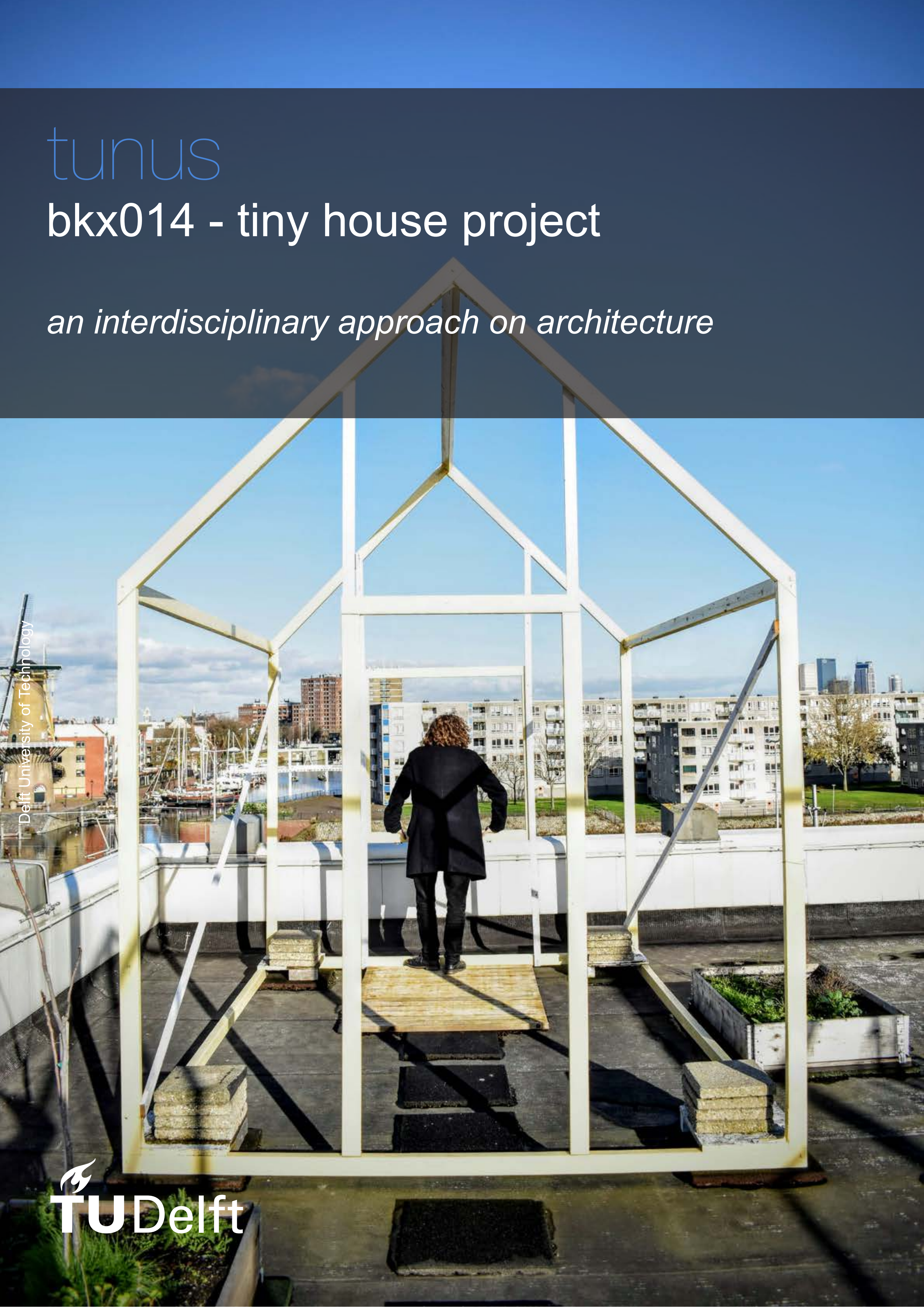
tunus

bkx014 - tiny house project

an interdisciplinary approach on architecture



Delft University of Technology

TU Delft

tunus

bkx014 - tiny house project

by

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TUDelft

preface

In this project, the future of tiny house communities is researched by an interdisciplinary team of four bachelor students of the TU Delft from the faculties of Aerospace, Mechanical, Electrical, and Industrial Design Engineering. This report presents a design of a tiny house as well as the intelligent network the tiny house is part of.

The research was done over two phases of ten weeks. The first one aimed at analysing existing tiny house trends and gathering information from a variety of courses to help in this orienting phase, ranging from architectural design to sustainable energy generation, from waste management to electrical grid design.

The second phase, the hands-on design of the tiny house and the network is concluded by this report. All findings and designs can be found in this report, for additional information and elaborated topics, the appendix is referred to.

We are an interdisciplinary team built up of four friends. This project is an objectification of that friendship. Our history leads us back to the city where we all grew up: Antwerp, Belgium. We are high-school friends constantly questioning and challenging the world around us, but most importantly, each other. The COVID-19 pandemic created an opportunity for us to rejoin forces and forge a new challenge, this project.

Apart from the contents of this project, its essence aims at teaching interdisciplinary cooperation and management of resources. It teaches not how to colour but how to draw the lines.

Delft, 20 January 2021

Korneel, Onno, Pieter, and Wim

acknowledgements

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We would also like to thank Marja Elsinga, Martina Gentili, Caroline Newton, Gerard van Bortel, Arend Jonkman, Franklin van der Hoeven, Harold Mooij, and Leo Oorschot, all members of the 1M Homes team. For all architectural help on the way, we want to thank, Leontine de Wit, Lodewijk van Es, Veerle de Vries, Cas van der Zanden, and Cristien Janssen. We would like to thank Mariette Overschie for sharing her knowledge and references throughout the project that have inspired us. We want to thank Marietta Haffner for her help in creating a view on the social implication of this project.

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To conclude we would like to thank the TU Delft and all her faculties and resources for helping us get to where we are today.

"Our mission is to create sustainable communities with a conscious way of living, by dynamically connecting people and their needs with an intelligent and collaborative system."

contents

1

envisioning the future

The world is in constant change, accelerated by human progress and innovation. It has become a wonderful place of knowledge and technology that would have seemed impossible only a few centuries ago. However, this rapid change brings many issues in its wake. In this chapter, a vision of a future world is discussed in which tunus tiny house could make a difference. A special focus goes to the Sustainable Development Goals (SDGs) set by the United Nations to better the world of tomorrow by developing the world of today (United Nations, 2015).

1.1. connection in the lone collective

Mankind is a biophile species, yearning for affiliation with other organisms. Living together keeps each other strong and connected to the world. In the last decade, this inter-connectivity is as never seen before. Globalisation led to the connection of the entire globe and digitalisation has helped tremendously for this to happen. Digital technology has made it possible to see what happens on the other side of the planet, live, from the sofa at home. However, sitting behind the safety of a screen has made people's perception of each other different. People only show the best of themselves and hide what is actually going on in their life. Friends only see the positive side and they get a distorted view of the other person's life. This induces alienation and can ultimately lead to a feeling of loneliness.

Another trend that plays a role here is urbanisation. By 2050, almost 70% of the people will live in cities and the urban environment is changing drastically (United Nations, 2018). Although closely living together with a lot, leads to a large collective, people feel a diminished connection with their neighbours as there are so many. The urbanisation thus leads to more individualism. The things humanity can achieve when collaborating, are incredible. However, the individual will suffer when a collective becomes too big.

Going tiny in such a collective gives the advantages of working together and helping each other in a small community. Not only for the feeling of solidarity but also because this is more sustainable. A tiny house in itself might not be the best option, but if all the tiny houses in a community work together for energy production and storage then so much more can be achieved. The United Nations have made SDG 11, Sustainable Cities and Communities for a reason and a difference can be made by going tiny. The goal is to create a community that is feeling connected because they are.

1.2. climate ambition

A drastic rise in pretty much everything can be seen since the 1950s. Together with Earth's population, there has been an exponential growth of transport, energy use and greenhouse gasses in the last few decades. Where population went from 2.5 billion to 7.8 billion (Macrotrends, 2020), energy use went from 28,000 TWh tot 159,000 TWh (Our World in Data, 2019).

The global consciousness about sustainability started to appear in the seventies and in 1987 the Brundtland Commission defined the following definition for sustainability: "Development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (UNECE, 2005). Architecture and households form a considerable part in the road to sustainability. In the European Union, construction alone accounts for approximately 30% of the raw material input. It is not without reason the United Nations have made SDG 13, Climate Action. People need earth and earth needs people to fix this problem.

By collaborating and shifting the current linear business model into a circular one, a lot of this growth in usage would stagnate. Using the energy of the environment like solar, wind and heat, homes can be maintained without the emission of greenhouse gases. Changing this mindset of single-use to one where people look to get everything out of a single product is essential. For humanity to live in symbioses with earth, a collaborative and circular mindset are necessary.

1.3. downsize consumption

Currently, people who live in a consumer society and the resources of the planet are getting depleted. To counter this, it is time to start *consuminderen* instead of *consumeren*. People need a lot less than they think. They see the riches of the 1% without realising it would not make them happier. However, appreciating what you have and comprehending its worth, can give feelings of gratification. Goal #12 of the UN is to have responsible consumption. By making people conscious of oneself and one's actions, this downsizing of consumption should be easily achieved. It is also in strong relation with the circular economy. Something should not necessarily be thrown away when it is broken but can be of worth elsewhere.

1.4. human habitation

With urbanisation in 6th gear, it is important to take a step back and not blindly follow the flow. There must be a third option for the choice of living in the city at unreasonable prices and living at a reasonable price in the countryside. There is a change in how people live. A rise in one-person homes is observed (Ortiz-Ospina, 2019). There is a trend of young people, trying to find a house but running against a wall of unaffordable and expensive homes. People need houses so something has to change. By building smaller, smarter and more inclusive, affordable urban houses can be possible again. Innovative technologies in the infrastructure will have to be used. Fortunately, this is exactly what the UN wants with its sustainable development goal number 9, about industry, innovation and infrastructure.

Figure 1.1: Sustainable Development Goals (United Nations, 2015)

2

brief

Setting the scene is an essential part of the design process. The following brief functions as the backbone of the project, defining what will be dealt with and what not. The concepts of a tiny house and a community network are explained and placed in a historical framework, resulting in what exactly will be created for a modern-day context. This context is geographically and demographically outlined by establishing the site and target group.

2.1. definition

First, the terms 'tiny house' and 'network' are given a definition.

2.1.1. tiny house

The term 'tiny house' is not explicitly defined. For consistency, in this report, a tiny house is defined as a building for permanent human habitation, that is specially designed to have a limited ground surface and a sustainable nature.

The comparison with a caravan is heavily discussed and no strict distinction can be defined, but an important difference is that a tiny house comes with a certain lifestyle and philosophy. An ecological way of living, with a strong focus on efficient living space and a 'less is more' mentality.

2.1.2. network

A network is defined by the Cambridge Dictionary as "a [large] system consisting of many similar parts that are connected together to allow movement or communication between or along the parts, or between the parts and a control centre" (Dictionary, n.d.). Translated to an architectural context, this definition describes a possibility for different houses to be connected on the level of electricity, heat, water, and social affiliation in a flexible and intelligent manner.

2.2. historical timeline

Communal housing is no new concept. Throughout history, mankind has found different ways to live together, from nomadic tribes to packed apartment buildings. Since the 1970s, the phenomenon of co-housing came to the Netherlands and it has gained popularity ever since. A way of living that exploits the financial, social, and practical benefits of living together Smeets, 2019.

Tiny houses as described in the previous section, have their origin at around the same time in the United States of America. The Katrina Cottages - $30\ m^2$ homes that were built after the disaster of Hurricane Katrina in 2005 - and the housing crisis in 2007 caused a great increase in popularity. People were looking for small, but comfortable and homely living spaces, without high mortgages to pay for van Orden, 2017. The concept spread out over the world and in recent years, tiny houses have been popping up in the Benelux as well. Nowadays, municipalities are offering temporary sites for tiny houses, like the *Pionierskwartier* in Delft (Pionierskwartier, n.d.).

2.3. business as usual

The philosophy of tiny houses includes being sustainable and not consuming much energy. Most tiny houses have a renewable energy source and try to be climate neutral. In general, there are three divisions to be made of tiny houses: full connection to the grid, zero-net energy, and off-grid.

The first one fully relies on the utility grid. People pay an energy supplier to receive electricity, water and gas, just like in normal houses.

The second one, zero-net energy, is also connected to the grid but produces its own energy as well. When there is a surplus of energy produced, it gets sent back to the grid. When there is an energy deficit, the tiny house can tap off from the grid to cover for it. At the end of the year, it should have produced equally as much as it used, ergo the name net-zero energy.

Lastly, the off-grid option, the peak of autarky: the tiny house is completely self-sustainable and is not connected to the grid. It produces its own energy and does not rely on an external energy supplier. It catches rainwater and cleans its own used water, too. It uses solar panels and wind turbines to produce the necessary electricity. One downside of this energy isolation is that lots of tiny houses use wood stoves to heat their house, which in itself is not very sustainable and climate neutral.

As it stands today, most tiny houses live together as a group; they form a community. This community invites social collaboration and stimulates neighbourliness, but lacks technical collusion and does not tackle energy problems together. It is as if they live alone in a collective of tiny houses.

Dealing with energy shortages and conscious consumption is a part of the daily routine for tiny house inhabitants. Upgrading storage, increasing production or boosting efficiency are solutions the inhabitants weigh up to each other. Some even go so far as to plan their yearly vacation in the darkest months of the year because of energy dearth.

2.4. global structure

This report will be dominated by two main parts and their implications:

- tunus: the tiny house; this is also the name of the overarching project
- tunect: the network of multiple tuni; in this report, a tunect of twelve tunus tiny houses is made

Researching these concepts entails an entanglement of a variety of academic disciplines. It is important to note which ones will be analysed and which not. Following listing summarises the topics that lie within the scope of this project:

- Climate conscious design choices of tunus and tunect
- Collaborative efforts between technologies and flows such as electricity, heat and water
- Optimising current deficiencies in tiny houses and their communities such as lack of technical collaboration, heat losses, lack of extensive sustainability
- Social implications of tiny roof communities and the technologies they bring about
- Social diverse accessibility of this project
- Financial evaluation and comparison to alternative

Following listing summarises the topics that do not lie within the scope of this project:

- The requirements of the supporting structure of the host building and roof
- The entrance and accessibility of the roof
- The fire safety of the building
- Policies regarding building on roofs, insurances and administrative requirements for creating such communities.

The aim is to create a future-oriented concept that ventures the field of possibilities, even if this does not always comply with current regulations and customs.

2.5. site analysis

In the early stages of this project, a connection with 'Dakdorpen' was rapidly made. Dakdorpen, a Rotterdam-based startup, invested in creating tiny house communities on the rooftops of Rotterdam, offered a case study: looking at possibilities of technically connecting these communities and establishing a methodological collaboration between tiny houses in the future. Eventually, they intend to build a proof-of-concept of their tiny roof communities.

Figure 2.1: Pictures that were taken on the roof of Dakdorpen

As the location of tunect, a roof is chosen, as part of the case study. However, no existing roof is chosen. Instead, characteristics, i.e. dimensions and data, of actual roofs are combined into an 'ideal' roof-model that serves the purpose of removing restrictions made by any single roof. The roof can be modelled as a smooth rectangle with a width of $50\ m$ and a length of $70\ m$. The roof will consist of twelve interconnected tuni, forming one tunect.

2.6. target group

The tiny house concept is one that appeals to a variety of people. According to Tiny House Nederland and testimonials of tiny house inhabitants, the most common motives to live tiny are lowering ecological footprint, monthly costs and living in a social community. It is a lifestyle about simplicity and downsizing consumption. The interest in this lifestyle has been increasing in the Netherlands since 2015. Where it was first an unknown adventure for the pioneers that saw the tiny homes in the United States, the market is now rapidly expanding (van Orden, 2017). The concept of a tiny house has the potential to accommodate a broad target group in society. Choosing for this type of housing is not a privilege, reserved for those who are passionate about sustainability. The goal is to create an accessible design, that can create consciousness for its inhabitants.

Fig. 2.2 portrays four potential households. The characters represent the diversity of the target group, varying in lifestyle, age, education, job, ethnicity and family status. What they do have in common is a stable income, the desire to live in an urban area, and being a household of one or two people.

