification concerns a simplification of the Stewart and Oke (2012) Local Climate Zone (LCZ) concept, which classifies urban landscapes. LCZ distinguishes ten "built" (e.g., combinations of compact/open, high-rise/ mid-rise/ low-rise etc.) and seven "natural" zones (e.g., low plants, water). From this concept Chen et al. (2020) focus on the 'built' zones from which they derived the vertical and horizontal density dimensions. The next sections will elaborate on vertical and horizontal density, contextualising the relation of these density parameters to other density indicators.

Vertical density

Vertical density is measured by Chen et al. (2020) according to the mean height of multiple buildings in a group of cells. However, the Stewart and Oke (2012) LCZ concept underlying the Chen et al. (2020) approach proposes a vertical density classification per building, rather than a group of buildings, that better matches the context of this study. In the LCZ concept, three vertical density classes can be distinguished based on the number of building floors: low-rise (1-3 floors), mid-rise (3-9 floors), and high-rise (>10 floors) buildings. This vertical density impacts urban form through its interrelation with other density indicators. This is explained by PBL (2022), who define this vertical density as Layers, which is one of four indicators of spatial density that together impact the urban form:

- *Layers* $(L = gross\ floor\ area/building\ footprint)$
- *Floor Space Index* $(FSI = gross\ floor\ area/total\ terrain\ area)$
- *Ground Space Index* $(GSI = Building\ Footprint(s)/\ total\ terrain\ area)$
- *Open Space Ratio* $(OSR = 1 - GSI/FSI)$

The FSI indicates how the total building floor area (m^2) relates to the total site area (m^2). The GSI indicates the share of the total site area covered by building footprints. This parameter relates to the horizontal density as well and will be further discussed in the following section, Chapter 4.2.3. The OSR represents the ratio of unbuilt terrain to the total building floor area, not just the building footprint. These density indicators are highly interrelated, an example is that the same FSI can result in different urban forms due to changes in the remaining density indicators. Figure X below illustrates this interaction. On the left is a high-rise building, which is more vertically dense, i.e. a larger number of Layers. For this building typology, the resulting OSR will be higher, indicating more open space relative to the gross floor area. As opposed to the GSI which will be relatively low, indicating a smaller building footprint relative to the total terrain area. But, if you were to change the vertical density by e.g. lowering the number of Layers like in the illustration on the right, your GSI and OSR will change accordingly to maintain the given FSI. This is illustrated in Figure 7 below, retrieved from PBL (2022, p.10).

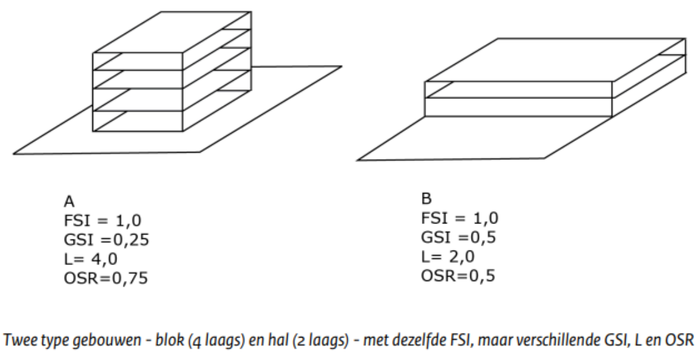


Figure 7: Impact of Spatial Indicators on Urban Form, retrieved from PBL (2022, p.10)

Horizontal density

Horizontal density is measured by Chen et al. (2020) according to the Building Area Ratio (BAR) per defined group of cells. Where the GSI measures the total building footprint area as a proportion of the total terrain area, the BAR measures the GSI per block. This makes the BAR a useful metric for assessing horizontal density at a more localised level, aligning with the block scale of this study. A block is considered compact if BAR ≥ 0.3, and open if BAR is between 0.15 and 0.3. The sparse BAR between 0.02 and 0.15, is excluded from the scope of this study, as it relates to rural areas or urban outskirts, whereas this study concerns a floating district with characteristics of a mixed-use urban centre (Reimann et al., 2023).

The interaction between horizontal and vertical density can impact the urban form. However, the degree to which this occurs depends on the total terrain area. A lower vertical density can result in a more compactly built area and vice versa. However, if the total terrain area is of sufficient size, it can become possible to realise an open horizontal density regardless of the vertical density.

4.2.3. Energy System

This section discusses the thermal energy system selected in Phase 1 (Appendix A), its production potential, and its systemic feasibility. According to experts, a closed SWTE system can create a locally balanced energy system that functions year-round with no storage required and thus could achieve a self-sufficient FD. Given the FD will be situated on the water, SWTE systems logically are the most apparent energy source to explore. However, the assumption that no thermal energy storage is required to achieve a local balance for the FD project contrasts with the Energy Island and SUI literature discussed in Chapter 4.2.1. These studies specifically focus on islands or island-like contexts and stress the key role of storage in overcoming seasonal differences in RES availability (Groppi et al., 2021; Hartog et al., 2017; Jansen, Mohammadi & Bokel, 2021). The integration of a storage component can help facilitate such flexibility to overcome seasonal differences and achieve a locally balanced system (Jansen, Mohammadi & Bokel, 2021).

A comprehensive overview of the selected system is set out in this section to understand and validate the expert assumption of sufficient SWTE potential for achieving a local energy balance. First, a brief explanation of SWTE is provided. This is followed by an assessment of the SWTE potential, specifically of the case study location: IJmeer. Lastly, the systemic potential is illustrated using a reference system. This analysis is limited to the technically extractable potential as defined by IF Technology et al. (2016), in line with the scope defined in research Chapter 1.4.

Surface Water Thermal Energy (SWTE)

SWTE is a form of aquathermia. Aquathermia encompasses the extraction of heat and cold from surface water (TEO), wastewater (TEA) and drinking water (TED) (IF Technology, 2019). In the case of SWTE systems, thermal energy is extracted from surface water (TEO) by aggregating existing techniques (Stowa, 2018). When SWTE systems extract heat from the water, it is returned to the surface water at a lower temperature. When cold is extracted, the water returns to a higher temperature (Stowa, 2023). The amount of thermal energy that the heat exchanger extracts in this process depends on the difference between the water temperature before and after extraction, the Delta T (ΔT). This extraction can be done via a closed or open system. While this research will focus on closed systems, both are briefly discussed.

In an open system, water is actively pumped into the heat exchanger via filters. In a closed system, the heat exchanger (e.g. in the form of a pipeline) is placed directly in the surface water where it passively extracts energy (Stowa, 2023). Due to the direct contact between surface water and the energy system, open SWTE systems are unsuited for year-round extraction regimes, whilst colder temperatures or freezing might affect the heat system's efficiency (Royal HaskoningDHV, 2022). In a closed system, there is no direct contact between the fluid inside the system and the surface water on the outside. Therefore, other fluids, such as the antifreeze fluid glycol, can be used as carrier fluids inside the system, enabling year-round extraction even at temperatures below 0°C (Stowa, 2023; Royal HaskoningDHV, 2022). Unlike the open system, the closed system exchanges heat twice, once from the surface water to the carrier fluid inside the heat exchanger, and once more to the HP. This results in higher losses (Aquathermie, n.d.). Both systems are visualised in Figure 8 below.

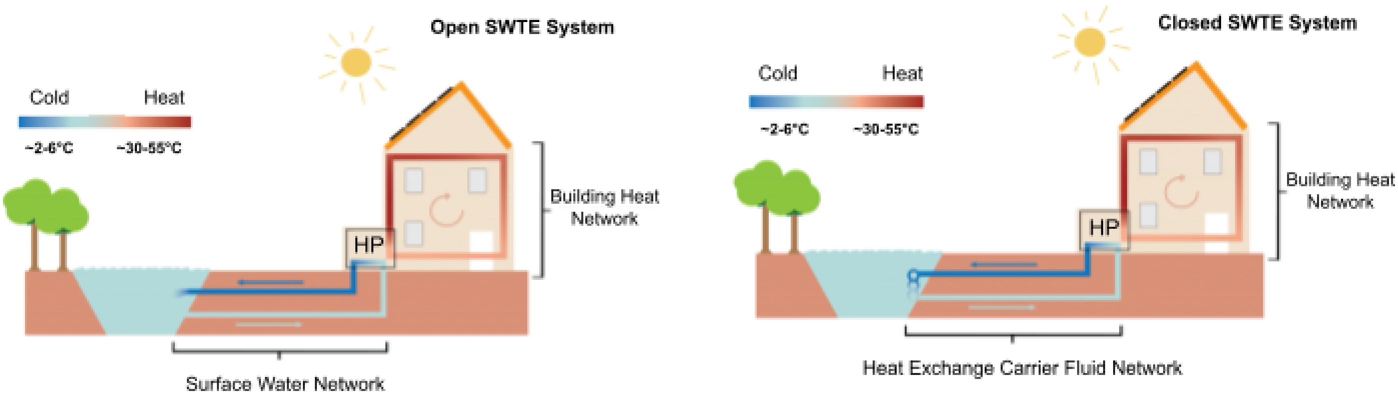


Figure 8: Open and Closed SWTE system visualised for extraction from a river, adapted from Aquathermie (n.d.).

The figures illustrate that when SWTE is extracted for (space or hot water) heating, the heat is transmitted to the Heat Pump (HP) directly (open system) or via a heat exchange carrier fluid (closed system). In case the heat is used directly, the HP increases the carrier to the desired Low Temperature (LT) heat, which is between 30°C-55°C (IF Technology et al., 2016; NPLW, 2023; STOWA, 2018, 2023; Warmtenetwerk, n.d.). A HP can reach these temperatures, since with 1 kWh of electricity, it can generate between 3 to 5 kWh of heat, depending on its efficiency. The HP efficiency is expressed in its Coefficient Of Performance (COP), indicating how much kWh of heat 1 kWh electricity can deliver (Stowa, 2023). Increasing the temperature is often done centrally for multiple buildings, but can also be done decentrally per building individually (STOWA, 2018).

Alternatively, to the described direct usage, heat extracted in the summer can also be stored to cover winter heat demand and vice versa (Jansen, Mohammadi & Bokel, 2021, Hartog et al., 2017). This helps overcome the seasonal mismatch between heat or cold availability and demand.

SWTE Potential

To validate the assumption no storage is needed, the extent to which the local SWTE is sufficient to meet the FD heating and cooling demand is assessed. This supply potential is calculated following the Waternet (n.d.) logic that indicates the area (A) required for temperature regeneration to restore the heat balance after heat extraction (E). The formula for still water is as follows:

$$E = A \cdot Z \cdot \Delta T \cdot h \cdot 0,0036/1000 = A \cdot 1,19\ GJ/m^2/year$$

- E Energy, or the heat that can be extracted $(GJ/year)$
- A Area of regenerative waterbody surface in contact with the atmosphere (m^2)
- Z Energy exchange between surface water and the atmosphere under the influence of solar radiation and wind speed $(W/m^2/°C)$
- ΔT Temperature extracted from the surface water $(°C)$
- h The number of hours per year during which surface water has a relatively high temperature and heat can be effectively extracted. In the Waternet formula, this is 2500 hours, corresponding to 3,5 months

This formula can determine if the area required to meet the specific project demand is sufficient, thereby validating the co-creation assumption. Since the formula was originally tailored to active open SWTE systems in the Amsterdam canals, it needs to be adjusted to align with the closed SWTE system characteristics of the FD project. With feedback from H. de Brauw, an expert from Waternet involved in developing the Waternet (n.d.) logic, the formula is adjusted accordingly. Appendix D provides the details of these adjustments. The formula resulting from these adjustments is as follows:

$$E = A \cdot 0,1434888\ GJ/m^2/year$$

This SWTE regeneration potential $0,1434888\ GJ/m^2/year$ results from correcting the ΔT, Z and h values to align them with the year-round extraction regime of this study's context, outlined in Appendix D.

The area of regenerative water surface required to support the project is found by:

$$A = E\,(heating + cooling\ demand)/0,1434888\ GJ/m^2/year$$

The demand can thus be met if:

$$A < Total\ Area\ Surface\ Available\ in\ IJmeer$$

According to H. de Brouw, the expert co-creation assumption is correct as the 80 km² surface area of IJmeer significantly exceeds the potentially required *A* for a 1.500 unit district (Ministerie van Infrastructuur en Waterstaat, 2023).[2] Therefore, the assumption that SWTE potential is sufficient to meet FD project heating and cooling demands can be confirmed in advance.

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[2] *This assumption is cross-checked in the assessment phase based on model simulation results*

SWTE System

A reference case is studied to validate the systemic potential of the closed SWTE system. Royal HaskoningDHV (2022) conducted a variant study for a SWTE project in Tiel. One of these variants (number 2B) concerns a closed SWTE system with passive year-round extraction and no storage. This variant is in line with the selected SWTE system. Note, the Royal HaskoningDHV (2022) study concerns a technical variant exploration of the most suited system for the heating of 8.500 houses in Tiel, not an existing implemented system. While limited research on such systems is available, this variant will serve as the main reference system for this study. The SWTE system design provided in this reference serves as an indication of the feasibility, sizing, and capacity of this type of SWTE system.

Heat Exchanger

The reference system can function year-round without storage due to the glycol carrier fluid of the heat exchanger which prevents freezing within this closed system and allows it to extract thermal energy even with temperatures below $0°C$. However, extracting below $0°C$ possibly impacts heat exchanger efficiency due to the risk of freezing or ice formation on the system's exterior (Royal HaskoningDHV, 2022). To mitigate this risk, as identified in Royal HaskoningDHV (2022), a conservative extraction regime with a relatively low ΔT could ensure that the system functioning will not be affected by the risk of freezing or ice formation $\leq 0°C$. As mentioned, although using glycol enables year-round extraction, this passive heat extraction decreases the heat exchanger's efficiency, as the heat must now be transferred between the system twice (Aquathermie, n.d.). Conversely, the system's efficiency can also benefit from heat recovery potential. According to the NTA 8800 (2024), different energy systems have varying heat recovery potentials. This reference system concerns a 'plate or tube heat exchanger', which has a heat recovery of 0.65, meaning 65% of the heat can be recovered from the system (NTA 8800, p.487; Royal HaskoningDHV, 2022).

Heat Pump (HP)

Besides glycol enabling year-round extraction, the FD SWTE system also needs HPs that function year-round, meaning 8.760 full-load hours (Royal HaskoningDHV, 2022, p.102). The COP is assumed to be 3.0 in the Royal HaskoningDHV (2022) study, indicating that 1 kWh of electricity delivers 3.0 kWh of heat in this system. This COP is based on a 70°C heat network. As this study regards a low-temperature heat network, HPs can achieve a higher efficiency (COP). In the case of year-round extraction, the Seasonal Performance Factor (SPF) variant gives a more realistic idea of HP efficiency throughout the year. According to NTA 8800 (2024), for a supply temperature of 45°C, a mean of 3.5 COP can be achieved (NTA 8800, p. 320), indicating 1 kWh of electricity delivers 3.5 kWh of heat in this system (Stowa, 2023).

System Sizing

The sizing of this system is calculated by the industrial heat pump manufacturer *MEFA Energy Systems*. Their design of a closed heat exchanger is 7.0m long, 3.0m wide and 2.5m high. These systems have a 150 kW capacity. According to Royal HaskoningDHV (2022), these are the largest closed SWTE systems that can be modularly installed. It allows for multiple modules to be connected in series or parallel to achieve higher potential, e.g. to meet the Tiel demand of 15.000 kW, 100 modules of the reference heat exchanger system are required. As for the FD project, the total number of residential and non-residential units is significantly lower, 1.500 in total as opposed to the 8.500 of the Tiel reference. Therefore, it is likely that the required capacity would also be lower. To know the required amount of heat exchanger modules for the FD project, the total heat demand (kWh/year) must be divided by the COP resulting in the required heating capacity for which the number of heat exchanger modules can be calculated.

This literature study thus confirms the SWTE potential of a closed system that functions year-round without TES, is sufficient for the FD project. Additionally, the feasibility of realising such a system is validated by the Royal HaskoningDHV (2022) reference study.

4.3. Theoretical Framework

The theoretical framework in Figure 9 below visualises the interrelation between the key theoretical concepts relevant to this research.

The FD project's objectives of *self-sufficiency* and *scalability* relate to Energy Island and Smart Urban Isle (SUI) theory. On the one hand, the FD project is in line with the island context of the Energy Island concept by its need to realise self-sufficiency through RES-based systems. To achieve self-sufficiency it must be determined if a local balance can be released with selected RES, possibly in combination with the help of storage.

On the other hand, the FD project's scalability objective of realising a district of 1.500 floating units, relates to the neighbourhood-scale energy planning of the SUI approach. The scalability of the urban form depends on the energy system's ability to achieve self-sufficiency through a local balance. Creating a self-sufficient energy system and the scalability of urban form are thus related. Furthermore, the urban form impacts the energy system. Urban design of both building-scale and urban block-scale, and mixing building typologies can positively affect the reduction and reuse potential, thus minimising RES demand.

The SWTE supply and systemic potential have indicated that this local balance is technically feasible for the FD project. Therefore, the effect of the specific block-scale urban form parameters, vertical and horizontal density, on the selected SWTE system is further assessed in this research.

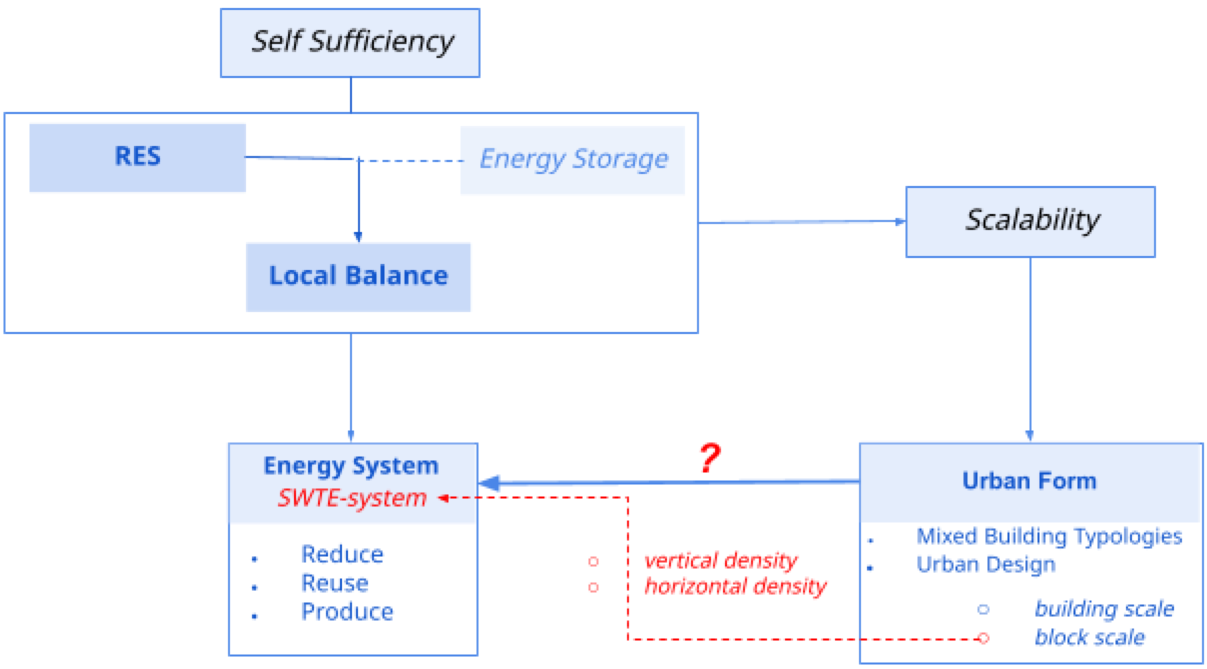

Figure 9: Theoretical Framework

4.4. KPIs

The KPIs of this project are based on the design objectives: scalability and self-sufficiency. According to the experts, the main challenge regarding a self-sufficient scalable energy system will likely relate to electricity demand (Appendix A). Since a thermal energy system relies on electricity to operate year-round, its ability to minimise thermal energy demand directly influences the electricity required. The thermal energy demand of the system can significantly lower the electricity needed, thus enhancing the potential for a self-sufficient, scalable energy energy system.

Therefore, the model aims to assess different scenarios on how urban form parameters, specifically horizontal and vertical density, affect the selected energy system in operational thermal energy demand, reuse potential, and production potential. A scenario can be assessed according to the following KPIs:

- The optimal scenario contributes to minimising the thermal energy demand, and therefore the associated electricity demand
- The optimal scenario contributes to increasing the reuse potential
- The optimal scenario has a high electricity production potential relative to the demand of the scenario

5. Phase 3 - Modelling

This modelling phase describes how the parametric energy model of this study is created. The objectives of this phase are:

Objective 3.1. Describe the steps taken to create a parametric 3D model of the block scale morphology and energy system logic

Objective 3.2. Define the different urban form scenarios to be assessed for their impact on the energy system

Objective 3.3. Describe the steps taken to validate the baseline model's performance

Objective 3.5. Describe the steps taken to create the final model according to the characteristics of the FD project

5.1. Method

This research operationalises energy planning and block-scale urban form design for the FD project by parametric modelling. Parametric modelling is particularly suited for early-stage design because it automatically generates variations of project elements based on provided parameters (Eltaweel & Su in De Sousa Freitas et al., 2020). This iterative model explores the interaction between scalability and self-sufficiency by simulating the block-scale geometry of six urban scenarios and the energy system logic of the selected system. To achieve this fixed and variable parameters are incorporated into the model simulation. Adjusting the model's variable parameters to the different scenarios, allows interaction between energy planning and block-scale design of new urban forms to be explored.

As visualised in Figure 10 below, the parametric model's energy and urban form simulation interact, where changes to the parameters of one component can influence the composition of the other. The arrows in the parametric modelling section illustrate this mutual influence, creating a feedback loop that explores the relationship between self-sufficiency and scalability in the FD project. The model's output consists of six different FD scenarios that will be manually assessed in the final phase of this research.

Tools & Software

The Rhinoceros 7 3D CAD modelling software with the parametric Grasshopper plug-ins is used. Grasshopper provides tools that give instant feedback on alterations in the model design (Roudsari & Pak in Dang, van den Dobbelsteen & Voskuilen, 2024). The Ladybug plug-in for Grasshopper enables energy simulations of the created morphology through Honeybee tools (de Sousa Freitas et al., 2020). Ladybug's energy simulations are based on EnergyPlus models, which use Weather files (.EPW) for climate data (Ladybug Tools in Roudsari & Pak, 2013; de Sousa Freitas et al., 2020). The Dragonfly plugin extends these capabilities to district-scale energy modelling (Charan et al., 2021). This integrated approach allows for simultaneous exploration of energy planning and design at the district scale, illustrating how both influence each other.