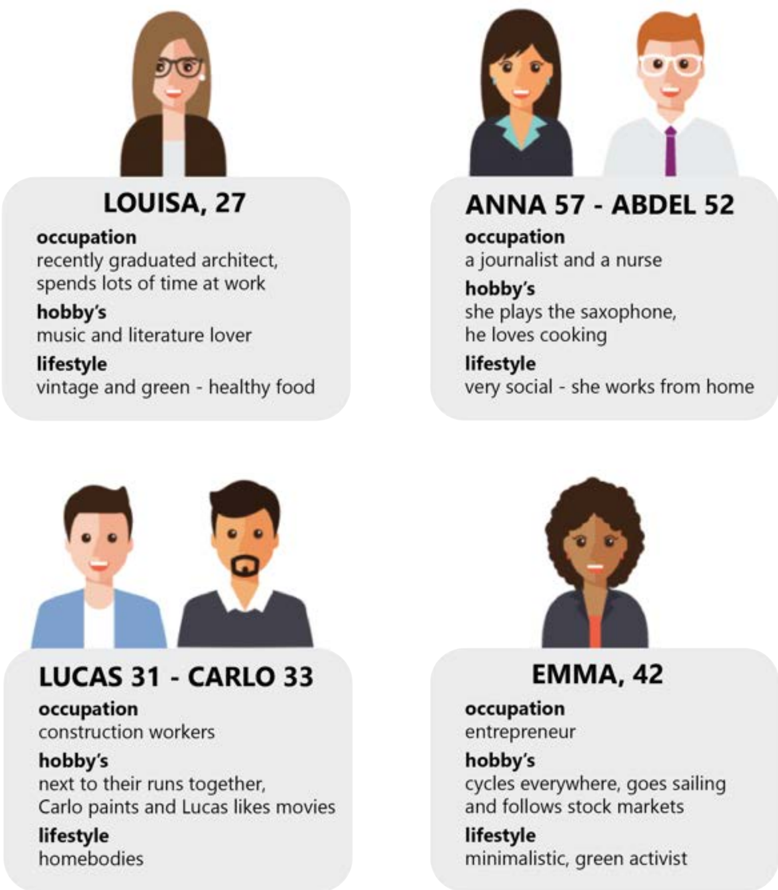


Figure 2.2: Future tunus inhabitants

3

tunus

3.1. form studies

Exploration and experimentation are the first steps in any design process. In Section A.1, an overview can be found of the iterations that led to the final design. Decision making during this first phase was led by the guiding themes that can also be found in the previously described vision, i.e. sustainability, functionality and collaboration. Adding to this, several form studies and a frame of reference were used to include the context and potential users in the design. The inquiry to create a living environment with little surface available was shaped by a utilitarian view, persistently considering what is pragmatic and how this adds up to a coherent whole.

Figure 3.1: Biennale Venezia, Julius Taminiau Architects (1); Kartasan House, Atelier Vens Vanbelle (2); Great Wall, Kengo Kuma Associates (3)

Creating a spacious feeling in a small space, yet still dividing it into several rooms is one of the challenges of tiny houses. The architectural references in Fig. 3.1 show how this interior relief and division can be achieved using light colours, unclosed walls and height differences within the same space.

Figure 3.2: Hex House, Architects for Society (1); Le Refuge Tonneau, Charlotte Perriand (2); HIVE Project, Gianluca Santosuosso (3)

The shape of the house is hexagonal, which comes with the structural stability that is inherent to this geometry. This form is a balance between the optimal use of space and practical design. It offers the biggest ground surface for the least amount of walls, creating a compact and comfortable living space. A circle would be even more efficient, but would also cause difficulties concerning the furnishing and would make the manufacturing costs rise. Moreover, the hexagon invites to combine the houses in a bigger community concept and to create a beehive structure, with or without connected walls. Finally, the shape has a recognizable particularity, which benefits branding and highlights the uniqueness of the idea.

Figure 3.3: Urban Rigid Origami Switch, students at TU Berlin (1); Green Exhibition House, Mechthild Stuhlmacher and Rien Korteknie (2); Hotel Jakarta, SeARCH (3)

c

Fig. 3.3 presents several architectural inspirations that led to some of the designed characteristics of tunus tiny house.

Since the concept should appeal to a wide target group with different possible locations, the exterior finishing and interior design remain flexible. They will, however, be worked out for the previously determined personas to give an idea of the possibilities.

3.2. concept design

Figure 3.4: tunus tiny house

The exploration in Section 3.1 led to the creation of a tiny house that will go by the name tunus. Its design is born from a combination of pragmatic necessities and the pursuit of integrated coherence. Fig. 3.4 shows one possible configuration, placed on a green roof. The general shape with the characterizing features, see Fig. 3.5, particularly identify tunus, but should not limit its flexibility to always be a unique cell in a bigger organism. Varying aspects like material choice and window arrangement can make every single tunus unique nonetheless. Design is an iterative process that can always continue, therefore some possible future developments of tunus are discussed in Chapter 7.

Figure 3.5: particular features

3.2.1. functionality & dimensions

The tunus tiny house is made to be a permanent living space. This implies that it provides space for a bedroom, kitchen, bathroom and living room, though not necessarily in the same room as is often expected. Additionally, ever since mankind started making and collecting objects, storage space became a necessity. However, in line with the tiny house philosophy of downsizing consumption, storage is only available to a limited extent.

The interior design of tunus is illustrated in Fig. 3.6. The biggest flat area in the house is located underneath the sloping roof on the ground floor, with a surface of $13\ m^2$. From there, the first floor lies at an elevation of $1\ m$ and the second floor is 2.2^m higher than the ground floor, both have a surface area of $6.5m^2$. Below the second floor, the only completely separated room can be found which is designated to be the bathroom. The second floor does not meet the dimensions to stand upright everywhere and is, therefore, best used as a bedroom. It is, however, right underneath the dome, giving the bedroom some extra space.

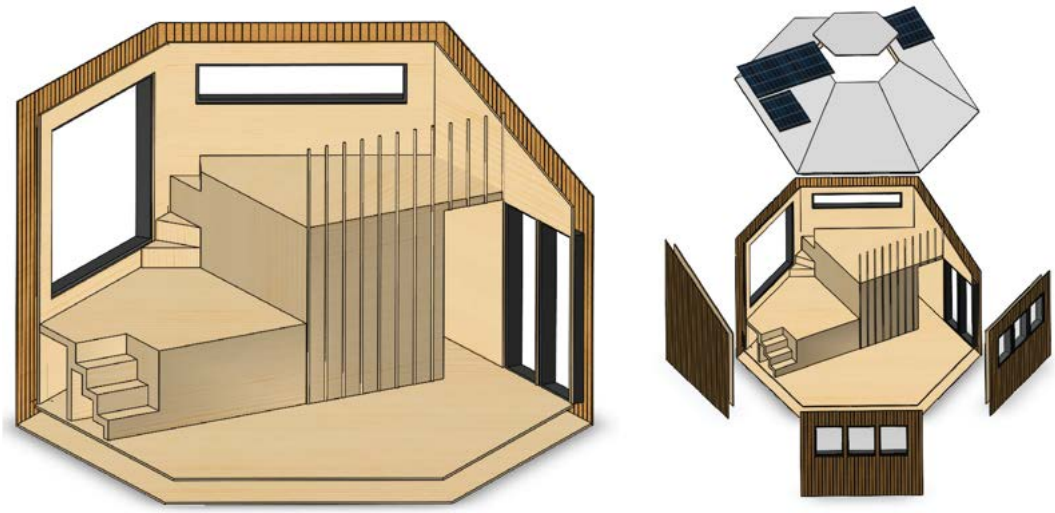


Figure 3.6: tunus interior design and exploded view

Fig. 3.7 shows where two horizontal cross-sections are made at heights of 0.8 and $3.2\ m$, which are shown in Fig. 3.8. The grey area in section A, underneath the first floor, represents the installation storage, which can be accessed from the outside, and normal storage space which can be accessed from the inside. The floorplans leave out any furniture, except for the shower in the bathroom. This shower is a specific part of the water network design, making it a permanent feature of the house, as will be described in Section 3.5.1.

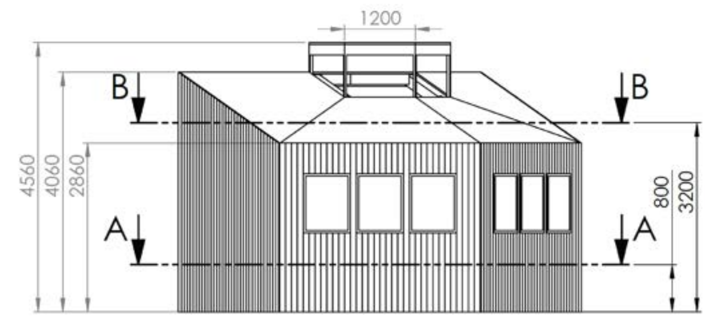
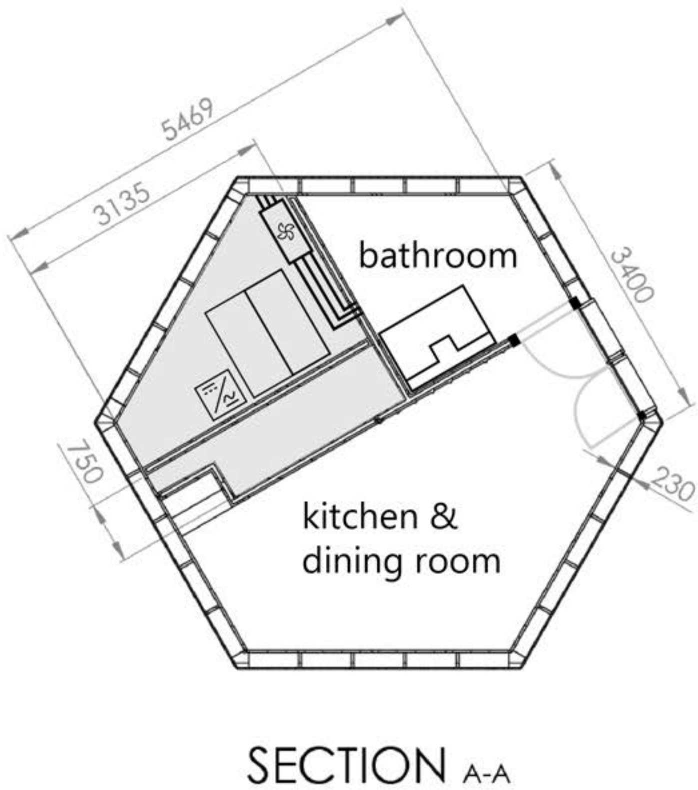


Figure 3.7: tunus outer-dimensions (in mm)



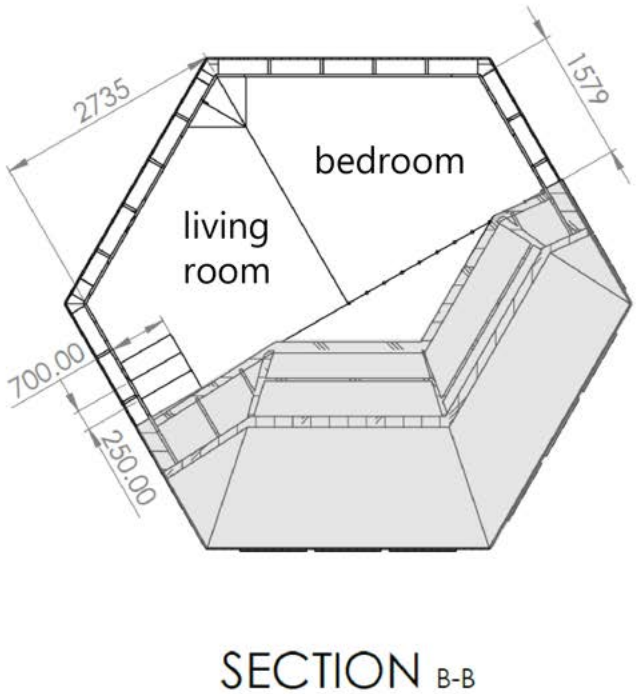


Figure 3.8: floorplans and inner-dimensions (in mm)

3.3. construction

3.3.1. materials & resources

The material selection is based on sustainability, integrability of the internal flows, affordability and lightweightness, in descending order of importance. A comparative research of different building materials with these requirements in mind leads to the reviving trend of building with wood (Rozinga, 2019) (van der Lugt, 2017).

Next to its lightweight properties, timber has great sustainable value as opposed to other building materials like concrete. When produced properly, it can be prefabricated in parts to make the construction quickly mountable on-site, with the potential for disassembly and reuse. Besides, wood has a low embodied energy and the property of storing carbon, making it a carbon-negative material.

Some legitimate concerns about building with wood are flammability and deforestation. The former is indeed a risk but can be taken into account during the design, as the burning behaviour of wood can be accurately predicted (Hakkarainen et al., 2020). The latter is dependant on the origin of the timber. In the past decades, afforestation work and natural growth have increased the forest coverage in Europe - 11 million hectares between 1990 and 2010. This progress, in combination with the regulations from the EU Forest Strategy, makes responsible timber production possible. Lastly, it is also important to remark that using wood for high-value products, i.e. as a building material, takes full advantage of the carbon-storing abilities, in contrast to low-value products, i.e. paper, pulp, etc. (Nègre, 2020).

laminated veneer lumber

The tunus tiny house is built with a prefab timber frame construction, as will be explained in Section 3.3.2. Laminated veneer lumber is manufactured from European pinewood, by glueing $3\ mm$ veneers together with phenol-formaldehyde (PH) in a hot pressing process. The production process, as shown in Fig. 3.9, can create wooden products with a wide range of sizes. The process eliminates defects and places some veneers perpendicular to the rest, creating high strength timber with virtually homogeneous material properties. Another benefit is the fact that it can be combined with other construction products and easily post-processed to implement the flow systems infrastructure (Hakkarainen et al., 2020). A table listing the material properties can be found in Section A.2.

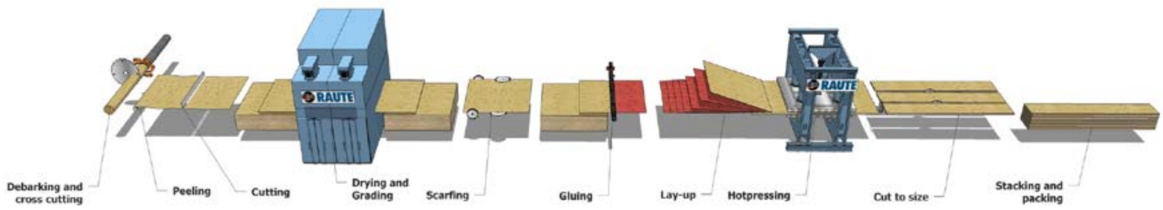


Figure 3.9: LVL production process (Hakkarainen et al., 2020)

One of the biggest manufacturers of LVL in Europe is Metsawood. Next to all of their wood being 100% traceable, they assure 85% of the wood to have international PEFC™ and FSC® forest certifications. The high-value products they make, store the carbon equivalent of $789\ kg$ CO2 per $1\ m^3$ LVL (MetsäWood, n.d.). The PH adhesive between the veneers compromises the purity of the wood to some extent, but it amply complies with the environmental norms, imposed by the Dutch government (NEN, 2004).

hemp

The timber frames are packed with insulation panels. Hemp is a natural bast fibre with high strength and lightweight properties that shows to be a promising material for thermal and acoustic insulation (Bhattacharyya et al., 2015). The annual plant is abundantly available and is supported by the European Union as a part of the non-food agricultural sector (Commission, n.d.). The production energy of natural fibres is about 60% less than their synthetic counterparts and they can be recycled. However, when synthetic fertilization and water retting is used during the production process, it compromises the sustainability of the material to some extent (de Beus et al., 2019) (Bhattacharyya et al., 2015). Hemp is also not the most optimized insulation material in terms of construction thickness, but, considering the specified prerequisites, it will serve as the insulation material in tunus tiny house. More extensive research on the use of natural fibres as insulation material can be seen Appendix B.

facade

The facade material depends on the inhabitants' preference. This creates variation amongst the tuni and the possibility for personalisation. It can differ in material, but even changing the pattern can give a different character to the tiny house. The four personas all have different exterior finishes as shown in Fig. 3.10.

Figure 3.10: facade materials per persona

Louisa prefers cedar wooden planks, just like Anna and Abdel. However, where they put it vertically, she likes it horizontally to be able to attach her planters. Carlo and Lucas choose the brick-like look, with cork as a material, giving them an extra insulating facade. Lastly, Emma found a very sustainable option with company Pretty Plastic, who produces building tiles from upcycled plastic (Pretty Plastics, n.d.).

3.3.2. timber frame construction

The tunus tiny house will be prefabricated in different parts to make on-site construction fast and efficient. A trade-off was made between panels of Cross Laminated Timber (CLT) and Timber Frame Construction (TFC), concluding that in this specific case TFC is more desirable due to its lightweight properties, on-site adaptability, limited use of wood, and it having thinner walls. Additionally, the TFC structure can be made vapour permeable which has a positive effect on moisture regulation (Orga Architect, n.d.). Fig. 3.11 shows what the TFC of tunus is expected to look like.

Figure 3.11: LVL framework of tunus tiny house

The floor is structured with beams of $45x260\ mm$ to facilitate the span length of $3.3\ m$ alongside the insulation panels. Above lie the floor heating pipes, carved into the first layer of the LVL panels (Hakkarainen et al., 2020) (de Graaf & Banga, 2002).

The inner layers of the walls likewise facilitate the cables and pipes of the heat and electricity network to run through the house, connecting the PVT panels to the other components, see Section 4.3 and Section 4.4 for further elaboration. The instantaneous deformation limit of the walls - considering the spacing of $600\ mm$ provided by the standard sizes of the insulation mats - is the height divided by 200. As the load-bearing wall structure never surpasses $3,000\ mm$, a stud size of $39x180\ mm$ should suffice (Hakkarainen et al., 2020).

Lastly, the roof structure has a maximum over-span of about $6,000\ mm$, since the bamboo wall inside offers negligible support. The weight of the roof and a variable load of $0.65\ kN/m^2$ result in beams of $45x260\ mm$ (Hakkarainen et al., 2020). A calculation of the deflection in the expected weakest point is done in Section 3.3.3. Fig. 3.12 shows the cross-sections of the different structures.

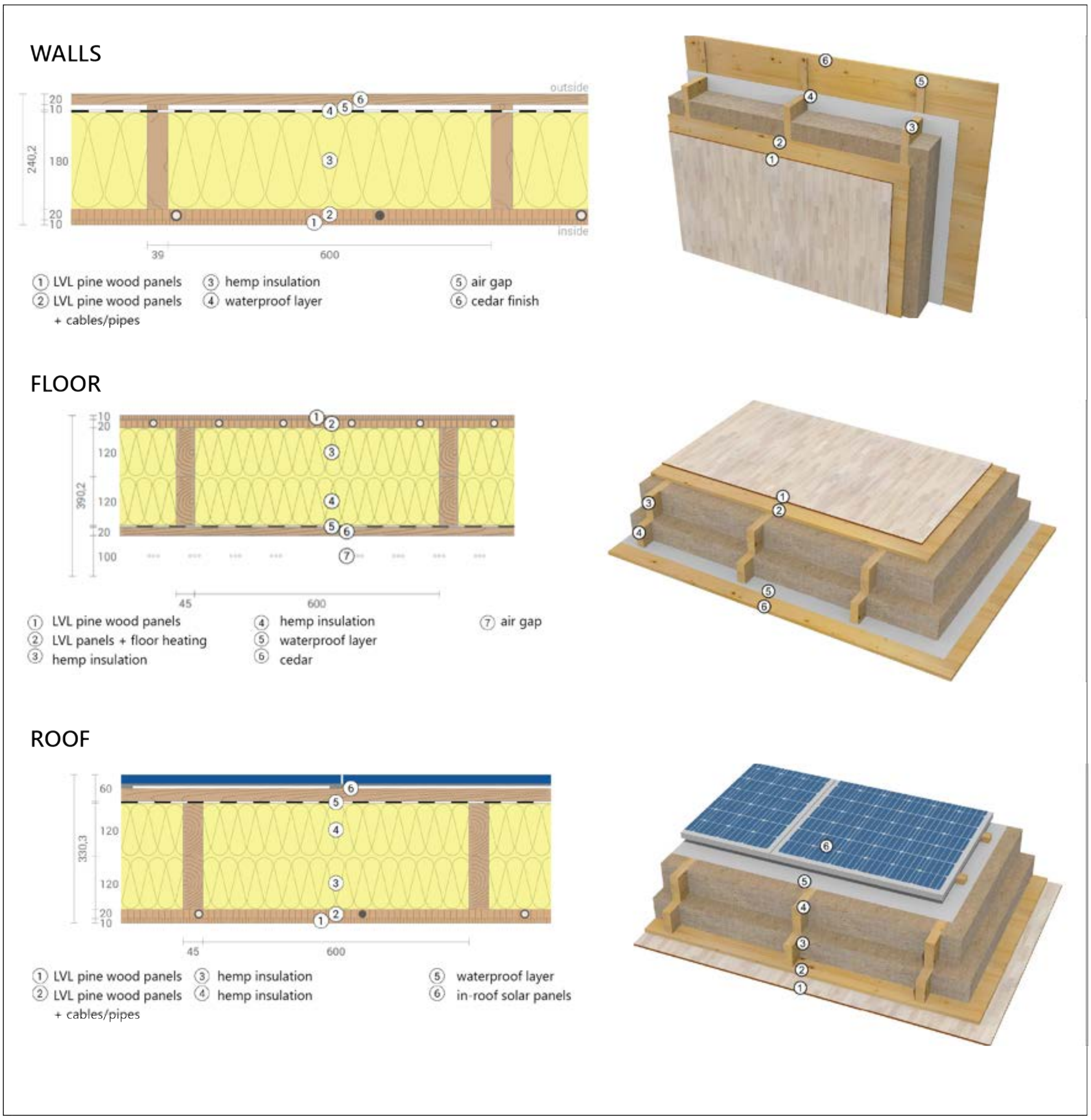


Figure 3.12: cross section of the wall, floor and roof (created with ubakus.com)

3.3.3. load bearing

Different actions, like wind and gravity, cause a variety of loads to work on the structure. To make sure the construction can hold its own roof force, some bending calculations are required. The beams most prone to deflection of their span are highlighted in Fig. 3.13. This because of their position in the construction and, as is depicted in Fig. 3.13, planes a, b, and c have the greatest surfaces thus carrying the greatest load. Their surfaces are $6.37\ m^2$, $7.82\ m^2$, and $6.26\ m^2$ respectively. Both ribs of surface b are coloured red because, due to the geometric form of the house, their difference in load is negligible. In this construction, the kink of the supporting beams is also negligible.

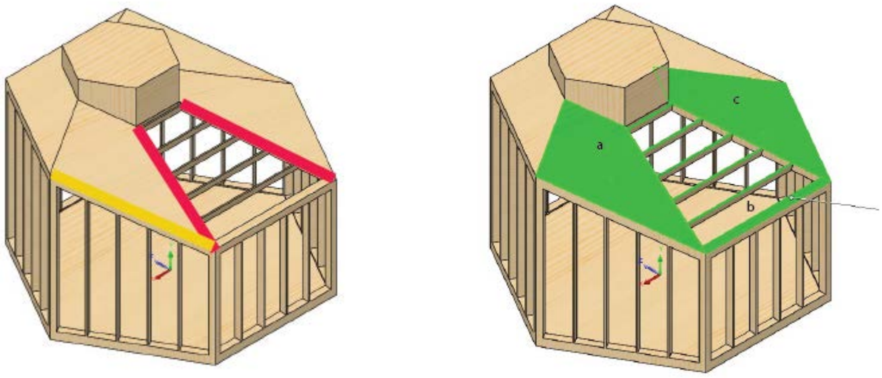


Figure 3.13: From left to right: highly loaded beams; greatest roof surfaces

A cross-section of the construction is taken, showing the supporting beams in Fig. A.5 and a variable load q. This variable is a rough estimate of $0.65\ kN/m^2$ based on the weight of the material, the solar panel, the weight of the dome, and unforeseen loads. The beams can be reduced to a beam hinged at both ends, calculations can be founds at Section A.3.

The maximum deflection δ for the orange beams Fig. 3.13 of length $3.61\ m$ is $4.13\ mm$, for the red beams of length $3.58\ m$ is $5.65\ mm$

3.3.4. foundation

A foundation is necessary for a building to prevent sinking and unintended sloping living spaces. When tunus is placed on the roof, it can use the foundation of the host building. The wooden structure is anchored to the beams that transfer the weight of the tiny house to the supporting structures of the building.

If tunus is installed on the ground, seven poles - strategically placed in all corners and the centre of the house to ensure a maximum span length of $3.3\ m$ for the floor - take care of the foundation of the house.

3.4. climate

3.4.1. ventilation

Ventilation requirements vary for different locations in the house. Since tunus is relatively small and it combines multiple functions in one space, one ventilation system with a flow through of $24\ l/s$ is appropriate (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012a).

The air supply will happen naturally with a ventilation grid right above the windows. The model used in tunus would be the EasyFit 50 'ZR', by ventilation and sun control company DUCO. The grid is specifically made for wooden window frames and has a ventilation capacity of $18.3\ l/s$ per meter with a pressure difference of $1\ Pa$ (DUCO, n.d.-a).

The air outlet will happen mechanically in the installation space between the bathroom and the first floor. The DucoBox Silent works with smart detection of carbon dioxide and humidity in the different spaces and can deliver a discharge capacity of up to $111\ l/s$, which suffices amply. The air will be circulated to the bathroom via the $20\ mm$ gap underneath the bathroom door, to the inlet of the DucoBox, which is located next to the shower. It is a compact and silent design, making it suitable for a tiny house. The ventilation cycle can be seen in Fig. 3.14. Heat recovery or pre-heating the fresh air are both possible with mechanic ventilation, but they are no viable options for a house as small as tunus.

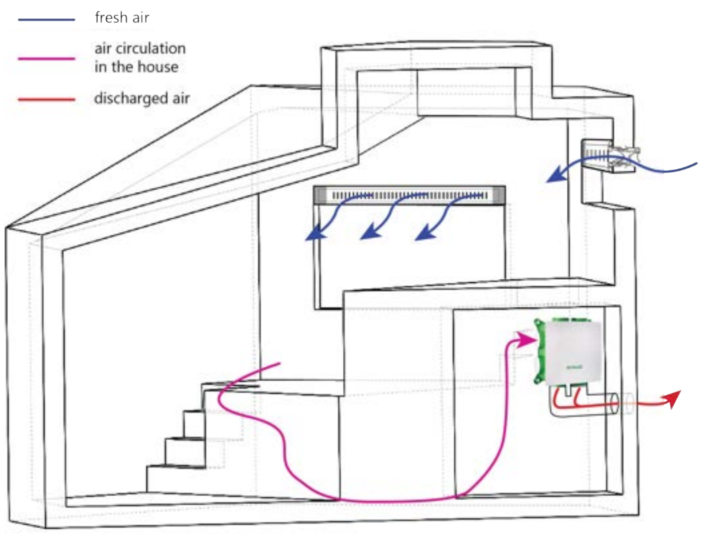


Figure 3.14: ventilation cycle

enclosed porch

In the Netherlands, regular houses have enclosed porches. However, in this case, the limited amount of space should be optimised, making it an abundant feature that is usually not found in tiny houses. If the inhabitants do prefer to have one, a curtain will do the trick of leaving the warmth in and wind out.

3.4.2. temperature

Western-Europe, the Netherlands especially, are confronted with a temperate maritime climate. This climate does not allow for much openness in architecture and is influenced heavily by insulation requirements and heating installations. In Fig. 3.15, a data set of the region of Rotterdam, the Netherlands, is used to determine how many comfortable hours a building has depending on dry-bulb temperature and the humidity with the Climate Consultant 6 software. This graph shows us that without evasive changes or implementation of specific design strategies, this building will only be able to provide a comfortable environment 5.2% of the time. By far the biggest impact on comfort in the house is made with a good heating and humidification system.

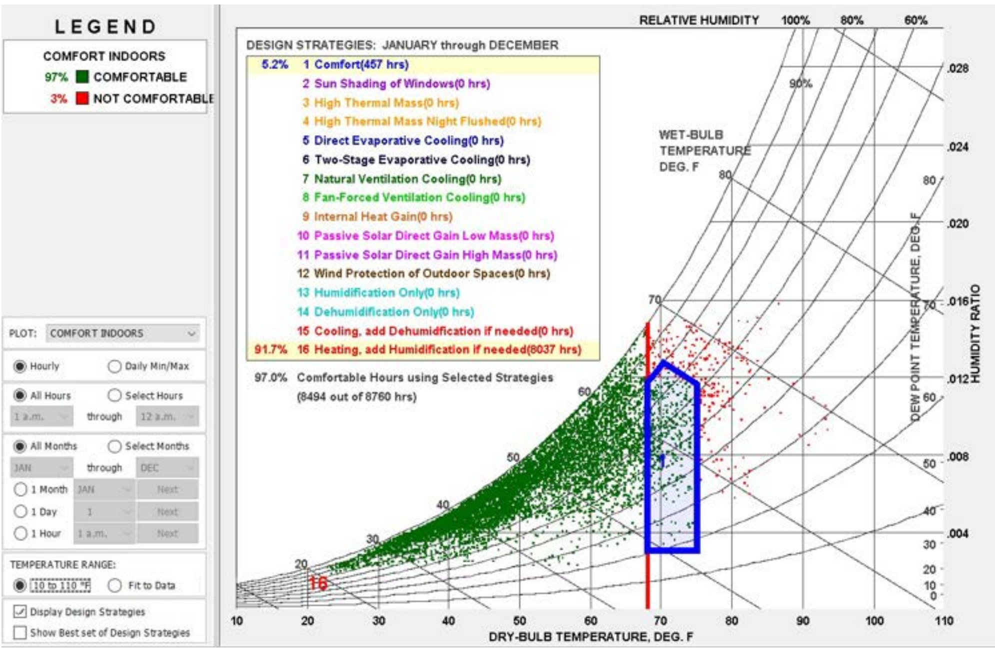


Figure 3.15: Climate Consultant analysis of Rotterdam region

regulation
Floor heating regulates the temperature in the house. In winter, by sending hot water through the pipes and in summer, with water that is just a few degrees colder than the environment - if it is too cold, condensation will form on the floor which is undesirable. A more extensive explanation of the heat system is given in Section 4.4.2.

insulation
As described in Section 3.3.1, hemp will be used as insulation material. According to the Dutch Bouwbesluit 2012, vertical surfaces, i.e. the walls, require an Rc value of $4.5\ m^2K/W$. The horizontal surfaces call for an Rc value of $6\ m^2K/W$ if they are not connected to a ground surface. When connected to the ground, only $3.5\ m^2K/W$ is needed (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012b).

The interior and exterior finish can vary and are therefore left out of the insulation calculations. If they have a significant impact on the R_c value, it will only be a positive one.

$$\text{hemp: } \lambda = 0.04\ W/mK \tag{3.1}$$

$$\text{insulation walls: } 4.5\ m^2K/W * 0.04\ W/mK = 0.18\ m \tag{3.2}$$

$$\text{insulation roof and floor: } 6\ m^2K/W * 0.04\ W/mK = 0.24\ m \tag{3.3}$$

For tunus this translates to an insulation thickness of $180\ mm$ for the walls and $240\ mm$ for the roof and floor. Since a wooden structure is used, an air gap between the floor and ground surface is necessary for ventilation, thus the floor requires the same Rc value as the roof.

The decision for LVL and hemp creates a vapour-permeable construction, which allows humidity to go out of the wall and therefore prevents moist.

3.5. water & waste

3.5.1. water

As water is getting scarcer and scarcer, the importance of sustainable water supply and systems in households becomes clear.

In this section, first of all, the appliances that will be used and what will be changed compared to normal households are discussed. A conclusion will be made on the savings and lastly, the water infrastructure will be explained.

current water consumption

There are multiple big water consumers in a house which do not necessarily need drinkable water. Table 3.1 shows the average water usage of regular houses and tunus. From this table, it is clear there is room for improvement to greatly reduce the amount of potable water used in appliances and activities not necessarily requiring the water to be potable.

Table 3.1: Water usage in different houses (Finvrij, 2016)

	normal house		**tunus**	
	l/day	%	l/day	%
Hygiene	107.1	90%	14	60%
Shower	51.17	43%	10	43%
Toilet	33.32	28%	0	0%
Washing machine	14.28	12%	0[1]	0%
Lavabo	4.76	4%	4	17%
Taking bath	2.38	2%	0	0%
Handwash clothing	1.19	1%	0	0%
Cooking	8.33	7%	6.19	27%
Handwash dishes	3.57	3%	3	13%
Machinewash dishes	2.38	2%	0	0%
Drinking	1.19	1%	2	9%
Cooking food	1.19	1%	1.19	5%
Rest	3.57	3%	3	13%
Other	3.57	3%	3	13%
TOTAL	119	100%	23.19	100%

water usage optimisation

For tunus, potable water is gained from the grid of the city, alternative solutions can be found in Section A.4.

Toilet usage can be reduced greatly with the use of a dry toilet, further discussed in Section 3.5.2. This reduces the water consumption of flushing the toilet to zero.

By changing the shower, immense water consumption cuts can be made. An average shower uses about $10\ l/min$ but a simple solution would be to use a savings shower of about $5\ l/min$. This immediately halves the use of the water, supposing the inhabitants would not shower for a longer period of time. Nevertheless, this is still a lot of water that is being used.

New, promising technologies reuse and filter the water used in the shower. An example is the closed-loop shower by the company Upfallshower (Upfallshower, n.d.). This shower gives $35\ l/min$ but only uses up $1.5\ l/min$. This means the inhabitants have a luxury rain shower without the downfall of immense water expenditure. The shower comes at a high cost of 4000 € but this high cost is compensated by the ecological counterargument of a water consumption reduction of 80%. It is advised to use organic soap and shampoo to maintain the filter for a longer time.