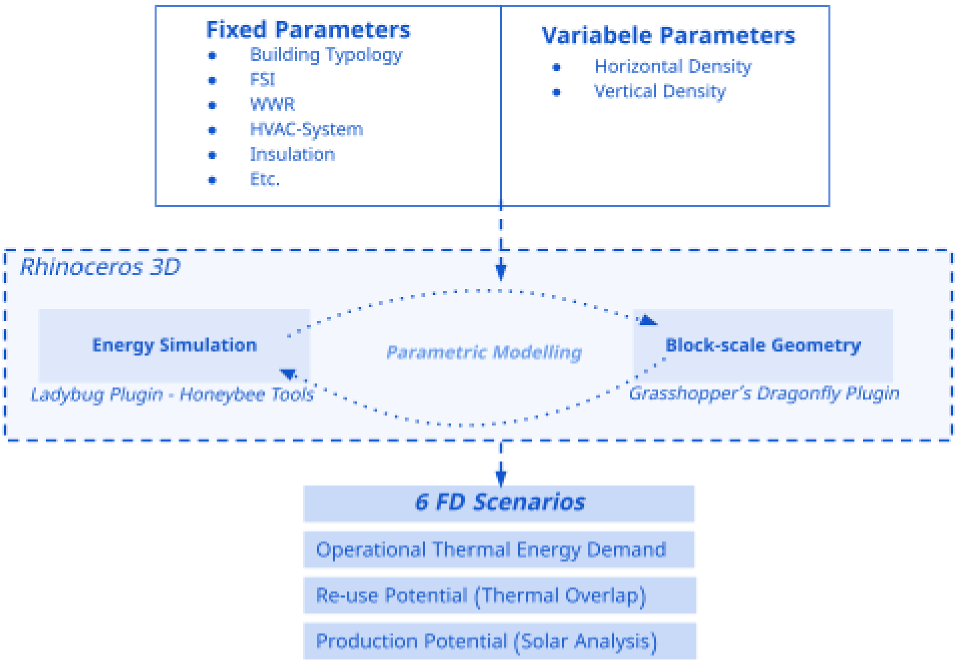

Figure 10: Modelling Method

5.2. Parameters & Assumptions

5.2.1. Fixed Parameters

This section applies the knowledge gained in the analysis to set up the basis of the model's morphology and energy logic, which are integrated as fixed parameters of this model. This information is discussed and set out in the following tables.

Urban Form

A 70% residential and 30% non-residential ratio is chosen for the mixed-use FD district. As the FD project comprises 1.500 units, this ratio results in 1.050 residential and 450 non-residential unit equivalents. For the FD project, the required floor area (m^2) for residential units is calculated using municipal benchmark values for the average gross floor (m^2) per typology (Gemeente Amsterdam, 2023-b). The residential units require a total area of 47.430 m², concerning 70% of the total district area. The remaining 30% encompasses 20.327 m² for non-residential functions. In consultation with the municipal issuer, the non-residential building typologies were defined based on the minimal requirements of social facilities and complemented with several other functions to enhance the FD's reflection of a conventional mixed-use neighbourhood (Gemeente Amsterdam. (n.d.-b). The total non-residential building floor area is 19.030 m², leaving 1.297 m² for greenery, which is excluded from the scope of this research for simplicity. The mean unit equivalent sizes resulting from the defined typologies are 45.2 m² for a residential unit and 46.9 m² for each non-residential unit. The resulting residential, non-residential, and district characteristics are detailed in Tables 1a,1b, and 1c below.

District Characteristics	
District Area (m^2)	425.000
Units	1.500
Typology share (%)	
Residential	70
Non-residential	30
Floor Area (m^2)	
Residential Floor Area	47.430
Non-residential Floor Area	21.101
Total Floor Area	**68.531**

Table 1a: District Characteristics

Residential		
Building Typology	Multi-family housing	
Typology Ratio (%)		
Social Housing		40
Medium Rent		40
Free Sector		20
Typology Mean Floor Area (m^2)		
Social Housing		
a. Students		28
b. Regular		45
Medium Rent		58
Free Sector		20
a. Expensive Rent		66
b. Privately Owned		83
Total Floor Area (m^2)		**47.430**

Table 1b: Residential Typology

Non-Residential	
Building Typologies	**Floor Area (m^2)**
Community Centre	249
Art Centre	375
Health Centre	465
Education	3770
Office	3000
Supermarket	959
Gym	783
Cinema	6429
Retail	3000
Total Floor Area (m^2)	**19.030**

Table 1c: Non-residential Typology

Additionally, Tables 2a, 2b, and 2c below outline how the block scale urban form metrics $layers$, FSI, GSI, and OSR are applied in this study. The vertical density, and thus the number of buildings $layers$ is based on the Stewart and Oke (2012) LCZ classification, which distinguishes low-rise (1-3 floors), mid-rise (3-9 floors), and high-rise (>10 floors) buildings. This classification is adjusted to align with the context of this study, the 1-3 floor building range as defined in co-creation (Appendix A, and Appendix B). Therefore, a low-rise building is considered a single floor, a mid-rise is two floors, and a high-rise is three floors high. The low-rise (single-floor) scenario reflects the common conventional houseboat typology to which mid-rise and high-rise density can be compared.

As the floor and district area are fixed in this study, the $FSI(gross\ floor\ area/total\ terrain\ area)$ remain constant regardless of the vertical density. This $GSI(Building\ Footprint(s)/\ total\ terrain\ area)$ implies that the more vertically dense the urban form, the lower the footprint area required to maintain the given FSI. This directly relates to more open space within the same area reflected by a higher $OSR(1 - GSI/FSI)$.

Given the extensive area of the IJmeer waterbody, a total terrain area of 850 x 500 metres is assumed which is sufficient for experimenting with different horizontal densities. Consequently, this results in a relatively low FSI GSI, and a relatively high OSR. This highlights the challenge of applying traditional urban density metrics to explore possible new urban forms in a water context. The distinct characteristics of large-scale floating districts are not reflected in conventional urban density metrics.

Floor Area (m^2)	
Residential Floor Area	47.430
Non-residential Floor Area	21.101
Total Floor Area	**68.531**

Table 2a: Floor Area (m^2)

Footprint Area (m^2)	Low-rise	Mid-rise	High-rise
Residential	47.610	23.805	15.870
Non-residential	24.265	12.103	8.088
Total Footprint	**71.875**	**35.908**	**23.958**

Table 2b: Footprint Area (m^2)

Urban Form	Layers	FSI	GSI	OSR
Low-rise	1	0.20	0.17	4.15
Mid-rise	2	0.20	0.08	4.60
High-rise	3	0.20	0.06	4.70

Table 2c: Density Indicators applied to the FD project

Energy System

The different components of the SWTE energy system are outlined in Table 3 below. The specific setpoint temperatures and on/off schedules assumed in this research are specified in Appendix F.

Energy System			Reference
Type		Closed year-round SWTE (TEO)	Royal HaskonignDHV (2022)
Heating Network			
	Type	Low Temperature (LT)	
	Temperature	43 °C	TKK (Appendix E)
Heat Exchanger			Royal HaskonignDHV (2022)
	Type	Modular	
	Capacity (kW)	150	
Storage		None	Royal HaskonignDHV (2022, p.102)
Heat Pump (HP)			
	COP	3.5	NTA 8800 (2024, p.320)
	Full-load hours	8.760	Royal HaskonignDHV (2022)
HVAC system			
	Senisible Heat Recovery	0.65	NTA 8800 (2024, p. 487)
Setpoint on/off schedule		Variable for night/day/week/weekend	Appendix F
Setpoint Temperature (°C)		Typology dependend	

Table 3: Energy System Characteristics

The key values regarding building insulation are displayed in Table 4 below. This table presents both building insulation values assumed by the NTA 8800, for model validation, and The Float. Note these values cannot be compared directly due to their difference in construction material, roof type, and possible differences in underlying calculation assumptions. The remaining building scale insulation values are based on additional sources. Concerning windows, highly insulated triple glass windows (HR+++) are assumed to mitigate the relatively high heat transfer occurring in water-bordering surfaces. The U-value is retrieved from an installer company (KJM Group, n.d.). Furthermore, the WWR for housing is based on Raji, Tenpierik, and Van Den Dobbelsteen (2026, p.4), and the ranges for non-residential parameters result from model validation to be discussed in Chapter 5.2.3

Building Envelope parameters		Values		Additional References
Window		HR+++		
	U- value	0.50		KJM Group (n.d.)
	Shgc	0.60		NTA 8800 (2024)
WWR Residential		all > 0.5		Raji, Tenpierik, and Van Den Dobbelsteen, (2016, p.4)
	North	0.1 - 0.4		Variable - based on model validation
	East	0.2 - 0.4		
	South	0.3 - 0.5		
	West	0.2 - 0.3		
Shading				Not Applied
	Count	_		
	Depth (m)	_		
	Facade Offset	_		
	Angle	_		
Extiror		**NTA 8800**	**The Float**	
	R-value Facade	4.7	4.06	
	*R-value Roof**	6.3	4.54	
	R-value Floor	3.7	4.01	
Construction				
	Material	Wood		Gemeente Amsterdam (n.d.-a)
	Insulation	New Built		ASHRAE (2021), Reimann et al. (2023)

** NTA 8800:2024 assumes a sloping roof instead of the Float assuming a flat roof.*
***The Float values for water-bordering surfaces are assumed*

Table 4: Building Insulation Values

5.2.2. Morphology

This study assesses the impact of urban form parameters, specifically vertical density and horizontal density, on the energy system. The two urban form parameters are the variable model parameters and define the model morphology. All other parameters were set out in the previous Chapter 5.2.1. are considered fixed. By parametrically changing the two variables, their effect on the energy system can be assessed. To achieve this, different model scenarios are defined which will be assessed in the next phase of this research. The method to create the different model scenarios is based on the established horizontal and vertical density framework of Chen et al. (2020) and the underlying LCZ (Local Climate Zones) framework of Stewart and Oke (2012), discussed in Chapter 4.2.2.

For the horizontal density, the Chen et al. (2020) classification of 'open' and 'compact' building arrangements are adopted. For vertical density, the adjusted Stewart and Oke (2012) classification is modelled: low-rise (1 floor), mid-rise (2 floors), and high-rise (3 floors) buildings are adopted. The low-rise (single-floor) scenario is included for comparability, serving as a baseline to which the effect of 2-3 floors on the energy system can be compared. This method results in the following model calibration scenarios: compact low-rise, compact mid-rise, compact high-rise, and open low-rise, open mid-rise, open high-rise. Figures 11a and 11b visualise the vertical and horizontal density scenarios. The method to create these scenarios is subsequently described for vertical and horizontal density.

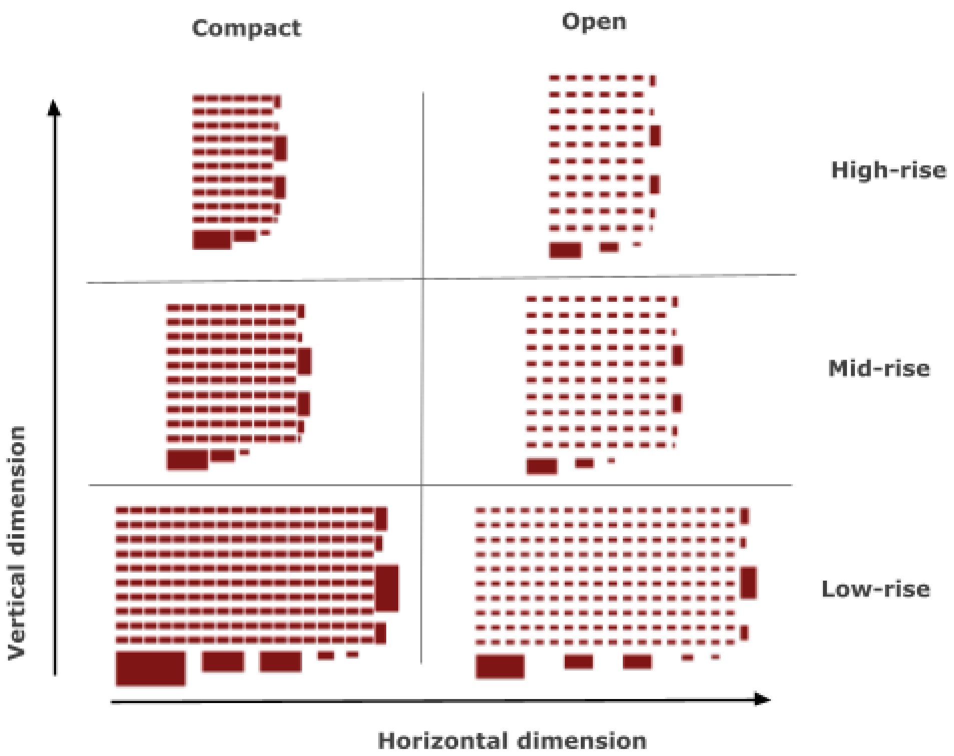

Figure 11a: Model Scenarios Top View

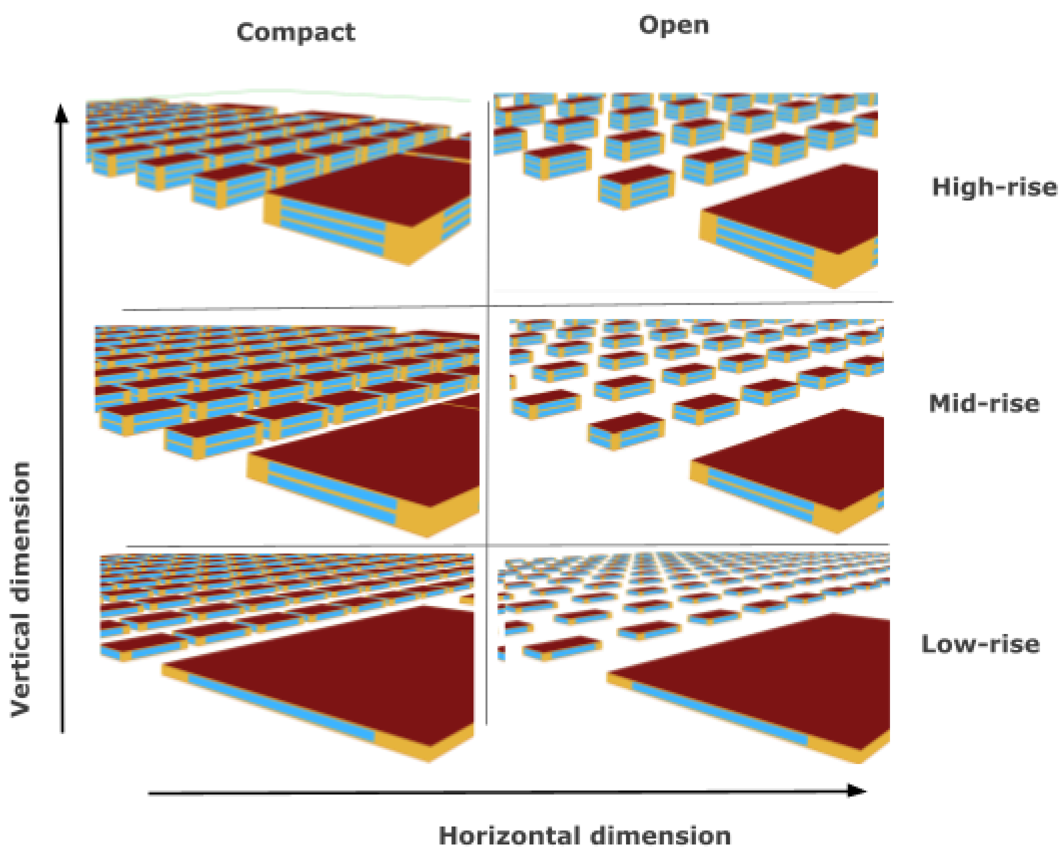

Figure 11b: Model Scenarios Side View

Vertical Density

Residential and non-residential geometries are created as rectangular buildings with fixed floor areas (m²) to model the vertical densities of building morphology. The residential buildings are arranged in blocks of 5 building units within clusters of 10 blocks per row, as illustrated in Figure 12 below.

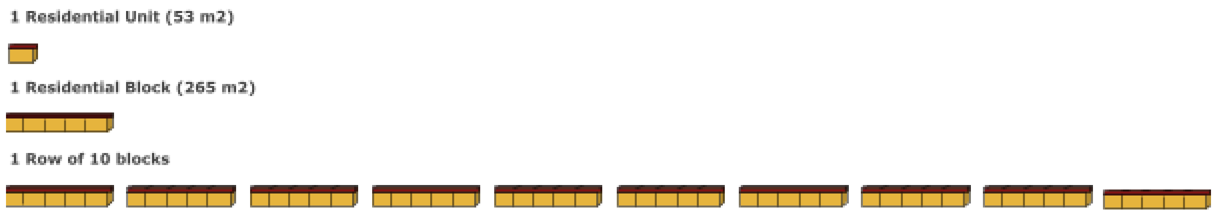

Figure 12: Construction of residential units, blocks, and rows

The created geometry reflects the total required residential and non-residential floor area defined in Table 2a (Chapter 5.2.1.). To maintain the fixed floor areas, the district's building footprint has to change per vertical density scenario. In other words, the GSI required to maintain the given FSI, varies per vertical density scenario, also illustrated in Tables 2b and 2c (Chapter 5.2.1). For the residential buildings, this is reflected in the number of residential blocks: 180 blocks for the low-rise scenario, 90 blocks for the mid-rise scenario, and 60 blocks for the high-rise scenario, as seen in Figure 11a. For the non-residential buildings, the number of buildings remains the same, but the building footprints vary per vertical density scenario. Figure 13 below illustrates how vertical density classification translates to the building scale in this study.

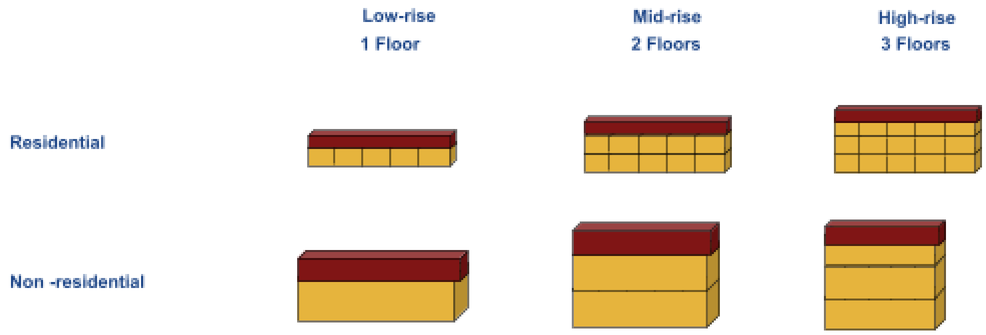

Figure 13: Schematic representation of residential and non-residential building typologies across vertical density scenarios

Horizontal Density

The general district layout is arranged within a fixed rectangular surface area of 850 x 500 metres to allow sufficient space for experimenting with a compact and open horizontal density. Within this area, both residential and non-residential buildings are placed along a square grid pattern. To compare the different model scenarios, the district layout remains the same for all scenarios: rows of residential building blocks and the 8 non-residential units placed along two outer sides of this grid, illustrated in Figure 14 below.

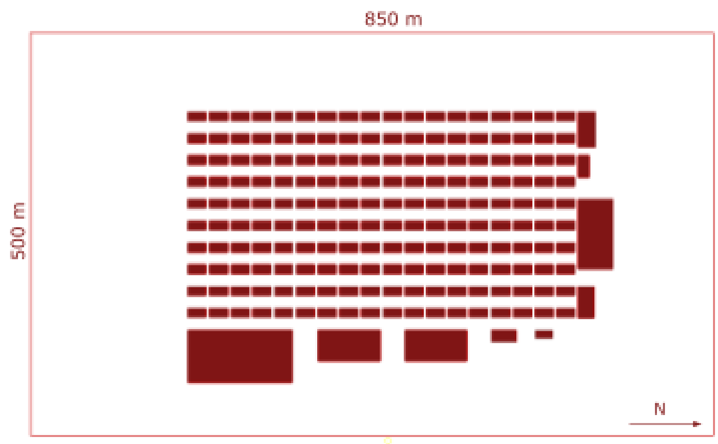

Figure 14: General district layout illustrated for the baseline compact low-rise scenario

To create an open and compact horizontal density scenario the Chen et al. (2020) Building Area Ratio (BAR) is applied. Although, normally used for measuring the existing urban form. In the context of this study, applying a different BAR can change the spacing between buildings. Applied to this study, the BAR is measured per grid cell with a residential block on each corner of the cell. This is illustrated in Figure 15 below.

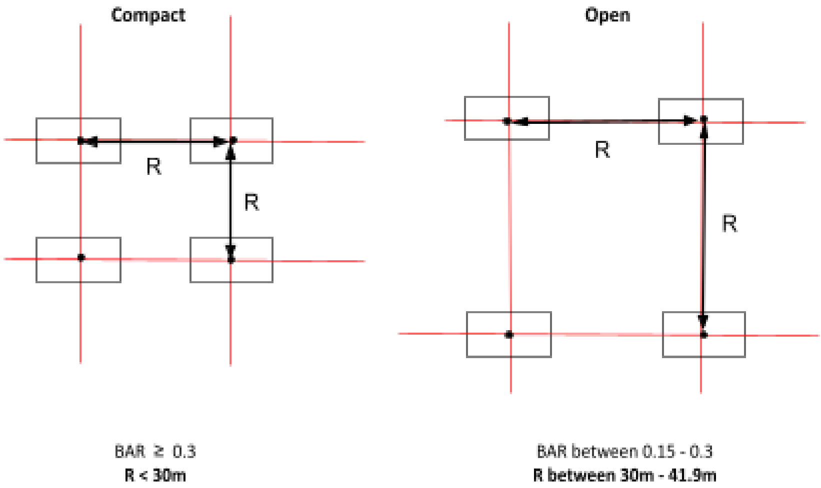

Figure 15: Open and Compact horizontal density based on Building Area Ratio (BAR)

The figure shows how a larger cell size (R) results in more space between different cells. To model the compact and open horizontal density scenario, the spacing between each residential block is adjusted by altering the cell sizes of the grid, such that it aligns with a compact or open BAR. The cell sizes resulting in an open and closed horizontal density are also provided in Figure 15. These follow Chen et al. (2020), who consider an area compact if BAR ≥ 0.3, and open if BAR is between 0.15 and 0.3. The BAR is calculated following the formula:

$$BAR_{cell} = A_{building} / R^2$$

- $A = Building\ Footprint\ in\ Cell\ (m^2)$
- $R^2 = Cell\ Area$
- $R = Cell\ Size$

For simplicity, this calculation only regards housing units, since their footprint (A) remains consistent for each scenario as opposed to the non-residential typologies. Due to the consistent mutual distance between cells, the overall horizontal density of the district changes according to alterations in the cell size (R). Increasing the cell size (R), results in a lower BAR_{cell}, indicating an open scenario, and vice versa.

To model the compact scenario, a R of 27m is selected, resulting in a BAR of 0.36 while maintaining a 4m distance between each residential building. To model the open scenario, a cell size of 40m is selected, resulting in a BAR of 0.16, and a R of 17m between each building. For simplicity, no direct adjacency between buildings is included in the model. This means that both the compact and open urban forms are modelled as unconnected buildings, only the open scenarios have larger distances between buildings.

5.2.3. Energy system

Since Rhinoceros' Grasshopper modelling software is based on American Standards, the heating and cooling demand resulting from the simulation do not accurately reflect the Dutch context. Therefore, a baseline model is validated against benchmark values for the Dutch context. These benchmarks are based on the BENG norm, obtained from the Total Chain Cost (TKK) model from the Energy Transition department of Ingenieursbureau of the Amsterdam Municipality (Appendix E). [3] Based on these benchmarks the model performance can be validated for the Dutch context before adjusting it to the insulation parameters specific to a floating context.