A washing machine also does not need potable water. The water from the shower and the sink can be gathered and this grey water can go through a filter. First, a bioreactor can break down all the organic components after which a membrane can take out all the little filth (MijnWaterfabriek, 2019). After this, the water is clean enough for use in washing machines. Accounting for the fact that on

[1] The washing machine does not use new water so has therefore no expenditure

average, people use $15\ l$ a day on washing machines, and tunus uses about 23 l per day, as can be seen in Table 3.1, the water supply for the washing machine should be sufficient. Especially when considering that people do not wash their clothes daily.

infrastructure
Not having a toilet connected to the water grid makes it less complex as so-called black water should not be accounted for. The infrastructure of the water grid is fairly simple and can be seen in Fig. 3.16. The water that exits both the faucets and the shower comes from the city network. As discussed in Section A.4, no rainwater will be used. The cold water from the tap is prohibited to exceed $25°C$ and the hot tap water will not be lower than $60°C$ to prevent the appearing of legionella (Agudelo-Vera et al., 2020) (Wilms, 2018).

A lot of the water in the shower will be reused to save 80% on water consumption and the leftovers will flow, together with the grey water from the sinks, towards a heat exchanger right before the boiler further discussed in Section 4.4.2. After this, the grey water flows towards the filters in or around the central hub. From there, the cleaned water can be used for the washing machines. If no washing machines are in use, it can go into a tank which will have to be emptied every two days to prevent colonies of bacteria to grow in the tank. When the water is used for the washing machines or is just left over, it flows towards the sewers of the city.

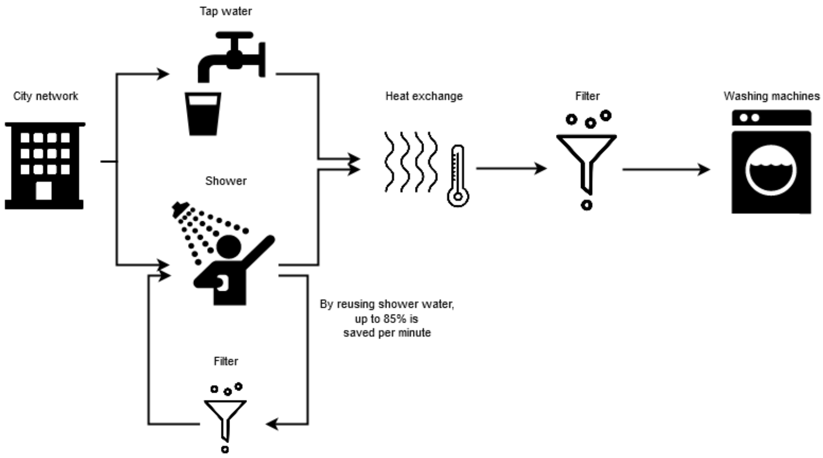


Figure 3.16: Water life cycle

3.5.2. waste

About 14% of waste comes from households. After building and demolition (40%) and industry (24%), it is the biggest waste source, adding up to about $1.35\ kg$ per person per day in the Netherlands. This amount has slowly been decreasing in the last years (Ministerie van Infrastructuur en Waterstaat, 2019). About half of the generated waste is currently separated. The best-separated streams are paper and glass (75% brought in separated), followed by GFT (60% brought in separated) (Milieu Centraal, 2018).

The issue of waste should be dealt with at the source, making sure that there is no waste in the first place. The waste management in tunus did not have a big impact on the design of the house, since reducing or managing waste is part of the lifestyle. It is a choice not to take a plastic bag every time you go to the supermarket or to use reusable containers for food. Providing a place for something like a freezer is taken into account because this has a direct effect on the reduction of food waste in one-person-homes.

The water plumbing system will not provide a connection for a toilet, which requires the inhabitant to make use of a dry toilet. In 2014, the Water, Sanitation & Hygiene program at the Bill & Melinda Gates foundation published a report on contemporary toilet designs that can operate without connection to water or sewer lines. It shows a list of possible solutions for the tunus inhabitants, like, for example, different models of a composting toilet (Water, Engineering and Development Centre, 2014).

Lastly, the use of wastewater is discussed in Section 4.5.2 and separate collection of the different waste streams is facilitated on the level of tunect, see Section 4.2.1.

4

tunect

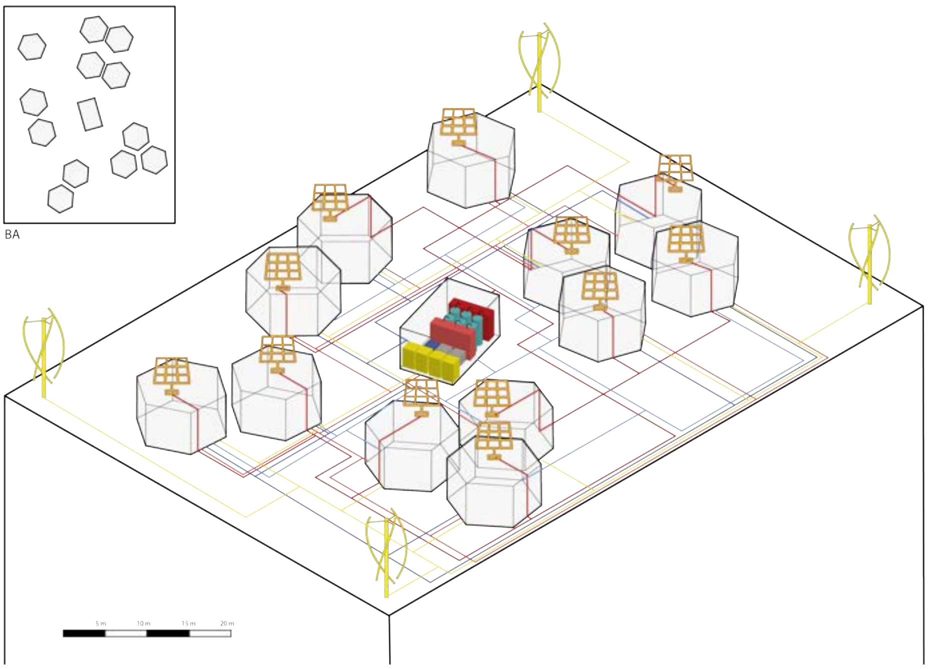


Figure 4.1: Visual view of tunect

Many tiny house communities today lack integrated cooperation. Not only on a social level, but also technically they should work together to intelligently generate, distribute, store, and use the different flows that run through the community, i.e. electricity, heat, and water. The following chapter aims to create this connection between twelve tuni on a roof, controlled from a central hub. This network of tuni goes by the name tunect and is visually presented in Fig. 4.1.

4.1. data analysis

To gain insight into the energy consumption and water usage in housing, a data analysis is constructed. Research was done into the average consumption of residential and tiny houses.

Energy

According to CBS (Central Bureau of Statistics in the Netherlands), $2,730\ kWh$ of electricity is used per house on a yearly basis, averaging all houses in the Netherlands as can be seen in Table 4.1. This only accounts for the electricity of particular residential buildings, given by energy companies. Therefore, shared appliances like elevators and gallery lighting are not included. Neither is the generation

by personal solar panels. Consequently, this number is quite a bit higher.
Especially when taking into account that natural gas is used for heating. Using the same datasheet, about $1180\ m^3$ on natural gas is used per year. When looking at the inherent energy of natural gas, $1,180\ m^3$ is about equal to $12,600\ kWh$ in electricity (U.S. Energy Information Administration, 2020). This means about 80% of energy is used on heating. This is also confirmed by the European Bureau for Statistics (Eurostat, 2020).

Table 4.1: Yearly energy use of private homes in the Netherlands (CBS, 2020)

	Average natural gas consumption $[m^3]$	**Average electricity consumption** $[kWh]$	**District heating [%]**
2016	1 300	2 910	5,5
2017	1 240	2 860	5,6
2018	1 270	2 790	.
2019	1 180	2 730	5,9

For a quick comparison, a well-documented tiny house in the Netherlands has measured their energy usage. The inhabitant only uses 350 kWh per year on electricity but uses LPG and propane for heating and cooking (Jonker, 2017). These are quite big consumers which would lead to a way higher total energy consumption.
Next to using gas or propane, many tiny houses use a wood stove or other forms of stoves to heat their house (Duindam, 2020).

Water
In 2019 a Dutch person used, on average, 119 l per day on potable water (Drinkwaterplatform, 2020). About 90% of this was used on hygiene like showering and flushing the toilet. Cooking and drinking amounted for 7% and the other 3% was rest. Showering and flushing of the toilet already count for 85 l of the daily water usage as seen in Table 3.1.

Most tiny houses, on the other hand, use rainwater. They use the land next to their home to catch and filter it. For the potable water, they are sometimes connected to the grid as well to not pay for the costs of maintenance and the filters (Bastek, n.d.). The tiny house mentioned above uses about 33 l a day on potable water (Jonker, 2019).

4.2. central hub

Villages used to be built around a square, church, or both. Cities are often structured around a central place where people come together and meet. The first pillar of tunus is about this connectivity: getting people to live together and intertwined. One of the ways this goal is supposed to be met is by introducing a central hub. This central hub will play a large role in the social structure of tunect. Further, it will be a key factor in centralising the flow systems of tunect: electricity, heat, and water.

What is it that makes people come together in the centre of a village or city? That is the question that must be answered to successfully develop the central hub.

4.2.1. shared features

One of many reasons people go to the city centre is to make use of shared features - think of the collection of garbage, doing the laundry at a laundromat, groceries, or even a walk through the illuminated streets at night. These can all be translated to the context of tunect.

waste

For the more common waste streams, i.e. paper/cardboard, glass, plastics and PMD, containers are provided at the central hub to ensure separate collection. Other waste streams like textile, electronics, bulky waste etc. are rarer and should be brought to facilities outside of the community. The general idea is that there should be little to no waste and the inhabitants are supported in this behaviour, as described in Section 3.5.2, where possible.

laundry

The laundry system is inspired by the contemporary situation in many student houses in the Netherlands: a multitude of inhabitants are sharing washing machines. That can be one washing machine for a house of six students or two washing machines for a house of fifteen students. This sharing is rarely experienced to be an issue. For civil use, the relative amount of washing machines per person could be increased since it is not always desirable to live like a student with little to no comfort. Nonetheless, increasing it avoids waiting times.

light

Lights in the streets have become so standard that people forget to be conscious of their presence. However, they play a valuable role in people's lives. They enable meeting together outside during the night, which would otherwise be entirely in the dark. Their addition to tunect is essential to promote social contact.

4.2.2. social

What the central hub offers socially depends on the layout of the roof and the situation of tunect's inhabitants. Simple options can be a common seating and dining area, or an honesty bar - where users can take the drinks themselves and are trusted to pay the appropriate amount. Such a payment system could be powered by the tunect app, making it very easy to grab a drink and have a chat with neighbours. These are parallels of parks and bars in city centres which are regularly frequented by city dwellers.

The possibilities for the central hub are countless. Existing cities provide endless inspiration. Entertainment can be offered in the form of big screens showing the latest movies or broadcasting live sports - think of cinemas and sports bars in cities. A stage can be constructed on which plays can be organised. Game nights and stand-up comedian performances can be arranged. Inhabitants can have outside workouts together. If it exists in a village or city, it can probably be done in tunect.

4.2.3. tunect app

This immense connectivity comes with huge complexity. A structure is needed to organise this. For this, inspiration is lent from social networks: how do they connect people and their hundreds of friends? Through the use of the internet and smartphone apps. However, the tunect app would be used mainly for practical purposes - like checking the laundry schedule or sharing food and tools - and not as a service to share posts. Neighbours can also send messages to each other to organise activities together and stimulate coherence. Individually the inhabitants can see their technology usage and adjust preferences as will be described in Section 4.6.2.

4.2.4. technology

The central hub is also an easy place to put infrastructure for the flow systems that provide the tunus tiny houses with electricity, heat, and water. Electricity and heat batteries will be stored inside the central hub, as well as a water filter. This will be treated more extensively in the following sections.

4.2.5. management

Having introduced several of the central hub's tasks and possibilities, it remains unexplained who is the organising factor behind this all. This is mostly dependent on the financial structure that is used to build and populate a tunect: if the inhabitants are renters, the organising burden may fall on the actual owner of the tunus tiny houses.

4.3. electricity

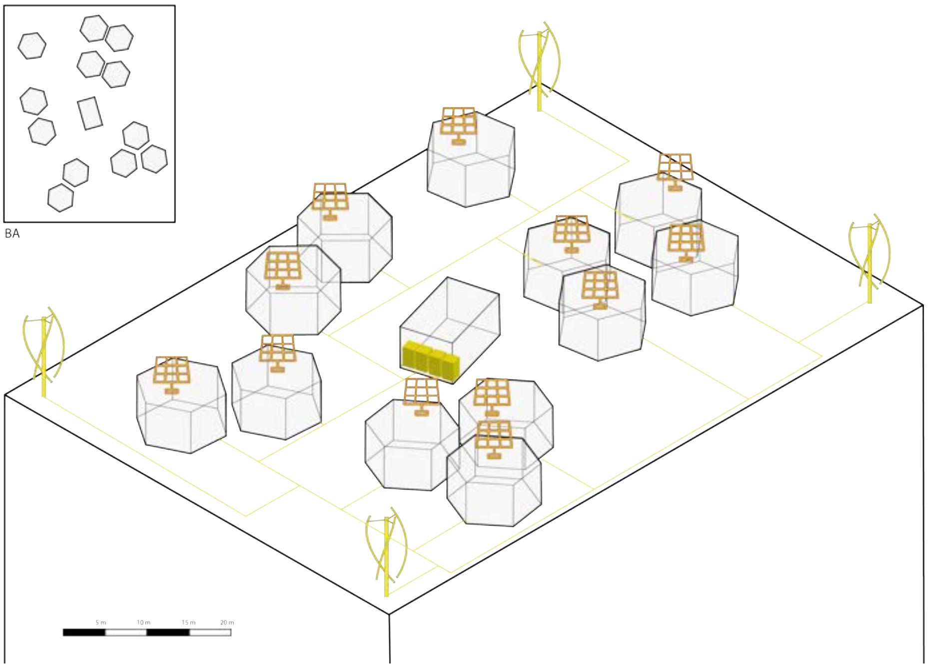


Figure 4.2: Visual view of electricity grid tunect

In the twenty-first century, access to electricity has almost become a basic human right. The United Nations state in their seventh Sustainable Development Goal that access to affordable, reliable, sustainable, and modern energy should be ensured for all (United Nations, 2015). It is used for a wide range of applications and enables the implementation of systems that can make a living space smarter and more efficient. Essentially, an electricity microgrid consists of three main elements: generation, storage, and distribution. After establishing the needs of tunect, these are discussed in the following sections.

4.3.1. usage

To keep a supply-demand balance, an assessment of the needs must be made before the design and presentation of the electricity microgrid. The usage of tunect consists of two components: the needs of the individual tuni and the needs of shared, tunect-features.

The electricity usage of a tunus is comparable with a small, regular home, in what it is used for. However, there are two notable exceptions: since tunus has a very reliable heating system, electricity is largely exempt from being used for heating purposes and since the washing machine is located at the central hub as described in Section 4.5.2, it is not a part of tunus.

Added together, all device and appliances in one tunus use $4,885\ Wh/day$, as seen from Section C.1. Adding a 20% buffer of $977\ Wh/day$ gives a daily usage of $70.3\ kWh/day$ for twelve tuni.

Shared features include only three parts: lighting, washing machines, and the control system.

The lighting is needed to lit up tunect during the night and LEDs are used they have a minimal impact on the environment. Using sensors and smart algorithms, the amount of light is minimised while optimising the amount of light that is perceived. Light pollution thus becomes manageable, even though it is not desirable. The tunect lighting is estimated to use up to $900\ Wh/day$ - six LED lampposts, some of which only use $73\ W$ according to the U.S. Department of Energy (Pacific Lamp Supply Company, n.d.), that are on for approximately two hours per day.

As described in Section 4.5.2, the washing machines are placed in the central hub. This makes them a tunect-feature. A total of four washing machines are implemented and estimated to use $1100\ Wh/day$ (Coolblue, n.d.).

The control system running all of the smart technology is placed at the central hub and estimated to use $1000\ Wh/day$ - which equals the use of three Raspberry Pi 4 Computers running 24/7 (RaspberyPi, 2020). All in all, this gives a total of $3,000\ Wh/day$ for tunect.

It can thus be concluded that, on average, the electricity usage of all tuni and tunect combined is the following:

$$70.3\ kWh/day + 3.0\ kWh/day = 73.3\ kWh/day \tag{4.1}$$

4.3.2. generation

Traditionally, electricity is generated centrally by coal-fired power plants (MacKay, 2009). In the past decade(s), a paradigm shift has occurred, moving towards distributed and renewable generation.

Several advantages surface when moving the generation of electricity to the consumer. The shorter distance decreases on-the-way losses. The dependency of the user on large electricity plants decreases as well - which is useful in off-the-grid configurations but has a limited added value in the city of Rotterdam with its reliable electricity supply. More interesting is the improved transparency. The origin of the electricity that one consumes becomes crystal clear: it is generated on the roof itself. When being climate ambitious, this transparency is essential.

These arguments make a reasonable case for moving the generation to the location of tunect.

PVT

Having established that the generation of electricity happens at tunect, the obvious - and increasingly mature - technology that comes to mind is solar panels, or Photo Voltaics (PVs). These are placed on the roof of the tuni, where they convert radiation from solar rays into electricity. If the tuni themselves are then placed on top of a building, this increases the incoming light, improving the panels' performance.

However, the sun's energy is also attractive to the heat grid, where it can be used to heat water or another liquid, competing with PV panels for the limited amount of available square metres. Fortunately, modern technology comes to aid here, with Photo-Voltaic-Thermal (PVT) panels. These combine the heating of a liquid with the generation of electricity. Moreover, the process that occurs in the Photo Voltaics actually becomes more efficient in a PVT configuration.

This peculiar phenomenon takes place because of the influence that heat has on the efficiency of a PV panel. Heat can lower the efficiency of a PV panel: an increase of $1°C$ can result in as much as a 0.25% loss in efficiency (Fox, 2017). The reverse is valid too: cooling the PV panel can result in a more efficient process. This is what happens when the heat is extracted from the PV panels, which is how a PVT panel produces heat.

As will be described in Section 4.4.1, using only two PVT panels suffices. Since there is not much to gain from an excess of heat, this means that only that amount of PVT panels will be installed. The remaining, available surface area of tunus' roof will be filled up with high-efficiency PV panels until the demand is covered by the supply.

Calculations of the power budget will, from here on, be done on tunect scale, not to neglect internal dependencies. PVT panels and regular PV panels are straightforwardly placed on the roof of every tunus.

Solar panels, such as the PVT panel of TripleSolar, have rated powers of roughly $190\ W/m^2$ (Triple Solar, 2020), with roughly equal efficiencies for high-end solar panels (National Academy of Engineering, n.d.). The solar panels are subject to an efficiency decrease due to the non-perpendicular angle of the incoming solar rays. This differs between the tunus tiny houses, as it depends on their orientation. It is assumed the PVT panels will have an angle of 30° on the steepest sides of the roof. It is preferably oriented to the south and has a range of 90°, meaning it can point to the east and west, but no further as to avoid large declines in received solar irradiance. This means an average efficiency decrease of 10% is used as seen in Fig. C.4, resulting in an overall rated power of $177\ W/m^2$.

To quantify the amount of incoming sun, the measure of 'Equivalent Sun Hours' is used: indicating how many hours the sun should shine at maximum power to transfer as much energy as the sun's actual fluctuations provide. The area of Rotterdam has on average $3\ ESH/day$ (OCW TU Delft, n.d.), equal to a capacity factor (CF) of $3/24 = 0.125$.

Using these numbers, it can be calculated how many square meters are needed for the solar panels to cover 100% of the buffered demand. The following formula is used:

$$E_{used}/day = \frac{CF * Time * Power/Area * Area}{day} \tag{4.2}$$

This is transformed in order to solve for the needed area.

$$A_{needed} = E_{used}/day * \frac{day}{CF * Time * Power/Area} = \tag{4.3}$$

$$= \frac{E_{used}}{CF * Time * Power/Area} = \frac{73,300}{0.125 * 24\ h * 177\ W/m^2} = 138.0m^2 \tag{4.4}$$

This is for all twelve tunus tiny houses and thus translates to $4\ m^2$ of PVT panels and $7.5\ m^2$ of PV panels per tunus.

Although this is already a reasonable start, with generation approximately equal to the requirements, it does not suffice due to a rather fundamental shortcoming of the sun's sunlight: it only shines during the day. Also during extended periods with little sun, problems can start arising. To prevent this from causing a blackout, besides an energy storage unit, something more is needed.

Fortunately, the sun offers more possibilities still: by heating Earth - and more specifically, by heating up some parts of the Earth's surface more than others - air starts rising in some places, and descending elsewhere. The subsequent pressure differences result in a horizontal movement of air, commonly known as wind (The NEED Project, 2013).

vertical axis wind turbines

Harvesting the energy from wind is done at an elevation, which means it can be seamlessly added to the PVT installations, without taking up desired surface space. The elevation of the host building makes wind energy especially interesting for tunect. Height is a crucial variable determining the potential of a wind energy installation. In a city, this altitude becomes essential as buildings decrease wind speeds considerably: "The flow of wind [...] is characterized by mean speeds that are 20 to 30 per cent lower than those of winds blowing across the adjacent countryside" (The Editors of Encyclopaedia Britannica, 1998).

Although wind turbines are ubiquitous these days, there is the persistent - but incorrect - sentiment that there is only a single design option, being the Horizontal Axis Wind Turbine (HAWT) as shown below.

Figure 4.3: Horizontal Axis Wind Turbine (EVwind, 2020)

This however, is a grave misconception. There are several variations of a HAWT. Also the turning axis itself can be turned around: introducing the Vertical Axis Wind Turbine (VAWT). Three main variations of these VAWTs exist as depicted in the figure below.

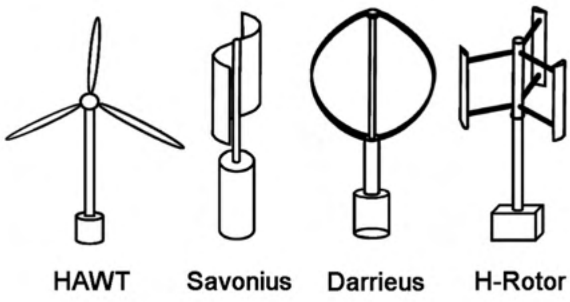


Figure 4.4: HAWT and Variations of Vertical Axis Wind Turbines (Kozak, 2014)

Several advantages lie in using these VAWTs instead of HAWTs.

They are omnidirectional and are more easily scaled to smaller sizes than turbines with a horizontal axis (Arcadia, 2017). As their blades revolve slower, they are quieter and safer for people and birds. VAWTs consist of fewer parts, increasing durability.

In contrast to the HAWT, which uses a rolling motion, the VAWT uses yaw. The vertical axis of the turbine's shaft allows an easier transfer of the rotational motion to the foot of the turbine. There it is converted into electricity by a gearbox and a generator. For a HAWT, these are placed at the top. This makes the VAWT easier to install. With more weight on the bottom, the shaft is less in need of strong and expensive materials for structural stability.

Further, Anna Craig, a Stanford mechanical engineering PhD candidate, says that VAWTs can be packed denser than HAWTs (Mangi, 2017). "The presence of each vertical-axis turbine creates regions of faster wind on its sides", adds John Dabiri, a Stanford mechanical engineer (Mangi, 2017). When placed close strategically, a cluster of VAWTs can thus create inter-turbine turbulence, increasing performance of the whole system (Arcadia, 2017).

Since there is already an abundance of solar panels (both PVT and PV) the two goals regarding the VAWTs are to support electricity generation during extend dark periods and to be relatively unobtrusive. The latter is treated as such because of the fundamentally intrusive characteristics of a wind turbine: moving parts that may produce sound at a certain wind angle.

As the VAWTs are mostly for support and considering their obtrusive nature, it is argued to place four installations: one at each angle of the roof. A $1\ kW$ turbine is chosen, such as the Aeolos-V 1kW vertical wind turbine (Aeolus, n.d.).

The Aeolus turbine, which is taken as a reference, produces less than $45\ dB$ of noise (Aeolus, n.d.), which is below the $50\ dB$ guidelines for outdoor living areas of the World Health Organisation (WHO) (WHO, 1995).

As is clear from its name, the Aeolus turbine is rated at $1\ kW$. However, it is not continually running at this power. In the Netherlands, the capacity factor for onshore wind turbines varies around 25% (Kling et al., 2007). Due to the urban environment, this seems too optimistic (Christiner et al., 2010). An approximation of 14% is made (Christiner et al., 2010), which suggests an optimal configuration. This would mean that every turbine is, on average, producing $3,360\ Wh/day$. Although this is approximately equivalent to what a single tunus generates per day, it is important to note that the timing of generation is significant here. As Sarah Kurtz of the U.S. Department of Energy explains, "Wind resource tends to complement solar resource," she takes Colorado as an example and continues "Here [...] the windiest time is during the winter and spring months. In winter, we don't have as much sunshine, but we tend to get more wind and stronger wind." (Jervey, 2016).

energy budget

The usage and generation are now compared, to be able to conclude that a sufficient amount of electricity is generated. In total, $86,718\ Wh$ is generated per day. The average daily usage, without buffer, lies at $61,620\ Wh$. This means that on average, daily there is a surplus of $25,098\ Wh$. Total production is thus 141% of what is needed. This considerable surplus is intended to partly solve the timing mismatch between generation and demand: when the generation system is operating at only 71% of total capacity, its output suffices to cover the demands. Deficits or surpluses that occur nonetheless, are supposed to be covered by the storage system that is described in Section 4.3.3. In the rare case that the storage is full and more is generated than being used, damaging the electricity network is avoided by disabling the VAWTs or blackening the solar panels so that the sun does not reach them.

4.3.3. storage

Humans love habits. Many habits have become fundamental to the way people spend their days - think of a shower and breakfast in the morning, a 9-to-5 job, a warm meal in the evening, watching tv afterwards, and brushing your teeth before going to bed. Unfortunately, this schedule is not directly compatible with the generation of much-needed electricity. This goes for day-to-day fluctuations - with the sun shining brightest at noon, but electricity demand reaching its peak in the evening - as well as for seasonal variations - both heating and electricity are needed most during the winter, which offers the least solar energy. Once again, technology can step in to bridge such generation-demand gaps.

In the 20th century, the most commonly used energy storage type has been fossil fuels (Smil, 2000). They are exceptionally energy-dense (IOR Energy, 2010) (Mitchell et al., 2011). However, retrieving their energy is done by incineration, which produces harmful particles. Further, they cannot be easily produced - crude oil, for example, takes millions of years to be formed from dead remains of organisms like algae and zooplankton (Howden, n.d.). This leaves fossil fuels unsuitable for use in tunect.

Two increasingly popular alternatives are batteries and hydrogen storage. The former is already omnipresent but has largely remained in use solely for small applications with the technology for large scale use only in adolescence. The latter is gaining popularity with the day, but not yet influential enough to steal the show.

batteries

There are two types of batteries, primary and secondary batteries, that are for a single use and for multiple charging cycles, respectively. Only the latter is of interest as only secondary batteries are "genuine electrochemical storage systems" (Kiehne, 2003). They are still heavily researched and a multitude of types exists "including lithium-ion (Li-ion), sodium-sulphur (NaS), nickel-cadmium ($NiCd$), lead acid (Pb-acid), lead-carbon batteries, as well as zebra batteries ($Na - NiCl_2$) and flow batteries" (Koohi-Fayegh & Rosen, 2020).

The lithium-ion batteries are currently "the fastest developing energy storage technologies, thanks to its fast pace of development for electric vehicles, as well as residential and utility scale applications" (Koirala et al., 2018). Companies like Tesla have been able to deploy Li-ion batteries with enough storage to successfully power a car for several hundred kilometres. With their experience and innovations in battery technology, Tesla developed battery packs for usage in a residential environment. Their offer includes a Powerwall, Powerpack, and Megapack (Tesla, n.d.-b) (Tesla, n.d.-a) (Tesla, 2019). Such a Tesla Powerwall can store $13.5\ kWh$, weighing $114\ kg$ with a peak power of $7\ kW$ (Tesla, n.d.-b). A Powerpack can store up to $232\ kWh$, weighing $1,120\ kg$ with a peak power of $130\ kW$ (Tesla, n.d.-a). Both have a round-trip efficiency of about 90 % (Tesla, n.d.-b) (Tesla, n.d.-a).

Considering their popularity and recent commercial advancements, Li-ion batteries are the most applicable candidate for implementations in the near future.

hydrogen

Storing energy in hydrogen is peculiar in that it is actually simply making hydrogen and dissolving it again later. To produce hydrogen, energy needs to be supplied. One feasible process is letting high-temperature steam react with natural gas, producing hydrogen, carbon monoxide, and carbon dioxide (US Energy Information Administration, 2021). Another - less polluting - possibility is applying an electrical voltage over a basin of water; hydrogen molecules will start forming on the negatively charged electrode or cathode, and oxygen will appear at the positively charged electrode or anode (The Editors of Encyclopaedia Britannica, 2020).

However, this process is still very expensive. Further, the low round-trip efficiency of 30% makes it undesirable for a system where too many on-the-way losses can result in deficits: if all generated energy or 141% of demand would go through the hydrogen system, only 42% of demand would remain.

storage calculation

Because of its expensive nature and low round-trip efficiency, storing the generated electricity in hydrogen is not feasible. It is thus decided that the cheaper and more efficient batteries will be used, for now.

Having chosen what type of energy storage is used, there remains the question of how much energy should be stored with this method. Unfortunately, a shortage of data makes this choice very arbitrary: there are no datasets of year-long day-to-day usage in a tunus tiny house. There is also no reliable way to simulate this due to a lack of data of year-long day-to-day usage in regular tiny houses. Substituting this with data from regular homes is also not an option as it would not be representative. This only leaves the previously calculated averages available. Considering the overproduction of the generation system - total production is 141% of what is needed - and the price of batteries - which is still high - the batteries are decided to contain the equivalent of three days of usage:

$$61.6\ kWh * 3 = 184.8\ kWh \tag{4.5}$$

This is roughly equivalent to fourteen Tesla Powerwalls, which would already cost about €$60,000$ (Lambert, 2016). As more information is gathered on how the inhabitants use their tunus tiny houses, better estimations can be made.

4.3.4. distribution

Having generated electricity, it needs to be brought to the user. Whenever there is a mismatch between the supply and the demand, the storage system is supposed to be capable of stepping in to eliminate the deficit or surplus. The system that manages these tasks is the electric power distribution system.

On a country scale, such a distribution system can be divided into three levels: low voltage or LV (ranging from $127\ V$ to $380\ V$, medium voltage or MV (around $13.8\ kV$), and high voltage or HV (ranging from $138\ kV$ up to $1000\ kV$) (Tcheou et al., 2014). Generation is generally done at the MV-level and household usage is at the LV-level. A typical scheme of such a power system is depicted in the figure below.

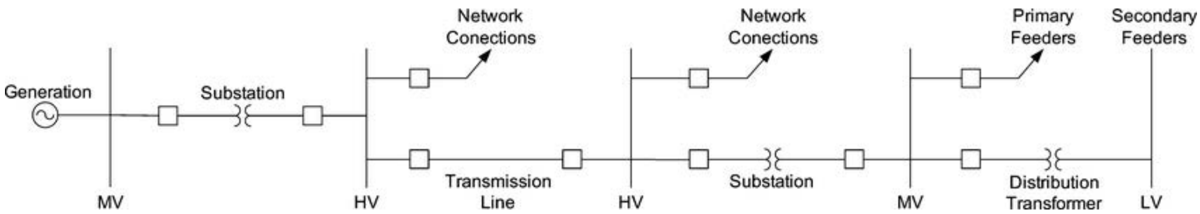


Figure 4.5: A Typical Power System Scheme (Tcheou et al., 2014)

In between generation and usage, electricity is temporarily converted to the HV-level. This transformation is made to minimise energy losses in long distance transmission: "The higher the voltage, the lower the current. The lower the current, the lower the resistance losses in the conductors. And when resistance losses are low, energy losses are low also." (Beta Engineering, 2020).

Fortunately, it was decided in Section 4.3.2 that generation will be done on location. This removes the need for both the HV- and MV-level since they are for long distances. Thus, it would suffice to keep the whole distribution system on the same LV-level.

grid trade-off

This national distribution system still exists though. Especially in a large city like Rotterdam, these distribution systems are well developed and are being made smarter with pilot projects (tdworld, 2017). This makes it attractive to connect a village on a city roof to the grid, as opposed to designing it as an off-grid community - i.e. with its own generation, storage, distribution. There are two different aspects to be observed here: technical and ethical.

The technical point of view favours a grid connection. With such a connection of the grid, surpluses can be solved by supplying it to the grid. Deficits could then be filled up by power, originating from the grid. Both of these reasons, make the need for a battery less urging. The battery can thus be made smaller or even discarded.

From an ethical point of view, good arguments can be made for both sides. Whenever surpluses are being supplied to the grid, this essentially means that a larger portion of the city's electricity is from renewables. On the other hand, an off-grid configuration is a significant proof of concept: living sustainable in tiny houses is being proven to be possible.

Since tunect is rather a real design for actual people that will hopefully be realised one day, than simply an attempt at proving a concept, it was decided to connect tunect to the electricity grid of Rotterdam.