The model performance is validated by creating a baseline model that aligns with the BENG norms and recalibrating it until an acceptable deviance of <10% from benchmark values is achieved. This is done by aligning the baseline model with the insulation characteristics of conventional newly-built construction as outlined in Tables 2 to 4 of Chapter 5.2.1. However, specific information on the assumptions or building characteristics underlying these benchmark values is lacking. To minimise deviance from the given benchmark values the Window-to Wall-Ratio (WWR), hot water flow rate, and ventilation parameters are adjusted. The parameters are recalibrated until an acceptable deviation of 10% from the benchmark values is achieved. The results of this validation can be found in Appendix E.*[4]

Only the typologies for which benchmarks are provided can be validated: Housing, Offices, Retail, and Education. The remaining non-residential functions are assigned the same parameters as the Retail typology. Non-residential typologies are validated in their low-rise (single-floor) setting. For the residential typology, a single block is validated according to its two-floor setting. This exception is due to the benchmark values for housing corresponding to 'meergezinswoning' or multi-family homes, which typically include at least an upper and lower floor. Therefore, the low-rise setting is not considered representative of common multi-family home typologies and thus not representative of the provided benchmark housing value. Once the model performance is validated for conventional new-built constructions, it can be tailored to the research context by adjusting the insulation values to the characteristics of floating buildings, as retrieved from The Float reference outlined in Appendix C. The resulting final parametric energy model is used to simulate the six scenarios defined in the previous section.

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[3] *Benchmark values outlined in Appendix E, also accessible via energietransitie@amsterdam.nl*

[4] *It is important to note that while the residential hot water demand was successfully validated for a single unit, scaling the residential geometry to the total required units increased hot water demand. This issue stems from a modelling limitation that could not be resolved within the timeframe of this research. Therefore, the results of hot water simulation are not reliable. (see Limitations, Chapter 7.4).*

6. Phase 4 - Assessment

This selection assessment compares the model scenario results before the final evaluation of the optimal scenario. The objectives of this phase are:

Objective 4.1. Discuss and compare the operational energy demand, the reuse potential, and solar production potential for each scenario
Objective 4.2. Evaluate to what extent the different energy scenarios minimise trade-offs considering the KPIs
Objective 4.3. Select the optimal energy configuration(s) by the KPIs

6.1. Method

This final assessment phase compares the results of the six model scenarios while manually conducting a final selection. The low-rise scenario is a baseline to compare with the mid-rise and high-rise scenarios, it is excluded from the final assessment. This final assessment evaluates the trade-offs between scenarios to find an optimal scenario considering the KPIs. This optimum is defined according to three KPIs. First, it minimises operational thermal energy demand compared to the low-rise baseline scenario. Second, maximising energy reuse potential relative to heating demand. Finally, it maximises solar production potential relative to the corresponding operational demand.

This result section will share and discuss the model results of all scenarios per theme:

- District Operational Thermal Energy Demand
- Re-use potential (Thermal Overlap)
- Total Solar potential

6.2. Results

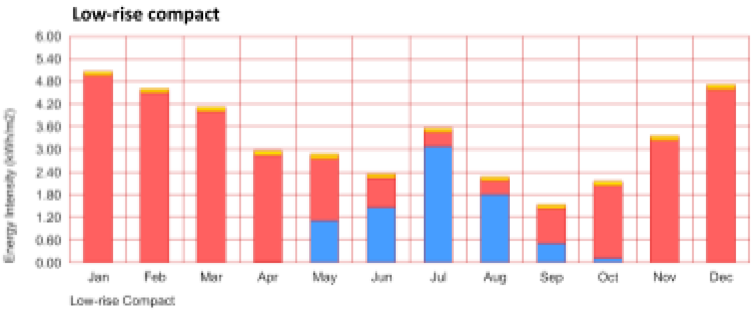
6.2.1. Operational Demand

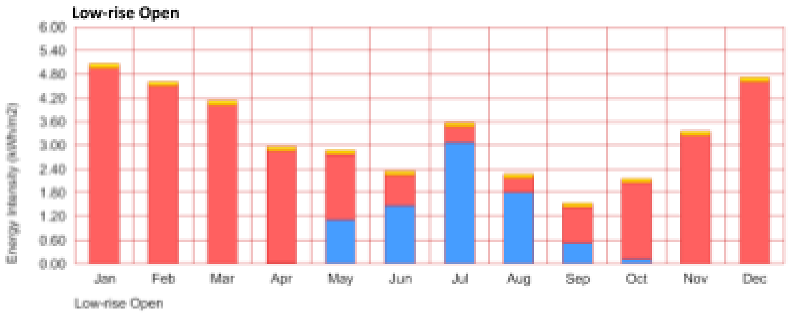
The operational thermal energy demand of each scenario is set out in Table 5 below. For horizontal density, no impact on the operational thermal energy demand is observed, with all values being equal for compact and open scenarios.

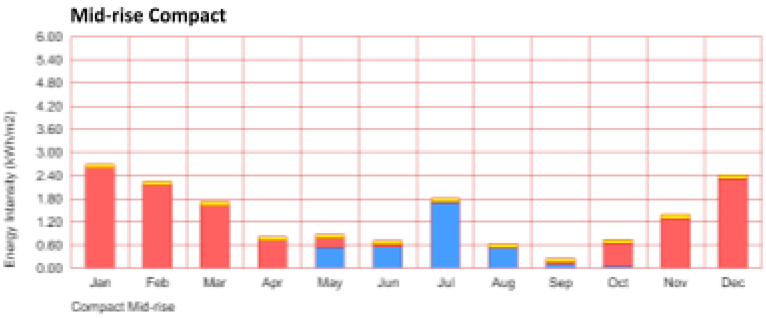
Demand (kWh/m²)	Space Heating		Hot Water		**Total Heating**		**Total Cooling**	
	Compact	Open	Compact	Open	Compact	Open	Compact	Open
low-rise	30.1	30.1	1.4	1.4	31.5	31.5	8.1	8.1
mid-rise	11.6	11.6	1.4	1.4	13.0	13.0	3.5	3.5
high-rise	9.3	9.3	1.4	1.4	10.7	10.7	4.0	4.0

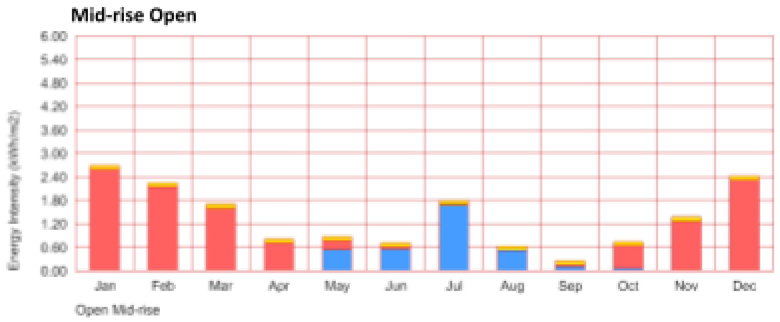
Table 5: Total operational heating and cooling demand per model scenario

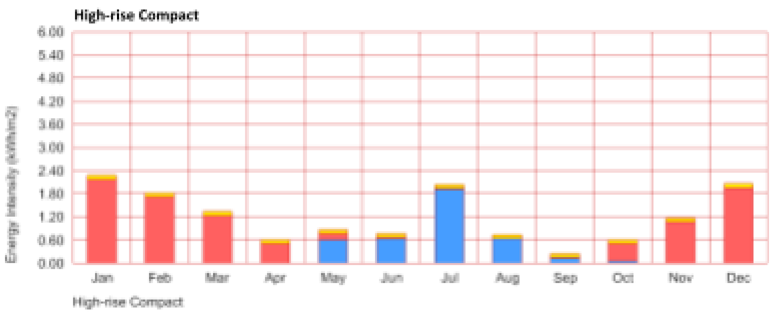
For vertical densities, the impact on operational heating and cooling demand is of significance. This is illustrated with the help of the bar charts in the figures on the next page. The charts are shown as reduced images. The real-size images (including legend) can be found in Appendix G. These figures show the hot water intensity (yellow), heating intensity (red), and cooling intensity (blue) per month for each scenario (in kWh/m²). As indicated by the model results the overall ratios of the different operational demand typologies remain the same for the scenarios, but their absolute values differ.

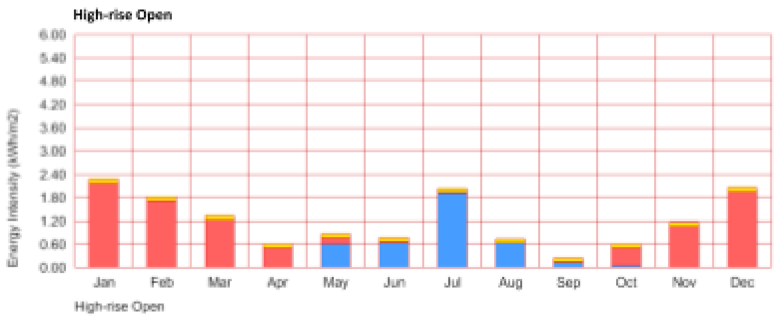












The differences between the vertical densities are quantified in Table 6 below for the total heating and cooling demand. The table shows the observed deviance of both vertical densities from the low-rise baseline scenario, to which the results of mid-rise and high-rise scenarios are compared. The distinction between hot water and space heating is left out of this overview since hot water remains constant for each scenario. Observed differences in heating can therefore be assumed to result from space heating. As the results of both compact and open horizontal density results are equal, the findings apply to both.

	Heating Demand (kWh/m^2)		Cooling Demand (kWh/m^2)	
		Deviation		Deviation
Low-rise	31.5	*Baseline*	8.1	*Baseline*
mid-rise	13.0	- 58.7 %	3.5	- 56.8 %
high-rise	10.7	- 66.0 %	4.0	- 50.6 %

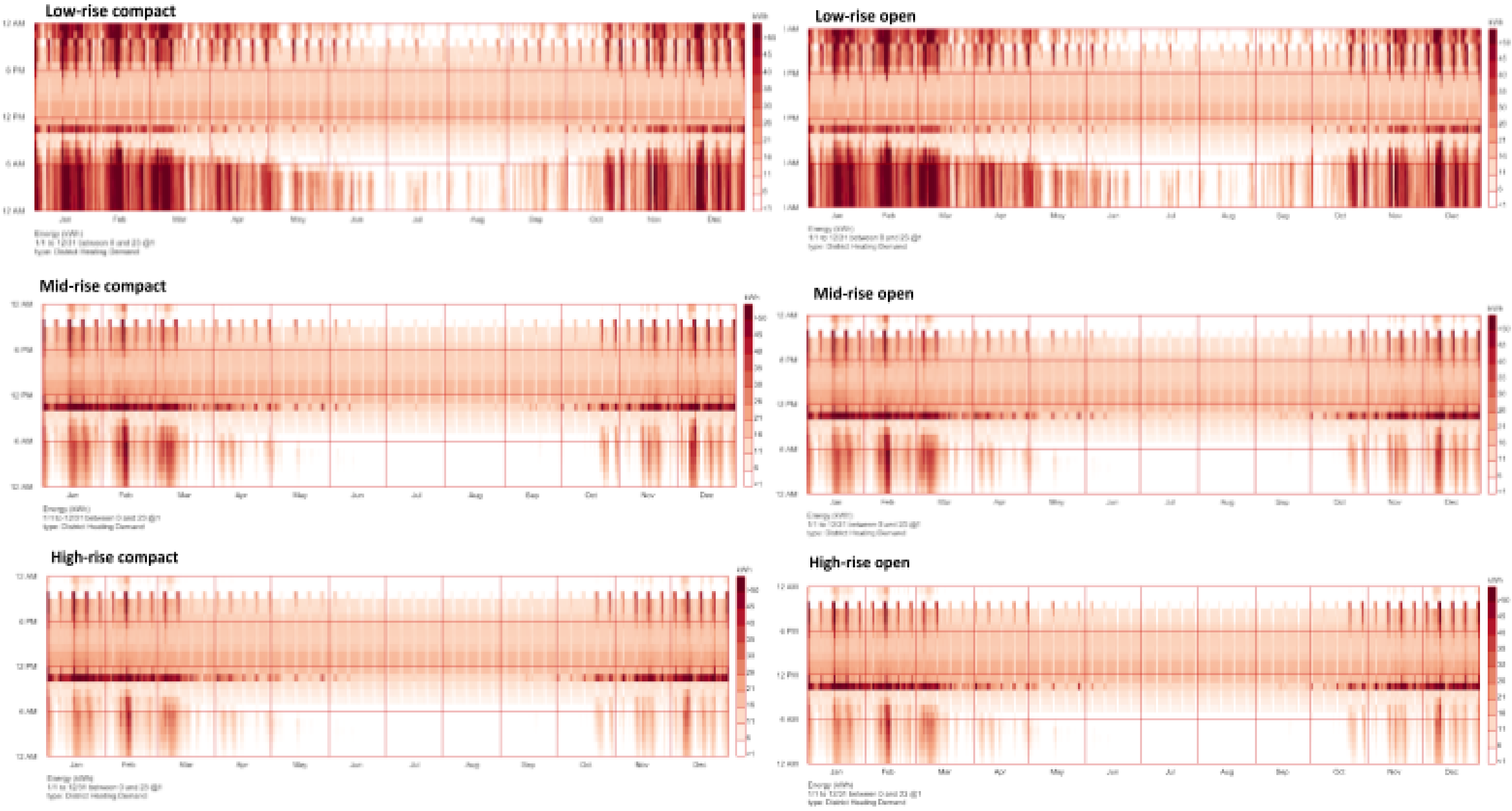
Table 6: Deviation of Operational Thermal Energy Demand

The baseline scenario results in the highest space heating (31.5 kWh/m^2) and cooling (8.1 kWh/m^2) demands. Relative to the baseline scenario, space heating demand decreases most in the high-rise scenario by 66.0%, compared to a 58.7% decrease in the mid-rise scenario. For cooling, the mid-rise scenario shows the largest decrease compared to the baseline, with a 56.8% reduction, compared to a 50.6% decrease in the high-rise scenario. This indicates that, unlike heating demand, cooling demand does not consistently decrease for the vertical densities. Therefore, the high-rise scenario is more favourable for reducing heating demand, while the mid-rise scenario is more effective for reducing cooling demand.

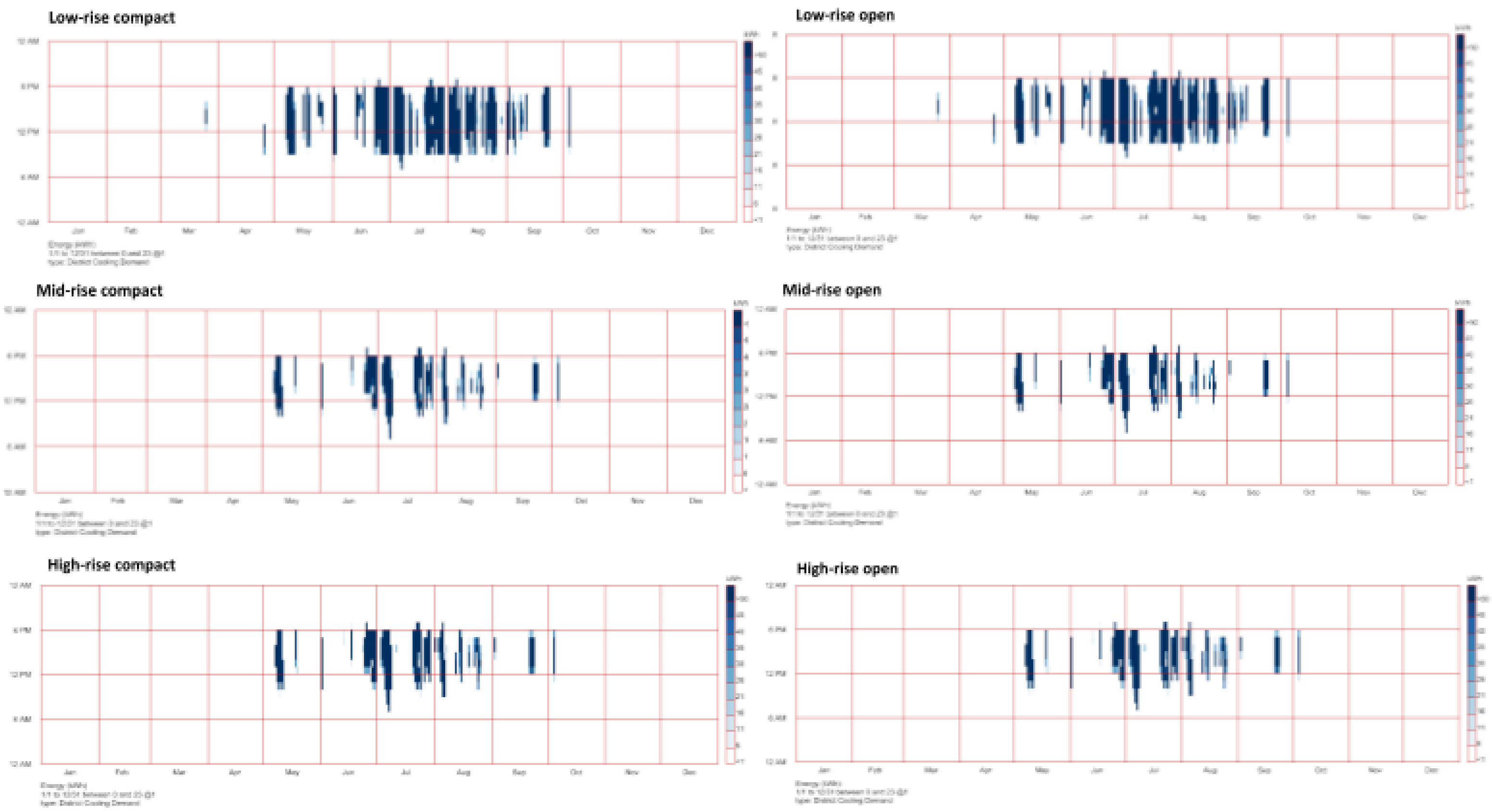
6.2.2. Reuse potential

As outlined in Chapter 4.2.1, simultaneous heating and cooling demand, or thermal overlap, allows the reuse of waste heat from cooling processes to heat other buildings. To illustrate when and how this waste heat can be reused, the following pages contain hourly plots of heating and cooling demand for each scenario, followed by plots visualising the reuse potential for each scenario. These graphs plot the energy in kWh (right Y-axis) over the months January to December (X-axis) for each hour of the day (left Y-axis), with the morning at the bottom of the left Y-axis and the middle horizontal line representing mid-day (12 PM). For horizontal density, the thermal overlap results are equal for both compact and open scenarios, which is also visible when comparing the plots on the following pages. Therefore, this section will focus on vertical densities for which differences are observed between the low-rise, mid-rise, and high-rise scenarios.

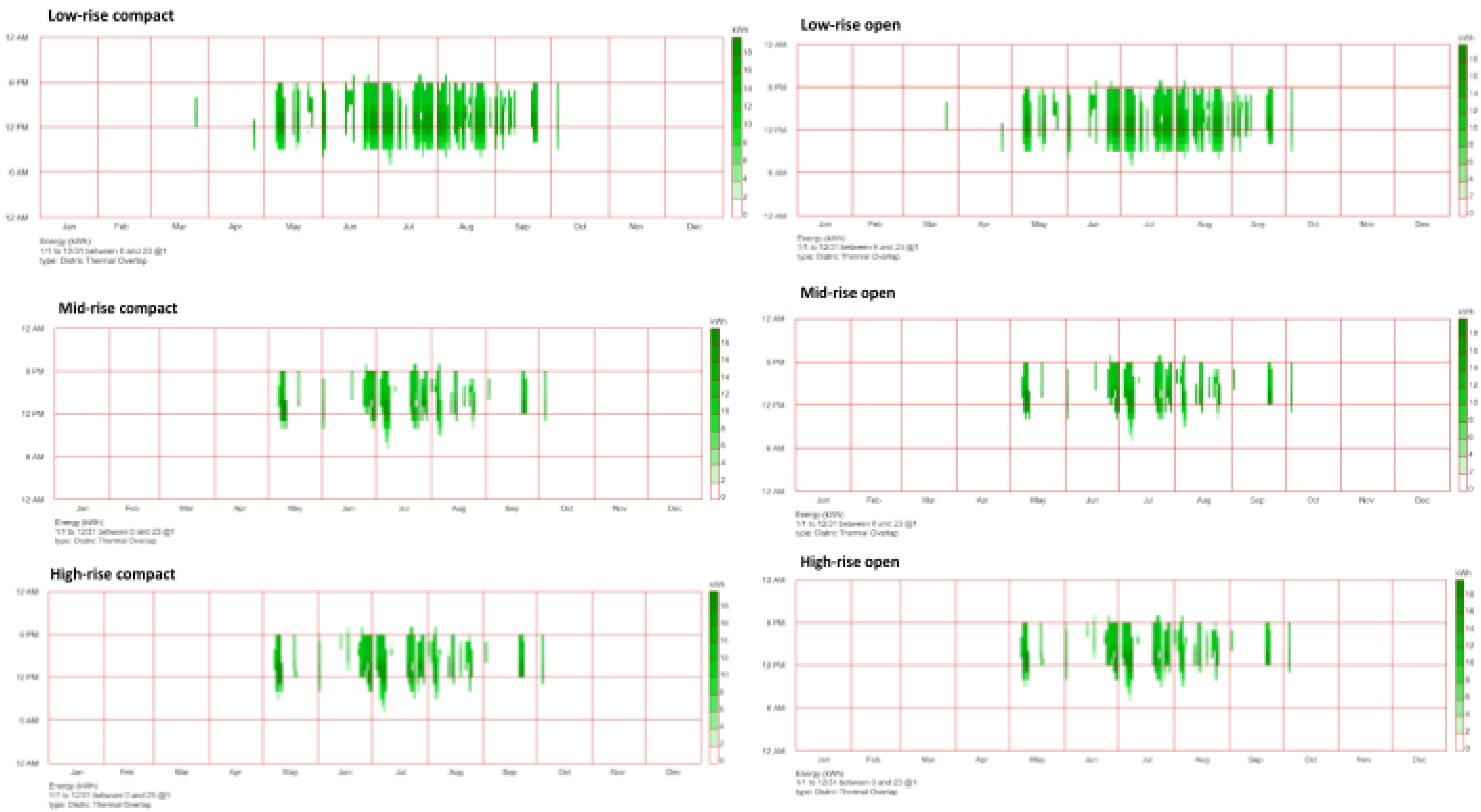
The plots are shown as reduced images. The real-size images can be found in Appendix G. The results of these graphs will be discussed separately for heating, heating, cooling and thermal overlap. For visual comparability, heating and cooling legends range from <1 to >50 kWh. The difference in the range of the total heating and cooling overlap is mentioned in the relevant text.



The hourly heating plots show the logical pattern of heating is highest in the colder months, October to April. These are represented by the darker red on the left and right sides of the plot, ranging from 77 kWh for the high-rise and mid-rise scenarios, and 83 kWh for low-rise scenarios. In the warmer months, May to September, found in the centre of the plot, the heating demand is significantly lower. Furthermore, looking at how demand is divided over the hours of the day, a pattern is visible where the mornings, 12 AM - 7 AM, and evenings, 6 PM - 12 AM show the highest heating demands. This finding is in line with the occupational schedule of residential functions as outlined in TNO (2021, p.21). The lighter red that is visible throughout the rest of the day possibly relates to the heating of non-residential functions and the use of hot water. Furthermore, the constant light red colour visible throughout the year can also relate to hot water demands remaining a somewhat constant factor in heating energy demand.



The hourly cooling plots show the logical pattern of the highest demand in the warmer months, May to September. These are represented by the blue in the centre of the plot, ranging from 1573 kWh for low-rise, 1435 kWh for mid-rise, and 1510 kWh for high-rise. As the plots show, cooling demand is absent in the colder months, October until April, on the left and right sides of the plot. Furthermore, looking at how demand is divided over the hours of the day, it can be concluded that cooling mainly happens during the daytime, when temperatures are generally the highest, between 6 AM and 6 PM. The mornings (12 AM - 7 AM) and evenings (6 PM - 12 AM) show no cooling demand. These results cannot be verified with findings from desk research, since no cooling schedules specific to residential or non-residential are successfully retrieved in the analysis.