DC smart grid

Another task of the distribution system is to offer the type of electricity that is desired. Usually, this entails an AC or Alternating Current voltage. However, for tunect, it is observed that multiple components of the system utilise a DC or Direct Current voltage. These include, but are not limited to PVT panels, batteries, electric vehicles, lighting, and electronics (such as cell phone chargers and televisions) (Morgan, 2017). With no reason to convert all generated electricity to AC, a substantial portion of what is generated can be kept in DC, essentially creating a DC Distribution Grid.

Such DC Grids have pilot projects in the Netherlands commissioned by the Dutch Ministry of Economic Affairs (Netherlands Enterprise Agency, 2015). DCSMART, a TU Delft project, will validate the concept of DC Grids in two demonstration sites, one in the Netherlands and one in Switzerland, as part of the European Research Area Network (van der Blij & Purgat, n.d.). In this DC context, they will also address the following topics: active demand-side management, autonomous grid management, ICT interfaces, and smart retail markets (DCSMART, n.d.).

In a household context, one rarely, if ever, needs to consider the difference between AC and DC. This is because all appliances and electronics are designed for simple use. This disregard is not possible when the distribution system is designed to separate DC and AC. It is therefore addressed here.

In Europe, the power socket outputs an AC voltage. This AC voltage can then be directly used for appliances like refrigerators, hairdryers, dishwashers, garbage disposals, and toasters (Morgan, 2017). For devices in need of a DC voltage, a rectifier or AC-to-DC converter is added. This can be internal (in the device itself) or external (as part of the power plug or in a dedicated block in the wire).

In the DC smart grid, the preference strongly goes to DC-powered devices. This means that devices with an internal rectifier will be hard to implement. Fortunately, a considerable part of contemporary devices is powered by USB, which use DC. Any electronics that run on DC and are powered with a classical AC power plug with external rectifier will be able to join the DC grid with a customised power supply (Jayceetoo, n.d.). This may include televisions and computers, both often supplied with an external rectifier (RWeCrazy, 2017).

In practice, that means that in tunus the amount of AC sockets will depend on the inhabitant but be kept at a minimum. DC sockets will be provided in the form of USB connections.

personas

The abstract concept of a personalised Electricity Grid will be illustrated with the four previously established personas.

As a recently graduated architect, Louisa rarely has the time for extensive cooking even though she is rather fond of cooking. So in the kitchen, she needs several AC sockets: She often uses her microwave and heat ovens for prepared meals. When she has the occasional opportunity to cook, she will also use several AC kitchen appliances.

Living rather archaically, Louisa does not need a television and only has a simple Nokia phone and record player. This leaves her in need of only USB sockets (Amazon, n.d.). She uses her office computer so she can avoid having to purchase a laptop. When she works from home, she writes and draws on paper. She often reads magazines and books, so some extra reading LED lights are added next to her couch and bed.

She is fashionable nonetheless and much of her magazines treat the latest trends. She can spend hours in front of her mirror, lit by a bright LED light, armed with her hairdryer. So an AC socket in her bathroom is also a must.

Anna and Abdel have a kitchen that is broadly supplied with AC sockets. Besides that, Anna has several DC laptop chargers lying around - as a journalist she often works from home - and both charge their phones using USB sockets next to their beds.

Carlo and Lucas like spending time at home. They have a moderate kitchen with a few AC sockets and have sufficient USB sockets for their phones. However, Lucas' passion for movies makes for a more elaborate movie setup than usual with a beamer - running on DC - and a white screen.

As a minimalist with a dislike for cooking and an ardent love for the climate, Emma has a minimal kitchen layout. Always busy with her job as an entrepreneur, she has a laptop charger and television for being up-to-date with the latest news. Both run on DC sockets.

4.3.5. infrastructure

Having designed an electricity microgrid with generation, distribution, and storage, the question arises of how this looks like in practice. Two scales are considered: tunus and tunect.

inside

In terms of structure, all tuni are equal: the roofs are filled with PVT panels. In a first stage, these will be of a certain model such as TripleSolar's Heat Pump Panels (Triple Solar, 2020) or DualSun's SPRING® Panels (DualSUn, n.d.). In the long run and as the concept is scaled up, a customized PVT installation will be designed for tunus, but this is a whole study on its own.

The PVT panels are directly wired to the voltage regulator under the first floor. This outputs both a pure sine wave AC and a steady DC voltage.

There are still several AC sockets, which makes a central DC-to-AC converter, or power inverter, more beneficial. This, in turn, is the rationale for cabling AC and DC separately.

As there will be less and less AC sockets - which is the goal of the DC smart grid in the first place - moving the power inverter towards the AC sockets may become more desirable in a later stage.

So from the regulator, both AC and DC cables run through tunus separately. However, they do not necessarily run alongside each other. Both AC and DC go to the kitchen, but only AC runs to the bathroom, and only DC appears at the desk, table, and bedside. When they reach their destination, the cables exit the walls to become either a classical AC socket or a DC USB socket.

outside

On the outside, cables run alongside the heat and water pipes. They connect all tuni, PVT panels, VAWTs, and other appliances, in one grid. At the central hub, all cables converge into another voltage regulator and the battery. This outside grid runs on DC, meaning that, at the VAWTs, AC-to-DC converters must be placed.

The reasoning for running the outside grid on DC is the following: either the VAWTs' electricity must be converted into DC or the electricity of the tuni, PVT panels, and batteries must be turned into AC. The former needs less infrastructure, especially as there are only four VAWTs, and contributes to the DC grid future that is envisioned.

4.3.6. conclusion

In short, the electricity microgrid consists of a generation system producing 141% of demand, a storage system that can store three entire days worth of usage and a distribution that minimises losses by removing unnecessary conversions.

4.4. heat

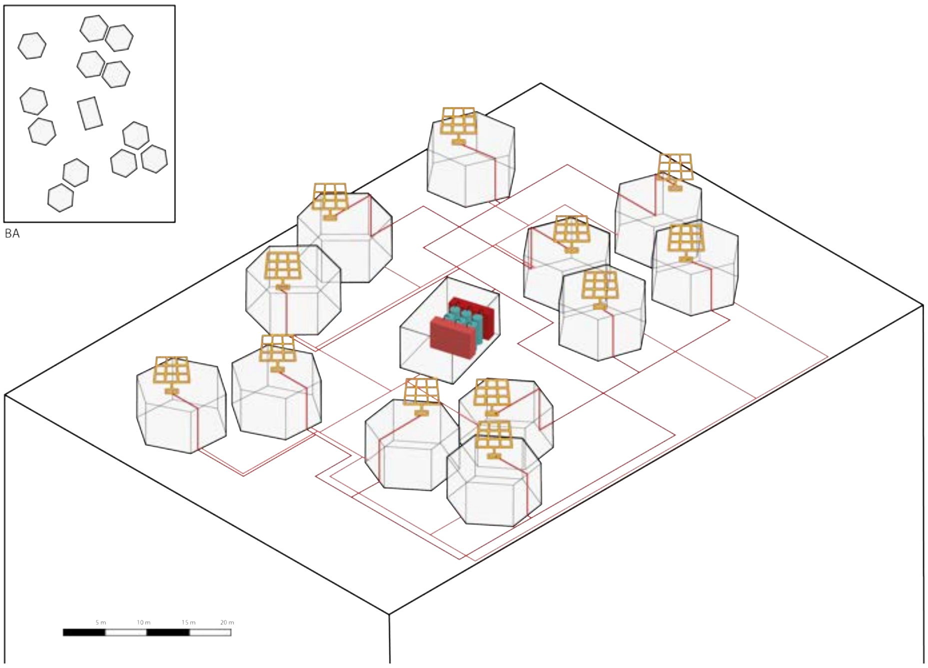


Figure 4.6: Visual view of heat grid tunect

The generation of heat in modern households accounts for approximately 80% (Eurostat, 2020) part of their energy demand. In 2017, 97% of houses were gas connected and still heavily relying on fossil fuels. Slowly, society is edging towards sustainable energy technologies. Heating electrically using new technologies is a good beginning, but is of no use if the energy production chain does not start investing heavily in renewable energy sources and delivers green power. In this chapter, research is done introducing a sustainable heating network between tiny houses and within. After all, a comfortable and safe house starts with appropriate heating. The generation, distribution and storage of heat will be explained with a schematic view of the system, visible in Fig. 4.7.

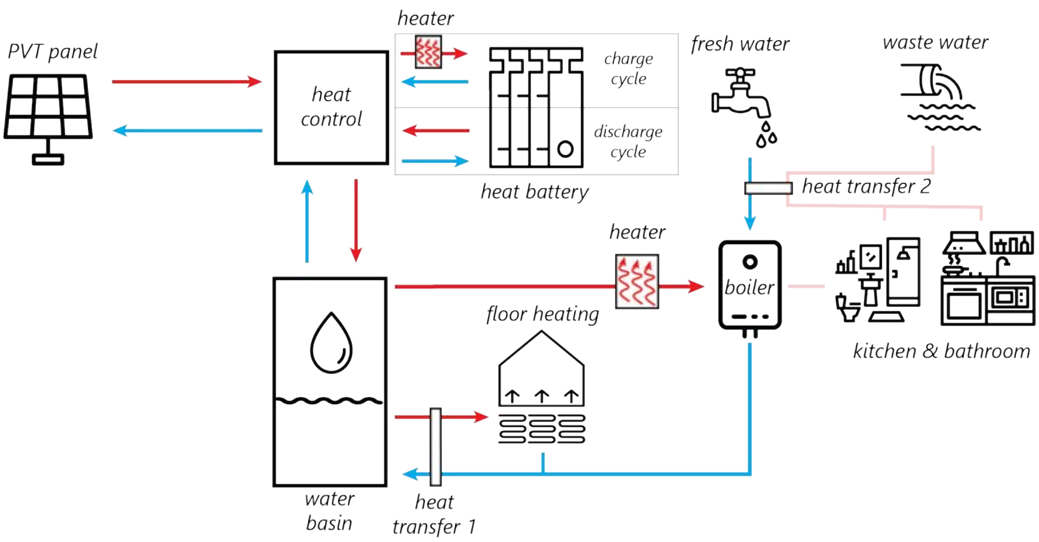


Figure 4.7: Schematic view heat grid tunect

4.4.1. generation

Heat generation, distribution and storage have certainly not yet reached their full potential. As it stands, heat is mainly generated through gas. The heat production is then strongly dependant on the energy generation of fossil fuels. The Netherlands has been keen on investing in ”city heat”(Niessink & Rösler, 2015), reusing the lost heat of industrial sites. Almere, Rotterdam, Amsterdam and many other cities have started implementing this city heat on a large scale. This is a promising and positive evolution, but for this research - in the search for autarky - reusing industrial waste heat is not an option. To this day only about 13 noteworthy heat networks like this have been set up (Niessink & Rösler, 2015) and thus do not account for a great part of heat generation and tiny house villages cannot always profit from an industrial plant nearby.

The heat generation is visible at the upper left of Fig. 4.7. It is a PVT panel, as is described in Section 4.3.2. These PVTs will warm-up a closed loop of a water-glycol mixture. The glycol lowers the freezing point of the mixture making sure the system does not freeze and destroy itself in wintertime. The mixture will subtract the heat from the voltaic cells, after which the temperature of the mixture will rise and be used to supply the house of heat and charge the heat battery, that will be discussed further in Section 4.4.3.

A Dutch-based company, Triple Solar produces these PVT panels and offers a variety of instalments. The choice was made to use their PVT panels and their specifications. Apart from being subsidised in Europe, they offer promising technical aspects.

Table 4.2: Specifications TripleSolar (Triple Solar, 2020)

PVT panel	Unit	M2 320 165 L
PV surface area	m^2	1.95
Bruto surface area	m^2	1.98
Weight	kg	32
Nominal power	W_p	380
Efficiency solar cell	%	21.6
Efficiency panel	%	19.5

For the sizing, Triple Solar provides some formulas to calculate the dimensioning of the PVT panels. All tables and figures used for these calculations can be consulted in Section C.3. First, the heat transmission loss is calculated:

$$33\ m^2 * 35\ W/m^2 = 1,155\ W = 1.155\ kW \tag{4.6}$$

For which $33\ m^2$ is the complete surface area of tunus and $35\ W/m^2$ is an indicative value of the transmission loss Fig. C.2. It is given from a rule of thumb for which it is assumed that tunus has a well-insulated house with heat recovery systems. This leads to a rough estimate heat demand of $1.155\ kW$.

The amount of panels is based on this heat demand. Triple Solar again gives an equation to calculate the surface area needed (Triple Solar BV, 2020). They use a factor of 2.67 as a criterion in the Dutch climate. This factor follows from the heat supplied by the panels and the heat pump together with what is required in a house located in the Netherlands. The factor complies with their attestation of equivalence.

$$1.155\ kW * 2.67\ m^2/kW = 3.08\ m^2 \tag{4.7}$$

As expected, this is a small area but it can be appointed to the fact that tunus has a very small surface area to be heated. However, the smallest heat pump has a power of $3\ kW$. This is excessive but they are not specifically made for tiny houses which is why a personalised system would be preferred. How this personalised system would look like will be considered more extensively in the future as mentioned in Section 4.3.5. For now, on the other hand, the system of a $1.2\ kW$ heat pump will be used. Extrapolation from Triple Solar's sizing recommends $3.2\ m^2$ on PVT panels. This requires 2 PVT panels of $1.98\ m^2$.

Heat demand	$1.2\ kW$
# PVT panels	2

Table 4.3: Heat demand tunus

4.4.2. distribution

An important role of the heat grid is to be able to intelligently decide where which heat gets redirected. The ”heat control” block, next to the PVT panel, in Fig. 4.7 makes sure this happens accordingly, the block itself will be further dissected in Section 4.6.1.

Throughout the whole grid, heat gets transported through water. This water can be transferred from one closed-loop system to another with the help of heat exchangers. These ensure that heat from one system is transferred to another. The water transfers its energy to the other water and heats it this way. The transfer of this water will be done through copper insulated pipes. Conventional piping for water systems in a domestic context is further exemplified in Section C.2.4.

When the system decides to allocate the heat to the house, it will transfer its heat to a central water basin located in the machining room of tunus. This water basin will be heated by, or the PVT panel, or the heat battery. The water exiting this water basin is used for two purposes: floor heating and for the boiler, that is used to warm up tap water. The boiler itself can be modelled as a water vessel equipped with a water-to-water heat exchanger.

The tap water itself should be heated to $60°C$. This means the water warming up the tap water through the heat exchanger should have a higher temperature than $60°C$. This temperature is achieved through the electrical heater that will cover the gap between the delivered power of the heat battery and water basin and the required power to keep the boiler operating in normal circumstances. On an average day, this is $1.71kWh/$day, the model and calculation can be found in Section C.2.1.

The floor heating has another minimal operating temperature. During winter the floor heating should exceed its surrounding by $\approx 2°C$, requiring a temperature of $\approx 30°C$. During summer, the water should be slightly cooler than the environment, $\approx 2°C$ with a minimal $\approx 20°C$.

After the water runs through the heat exchanger in the boiler it exits it at a lower temperature and reunites with the cooled down water from the floor heating that just ran through the floor heating system and warmed up the house. This stream enters the water basin and is warmed up again and continues on this cycle.

Both streams have different required minimal initial temperatures to operate. The boiler destined water should be heated and the floor heating destined water should be cooled. the cooling of the floor heating is done through the ”heat transfer 1” block, another heat exchanger. The cold water exiting the boiler and floor heating passes through the ingoing floor heating water. This water has a too high inlet temperature. The temperature will drop due to the exiting cold water passing around it. By cooling the hot water, the cold water also gets heated meaning less power is required to bring it back to operational temperature. A similar system is implemented at the ”heat transfer 2” block that is described in detail in Section 4.4.4.

4.4.3. storage

The heat storage will be done through the use of a heat battery. This type of storage has been investigated for some time now and lately, research has started to pay off. The heat is stored directly as heat, instead of generating and storing electricity in regular batteries, to afterwards reconvert that electricity back into the grid and produce heat. The heat battery goes around the conversion to electricity and stores heat directly by using (de)hydration cycles of sodium carbonate (Na_2CO_3), see section Section C.2.2 for trade-offs.

The heat battery consists of a water tank connected to an internal valve and a vacuum barrel filled with salt grains intertwined with a complex network of copper channels acting as a heat exchanger. On a warm and sunny day, an overproduction of heat is a coherent consequence. This heat will be used to dehydrate Na_2CO_3. This dehydration occurs at $80°C$. As the salt dehydrates, the recovered water is stored in a reservoir. When heat demands rise and additional stored heat needs to be recovered on a colder winter day, a valve allows the water to be exposed to the salt again. This exothermic reaction heats up water that can be used for heating necessities in the house. A schematic view of the reaction is visible in Fig. 4.8.

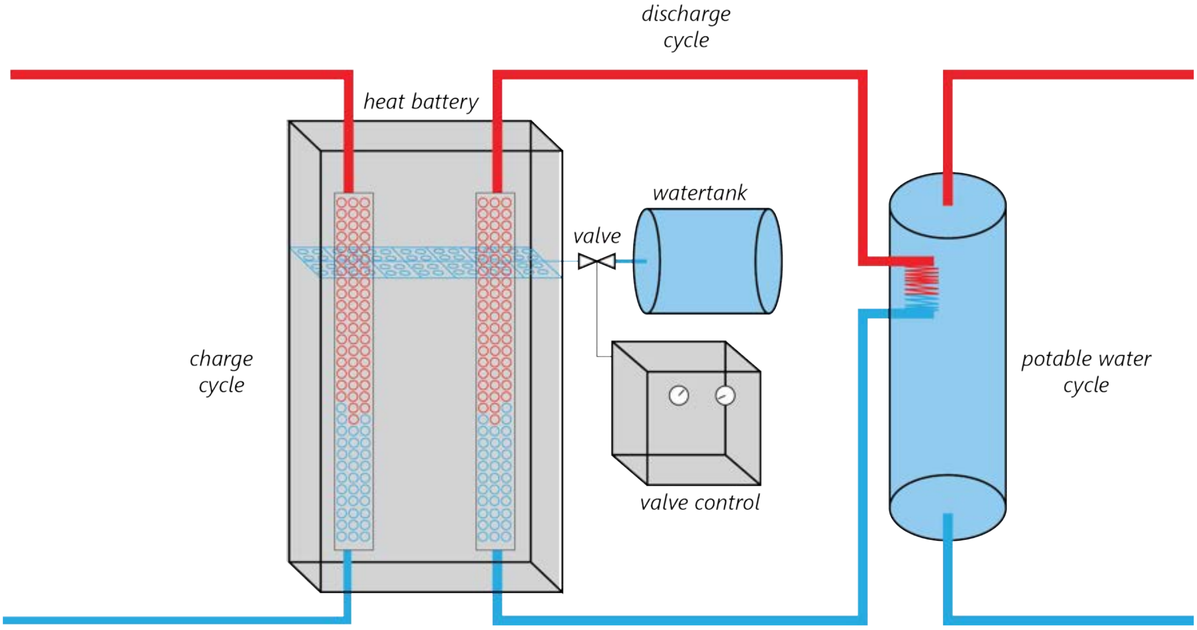


Figure 4.8: Schematic view heat battery

When the system decides to allocate heat to the battery it should be able to deliver it at $80°C$. Because of daily and seasonal temperature differences, the system cannot always deliver this. As done for the boiler in Section 4.4.2, a heater is placed to cover the energy difference. Deciding this difference is complex for a variety of reasons. First, the daily and seasonal temperature fluctuations and secondly, because the control strategy states that the battery will only be charged if the heat is not immediately necessary elsewhere. For the scope of this project, it was decided to be aware of a missing point in the energy balance but should be taken up in Section 7.5.1.

Heat batteries are a new concept that has not been commercialised for household usage. TNO has started researching heat batteries back in 2008(Keizers, 2017). They are planning on bringing a domestic use battery on the market in 2022. It was decided to use their heat battery because of the available information, transparent data and the quality TNO is known to offer. The heat battery is scalable, which is important, especially in this project. As size increases efficiency decreases to a minimum, but this difference in performance is insignificant if the volume remains below $170m^3$. Therefore, this technology can be used for tiny house usage and even grid-connected tiny-house-villages.

The promising aspect of salt-based heat storage is its ability to cover seasonal temperature fluctuations. Phase change materials (PCM) are not yet conventionally implemented in architecture to cover this seasonal change(Pasupathy & Velraj, 2006). Thermal mass PCM isolation materials have already been used as a low-tech alternative to cover day and night temperature discrepancies but are useless on an annual scale(Zhou et al., 2008). TNO states that a battery with a volume of $200\ l$ is enough to cover the seasonal heating needs of a traditional household of four.

Table 4.4: heat battery TNO

battery scale	total volume	water tank size	power	capacity	expected cost
regular household	$200\ l$	$50\ l$	$3\ kW$	$27.8\ kWh$	2000 €
tunus	$60\ l$	$15\ l$	$1\ kW$	$8.5\ kWh$	610 €
tunect	$730\ l$	$183\ l$	$11\ kW$	$100\ kWh$	7300 €

4.4.4. heat recovery

A substantial part of the usage and consumption of heat is the reusage of heat. A lot of household appliances produce heat as a waste energy stream. By harvesting this waste-heat and reusing it, the overall efficiency of the energy balance is increased. This on its turn diminishes this energy demand creating a more sustainable community.

Heat recovery can be done in many ways and will not always result in the same rise in efficiency. In this section, different strategies are discussed and conclusions are made to decide which of these will be feasible for the purpose of this research. These varying approaches entail an everlasting trade-off of relative and absolute heat recovery; on top of that acceptable energy recovery should be balanced with financially suitable solutions.

waste water heat recovery

One of the promising fields where waste heat can easily be recovered is in the grey wastewater of the house. This process is called wastewater heat recovery (WWHR) and has been thoroughly researched by the Swedish Institute for Water Science & Technology (Wärff et al., 2020). This research is aimed at multi-family households in a Swedish climate. The Swedish water agency is not the only one researching this waste heat recovery. ”De Warmte”, a *Delftian* startup, provides solutions to reach climate sustainability goals and makes these viable technologies accessible to a greater public. Heat recovery is a cost-effective and sustainable solution. However, the Swedish WWHR and the Dutch startup offer good solutions but are not interesting in a tiny house scaling. Producing and installing these systems for tiny houses exceed their original intent. A tiny house in itself uses little energy. During the course of this research, by making sustainable choices and selecting appliances and systems according to their very low energy consumption, the energy payback time of the acquired WWHR installation would be far too great for the current tunus consumption. Thus, the choice was made not to implement them.

The concept of WWHR is implemented in the design without acquiring expensive technologies and installations. This is done by making the grey wastewater tube pass by the incoming cold water tube that is destined for the boiler. This passive heat exchange through the two flows results in a transmission of energy. Depending on how the tubing is done the energy transfer varies between $630\ J$ and $5728\ J$. Calculations and reasoning can be found in Section C.2.4.

fluid cooled refrigerator

Currently, most refrigerators are air-cooled. In the refrigerant’s vapour compression cycle, most heat is rejected to the outside environment when it condensates. With the help of a heat exchanger, this heat can be withdrawn from the refrigerant through a fluid and can be stored or used immediately.

Section C.2.5 concludes that for the rated power of the refrigerator chosen in this project, determined by Table C.1, the $20\ W$ return of power is an increase of 200% of the fridge’s rate power but $20\ W$ is not energy-viable as well as cost-effectively. The increase in overall heat system complexity, the additional heat losses of tubing and the increase in cost led to the choice of not implementing the fluid-cooled refrigerator as a waste heat recovery system.

4.5. water

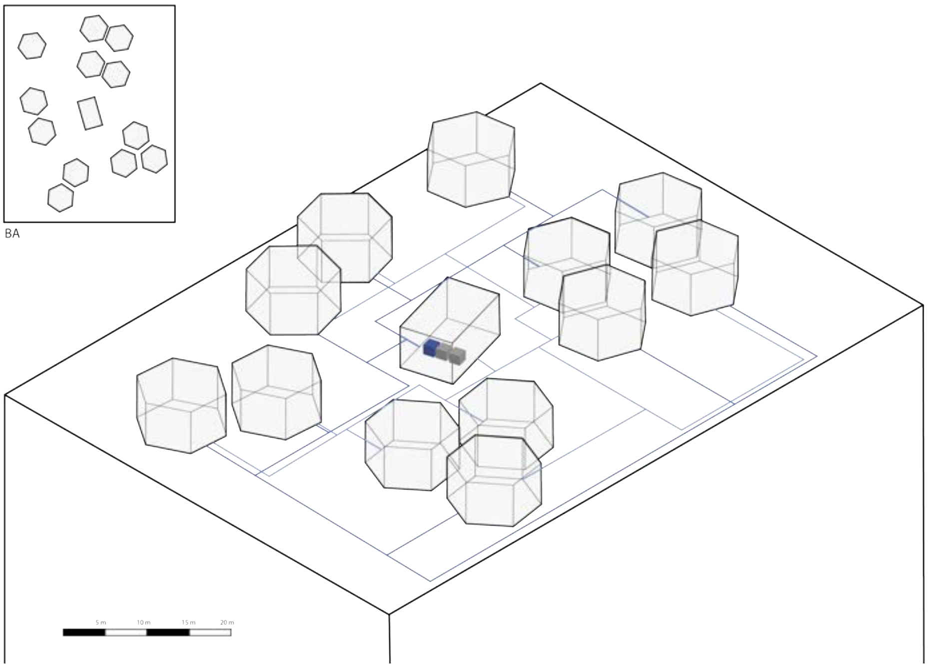


Figure 4.9: Visual view of water grid tunect

Water is largely discussed in Section 3.5.1 network sized water distribution and network-based appliances will be further elucidated in this chapter.

4.5.1. distribution

A schematic on this water filtering of tunect can be seen in Fig. 4.10. All greywater from the tiny houses gets collected and goes through a grease trap which removes the grease, oil and other parts from the water. These particles often cause an obstruction and are very hard to break down.

The water goes into a reservoir before going into the helophyte filter. This way, the pump can drain the same amount of water every once in a while. The water comes in from the top of the helophyte filter and goes through several layers that work with the principle of percolation. By letting it fall from the top, gravity does most of the work during filtering. A helophyte filter removes up to 99% of the waste in water (Wetlantec, n.d.). When using the "achtkanter", for example, a helophyte filter with a surface area of $1.2m^2$ (Technisch Bureau Hamar, 2016). The "achtkanter" uses a rock wool filter which is a recycled product of greenhouse horticulture (DeTwaalfAmbachten, n.d.).

It can filter $160\ l/m^2$ in 24 hours. With a size of $1.2\ m^2$, this means $192\ l$ per day. With a usage of about $24\ l/day$ per tiny house, it leads to $288\ l$ of water per day in the community. Considering that fairly economical washing machines are taken, which each use about $50\ l$ per load (V., 2020). Taking into account 18 people (12 tunus households) that all do their washing about once a week, gives us $900\ l$ a week on washing clothes. With only one helophyte filter, $1344\ l$ per week can be purified. This is aplenty for this demand, especially when counting that $2016\ l$ are used per week.

A reservoir should be made after the filtering as it can build a stock of clean water when multiple machines are used at once. This tank should be emptied every few days to prevent the growth of bacteria and algae and to reduce maintenance. This water goes into the city sewer not only with the water from the washing machines but also with that which did not go into the helophyte filter in the first place.

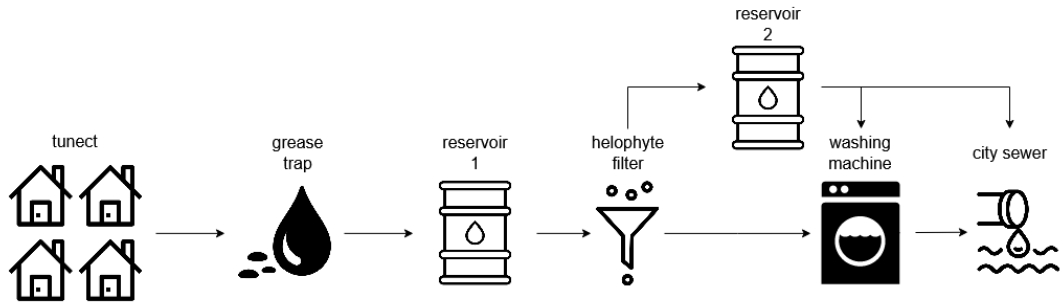


Figure 4.10: Schematic view of water filtering

A few questions might arise when looking at the schematic and the numbers in Table 4.5. It was chosen to let all the water go through the grease trap and the helophyte filter as it only helps the sewer system of the city if extra cleaning is done. The use of an extra filter is not very space-consuming and neither is it expensive. This means that all the water coming from tunect has zero discharge and is as clean as the water from little ponds. The positive effect on sustainability is beneficial for everyone for little effort. A recommendation could be to get disconnected from the sewer and use the water for something else. For now, however, the research will not go deeper into this.

Table 4.5: Water filtering sizing

# helophyte filters	2
Filtering speed	$160\ l/m^2$
Surface area single filter	$1.2m^2$
Used washing machine per week	$900\ l$
Filtered per week	$2688\ l$
Used per week tunect	$2016\ l$

4.5.2. washing machine

The washing machine will be placed in the central hub, this has three main advantages. First, it saves space. The usage frequency of low to such an extent that having a personal washing machine is an extensive luxury. Secondly, it eases the infrastructure. The filtering system can be placed central as well and the pipelines are close to the heat battery which makes heating the water easier, too. Lastly, the electricity peak when using all washing machines is flattened as there are not as many washing machines as tiny houses. This makes it easier to design for an optimal electricity grid as no extreme peaks need to be accounted for and supplied for. However, centralising washing machines and making it community property obviously leads to social conflicts. It is not desired that the inhabitants have to wait for ages to do their washing. This can be controlled with the help of time-slots discussed in Section 6.5.

4.6. control

The electricity, heat, and water networks have now been designed, but there is still no mechanism or algorithm controlling them. Here, a control strategy is given for the multiple elements of tunect.

The control of generation and storage for both electricity and heat is straightforward. This is because there is little influence to be exerted on the conditions of the generation system: either there is the sun, or there is not, there is not much to do about it. The generated energy first goes to the usage and if there is an excess, this is used to charge the batteries. Whenever there is a deficit, i.e. more is being used than being generated, the storage system supplies what is needed. This principle is demonstrated Section 4.6.1 with a finite state machine for the heat grid.

Where the control system does have influence, is on the usage of electricity and heat. How this is done will be discussed below in Section 4.6.2

4.6.1. generation and storage of the heat grid

In Fig. 4.6 a schematic view of the total heat grid is visible. To ease out thinking and gain a better understanding of its working, a finite state machine of the control block was made, portrayed by Fig. 4.11. With 5 different states:

- *idle* = idle initial state
- *heat* + *charge* = This state will use the generated heat to fulfill all household heating needs and will charge the heat battery with the remaining heat.
- *heat* = This state will use the generated heat to fulfil all household heating needs.
- *heat* + *discharge* = This state will use the generated heat to fulfil household heating needs and use complementary heat from the heat battery to be able to fulfil all needs.
- *discharge* = This state will use the heat from the heat battery to fulfil all household needs.

And three variables variables:

- t = heat produced by the PVT panels
- b = battery charge
- h = required household heating needs (warm tap water, floor heating)

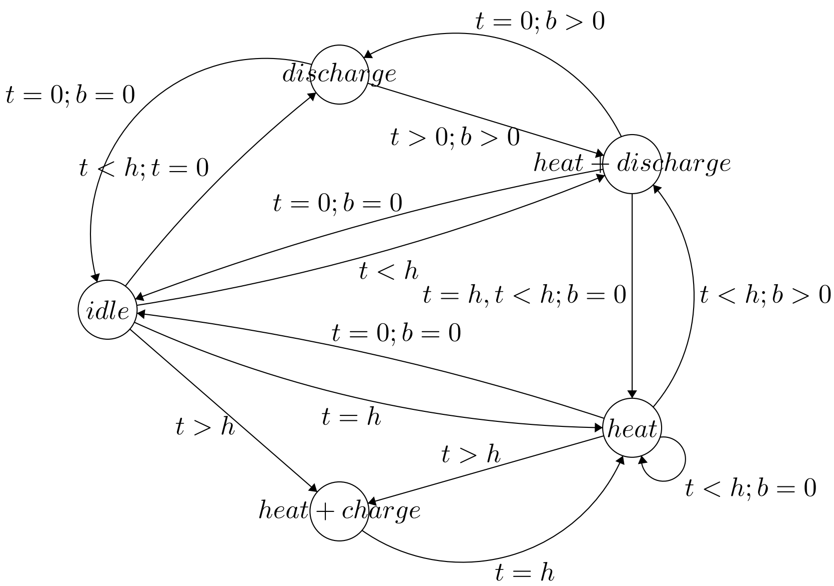


Figure 4.11: Finite State Machine Heat Control

4.6.2. usage

Before changing the usage, it has to be monitored by the control system. In this, sensors act as the control system's eyes and ears.

sensors
The more useful information is gathered, the more data can be used to make a thoughtful decision. These sensors include, but are not necessarily limited to (Northern Nomad, n.d.):

- Temperature sensors in the floor, the wall, and the roof
- Moisture sensors in the floor, the wall, and the roof
- Sensors that sense the presence of people, by movement or infrared cameras
- Sensors that measure pressures in plumbing
- Sensors that track use of electricity of different devices

Besides internal changes, sensors can also monitor the environment of tunect. Devices to observe these external influences can include:

- Sensors for measuring solar radiation
- A wind-driven rain gauge
- A wind speed meter
- Pressure sensors
- Sensors that monitor the temperature in the host building

app inputs
Unfortunately, sensors are not (yet) able to sense people's preferences regarding indoor climate or use of shared features. This data must be retrieved with another method. For this, the tunect app is used. With the app, people will be able to indicate their personal preferences on several topics including, but not limited to:

- The temperature inside at different times of day
- A wake-up time and bed-time
- A preferred colour of lighting

Even more input from the inhabitants of tunect can be used still. However, a new category is introduced here, as these inputs are not directly in the interest of the user. COMI (community oriented manual input) is information that the residents provide in the best interest of the community. Most COMI is about the use of energy-intensive devices like using:

- The shared washing machines
- A vacuum cleaner
- The upfall shower
- Cooking appliances
- Chargers of power-intensive electronics

Lastly, this is complemented by data from the internet. This will mostly be regarding weather forecasts, as much more accurate projections will be available online than what can be predicted from only sensors at tunect. Combining both the online information and data from on-location sensors will deliver the best results. Other information that can be retrieved from the internet are the times of sunrise and sunset and the angle of the sun during the different seasons.

putting the smart in smart control
These immense amounts of data must be put to good use. All data is fed to an algorithm that will eventually control the electricity and heat systems. It would be difficult to design control software that incorporates the very individual behaviour of the users. However, this behaviour, though very different from person to person, is much a subject to repetition: as mentioned in Section 4.3.3, people love habits. This individual and repetitive behaviour is the perfect feeding ground for implementation of Artificial Intelligence (AI) software that monitors and learns from the daily behaviour of the inhabitants.