The hourly overlap plots show how overlap occurs in the same months and hours of the day as cooling occurs. This is logical since thermal overlap concerns waste heat from the process of cooling. However, as the heating plots show, the heating demand is lowest in the warmer months. Therefore, the waste heat that can be directly reused is also lower since heating must simultaneously occur with cooling. The simultaneous heating and cooling logically result in a lower energy range up to a maximum hourly overlap potential of 18 kWh.

Logically, as operational heating and cooling demands do not differ between open and compact scenarios, the same pattern will apply for overlap load. For overlap to change between different scenarios, the heating or cooling demand has to change to result in differences in their simultaneous occurrence.

Since the hourly plots do not visualise the overlap relative to the corresponding heating demand of that scenario, the thermal overlap is quantified per model scenario and the results (in GJ) are outlined in Table 7 below.

Vertical Density	Total Heating Load (GJ)	Thermal Overlap (GJ)	Heating Demand Coverage
Low-rise (baseline)	*534.4*	*29.8*	*5.58%*
Mid-rise	334.7	13.5	4.03%
High-rise	310.1	14.8	4.77%

Table 7: Thermal overlap relative to the corresponding total heating load

The baseline low-rise scenario has the highest thermal overlap potential relative to the total annual heating load, as 5.58% of the total heat demand can potentially be covered with waste heat from cooling. When comparing the mid-rise and high-rise scenarios, the high-rise scenario has a slightly higher overlap that could cover 4.77% of the total heating demand for that scenario, as opposed to the 4.03% of the mid-rise scenario. As all results indicate a demand coverage lower than 10%, this is a relatively low share of the total demand. This is illustrated for the high-rise scenario in the bar chart of Figure 16 below, where the absolute overlap potential (in kWh) is displayed together with the total heating, and cooling demand in kWh. The figure further illustrates that simultaneous heating and cooling is minimal compared to the total load.

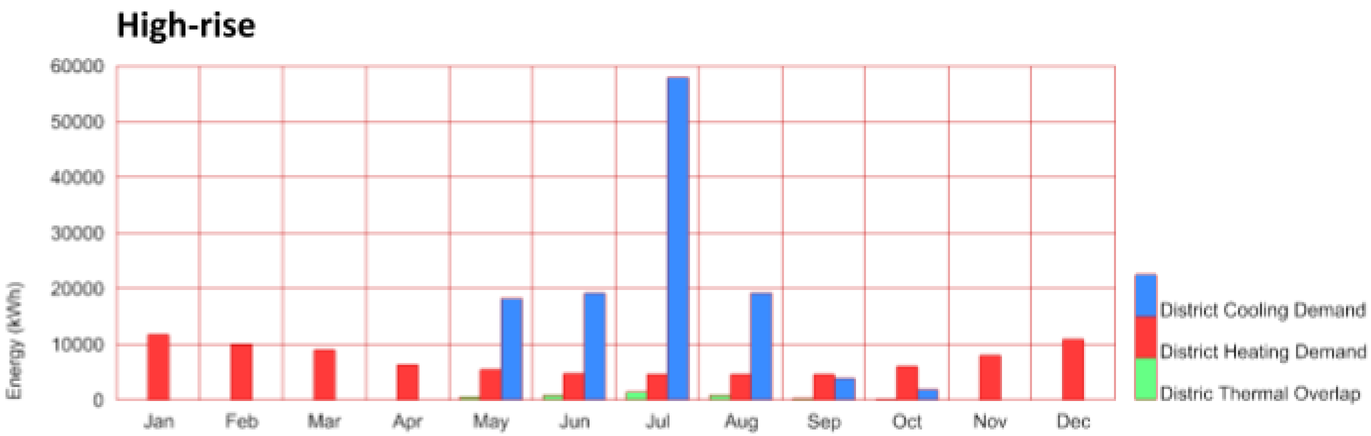


Figure 16: Absolute operational thermal energy demands (kWh) and thermal overlap

6.2.3. Solar Potential

After the impact of urban form on the demand reduction and reuse potential are assessed, the RES production potential can be determined. First, to double-check, the SWTE supply condition provided in Chapter 4.2.3. The created adaptation to the Waternet (n.d.) logic is applied to the model results:

- $A = E\,(heating\ +\ cooling\ demand)/0,1434888\ GJ/m^2/year$

Where sufficient supply was validated if:

- $A\ <\ Total\ Area\ Surface\ Available\ in\ IJmeer.$

This is calculated for the highest total load, the low-rise baseline scenario heating demand. The calculation shows that the total heating load of 534.4 GJ requires 37.243 m^2 of regenerative surface (A). The FD demand can thus be met since 37.243m^2 < 80.000.000m^2 IJmeer water body surface (Ministerie van Infrastructuur en Waterstaat, 2023).

Now the analysis finding of largely sufficient SWTE supply potential is confirmed, the RES electric production potential needed to cover the electricity demand of this SWTE system is assessed. According to the co-creation findings, this is crucial in making a SWTE-system function (see Chapter 3 and Appendix A). The potential RES electricity demand is assessed by conducting a solar analysis, i.e. incident radiation analysis, for each model scenario. Incident radiation analysis measures the kWh of radiation received per m^2 according to a specific incident, or measure point. For simplicity, this assessment concerns the cumulative annual solar energy potential and does not account for seasonal changes in solar radiation. This is an important subject for further research.

Orientation

The key factor impacting solar potential is orientation. This can be illustrated through a skydome, visualising the intensity of radiation for each sky patch within the skydome, in other words, it indicates the sun's location respective to the buildings being analysed. Figure 17 below illustrates the impact of orientation, showing that the north side of the district receives no to very little radiation as opposed to the South, Southwest, and Southeast. This pattern reflects the sun's path across the sky in the Netherlands, where it rises in the East and sets in the West. Consequently, the most direct sunlight is found south of the radiation dome centre and accumulates the most radiation.

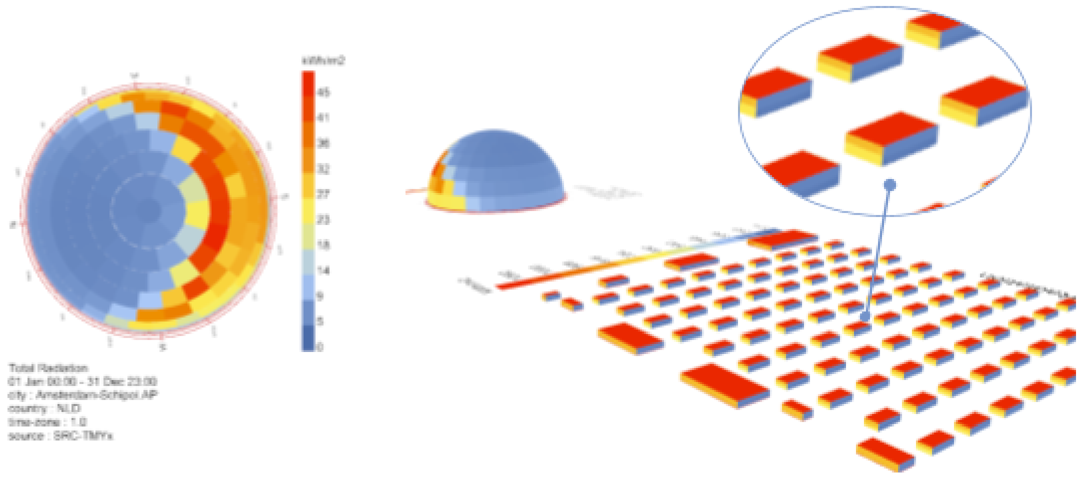


Figure 17: Skydome and incident radiation analysis of the mid-rise open scenario

However, the skydome does not consider the context of urban form, such as building shades. Therefore, this effect is illustrated by the incident radiation visualisations in Figure 18 below. The figure compares the open (left) and compact (right) mid-rise scenarios, showing that the compact scenario has a shading effect that limits incident radiation, particularly on the west and east sides of the buildings. In the open scenario, the shading has less impact, although shadowing on the lower facade is still visible, leading to slightly lower incident radiation. Although orientation appears to affect the incident radiation of a compact scenario more than an open scenario, these effects are not reflected in the operational heating and cooling demand, where differences in horizontal density did not impact the thermal energy demand. Incident radiation thus shows that solar potential is affected by horizontal density and building orientation. The effect of vertical density on solar potential is discussed next.

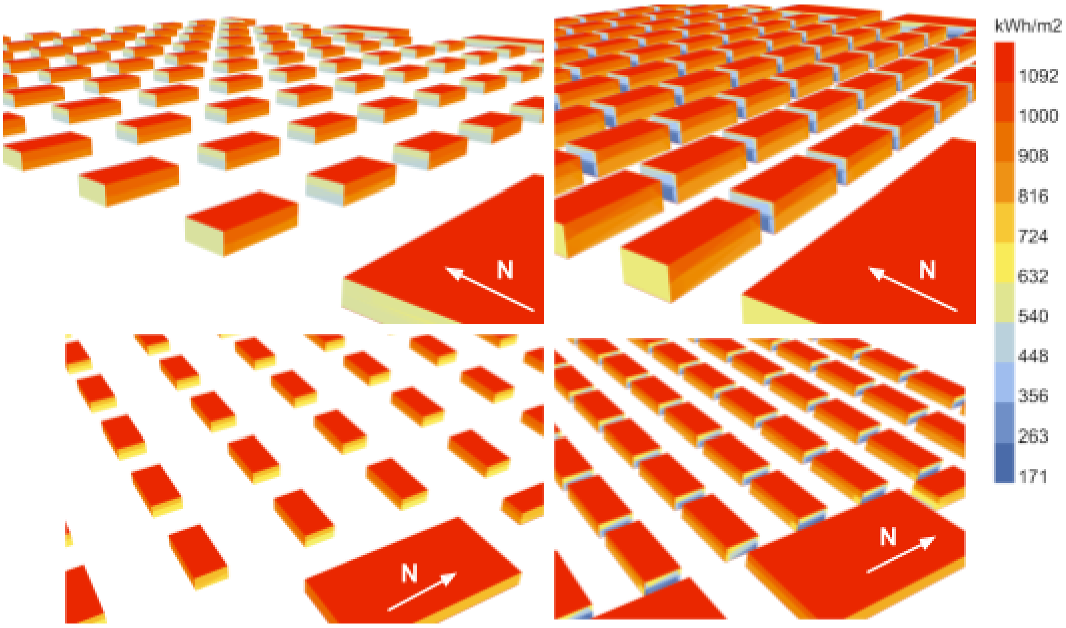


Figure 18: Incident radiation of buildings, roofs, facades, and apertures for an open (left) and closed (right) mid-rise scenario

Photovoltaic (PV) area

Specifically focussing on roof surfaces, the cumulative incident radiation received over a year concerns 1092 kWh/m^2. This is illustrated in Figure 19 below. The figure shows the incident radiation of roofs remains constant regardless of horizontal or vertical density. This can be attributed to a lack of shadowing effects while each building has the same height across the different vertical density scenarios.

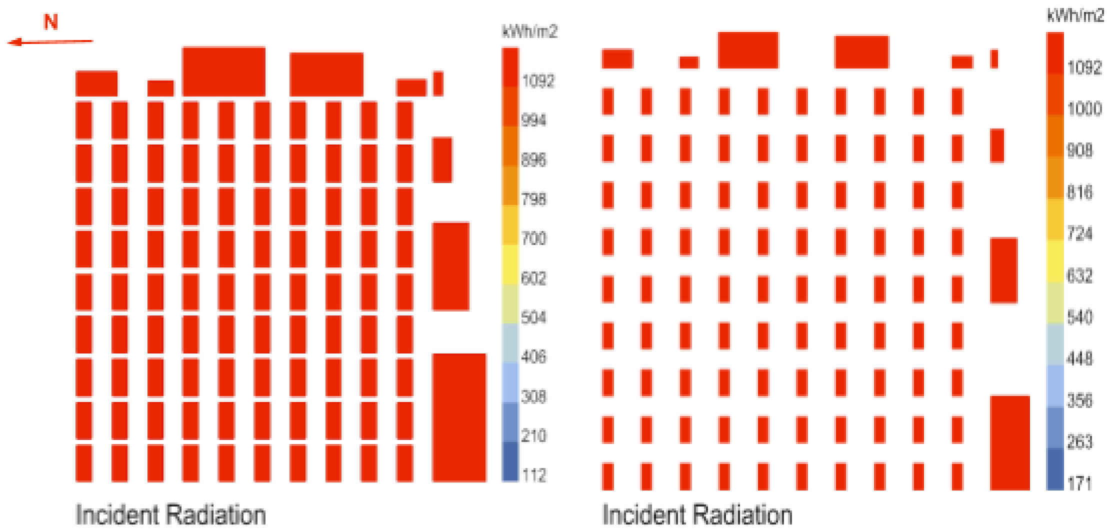


Figure 19: Top-view incident radiation of the compact (left) and open (right) scenario

With this roof surface incident radiation analysis, an indication of the solar potential of the FD can be made. Two key factors help to indicate the solar potential: the available roof surface area (m²) for PV installations and the related PV conversion efficiency, which is the percentage of incident solar energy converted into electricity. The effect of both these factors is illustrated in Table 8 below. This table shows the solar potential per vertical density scenario, assuming PV can effectively convert 20% of the 1092 kWh/m² incident radiation into electricity. Additionally, the table indicates the energy required for the SWTE system to function, assuming an HP COP of 3.5 and pipeline losses of 20% ($Q = E_{heat} * 1.2 / COP$). The calculation is done for heating demand as this is the highest operational demand for each scenario (Table 7 in 6.2.2.). The last column in the table provides the PV area required to meet HP electricity demand, again assuming the 20% PV conversion efficiency ($PV = E_{HP} / 218.4$).

Vertical Density	Roof surface (m^2)	Solar potential (kWh)*	HP electricity demand (kWh)**	PV area required (m^2)
Low-rise	71.875	15.697.500	740.135	3.389
Mid-rise	35.908	7.842.307	305.452	1.399
High-rise	23.958	5.232.427	251.411	1.151
** Assuming 20% of PV conversion efficiency* *** Assuming a COP of 3.5 and pipeline loss of 20%*				

Table 8: Solar Potential Indication

These findings show that the roof surface area available for PV depends on vertical density, with solar potential decreasing as vertical density increases. For instance, the highest potential is found in the low-rise scenario, where the roof surface area is the largest relative to the total building floor area. This negative relationship between solar potential and roof surface area is important in FD design, as experts from Co-creation 1 (Appendix A) suggest that electricity demand will be the most challenging factor in achieving self-sufficiency.

When comparing both blue columns, it is clear that the available roof surface is adequate for the required PV area in each scenario. Additionally, each model scenario indicates a 23.7 kWh/m² electricity demand for electrical equipment. This demand is equal for each scenario, regardless of horizontal or vertical density. To meet this demand approximately 7.437 m² of additional PV area is required, yet the roof surface and solar potential remain sufficient in every scenario.

6.2.4 Final Evaluation

In conclusion, the total district operational energy demand and consequently the thermal overlap show no differences between horizontal densities (open and compact). This contrasts with literature stressing the effect of block scale horizontal and vertical density on energy demand (Wu & Liu, 2023). This is likely a result of model simplicity since building heights are modelled to be equal in each scenario and no direct building adjacency is included. This limits the effects of daylighting, solar potential, and efficient energy utilisation on the thermal energy demand. However, when considering vertical densities, the high-rise scenario is most effective, achieving a 66.2% reduction in heating demand compared to the baseline scenario. This reduction is 9.2% greater than the largest decrease in cooling demand observed in the mid-rise scenario. If differences in horizontal density had occurred, selecting an optimum could be seasonally dependent. Adjusting the placement of floating buildings to the scenario that benefits the cooling or heating demand most. However, vertical density is not a parameter that could be flexibly changed in a floating design. Therefore, the highest decrease compared to the baseline scenario is deemed most favourable. This results in the high-rise scenarios being the most desirable with the highest reduction in operational thermal energy demand.

Considering thermal overlap, this occurs in the warmer months when cooling demand is high, and buildings still require heating e.g. for hot water. The baseline scenario shows the highest demand coverage and thus relative reuse potential but is excluded from the final evaluation. In both the mid-rise and the high-rise scenarios the overlap potential is minimal as the heating demand coverage is <5% for both. However, the high-rise scenario is slightly more desirable considering the relative reuse potential.

Lastly, the incident radiation analysis shows horizontal density negatively impacts facade incident radiation. As mentioned, this does not result in observed differences in thermal energy demand between horizontal density scenarios. However, since only roof surfaces are considered for PV solar generation, the available roof area remains sufficient to meet the FD electricity demand for the HP and electrical equipment in all scenarios, despite decreasing roof surface area as vertical density increases. Therefore, the KPI of maximising relative solar production potential is not a determining factor in evaluating an optimal scenario. Concerning the other two KPIs, the high-rise scenario, irrespective of its horizontal density, is most optimal in terms of minimising operational thermal energy demand, and maximising relative energy reuse potential.

7. Discussion

7.1. General

This research explores how block-scale urban form parameters, specifically horizontal and vertical density, impact the operational thermal energy demand, reuse and production potential of the FD project. The study addresses the need for design-based research to explore how new large-scale urban design can impact energy planning, specifically of a floating district resulting in a focus on thermal systems for SWTE. In four phases, a parametric energy model is created to assess the effect of various block-scale urban form scenarios on the reduction, reuse and production potential. The latter focuses on the electricity required by the SWTE system rather than thermal energy production, as this is confirmed to be largely sufficient.

The model results indicate that variation in compact or open horizontal density shows no observable impact on the operational energy demand and consequently not on the thermal overlap. This lack of difference underlines the interrelation between demand reduction and reuse potential, as reuse potential will only change if differences in simultaneous heating or cooling demands occur. The lack of difference in thermal energy demand contradicts the solar potential analysis findings, where incident on facades, particularly the east and west-oriented ones, decreases as horizontal density increases. However, the results indicate that the observed differences in incident radiation do not significantly impact the operational thermal energy demand. The lack of difference could be attributed to model simplicity. For the variable scenarios, this regards assumptions like equal building heights across all vertical density scenarios and no direct building adjacency incorporated into the horizontal density scenarios. These assumptions limit variations in factors like daylighting, solar potential, and efficient energy use addressed in the literature. The fixed model parameters could also be of influence, relating to factors like lack of variation between building orientation or the chosen WWR.

In contrast, variations in vertical density did impact the thermal energy system. First, modelling results indicate that the high-rise (3-floor) resulted in the most relative demand reduction compared to the low-rise (1-floor) baseline scenario. Second, while the potential for waste-heat reuse is minimal, the high-rise scenario shows slightly more relative overlap. Third, even though roof surface solar potential decreases as vertical density increases, all scenarios provide sufficient potential. This results from equal building heights being assumed, preventing shadowing on the roof surfaces. The final evaluation of these findings suggests that increased vertical density leads to the greatest relative operational thermal energy demand reduction and reuse potential for the FD project while still having sufficient thermal and electricity production potential.

7.2. Interpretation

The findings of this research indicate that block-scale urban form parameters can impact the energy system in terms of thermal energy demand reduction, reuse, and production potential. The impact depends on which urban form parameters are considered, e.g. horizontal or vertical density, and the energy system components under consideration, e.g. thermal or electric. When analysed individually, these parameters and components show complex interactions of different elements. For urban form, this concerns the interrelatedness of density indicators on the urban block scale, where the constant FSI results in relational changes between the other indicators: Layers, GSI, and OSR. For the energy system, there is interaction between supply-side components (e.g., HP efficiency, heat exchanger type, HVAC operational settings) and the resulting demand, particularly concerning operational thermal energy demand and thermal overlap. This emphasises the need to analyse different parameters and components individually.

Furthermore, this study highlights the complex interaction between urban form and the energy system, particularly horizontal and vertical density. The findings indicate that vertical density scenarios have a variable impact on the energy system, with high-rise scenarios proving to be the most favourable. The effects of vertical density vary in significance, with minimal thermal overlap potential observed despite notable differences in operational energy demands. This may be attributed to the chosen building typologies, as the literature suggests that varying operational schedules can positively impact thermal overlap potential. In contrast, no differences were found between horizontal densities, this contradicts existing literature but could be explained by certain modelling assumptions, such as constant building heights across vertical density scenarios and the exclusion of direct building adjacency. These simplifications could affect energy demand, reuse and reduction potential. This is further illustrated by the solar analysis, which shows an apparent effect of horizontal density on incident radiation of facades. However, this effect does not result in changes between open and compact horizontal density. This highlights the need for further detailed exploration of this parameter.

The findings of this research highlight that urban form and energy systems are highly interrelated and need individual assessment to understand their potential effect. Understanding the connections between urban form and the energy system is important before translating theoretical insights into practice. While this research primarily focuses on horizontal and vertical density, more parameters are relevant to further explore, such as function placement, function typology, building orientation, building heights, WWR, shading, insulation, or roof slope. Understanding the interaction of other block- and building-scale parameters with the energy system can support a comprehensive understanding of their role in FD design and energy planning. Therefore, this research supports the need for further design-based studies in early-stage urban development and highlights the role of parametric modelling as a powerful tool for evaluating the interaction between urban design and energy systems.

7.3. Implications

This research combines Smart Urban Isle (SUI) and Energy Island literature to create a theoretical foundation for the scalable and self-sufficient design of floating urban forms, with the prerequisite of creating a locally balanced energy system. Additionally, this research provides specific insights into a thermal system that allows for flexibly moving floating design and the theoretical differences in insulation between conventional and floating construction. Both insights could be relevant in future assessments of floating designs at any scale.

Furthermore, this research results in a framework for assessing the impact of urban form parameters on early-stage development, focussing on new urban forms for large-scale floating developments. Applying this workflow to similar block-scale or building-scale urban design projects, both floating and non-floating, allows for anticipating interactions between urban form and energy systems during the design phase.

Finally, the parametric model developed in this study operationalises the assessment of these interactive effects between urban form parameters and energy system components. This model provides a tool that supports more informed decision-making during the design process. It lays the groundwork for further testing and refinement, ultimately leading to more optimised and efficient floating urban designs.

7.4. Research Limitations

Research Scope

Technical potential

The scope of this research is limited to the technical potential and thus does not regard the other types of potential, financial feasibility and social acceptance, that influence the practical feasibility of the FD project.

Parameters

The scope of this research is limited to thermal energy, specifically SWTE systems. This excludes other RES like electric energy, and biogas that could be employed within the broader urban energy system. As a result, the interactions between different RES-based systems within the overall energy system are not considered in this research.

Additionally, the research scope is limited to two urban form parameters related to density. This allows the isolated assessment of how the selected urban form parameters impact the energy system. Other variables are therefore considered fixed in this research. The results of this research must be interpreted with the notion that this study only examines horizontal and vertical density, meaning findings are specific to these parameters and cannot be directly generalised to all factors influencing urban form.

Scale

The scope of this research is limited due to the block-scale modelling of urban forms. Consequently, certain levels of detail are beyond the scope of this research. Some building-scale parameters are included with limited detail, for example, WWR is considered, but window shading is not.

Research Assumptions

Subjectivity of Research Assumptions

The fundamental assumptions underlying this research are the product of co-creation. Even though co-creation participants are experts in energy planning, urban design and floating construction, this method still implies a subjective result. The results are embedded in the context of this co-creation like the background of the participants (e.g. expertise, age, gender, etc.), the background information presented in the co-creation, the format of the co-creation, the dilemmas, and considerations raised in the session's discussions, etc. All these factors contribute to some degree of subjectivity.

Moreover, subjectivity is implied in the modelling decisions throughout this research. These decisions are influenced by personal biases, e.g. the incorporation of houseboat-like characteristics in the geometry shape. Additionally, the current level of proficiency with the software also plays a role, limiting the capacity to which software functionalities are fully utilised.

Model Representativity

Model Simplification

The model concerns a simplification of reality. Therefore, certain assumptions in creating this model limit the accurate representation of urban form characteristics. Such simplifications concern assumptions about the main variable parameters, like constant building heights in the vertical density scenarios and no direct building adjacency in the horizontal density scenarios. Furthermore, the fixed parameters imply simplification for parameters like the constant building orientation, WWR, unit size, and monofunctional building typologies. An important example is that the variety of building facade insulation is not addressed. All buildings were assumed to have the same insulation values as The Float reference facades that border water, rather than accounting for a mix of water-bordering and air-bordering surfaces. Finally, relevant parameters are also excluded from modelling due to simplification. These concern parameters like the placement of green spaces, which could impact energy demand due to their cooling effect, or accounting for seasonal variations in solar potential.

All the mentioned simplifications limit the model's representativity of reality as they are likely to impact factors addressed in literature like shading, solar potential, operational energy demand, reuse potential, and production potential.

Building programs

Certain building programs are not available in the Ladybug software. These concern community centres, art centres, a healthcare centre (like GP practice), and a commercial gym. Such missing building program types are replaced with programs or a combination of program components that share similar operating hours and occupancy schemes. To illustrate, for the art centre a library program is used. Once building typologies are defined in a later stage of project development, the expected operating and occupancy schedules can be customised and the energy loads corresponding with the program can be modelled more specifically.

A second limitation regarding building programming is that various programs miss data on hot water demands, resulting in missing data in the final results. These gaps were filled by manually assigning the school program’s hot water values

Urban form metrics

Block-scale urban form metrics of new large-scale developments, particularly for floating urban forms were not found. As a result, metrics used for existing urban forms are adopted to create the scenarios in this study. This approach limits the extent to which model results represent new large-scale floating urban developments. This is because conventional metrics do not consider potential differences between floating and traditional urban forms. For instance, floating urban forms may offer unique opportunities for adaptability and flexibility in horizontal density that conventional metrics do not capture.

Furthermore, the way urban form metrics were applied can also impact representativity. As for vertical density, using a constant floor height and a fixed number of floors does not accurately represent the dynamic nature of urban forms, which are known to impact energy systems, as highlighted in the literature. Similarly, for horizontal density, the decision to focus on open and compact BARs, while excluding sparse BAR (0.02 - 0.15), may have contributed to the lack of difference between horizontal density scenarios. The same applies to excluding direct building adjacency in horizontal density scenarios.

Validation

The Rhinoceros Grasshopper modelling software is based on American standards, which differ from Dutch building codes, such as the BENG norm. To increase the model's relevance to the Dutch context, adjustments were made to key parameters, including HVAC setpoints, temperature settings, heat recovery rates, and building envelope insulation values. However, to align the simulation outcomes with provided benchmark values, additional parameters like water flow, window-to-wall ratios (WWR), and ventilation rates are recalibrated to minimise deviation from these benchmarks. While this recalibration ensures closer alignment with benchmark values, it also limits the extent to which all model parameters accurately represent real-world conditions.

Furthermore, references to multi-family floating buildings are not found. Instead, the model uses the insulation values of the single-house boat typology of The Float, which aligns with most FD characteristics while meeting BENG and circularity requirements. However, this does mean that possible differences from multi-family floating typologies are not accounted for.

Finally, model performance is validated per single unit. Validation is conducted successfully for all typologies. However, for hot water demands of the housing typology, a modelling issue occurred when scaling up the geometry to the desired FSI[5]. Therefore, the representability of tap water values is not reliable. However, since tap water demand remained constant across all scenarios, the differences in model results can safely be assumed to relate to space heating and cooling.

Future proof

This research is an early-stage design exploration for a project that may be implemented in the future. Creating a model for such a project is challenging, as potential changes in future boundary conditions can only be accounted for to a certain extent. Throughout the research, efforts are made to consider future contexts, such as assumptions regarding construction materials and progressive HVAC setpoints. However, many parameters are difficult to predict for future scenarios. These could include changing benchmark values due to improved building insulation standards, climate change, or even lower tap water temperatures due to new techniques preventing bacterial infection. The uncertainty in future boundary conditions further limits the extent to which research outcomes are reliable and scalable.

[5] *The error likely relates to data tree management but was not successfully resolved within the timeframe of this research. For a more detailed discussion on this issue see:* *https://discourse.ladybug.tools/t/hot-water-value-changes-when-geometry-is-multiplied/30960*

7.5. Future Model Use

The parametric model developed in this research can have different use cases that could help further explore the FD project's feasibility. The main future applications are discussed here.

Extended Density Scenarios

The parameters assessed in this research can be further tested for a greater range. This way vertical and horizontal densities that exceed the scope of this research could be explored. For vertical densities, this means testing scenarios that exceed the defined maximum of three floors or scenarios differentiating vertical densities per scenario, to gain insight into the possible effect on incident radiation. For horizontal densities, this means testing more cell sizes and including direct building adjacency in horizontal density scenarios. This way it can be further assessed if horizontal density impacts the energy system significantly, and if so, at which BAR_{cell} .

Different Parameter Calibrations

The current model provides the basis for testing parameters other than horizontal and vertical density. For the context of this research, many parameters are considered fixed to assess the effect of different densities on the energy system. However, this does not imply that these remaining parameters do not affect the energy system. These could be tested with this model by parametrically changing their current settings. To illustrate, some parameters that could be calibrated differently include the sizing of buildings, sizes of building blocks, function placement, building orientations, WWR, window shades, construction materials, heat pump efficiency, system heat-recovery, or setpoint temperatures.

Additional Parameters

The current model is a simple block scale model, containing only a series of key components that could be important in assessing the relationship between urban form and the energy system. A higher level of detail can be achieved by elaborating the building-scale characteristics included in the simulation.

Additionally, more detail could be achieved by expanding the morphology and energy system components integrated into the model. This way the simulation can assess more parameters and account for their interactive effect. Some examples that could be relevant for the model extension are integrating storage components, shading effects of greenery, heating and cooling networks, collective and individual scenarios, and the energy potential of other RES (e.g. wind, biomass, etc.).

Expanded Energy Assessment

The current model assesses space heating, hot water, and cooling demand. However, different types of energy data can be simulated using the same model. Some relevant examples are lighting, (electric) equipment, fan electricity, pump electricity, occupant heat gain, solar gain, infiltration, (natural or mechanical) ventilation heat gain and loss. The interaction between the parameters mentioned in the sections above and these energy components could be assessed.

Application on other Case Studies

Finally, applying this model to other newly built large-scale floating developments could improve its ability to represent this new urban form. Insights from these additional cases could be integrated into the model. This would enable validation of the model against the features of existing floating urban forms, enhancing its performance and the reliability of its outcomes.

8. Conclusion

To conclude, the municipality of Amsterdam is exploring the feasibility of creating a scalable floating district with a self-sufficient energy system. Since this project involves a new urban form, there is an opportunity to consider how design choices can influence the energy system. This research assesses the impact of specific urban form parameters on the energy system's operational thermal energy demand, potential for reuse, and renewable energy production through parametric modelling. The research comprises four phases.

In the first phase, key parameters were selected for investigation, as the FD project involves a new design without predefined parameters. Through co-creation, the main research parameters were chosen. An energy system aligning with the FD objectives was selected, with experts identifying a closed SWTE system as the best option. This system requires no storage for functioning year-round, ensuring a self-sufficient, scalable system that allows for free movement. Vertical and horizontal density were chosen as the urban form parameters to be assessed for their impact on the energy system. These findings form the foundation of this research.

The second phase involved desk research, resulting in a comprehensive literature review that analysed the project context, the SWTE system, and the urban form parameters of vertical and horizontal density. KPIs were also defined. The project context analysis provided a theoretical foundation for understanding the FD's role in the energy transition. The island-like context of the FD can serve as a case study for operationalising a locally balanced energy system, which is crucial for overcoming the unpredictability of RES and essential for scaling up self-sufficient energy systems. The literature review also explored the interaction between urban form and the energy system, explaining how urban form changes at the block and building scales impact the energy system's reduction, reuse, and production potential.

When analysing the block-scale urban form parameters, it was found that no metrics specific to floating or new large-scale urban form development exist, so existing metrics were adopted. Vertical density was highly interrelated with other block-scale urban form density indicators, such as FSI, GSI, and OSR. Alterations to one can affect the others. For horizontal density, the BAR, which concerns an area-specific GSI, was applied to define compact and open urban forms.

The technical analysis of the selected closed SWTE system revealed that the regenerative surface of the IJmeer pilot location is largely sufficient to meet the required SWTE potential to create a local balance. Additionally, the scalability of the SWTE system was demonstrated through its modular heat exchangers, confirming the system's potential for wider use. This analysis verified the key assumption that there is adequate SWTE supply and systemic feasibility to support this supply, indicating that a local balance can be achieved and the FD project can be scalable. Consequently, the production analysis focused on the RES production potential required to meet the SWTE system's electricity demand.

The third phase involved creating the parametric energy model for the FD project. The model assessed the impact of the variable urban form parameters of vertical and horizontal density on the energy system. First, the block-scale residential and non-residential morphology was created. Then, the energy system logic and building insulation characteristics were integrated into the model as fixed parameters based on reference values, including WWR and HVAC operational settings. The model's ability to simulate the operational energy demand of these typologies was validated according to conventional building insulation standards before being adjusted to FD characteristics. Once the model was finalised, six block-scale urban form scenarios were created by combining open and compact horizontal densities with three vertical densities: single-floor low-rise, two-floor mid-rise, and three-floor high-rise.

In the final phase, the model results were assessed to evaluate which scenario minimised the trade-offs between the urban form and the energy system according to the KPIs. The results indicated no significant differences in operational thermal energy demand or overlap demand between scenarios with open and compact horizontal density. While compact horizontal density reduced incident radiation on building facades, particularly those facing east and west, this did not translate into differences in thermal energy demand. The finding that horizontal density does not impact the energy system could be attributed to the model's simplicity, as it did not include direct building adjacency and assumed equal building heights for each horizontal density scenario.

In contrast, the vertical density scenarios did show differences. The high-rise scenario performed best in minimising trade-offs between KPIs. It achieved the greatest reduction in operational energy demand relative to the baseline scenario resulting in the highest thermal overlap potential relative to the total heating demand, although these effects were minimal. While higher vertical density led to a decrease in solar potential due to a reduced PV area, this was not a determining factor in the assessment. Each scenario provided sufficient solar potential to meet the SWTE system's electricity demand and the additional demand for electric equipment.

This research provides a foundation for optimising early-stage design, specifically large-scale floating urban districts. It offers insights that contribute to sustainable urban development and the energy transition. By integrating parametric modelling, this study provides a framework for assessing the interaction between urban form parameters and energy systems, laying the groundwork for further exploration of the technical, economic, and societal potential of the FD project. Although the study is limited by its focus on specific parameters and model simplicity, it offers a valuable tool for future research and design in the evolving field of floating urban development.

9. Recommendations

Based on the findings of this study, recommendations for future research are provided.

Widen the Scope

Future research could adopt a more holistic approach by investigating how the technical potential of the energy system is affected by other systems, such as mobility and sewage, as well as by components of the energy system like electricity. Additionally, future research should explore the economic and societal potential of the floating district (FD) project. Such research would provide a more comprehensive feasibility assessment, accounting for financial and legislative factors and anticipating how these may evolve in the future.

Model Expansion

Future research can assess more urban form parameters with the model outlined in Chapter 7.5. As for energy, the model could be utilised to test the scalability and self-sufficiency of other RES. In this respect, it would also be valuable to look at the integration of storage solutions, specifically, electrical storage, as this is expected to be most challenging when aiming for a locally balanced system according to experts. Furthermore, evaluating varying degrees of collectivity could be valuable as this also highly relates to urban form. This type of research could help explore a wider range of energy systems and urban form scenarios, enhancing the feasibility analysis of the floating district.

Adaptive urban design

Future research could explore the unique flexibility of floating urban forms, particularly their potential to adapt to seasonal or climatic variations. Such studies could focus on how floating districts represent an adaptive urban form. Findings from this research can serve as a foundation for further investigation, especially through parametric modelling, which can simulate these adaptive scenarios. Furthermore, developing specific metrics for floating and adaptive designs is recommended to enhance the evaluation and optimisation of these dynamic urban forms.

Practical applications

Future research could investigate the practical interaction between design and the energy system, e.g. through small-scale pilot studies. These studies could aim to achieve local balance while considering interaction with urban forms. Testing the practical feasibility of concepts discussed in this research, like the theoretical potential of the SWTE system, is necessary before scaling up to the urban block level. The FD project offers a relevant use case for pilot studies that further test the interaction between urban form and energy systems.

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11. Appendices

Appendix A. Co-creation 1

14-06-2024, Gemeente Amsterdam Weesperplein.

Two conceptual drafts of an optimal energy system (self-sufficiency/reliability optimum) are designed in co-creation with 16 attendees who have expertise relating to energy systems, floating structures or other related topics. The two design groups were given boundary conditions relating to the case study which consisted of 1500 units, self-sufficient, relying upon locally available Renewable Energy Sources (RES), Mixed district (60% residential functions, 40% non-residential functions), New Built, Low Temperature (LT) heating & cooling network (30-55 °C) and lastly degree of independence. Regarding the latter, the degree of independence means to which extent floating structures and their energy system can move around. Three degrees were distinguished: A - connected to the mainland energy system, B - Self-sufficient but in a fixed location (can use geothermal storage), and C - Self-sufficient free-floating (cannot use geothermal storage). Only degrees B and C were considered throughout the design assignment since the self-sufficiency requirement is not met in the degree of freedom A. After the designs were pitched Part II of the co-creation started. In this part, the groups discussed core dilemmas, trade-offs, and findings that came up in the discussion. It was asked to focus on the interaction between building design (geometry) in interaction with the energy system. This appendix shares a brief overview of these results in the following order: Expert Attendee List, Part I results (Group I, Group II), and Part II results.

Expert Attendee List:

Participant	Organisation	Expertise
1	Waternet, HvA	Aquathermia
2	Blue21	Floating construction
3	Municipality of Amsterdam, CWA	Energy/Heating & Cooling
4	Koster Innovaties	Innovation Advise (Delta/Maritime focus)
5	Bartels & Vedder	Floating construction
6	Municipality of Amsterdam, IBE	Engineering
7	Municipality of Amsterdam, Houseboats	Houseboats
8	TU Delft, AMS	Architectural Engineering + Technology
9	MSc Student, Intern Municipality of Amsterdam, CWA	Energy/Heating & Cooling
10	Municipality of Amsterdam, CWA	Energy/Heating & Cooling
11	Smart City Amsterdam	Engineering
12	Municipality of Amsterdam, IB	Houseboats
13	Municipality of Amsterdam, CWA	Energy/Heating & Cooling
14	Student HvA	-
15	TU Delft	Environmental Technology and Design
16	FlexBase	Floating construction

PART I: ***Energy Design Game***

Group I - Discussion Notes

Sizing:

- Dilemma: Is every unit autarkic or not?
- Not every dwelling can be self-sufficient.
- Don't have social cohesion either.
- Min 1000 dwellings to make wastewater profitable.
- 1 unit is not the same as 1 dwelling (high-rise).
- You need a focal point / central square.

Is 1 square even enough for 1500 homes? Yes, as it is a form between a district and a neighbourhood. The midpoint serves as a distribution point and provides social cohesion. Allows connection with other 1500 clusters.

- Integrality is key.

Geometry: 3 levels

1. Large generation of 1500 homes
2. Block (clusters)
3. Individual homes or rooftops (useful to make all rooftops collectively owned, so that PV panels can be compulsorily put on everything).

Density:

- Compact buildings.

Scalability:

- You have to build high, but the lake is only 4 metres deep.
- Stability is also in the width, and: only 4 layers high.
- From 4 layers upwards, a lift does come into play, again costing electricity. Floating office in Rotterdam is a good example, here they have 3 layers + lift. Here, the heat exchanger is in a concrete container.

Energy System:

- Rely on everything that is familiar and known and innovations. So both PV + solar boilers + PVT. In terms of heat; TEO with a heat pump and as a buffer biogas (can be from wastewater).
- TEO can affect water quality, but: water never cools to below 4 degrees Celsius (even under ice caps).
- Passive systems
- Heat battery (salt) is also an option (could also be collective, the boats as floating batteries
- CHP is mostly fixed, but can also be connectable (flexible).
- 1500 dwellings, 2 sources is sufficient (1WKO)
- Can also have multiple WKOs spread across the lake.
- IBA sewage systems

Mobility:

- Cars are unlikely to be an option as a form of transport, but perhaps electric boats. Will also make facilities like sports fields, and schools important. In terms of transport, bike lanes/walkways between blocks (also as an incentive to exercise).
- Walkways under which everything hangs.
- Land system or water, or own system (water system with pedal boat or boats)
- Pedestrian circle within the centre

Wave Impact:

- Wave energy is not useful but breakwater (wave action is a major drawback with floating homes)
- Floating breakwater? Efficiency not known (and then as a kind of circle around the neighbourhood, floating arena, this can also be flexible/moveable)
- Large stable buildings as a breakwater

Group I - Final Design Concept

Pitch: Scenario C - Self-Sufficient Free Floating: Movable and not connected to the mainland
This scenario is selected because if you aim to be fully flexible (degree of independence C) you can always fall back on a self-sufficient but fixed system (degree of independence B)
Apartment blocks.

Simplified System Layout: Heating + Cooling: TEO + HP (no storage needed)
Energy: PV + A few Wind Turbines, Sewage system + Generator → Small Grids to connect blocks

Group II - Discussion Notes

Geometry:

- stacking houses (3-4 layers), one unit consisting of multiple houses with a structure underneath
- Small floating apartment blocks
- High density

Electric Storage: most challenging

- Batteries currently cannot cover seasonal differences
- Include some type of hydrogen in wintertime (e.g. biofuels)

Energy System:

- A system that moves with your buildings vs. docking your buildings to a central platform
- Create a type of enclosed water body where you increase the water level at times of energy storage and lower your level to generate energy in case you have an energy shortage
- If you select option B (self-sufficient but fixed location) you could use heat and cold storage where you store a surplus that can be used for mainland energy supply.
- PV panels on the roof of the facade

Heating + Cooling:

- Each unit has a heat exchanger at the bottom of the platform addressing TEO/SWTE
- COP (4-5) for well-insulated buildings
- HP (powered by electricity
- Block heating

Central platform:

- Central energy platform

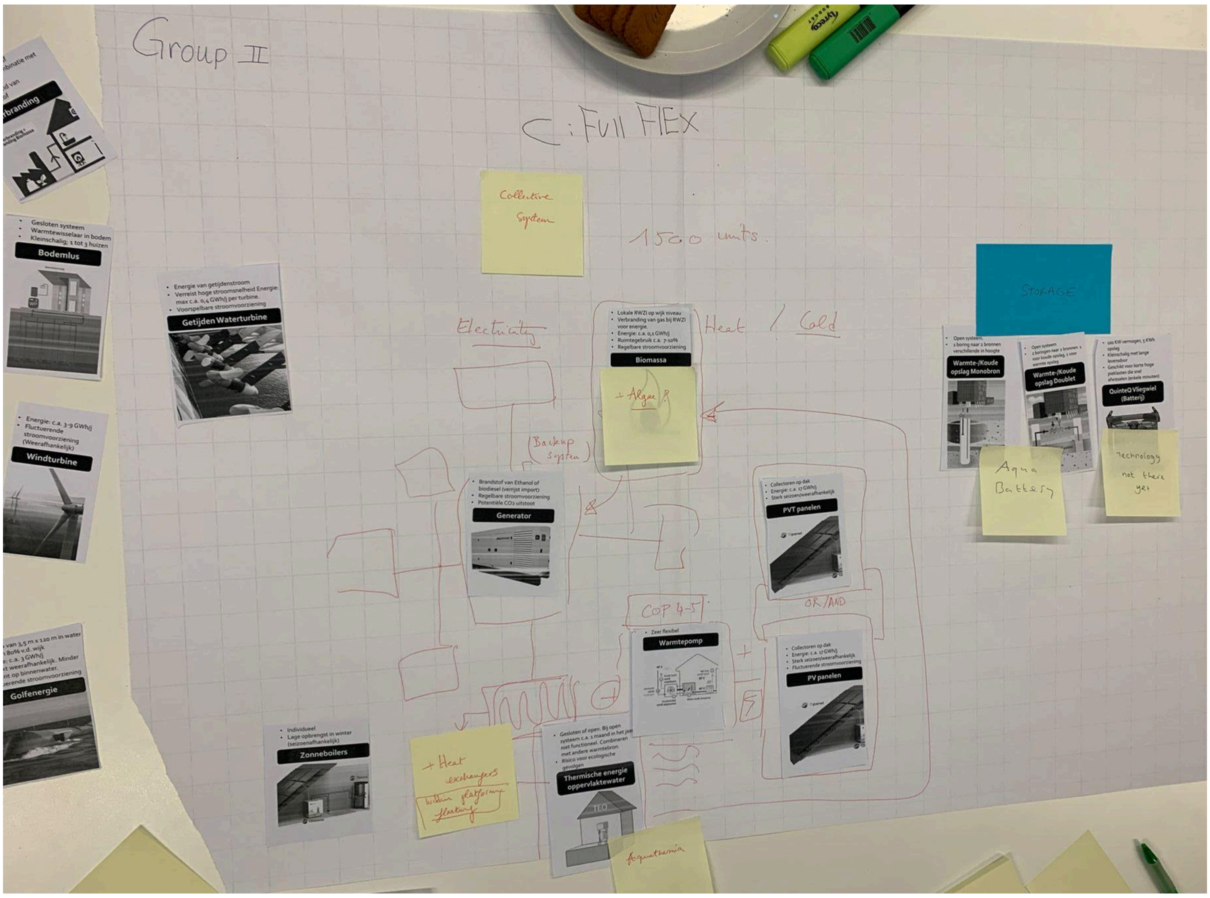
Utilise Blue:

- transport

Green spaces:

- Parks/sport fields
- Local food production

Group II - Final Design Concept



Pitch: Scenario C - Self-Sufficient Free Floating: Movable and not connected to the mainland

This scenario is selected because it is more innovative.

Simplified System Layout:

Heating + Cooling: TEO + HP (no storage needed)*

Energy: PV, Main energy square + Generator (fed with biofuel/storage system)

*Note: density can influence temperature/bioclimatic life

PART II: ***Trade-offs/Relationships/Dilemmas that might impact the modelling of heat and cold energy networks***

Geometry/Morphology:

- Density/Compactness – (4)
  - Not to dense to avoid heating in summer
  - Density vs. thermal capacity TEO/SWTE system
  - Compactness Buildings vs. Amount of wall exposed to outside (more losses)
  - density/wko as a means of limiting ecosystem disruption

A high density is efficient for heating & cooling, but with a higher density and centralised heating and cooling system,the thermal impact will increase. Whereas, if you have a low density the energy efficiency is lower but the thermal impact will also decrease. If you then value a high density you could see geothermal storage (WKO/ATES) as a means of limiting the impact of your centralised system on the surface water.

- Sizing of units:
  - Platform size/Number of Loops in your platform for the TEO/ SWTE system
  - Apartments vs. single units structure (2)
  - Efficient Size vs demand
- Stacking of units (3)
- Layout of the district vs . heat distribution system
- Mix of high vs. low-rise buildings providing shading
- Roof surface vs. PV – (2)
  - Roof/building rotation for optimal sunlight exposure

Electricity:

- PV/PVT panels vs. Surface harvest sun energy vs. Stacking & Compactness

Functions:

- Mixed-use buildings or not
- Functions that generate heat for residential buildings

Flexibility:

- WKO/ATES vs. No WKO/ATES

Collectivity:

- Degree of collectivity: Number of Residential/Non-Residential Units per Heat pump
- Collective exchange options
- More units (apartment building) on one system

Transport system:

- Transport system/infrastructure impacts your energy system
- Desirable modes of transport
- Charging stations for electric vehicles (boats) – (2)
  - Opportunity to use this for balancing/storage

Other:

- Wind, shade, Solar, Wave areas/impact

- Green (trees, sports facilities, Local food production/gardens): Heat stress reduction
    - shadowing/overhang
- Sport facility

The main findings about heating and cooling are that both groups came up with the same system existing of SWTE/TEO complemented with a Heat Pump (HP). This system makes use of passive cooling throughout the year. Storage was not a problem according to experts.

Appendix B. Co-creation 2

20-06-2024, Hogeschool van Amsterdam (HvA).

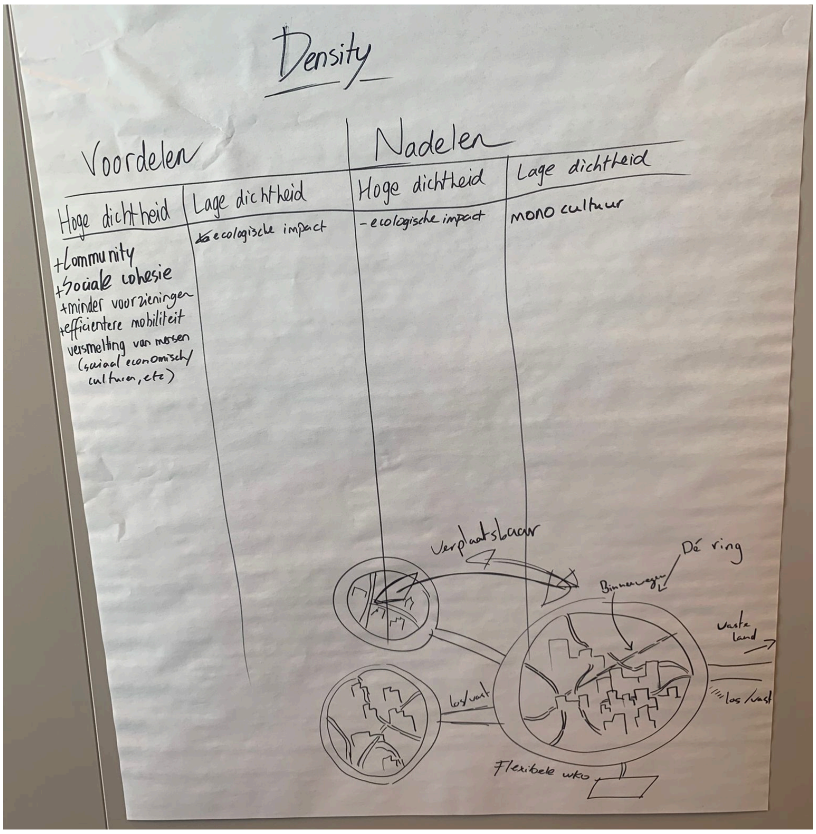
The second co-creation was held during an Amsterdam Smart City Demo Day, attended by 9 members of the Amsterdam Smart City knowledge partner network. This session reflected on the dilemmas raised during Part II of the first co-creation, where attendees discussed core dilemmas and trade-offs encountered in the Part I design process. The discussion focused on the interaction between building design (geometry) and the energy system. Four main dilemmas were identified, excluding how mobility affects the energy system and district design, as it is beyond the scope of this research: the Dilemma of Density, the Dilemma of Flexibility, the Dilemma of Function Placement, and the Dilemma of Unit Stacking. During Co-Creation 2, a presentation of the project context, technical background of the program and elaboration on the four dilemmas was shared. After the context was clarified the 9 attendees split into 4 groups, each discussing a different dilemma and documenting their process on a poster. After the brainstorm in groups, the results were shared by short pitches elaborating on the poster content. This co-creation served as a reflection from a non-expert perspective on trade-offs and dilemmas that were raised from an expert perspective. This Appendix shares a brief overview of these results in the following order: Expert Attendee List, Results Density Group, Results Flexibility Group, Results Function Placement Group, Results Unit Stacking Group.

Expert Attendee List:

Participant	Organisation
1	MSc Student
2	Lecturer HvA
3	Smart City Amsterdam
4	Gemeente Haarlemmermeer
5	Sociaal coöperatief Lokaal Geld u.a.
6	Smart city
7	Smart city Amsterdam
8	HvA
9	Smart City Amsterdam

1. **Dilemma of Density**

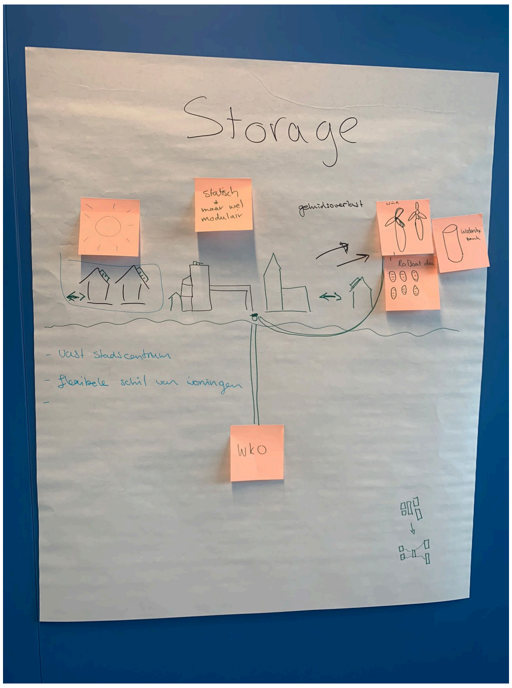
- Context given:
    - ***High density*** = more ecological impact (due to central TEO system), more heat formation in summer, energy advantage in winter
    - ***Low density*** = less ecological impact (due to spread effect of TEO system), less heat formation in summer, more heat demand in winter



- Poster Pitch:

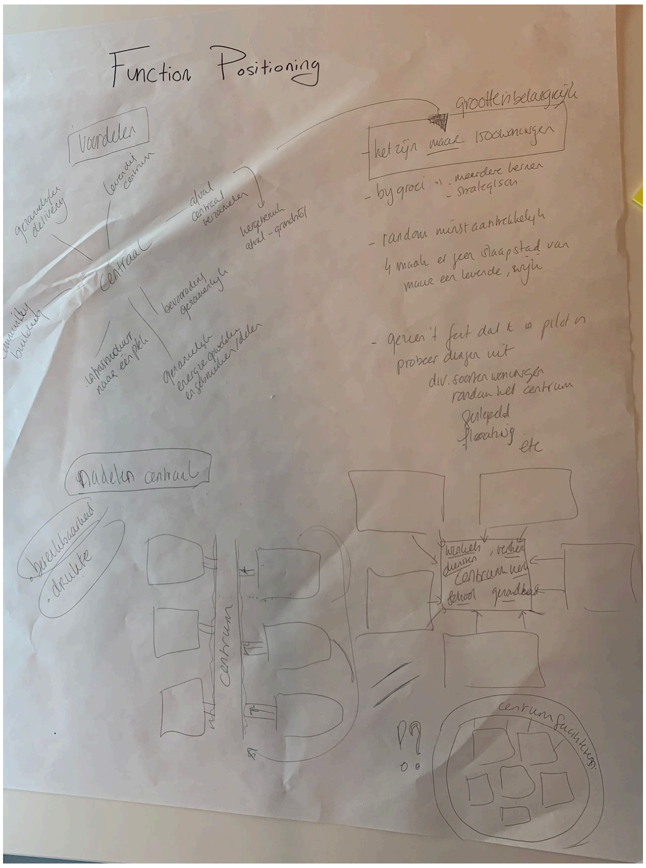
- High density: social cohesion, fusion of socio-economic positions/cultures
- Low density: risk of mono-culture
- Moveable units mean flexible density and functional placement
- Make it modular so you can play and expand with density and placement
- Moveable means you can place your units seasonally to reduce ecological impact

2. Dilemma of Flexibility (Storage or No Storage)



- Much overlap with the density group
- Objective of living in a fully moving neighbourhood (work, school, city life etc.)
- For storage a fixed district core is desirable and this can be the core of the districts
- Flexible ‘schil’/shell of houses on the edge, that are movable

3. Dilemma of Function placement



- Central functions, surrounding residential functions
    - Only if it regards 1500 homes (larger district, means more city cores)

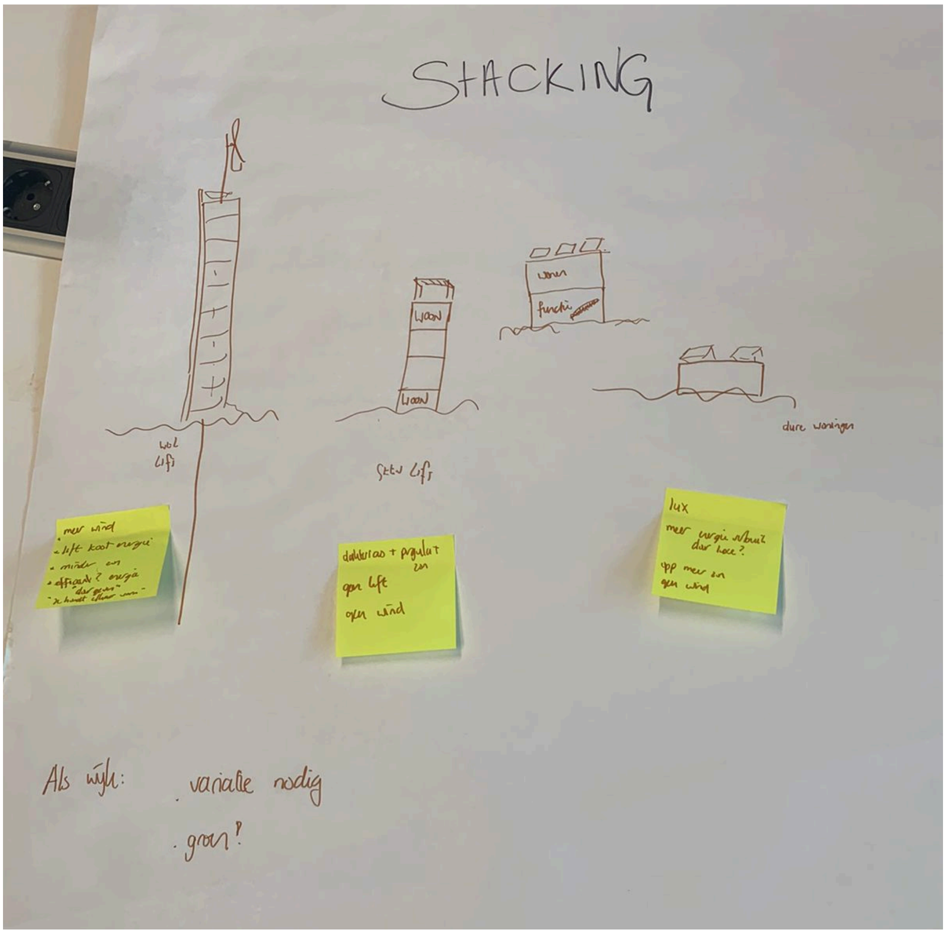
Pro's:

- Lively centre (supporting community creation)
- Exchange of companies possible (waste/raw materials)
- Joint supply chain for companies in core
- Central point for infrastructure
- Create a cohesive residential area
- Use it experimental character to test success of the dilemmas

Con's:

- Mobility: hard to reach the centre/crowded core
    - possibly solved by extending the centre along a linear shape rather than a core
    - Possibly turning it inside out, functions on in a circle on the edge and living in the centre

4. Dilemma of Stacking



- Elevator is needed from ≥ 4 floors (costs energy)
- Stacking does make energy efficient by heating each other up, so smart function placement within stacking allows energy re-use
- Building high allows you to catch wind energy (but noise nuisance)
- Variable heights (social benefits)

Appendix C. The Float

.

This appendix contains screenshots of pages used in this research. The pages are part of the Bouwbesluit (building code) and EPC (Energy Performance Coefficient) calculation for The Float reference case. This document is not publicly accessible but is provided by the owner of this sustainable houseboat in Leiden (The Netherlands). The screenshots are included with the permission of the owner.

RESULTATEN EN CONCLUSIES

Bouwbesluitberekening	**Voldoet/Voldoet Niet**
• Oppervlakte GBO/VG Toets	✓
• Daglichtberekening	✓
• Ventilatieberekening	✓
• Spuiventilatieberekening	✓
EPC Berekening	✓

EPC - Score	**0,77**
EPC- Eis	0,80
RC-waarde (m².K)/W Vloer Gevel Dak	 4,01 4,89/4,06/3,39 4,54
Kozijnen en Glas Uw-waarden W/(m².K) ZTA glas (g-waarde)	 1,1 0,6
Verwarmingstoestel Verwarming Tapwater Afgiftesysteem Douche wtw	 Infraroodpanelen Elektroboiler Lokale verwarming -
Koeling	-
Ventilatie	Mechanische ventilatie met 100% bypass
Duurzame Energie Zonneboilersysteem Aantal PV-panelen	 - 16 x 300 watt/s

Algemene gegevens

Bestandsnaam	:	2020-1818.epg
Projectomschrijving	:	Schelpenkade 48a, te Leiden
Opdrachtgever	:	--
Projectinformatie	:	--
Omschrijving bouwwerk	:	Schelpenkade 48a, te Leiden
Soort bouwwerk	:	nieuwbouw
Berekeningstype	:	woonfunctie - drijvend bouwwerk - bestaande ligplaats
Gebruikte eisentabel	:	Eisen Bouwbesluit 2012, aangewezen op 1 januari 2018
Status	:	Aanvraag omgevingsvergunning
Adres	:	Leiden
Jaar van oplevering	:	2020
Eigendom	:	onbekend
Gebouwtype (uitvoeringsvariant)	:	vrijstaande woning (vrijstaand gebouw, plat)
Hoogte gebouw [m]	:	2,70
Lengte gebouw [m]	:	16,00
Breedte gebouw [m]	:	5,50
Aantal woningen van dit type	:	1
Totaal aantal woningen bouwproject	:	1
Overige gebouwgegevens	:	--

Schematisering

Klimatiseringszones

Omschrijving	*Transport warmte*	*medium koeling*	*Verwarmings-systeem*	*Koelsysteem*	*Ventilatiesysteem*
A - Klimaatzone 1	water	n.v.t.	Verwarmingssysteem 1	(geen)	Ventilatiesysteem 1

Rekenzones

Omschrijving	*Gebruiksfunctie*	*Ag [m²]*	
A.1 - Woning	woonfunctie - drijvend bouwwerk - bestaande ligplaats	72,05	
		————	+
	Totale gebruiksoppervlakte energiegebouw (Ag;tot)	72,05	m²

Transmissie

Definitie scheidingsconstructies rekenzone A.1 - Woning

omschrijving scheidingsvlak - begrenzing	*oriëntatie*	*A [m²]*	*Rc [m²K/W]*	*U [W/m²K]*	*hoek [°]*	*g [-]*	*zonwering*	*belemmering*
Voorgevel - buitenlucht								
-Voorgevel	zo	9,55	4,06		90			minimaal
-Voorgevel	o	9,40	4,06		90			minimaal
-Voorgevel	z	4,70	4,06		90			minimaal
-V0.1	zo	1,28		1,10	90	0,60	geen	minimaal
-V0.2	o	4,15		1,10	90	0,60	geen	minimaal
-V0.3	o	3,79		1,10	90	0,60	geen	minimaal
-V0.4	o	2,40		1,10	90	0,60	geen	minimaal
-V0.5	o	0,98		1,10	90	0,60	geen	minimaal
Voorgevel - water								
-Voorgevel	zo	15,86	3,39		90			minimaal

omschrijving scheidingsvlak - begrenzing	oriëntatie	A [m²]	Rc [m²K/W]	U [W/m²K]	hoek [°]	g [-]	zonwering	belemmering
Achtergevel - buitenlucht								
-Achtergevel	nw	3,93	4,06		90			minimaal
-Achtergevel	w	8,17	4,06		90			minimaal
-Achtergevel	n	5,11	4,06		90			minimaal
-A0.1	nw	2,26		1,10	90	0,60	geen	minimaal
-A0.2	w	3,44		1,10	90	0,60	geen	minimaal
-A0.3	w	3,81		1,10	90	0,60	geen	minimaal
-A0.4	w	4,17		1,10	90	0,60	geen	minimaal
-A0.5	w	1,29		1,10	90	0,60	geen	minimaal
-A0.6	nw	3,89		1,10	90	0,60	geen	minimaal
Achtergevel - water								
-Achtergevel	nw	15,86	3,39		90			minimaal
Linker zijgevel - buitenlucht								
-Linker zijgevel	zw	11,30	4,89		90			minimaal
Linker zijgevel - water								
-Linker zijgevel	zw	5,25	3,39		90			minimaal
Rechter zijgevel - buitenlucht								
-Rechter zijgevel	no	11,30	4,89		90			minimaal
Rechter zijgevel - water								
-Rechter zijgevel	n	5,25	3,39		90			minimaal
Plat dak - buiten boven								
-Plat dak	no	72,00	4,54		0			minimaal
		——— +						
		209,14						

Definitie vloerconstructies rekenzone A.1 - Woning

vloer	begrenzing	boven mv	A [m²]	Rc [m²K/W]	Rbw [m²K/W]	Rbf [m²K/W]	Rcav [m²K/W]	z [m]	h [m]	dbw [m]	folie
Vloer	water	ja	72,00	4,01	-	-	-	0,93	-	-	nee

Appendix D. SWTE Extraction Potential Calculation

This Appendix serves as theoretical exploration of the SWTE potential specific to the FD project study. This is done according to the Waternet (n.d.) 'Omgevingswarmte Kaart' logic:

$$E \ = \ A \cdot Z \cdot \Delta T \cdot h \cdot 0,0036/1000 \ = \ A \cdot 1,19 \ GJ/m^2/year$$

- E Energy, or the heat that can be extracted ($GJ/year$)
- A Area of regenerative waterbody surface in contact with the atmosphere (m^2)
- Z Energy exchange between surface water and the atmosphere under the influence of solar radiation and wind speed ($W/m^2/°C$)
- ΔT Temperature extracted from the surface water ($°C$)
- h Number of hours per year during which surface water has a relatively high temperature and heat can be effectively extracted. In the Waternet formula this is 2500 hours, corresponding to 3,5 months

The formula provides insight into how much water surface area (A) is needed to regenerate the thermal energy (E) that needs to be extracted to meet the demand, based on the regenerative potential of SWTE in $GJ/m^2/year$. To calculate this the FD demand, or required thermal energy (E), is divided by the potential ($1,19 \ GJ/m^2/year$), resulting in the required Area (A). This A is then compared to the project context to see if sufficient Area is available to generate the required SWTE potential.

However, the Waternet formula is based on an active open system in the Amsterdam canals. As this study regards a passive closed system, the parameters assumed in the Waternet formula are adjusted to match the study context. This is done with the help of feedback from an expert from Waternet involved in the development of this logic. The process of adjusting the variables to match the project context will be discussed below.

- A

A (m^2) is the area required for efficient regeneration of surface water temperature to restore the heat balance. The minimally required Area is calculated by dividing the demand by the potential, determined by adjusting the following parameters.

- Z

Z ($W/m2/°C$) regards energy exchange between surface water and the atmosphere under the influence of solar radiation and wind speed. Since this parameter is dependent on meteorological conditions it must be adjusted to the year-round extraction regime of this study. In case of year-round extraction, regeneration of heat is also done in periods other than the summer and therefore a lower energy exchange is expected due to e.g. more times of rainy conditions. Waternet data provided by the Waternet expert illustrates the different Z values corresponding with different meteorological conditions. For simplicity the Z value of 22 $W/m2/°C$ is compared with the Z value corresponding with the same wind speed and humidity conditions for spring and fall. For both seasons this concerned a Z value of 16.4 $W/m2/°C$ instead of the 22 $W/m2/°C$ assumed in summer. Because year-round extraction regeneration will take place in spring, summer and fall, as is further elaborated in the ΔT section below, the Z value is set to 18.2 $(W/m2/°C)$ which is the mean Z value of the three seasons.

- ΔT

ΔT regards the temperature extracted from the surface water. In other words how much the surface water is cooled down due to heat extraction. In consultation with the Waternet expert, it was concluded that the passive system of this study context will not likely reach a ΔT larger than 0.5°C due to the heat transfer mechanism caused by density differences between hot and cold water: the colder water molecules sink, facilitating new molecules (with a higher temperature) to interact with the heat exchanger. Consequently, the cold descends and spreads. The cooling effect or ΔT, caused by this process is thus minimal in this context compared to an active system. This knowledge is based on a non-public research report provided by Waternet during the feedback discussion.

- h

h regards the hours of effective heat extraction for heat regeneration. h is adjusted to 4380 (6 months). The Waternet formula is based on an extraction regime at a minimum heat extraction of 10°C water temperature to mitigate the cooling effect on a still canal waterbody which can limit the possible extraction. However, according to Waternet expert feedback, it can be assumed that in the case of IJmeer, this cooling effect will be negligible on the volume of the water body. Furthermore, the expert outlined that wind or other conditions will significantly minimise the cooling effect of the SWTE on the water body. But for the calculation h is assumed to be 6 months or 4380 h, based on the reference system of RHDV (source), variant 2B. The heat is mainly extracted in the coldest 6 months and the heat balance can be restored in the warmest six months, as illustrated in Figure 20 below where reference data on surface water temperatures are plotted for the FD project context from the most recent year available (2022). The heat balance can only be restored when the water temperature is increasing, and this is possible until the temperatures start to drop significantly. This extraction period is indicated by the red dashed lines.

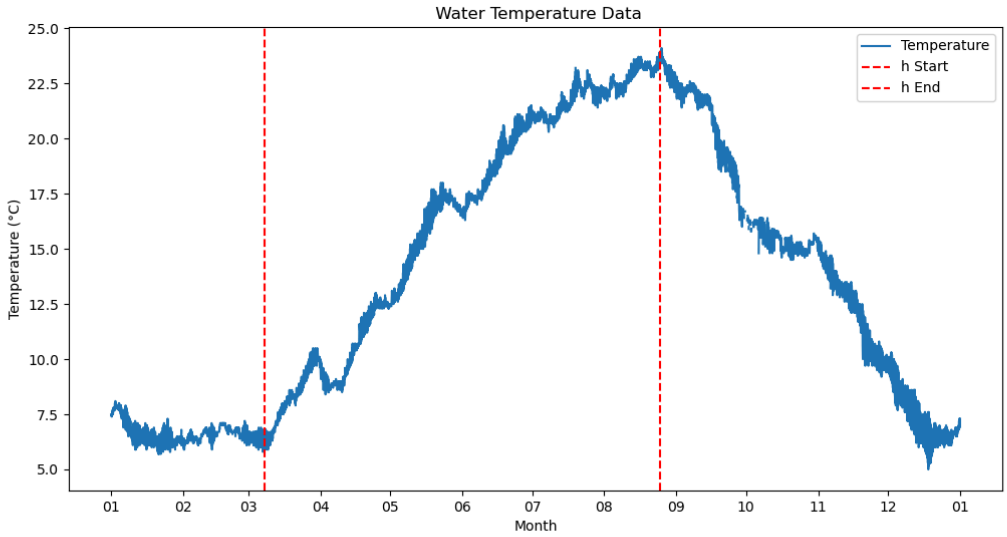


Figure 20: Surface Water temperature data 2022 IJ river near NDSM (based on RWS data)

When incorporating the adjusted parameters the resulting formula is as follows:

$$E = A \cdot Z \cdot \Delta T \cdot h \cdot 0,0036/1000 = A \cdot x\ GJ/m^2/year$$

$$E = A \cdot 18.2 \cdot 0.5 \cdot 4380 \cdot 0,0036/1000 = A \cdot 0,1434888\ GJ/m^2/year$$

This SWTE regeneration potential of 0,1434888 $(GJ/m^2/year)$ results from correcting the ΔT, Z, and h values to match the year-round extraction regime of this study's context as described in the sections above. The area of regenerative water surface required to support the project is found by

The area of regenerative water surface required to support the project is found by

$$A = E\,(heating + cooling\ demand)/0,1434888\ GJ/m^2/year$$

The demand can thus be met if

$$A < Total\ Area\ Surface\ Available\ in\ IJmeer$$

Appendix E. Model Validation Results

This appendix provides the available benchmark values of new built energy demand (kWh/m^2/year), obtained from the Total Chain Cost (TKK) model from the Energy Transition department of Ingenieursbureau of the Amsterdam Municipality.[6] Furthermore, the additional tables provide the model simulation results per typology.

Benchmark per Unit Typology	Space Heating	Hot Water	Total Heating	Total Cooling
Housing	25.0	20.0	**45.0**	**8.0**
Office (<5.000 m^2)	14.5	1.4	**15.9**	**6.6**
Store (<5.000 m^2)	28.0	1.4	**29.9**	**7.2**
School (> 3.500 m^2)	21.3	1.4	**22.7**	**9.7**

Benchmark & model values of newly built energy demand (kWh/m^2/year) of multi-family units

Multi-family Building	Space Heating	Hot Water	Total Heating	Total Cooling
Benchmark	25.0	20.0	**45.0**	**8.0**
Model	24.0	18.5	**42.5**	**8.3**
Deviance (%)	- 4.0	- 7.5	**- 5.6**	**+ 3.8**

Benchmark & model values of new built energy demand (kWh/m^2/year) of Office unit

Office *(<5.000 m^2)*	Space Heating	Hot Water	Total Heating	Total Cooling
Benchmark	14.5	1.4	**15.9**	**6.6**
Model (3.000 m^2)	13.9	1.5	**15.4**	**5.7**
Deviance (%)	- 4.1	+ 7.1	**- 3.1**	**- 9.1**

[6] *Accessible via energietransitie@amsterdam.nl*

Benchmark & model values of new built energy demand (kWh/m²/year) of Retail unit

Retail *(<5.000 m²)*	**Space Heating**	**Hot Water**	**Total Heating**	**Total Cooling**
Benchmark	28.0	1.4	**29.9**	**7.2**
Model (3.000 m²)	27.2	1.4	**28.6**	**7.1**
Deviance (%)	- 2.9	0.0	**- 4.3**	**- 1.4**

Benchmark & model values of new built energy demand (kWh/m²/year) of School unit

School *(>3.500 m²)*	**Space Heating**	**Hot Water**	**Total Heating**	**Total Cooling**
Benchmark	21.3	1.4	**22.7**	**9.7**
Model (3770 m²)	20.5	1.4	**21.9**	**10.4**
Deviance (%)	- 3.8	0.0	**- 3.5**	**+ 7.2**

Appendix F. Setpoint Table and On/Off Schedule

The table below shows the setpoint temperatures and on/off hours of the HVAC system that are assumed in the model of this research. Heating is needed when temperatures fall below the heating setpoint. Cooling is needed when temperatures rise above the cooling setpoint. All values are retrieved from the NTA 8800 (2024, P.200 -203), except the housing on/off schedule. The housing on/off schedule is adjusted to the TNO (2021, p.21) reference that provides a more detailed occupational pattern. The original NTA 8800 assumption is 10 off hours on a weekday and 0 off hours on a weekend day. Furthermore, the table shows how the heating setpoints vary per function typology. The cooling temperature setpoint of 24°C is assumed by the NTA 8800 for all residential and non-residential typologies. However, research increasingly acknowledges cooling setpoints can be increased up to 26°C without compromising thermal comfort (Van Hattum, 2021; Papadopoulos et al., 2019). Therefore, it is chosen to assume the mean of both the NTA 8800 assumption and the progressive TU Delft assumption resulting in a cooling value of 25 °C for all non-residential functions. For housing the 24°C defined by NTA 8800 is used since model validation showed that for this setpoint the model results deviate less from the benchmark values.

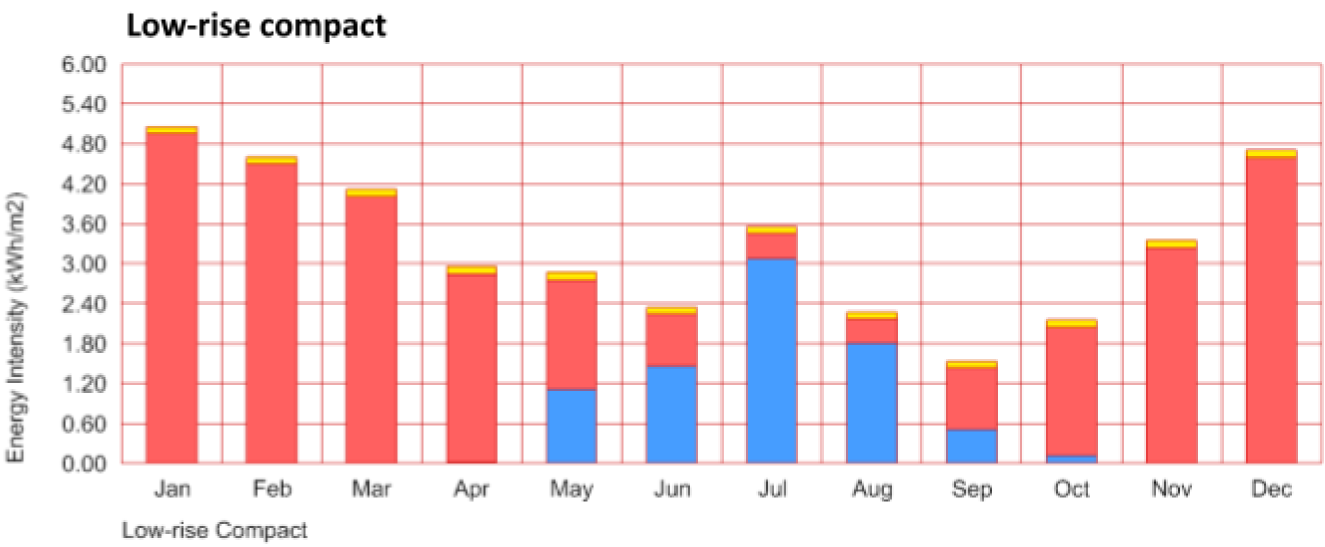
NTA 8800 (2024)	**Setpoint Temperature Heating (°C)**		**Hours heating/cooling system is turned off**	
	Day-time	**Night-time**	**Weekday**	**Weekend day**
Housing	20	16	17	10
Community Centre	21	16	14	48
Art Centre	21	16	13	24
Health Centre	21	16	14	48
Education	21	16	14	48
Office	21	16	14	48
Supermarket	21	16	13	24
Gym	16	14	14	48
Cinema	21	16	14	48
Retail	21	16	13	24

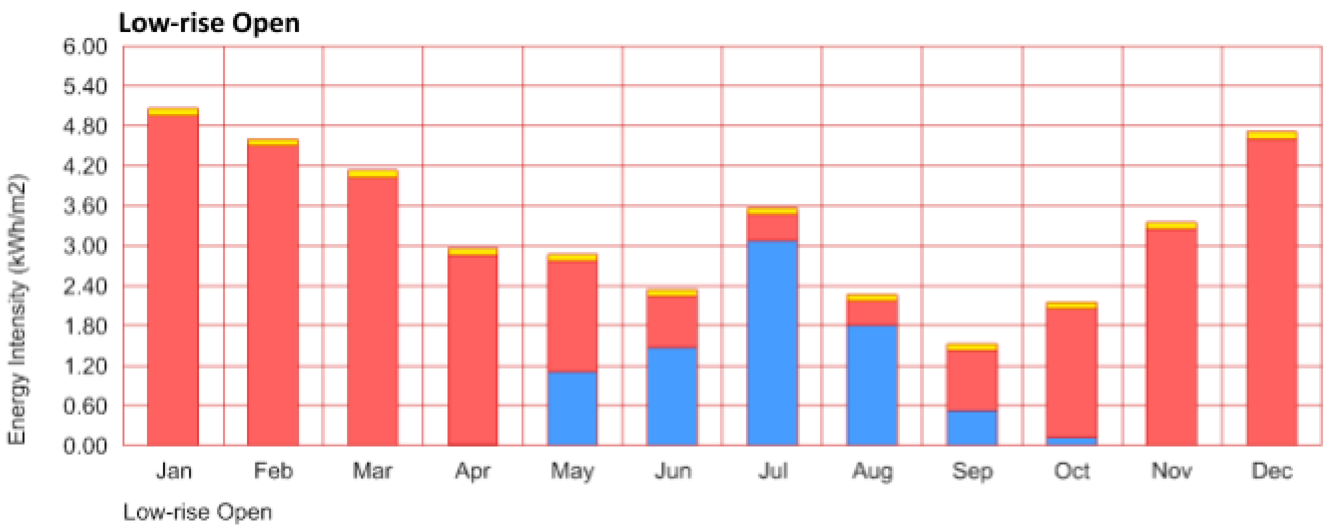
Non-Residential Setpoint Temperature Cooling: 25°C

Residential Setpoint Temperature Cooling: 24°C

Appendix G. Model Results

This appendix provides full-size versions of the images shared in reduced size in Chapter 6.





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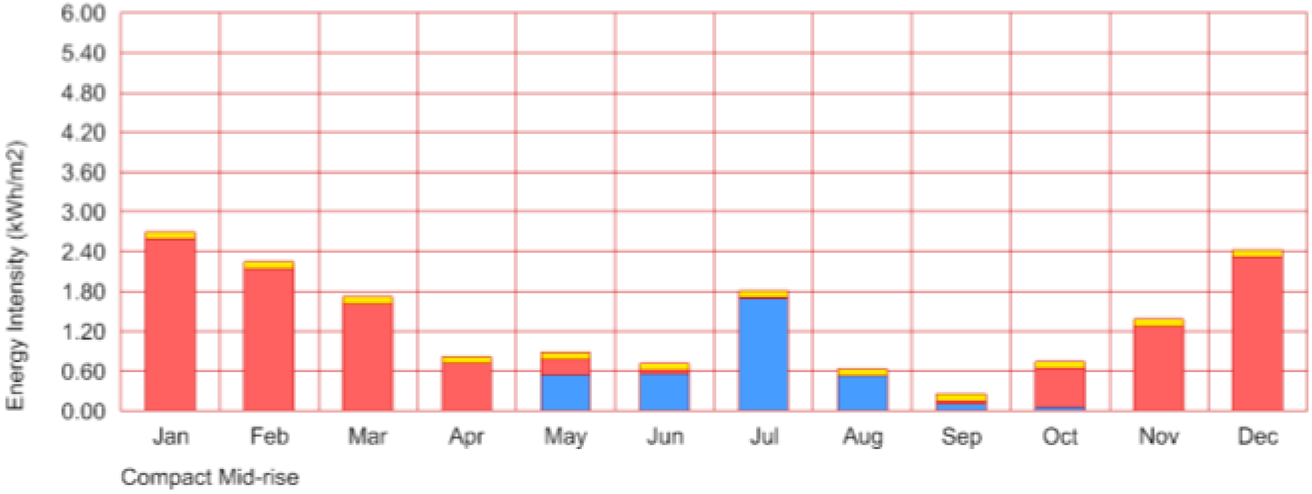
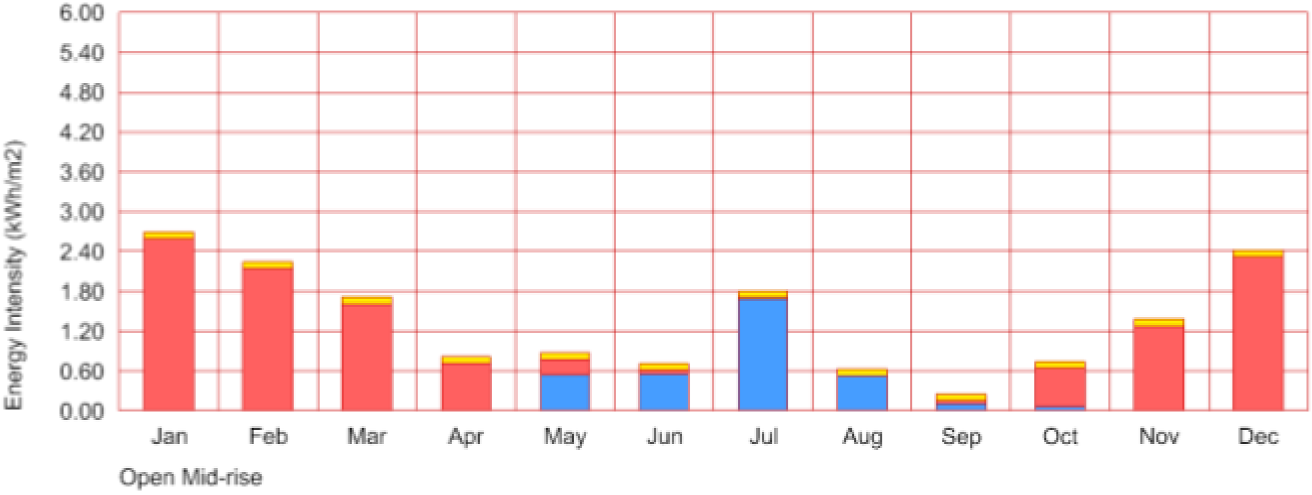
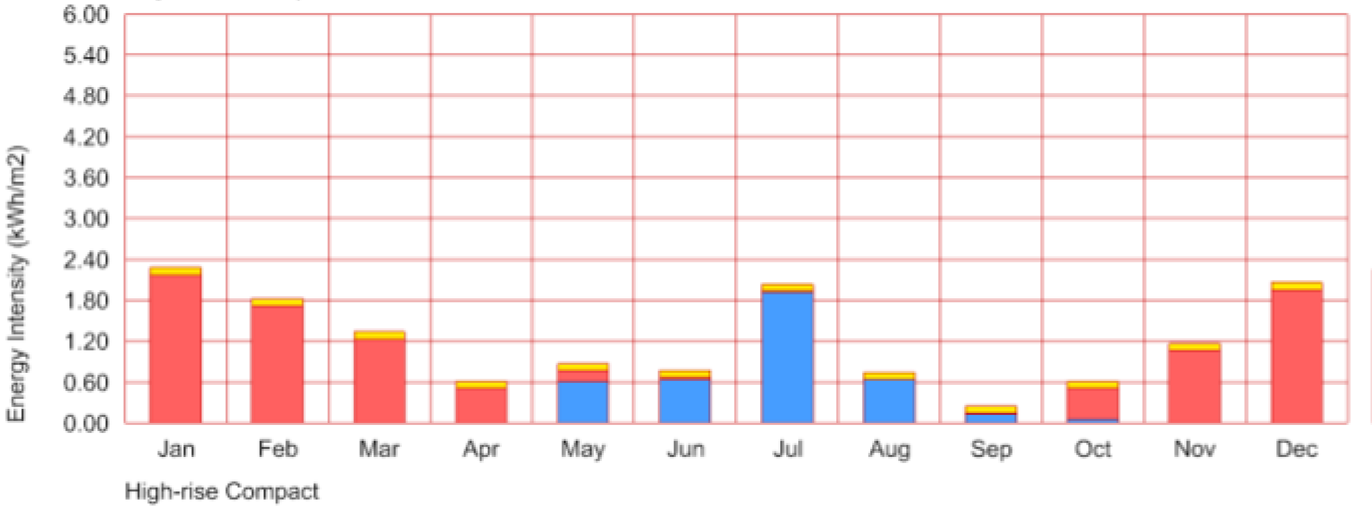


Mid-rise Open



High-rise Compact



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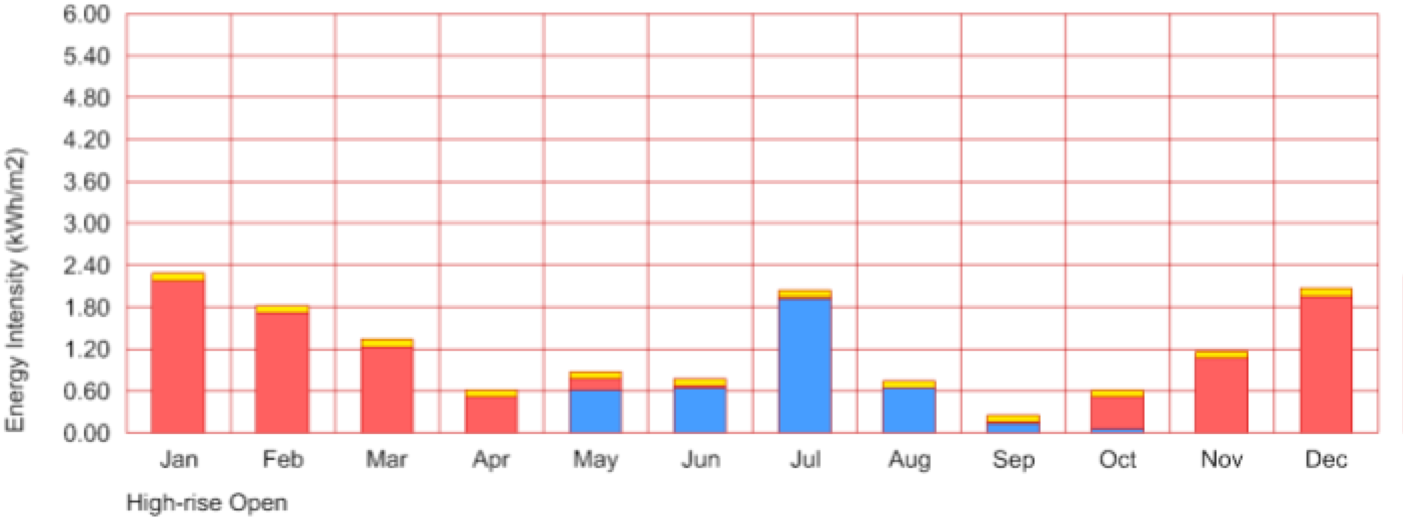
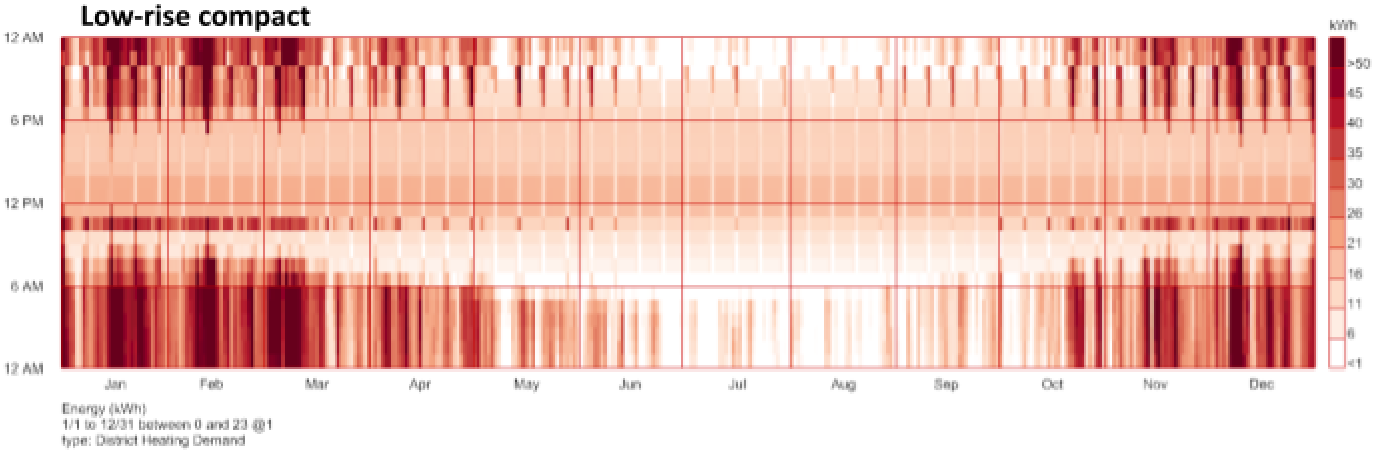
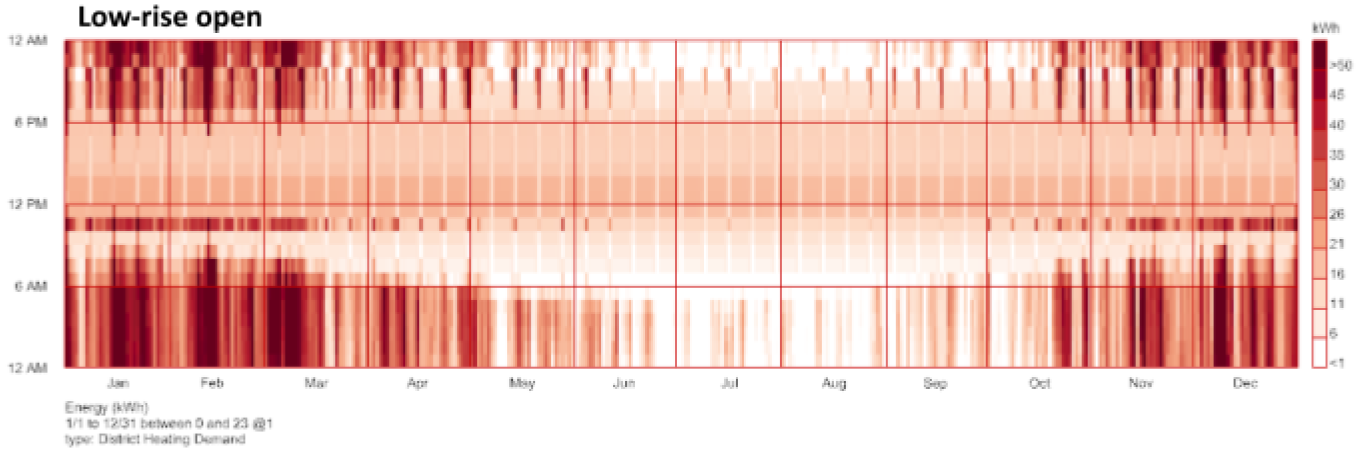


Low-rise compact



Low-rise open



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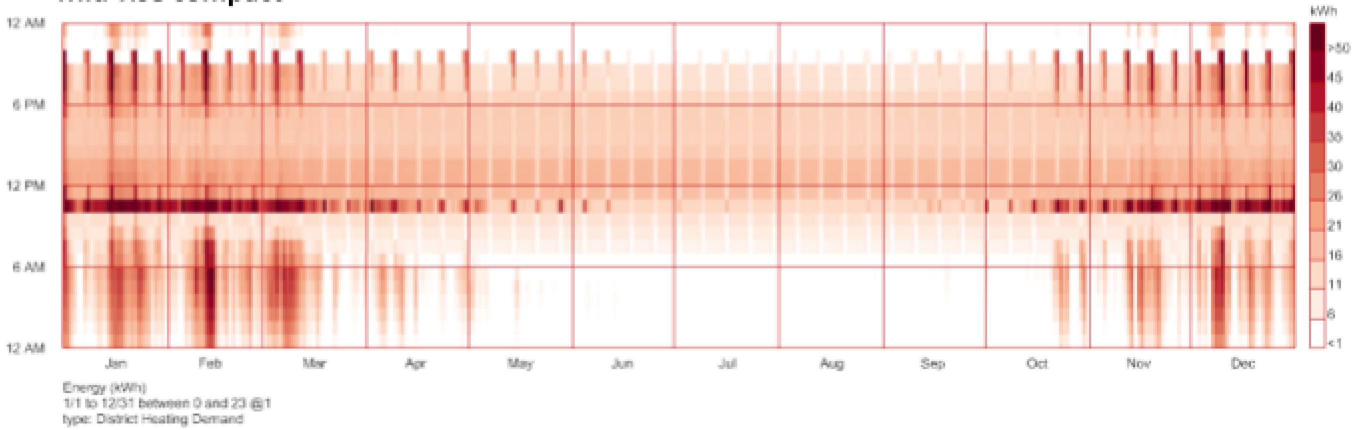

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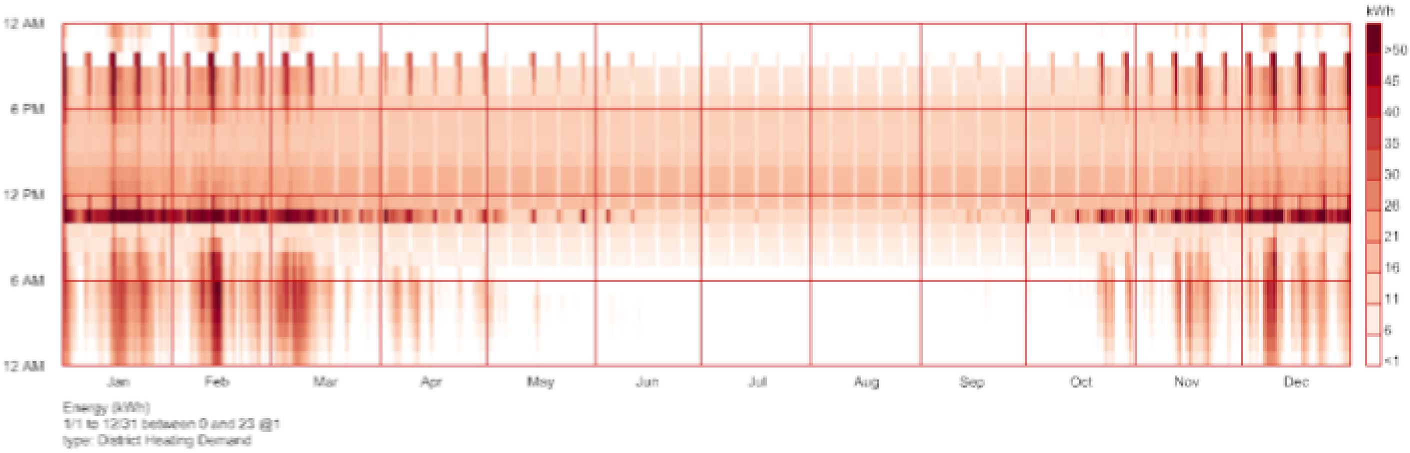

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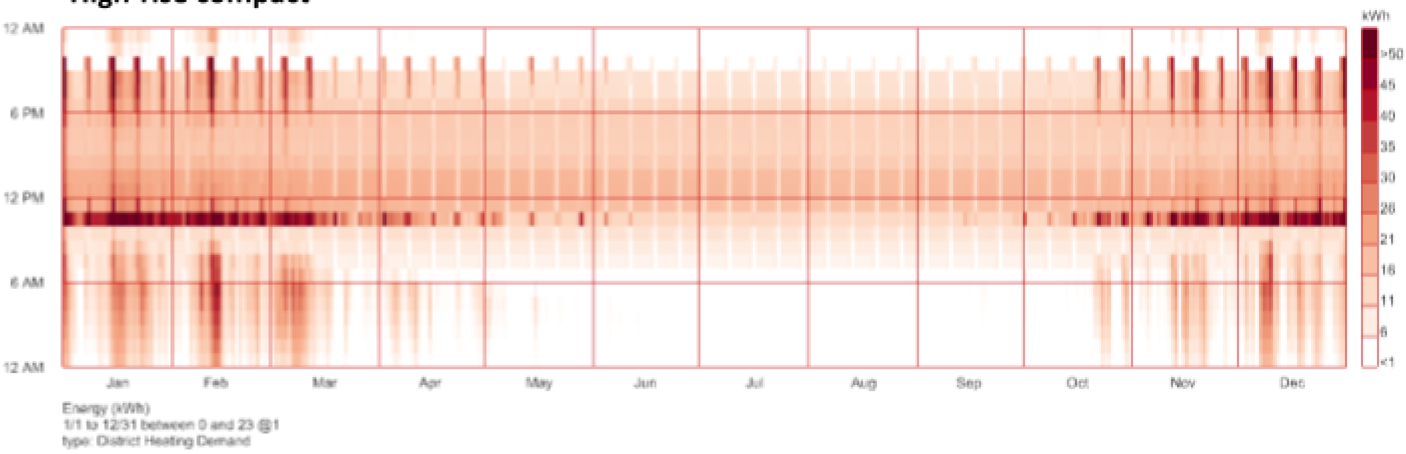

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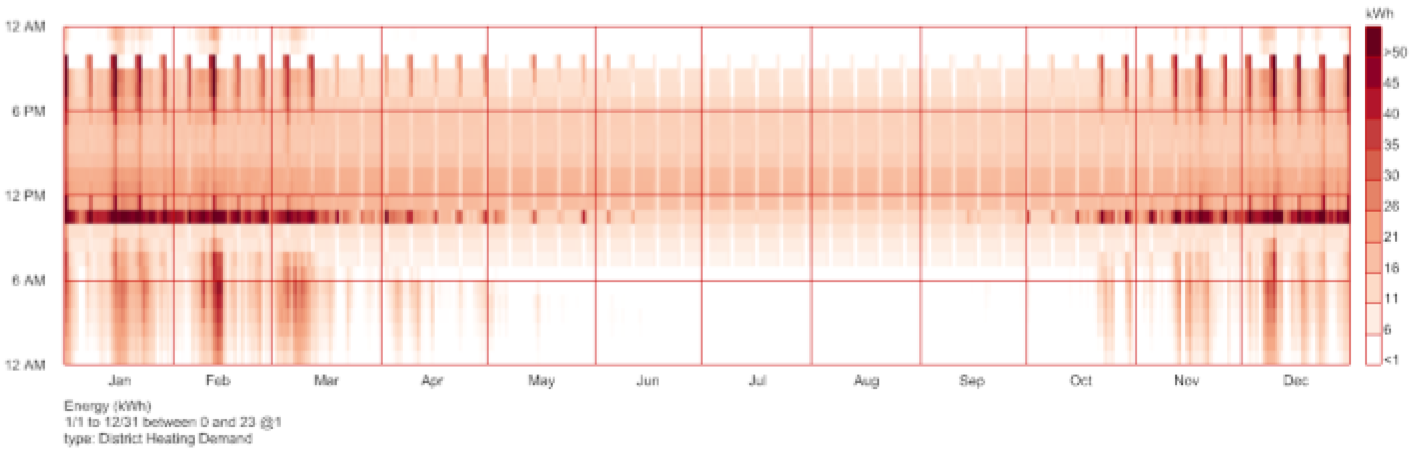

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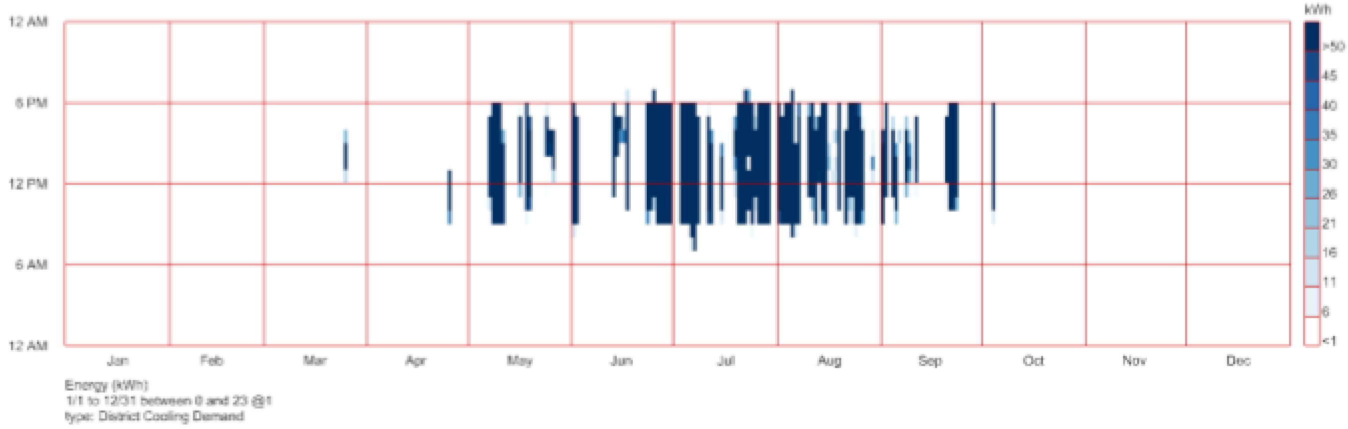

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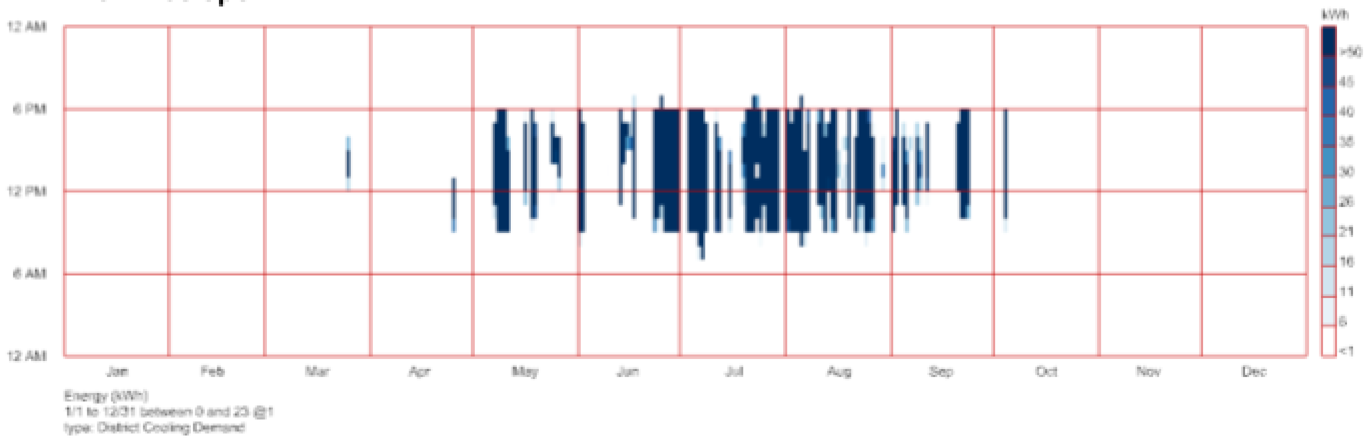

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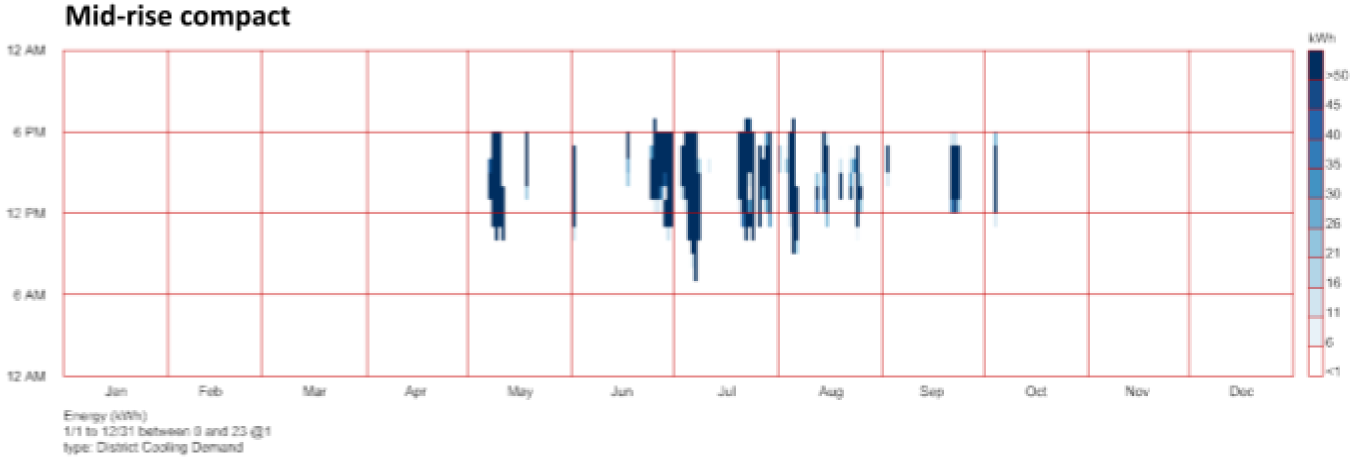

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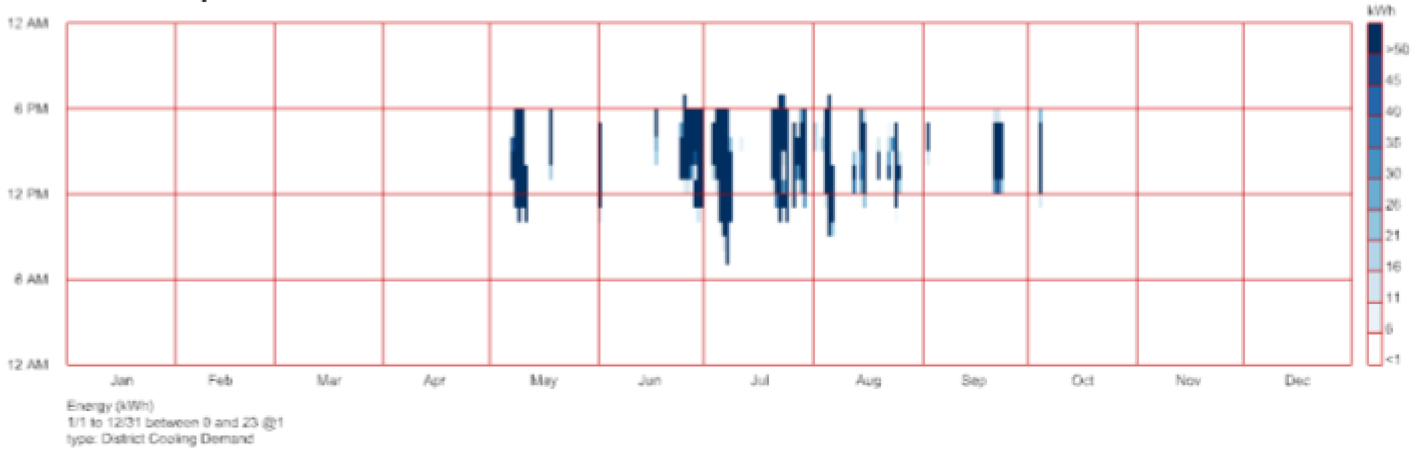

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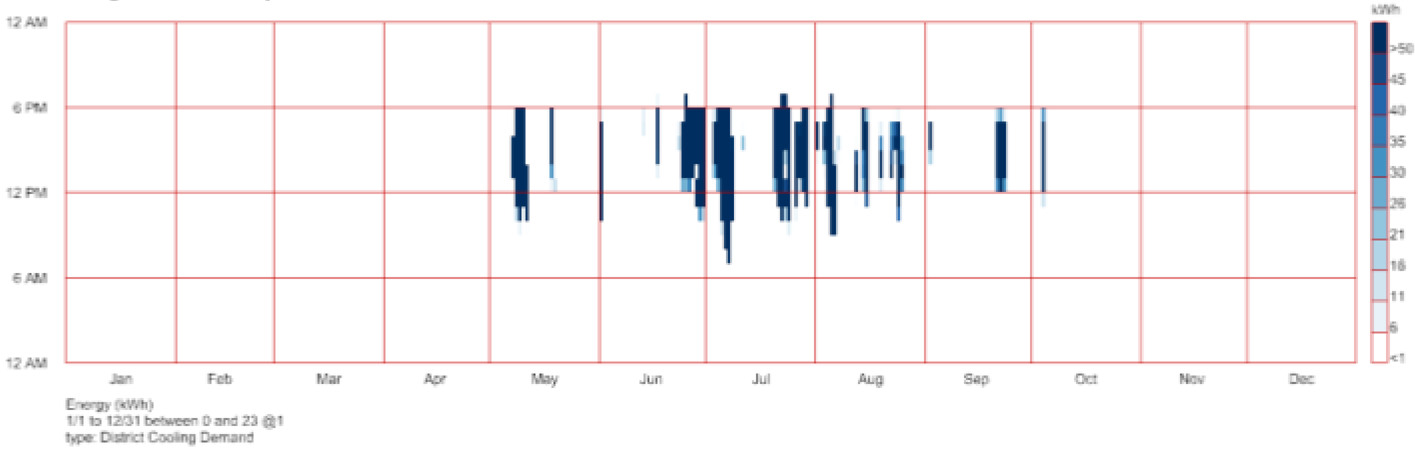

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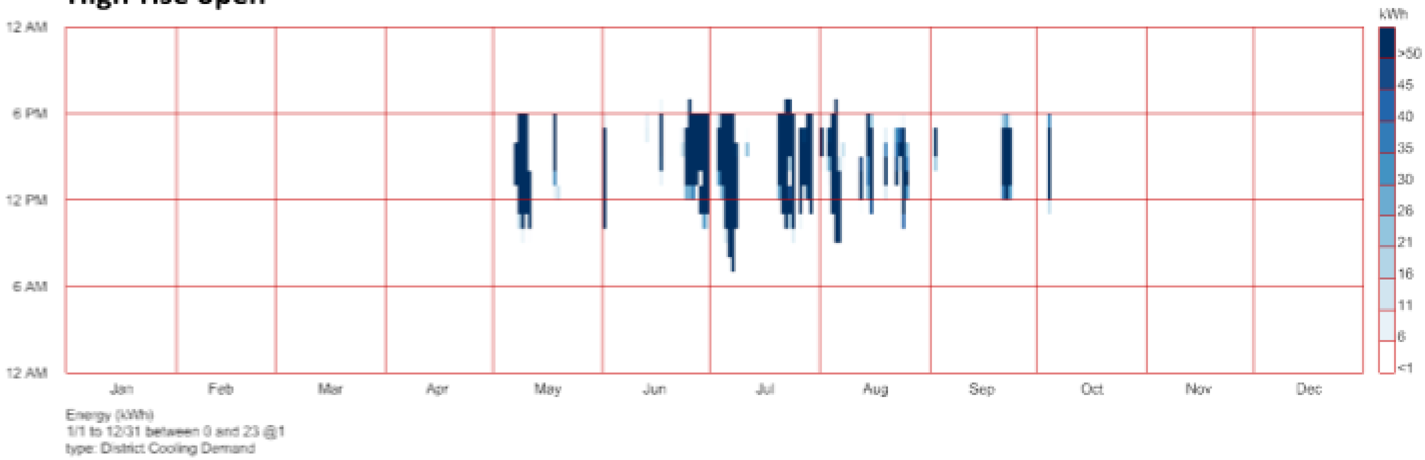

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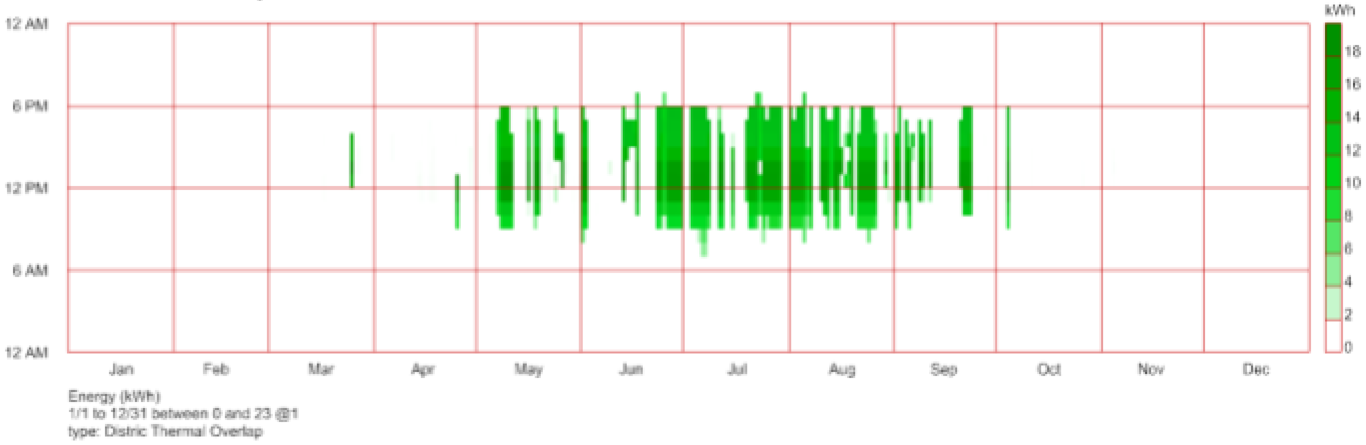

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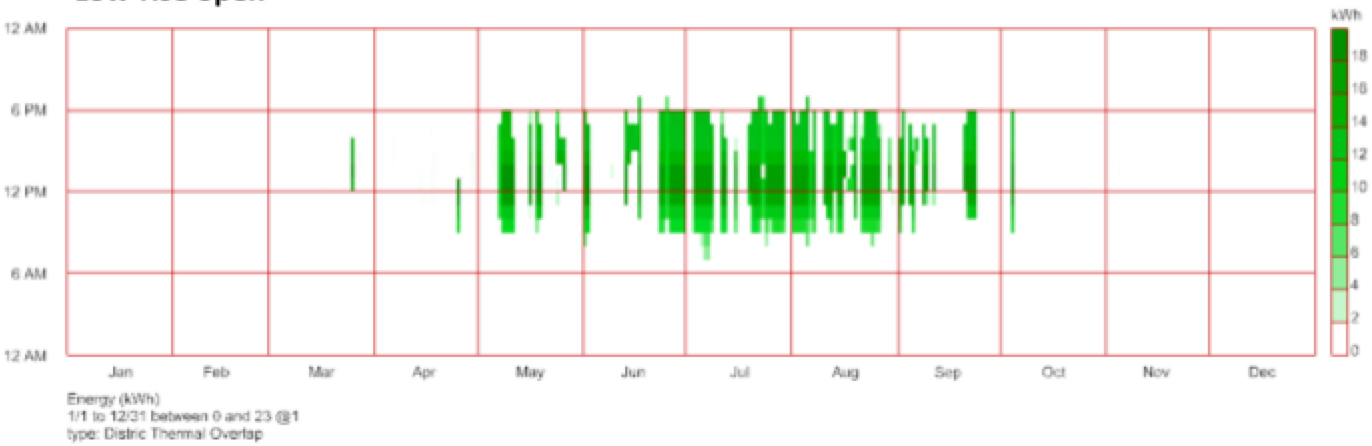

Mid-rise compact