Another argument in favour of the use of AI is the absence of reliable references: there is little precedent for connected tiny house communities. Trying to design a pre-programmed algorithm anyway would be destined to fail. This is exactly where the power of AI lies: adaptability.

implementation
Elaborating on every sensor and writing the code for the AI software would be a study on its own and is thus, unfortunately, not covered here. However, there are several examples that can be presented to get an impression of the (endless) possibilities of implementation of AI.

The control system receives information that next week will be cloudy. Since this will lower generation through solar panels, the system immediately starts anticipating by cutting some uses: the lampposts that usually remain on for 10 minutes after detecting someone, will now turn off after 5 minutes. It also informs the inhabitants about the situation, asking them to reduce how often they use their vacuum cleaner or cook extensively - although this is still only a suggestion.

Through the app, Anna and Abdel let the system know that in two days they will be having some friend over and will cook extensively. Since the battery is starting to deplete, the system once again decides to cut some uses.

At tunect, Wednesday is a busy washing day. Louisa, Emma, Anna, and Abdel have informed the app - and thus each other - that they would be using the washing machine on Wednesday afternoon. Lucas sees this on Tuesday afternoon and thus decides to postpone his visit to the central laundry location by four hours on Wednesday.

Every Thursday, Emma goes cycling through the Dutch tulip fields. Upon returning, she opens a few windows to let some fresh air inside. However, she often forgets to close them again and only does so after a long while. The control system notices this steep temperature drop and it informs Emma through the app that it would be beneficial to the climate system if all windows were closed. In the weeks thereafter, Emma does an effort to close the windows after a few minutes and whenever she forgets, she gets a quick notification from the app.

pilot dakdorpen
As pilot projects of tiny houses on roofs or connected tiny house communities occur, it may be necessary to change some of the described systems and concepts. Dakdorpen, for example, is working on a pilot project on their roof, De Kroon. In doing this pilot, they will be gathering information that can later be put to use in the general concept. The obtained data could also be utilised to optimise the control system. This changing nature is not a problem since this evolution is part of the iterative design process and as was said in Section 3.2: a design process is never really finished.

4.7. scalability

Modularity and adaptability have been central in the design of tunus and tunect. These characteristics must now be put to use. One way to do this is by making the design scalable. So far, tunect has been designed as for a roof with twelve tunus tiny houses. But there is no fundamental reason that this number cannot be called up, provided that the roof is structurally able.

The three flow systems are treated separately because of their differing scalability properties. The conclusions will then be fed back to the central hub because that is where all flow systems converge.

4.7.1. electricity

Compared to heat installations, an electricity grid is relatively easily scaled up. All three main elements of the electricity microgrid are considered: generation, storage, and distribution.

It is rather straightforward to argue that as more tuni are added to tunect, the amount of solar panels rises since they are installed on every new tunus. Scaling up the VAWTs is more elaborate. On small roofs, there is only a limited amount of space, since it is undesirable to place many VAWTs in close proximity to the tuni. This makes it attractive to simply scale up the rated power of the turbine. Installations, suitable for roofs, of $2\ kW$ (Aeolos, n.d.-b) or $5\ kW$ (Aeolos, n.d.-a) exist. On larger roofs, small farms of turbines near each other could be added.

Because of the way larger batteries are made up of smaller cells, they are easily scaled up. Tesla advertises their battery packs, the Tesla Powerwall and the Tesla Powerpack, as easily scalable to the needs of the user and adaptable to the available space (Tesla, n.d.-b) (Tesla, n.d.-a). Thus, in a different configuration of tunect - with more tunus tiny houses - the desired storage capacity can simply be recalculated and then a battery pack of this size can be installed. There is no major reason to split the battery storage, so it can remain in a central space on the roof.

The distribution of the electricity in tunect consists of two parts: the way the electricity is treated inside tunus and the way the different tunus tiny houses are interconnected. The former is simply duplicated with every new tunus tiny house. The latter becomes more complex as more tunus tiny houses are added. But, by adding more capable voltage regulators, it is estimated that there will be no necessity to split the grid into more than one component. Rewiring with more robust cabling might prove to be necessary. However, working such configurations out in full would be a project on its own.

To conclude, the electricity microgrid of tunect should be scalable to a size which should support a high amount of tunus tiny houses, without having to split up into multiple microgrids.

4.7.2. water

The scalability of the water network is fairly straightforward. A simple calculation can be done on how many tuni produce how much water and thus, how many helophyte filters are necessary. For the sake of simplicity, the same ”achtkanter” is used as in the discussion in Section 4.5. In Table 4.6, the amount of filters is shown for the amount of tunus tiny houses. This is only for the model, ”achtkanter”, other helophyte filters exist too with a different capacity.

Table 4.6: Sizing of scalability for water

# tunus tiny houses	water produced per week [l]	# filters needed
<8	1344	1
<16	2688	2
<24	4032	3
<32	5376	4
⋮	⋮	⋮

Each basin will have two helophyte filters with up to 15 tunus tiny houses connected to it. This will save on extra costs by pumps and extra pipelines. It will also flatten the water usage peaks so there is less trouble when someone uses too much water in a day as it will be more averaged due to the amount of tiny houses. When scaling the amount of houses up, there is a possibility to centralise it all in one big reservoir, but this basin might become needlessly big.

4.7.3. heat

The scalability of the heat grid strongly relies on heat storage. The generation of heat is done by PVT panels which can be placed on every house. As is described in Section 7.5.4 optimizing heat production can be done through smarter PVT panel positioning on roofs. By scaling up communities it is necessary to research the effectiveness of this strategy to greatly reduce heat grid infrastructure (avoidable tubing, futile control blocks and excessive heat loss). Distribution-wise, bigger communities result in a significant increase in the absolute amount of tubing and the complexity thereof but still surveyable.

As is described in Section 4.4.3 the salt-based storage is easily scalable. For tiny house communities increasing the size of the central heat battery would barely result in a decrease of relative power or capacity. The amount of the cycles the battery undergoes could, however, pose a problem. Constantly charging and discharging the battery for 30 tiny households is a specific type of load the battery is not designed for. Since TNO has not yet figured this out for their own products in normal circumstances. In addition to a possible malfunctioning battery, the plumbing of the heat network lends itself to be more efficient in smaller communities. This leads to deciding that the maximum amount of houses for one central heat battery is set at 15 tiny households.

4.7.4. central hub

In all flow systems, the central hub plays a key role. As more tunus tiny houses are added, one central hub does not suffice to meet the network's need as explained above. But also when scaling down, instead of up, the relevance of the central hub must be reviewed.

The goal of the central hub is to make processes more efficient by combining and collaborating. However, when there is only a small amount of tunus tiny houses, it would actually become an expensive installation that adds limited value. So it is decided that tunect is only supposed to be installed when it is supplying the connection between four or more (tunus) tiny houses.

4.8. plug and play

The tiny house concept embraces the power of cooperation; oriented by this mindset, the plug and play concept is introduced. There is a lot to be gained from the flexible designs of tunus and tunect. Besides making tunect scalable, so that tunus tiny houses can be added, the flexibility makes tunect accessible. External tiny houses can be connected to tunect and thus participate in the sharing of electricity, heat, and water. This principle is called: Plug & Play.

For the three flow systems, the capability of adding non-tunus tiny houses to tunect is discussed: how easily can an external tiny house be added to and participate with tunect.

4.8.1. electricity

As with scalability, the principle of plug and play is reasonably easily applied to the electricity microgrid of tunect. Once again, generation, storage, and distribution are looked at.

There are no technical requirements on generation for an external tiny house to join the microgrid: it can simply tap off the power that is generated elsewhere in tunect, as long as there is an excess. However, to prevent such an excess to come into being, it is very much preferred that joining tiny houses would be able to contribute to the electricity generation.

Since storage is handled centrally, there are no technical requirements for new tiny houses to be able to get a place at tunect. That is, as long as the storage capacity is in balance with what is needed of tunect: as more tiny houses are added, more battery capacity will have to be added as well.

How electricity is handled inside an external tiny house has a minimal influence on tunect. However, as it is added to the distribution of the electricity microgrid, it must be technically compatible with what is used to transport the electricity in tunect: DC. This requirement will force the majority of tiny houses to add a capable DC-to-AC inverter to be able to join the microgrid, as they will be using AC for their power supply.

All things considered, external tiny houses can join tunect and its electricity microgrid by adding an inverter. This makes tunect very accessible for others to connect with.

4.8.2. water

Compared to scalability, more complications emerge for the Plug and Play of water. The first and foremost is the use of a normal toilet in tiny houses which uses water to flush. This means a black water stream comes into the equation which is not a necessity for tunect.

In case there are only houses with black water streams, so no tunus tiny houses, there is the possibility to extend the filtering systems with a septic tank before the grease trap as seen in Fig. 4.10. This removes the solid parts of the black stream. For the rest, the filtering is the same. This filtered water can then be reused for flushing the toilet again.
However, when only one tiny house with such a toilet joins, it might be better to let the water go into the sewers immediately to prevent excessive costs. This is not preferred as this would be a waste of recyclable water which could, in fact, be used to flush the toilet.

In case the tiny house has a personal washing machine. It could use the filtered water from the community but a regulator on water use might be needed. This can prevent any social conflicts on a single tiny house using all the water the community saved. However, these tiny houses will use more water during showering so this might be a self-sustaining problem. Further research is possible here.

An important aspect of letting a tiny house join is the measurement of how much water they use. The sizing of the filter depends on it. Next to that, the possibilities of using filtered water for the toilet and washing machines should be considered. Based on these two outcomes, the tiny house can be connected with the community.

4.8.3. heat

The grid-size-adaptability of a tunus in terms of heat is designed in such a way that no necessary investments for connection to or of the grid should be made, excluding the heat battery. As is visible in Fig. 4.7 the division between battery intended heat and direct household usage is already made. The tiny house centralises all incoming and outgoing heat streams. This way a disconnection of the grid only requires the user to connect a smaller heat battery working according to the same system and a heater that heats the incoming heat stream in order to make the battery's dehydration process a success. This battery can be stored externally or be rearranged in the interior under the first floor of tunus.

For non-tunus tiny houses connection to the grid is also possible. Albeit this depends on the way the house is built. Step by step functions of the net are available for non-tunus users. The most important aspect is whether the tiny house is heated using water and heat exchangers. When the residences use electrical heating or gas, the centralised heat battery and PVT panels offer little scalding aid. The heating requirements of these homes should be based around the use of heat exchangers of fluids to fluids, preferably water to water.

5

affordability

An important motive for people to move to a tiny house is the reduced costs it entails. The simple facts that the living space is relatively small and (partially) autarkic make it an affordable housing option. Nonetheless, the complexity of the concept of affordability renders it difficult to measure. It is an assessment that requires input from different disciplines, touching subjects like the income of the target group, location, availability of facilities or services and quality of life (Haffner & Hulse, 2019).

The following chapter is an attempt to frame the affordability of tunus and tunect, but at this early stage of development, it rests largely on assumptions and estimations. The goal is to give a frame of reference by analysing housing costs in Rotterdam and to give an economic strategy, which is dependant on the different stakeholders involved.

5.1. housing cost

The prices on the housing market in Rotterdam have been steadily increasing over the past years (CBS, n.d.-b) (CBS, n.d.-a). In 2019 rental prices in this region of dwellings between 50 and 300 m^2 were between 12.10 €$/m^2$ and 18.93 €$/m^2$, as shown in Fig. 5.1 (Pararius, n.d.).

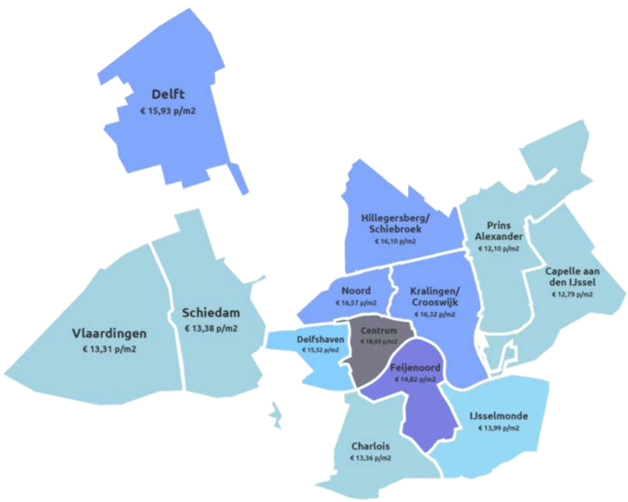


Figure 5.1: renting prices per month in region Rotterdam (Pararius, n.d.)

The data above is not directly translatable to tunus, since it is a tiny house of about 30 m^2 that can also be bought. It does give an indication of the monthly costs without utilities like gas, water and electricity, which add about 163.95 € per month in an apartment of 85 m^2 (NUMBEO, n.d.).

Buying an apartment in the Rotterdam region accumulates to an average of $4,091.50$ € per square meter in the city centre and $3,000$ € per square meter outside of the centre (NUMBEO, n.d.).

5.2. tunus and tunect

Based on tiny house retailers that provide similar constructions, the price of a casco tunus is estimated at $30,000$ € - casco meaning bare structure without any installations or appliances (Tiny House Belgium, n.d.)(Tiny House Store, n.d.). What can be calculated more precisely are the technologies used in this casco, which add about $9,000$ € to the total, see Section D.1 for more details. The interior design is left to the inhabitant to decide, but for the sake of totality, it can be estimated that the instalment of a bathroom - without the shower as this is one of the basic features in the tunus - and kitchen adds another $7,000$ €. This brings the total price to an approximated $46,000$ €.
In tunect, there is a number of shared machinery that also needs to be paid for. The different installations, software development and an extra variable cost of $20,000$ € add up to a total tunect cost of roughly $120,000$ €.

If the twelve tuni and tunect would be owned by the community - disregarding the monthly cost of rent and maintenance - , the investment cost would be $56,000$ € per household, which is well below housing cost in Rotterdam.

5.3. cost allocation

Placing tunect on a roof in Rotterdam creates very desirable living spaces, regardless of who pays for it. Transportation costs will be low and services abundantly available. It will be challenging to keep tunus affordable in a competitive area like this. The tiny houses and the networks must be bought, but there would be no utility costs except for water - which comes down to 0.64 € per month for the $0.775\ m^3$ water used, see Section 3.5.1 - and maintenance of the systems, which is considerable.

Not only tunus but also tunect comes with a price tag because of the shared facilities and infrastructure. Several distributions of cost are possible when considering the different stakeholders.

First of all the roof where the tuni are placed could be owned by the host building or bought by an external party. This would mean the owner vouches for the tunect costs and rents out parcels to dwellers who bought their own tunus.
Scenario 1:
Tenants buy tunus which delivers a monthly cost of 311 € per month with an instalment period of 15 years. Even though tunus is not made to be nomadic, it can be dismantled to build it up at another location of choice. On top of this, the tenants would rent the parcel and central utilities. For the owner, this should cover the central maintenance costs and some profit. This profit does not have to be a substantial amount of money, as it can be in the form of social control - on an otherwise empty roof - or green energy excess from the village for the host building.

On the other hand, both the tunect and the tuni could be owned by an overarching contractor that rents out a living space in their community. In this second scenario, all maintenance is paid by the owner and the tenants have a fixed all-inclusive monthly rent.
Scenario 2:
Tenants rent living space in the tunect community. In this case, the rent should cover the investment cost of all tuni and infrastructure - which is about $672,000$ € - on top of the central maintenance costs and profit that are described in scenario 1. If this rent could be kept below 750 € per month, it would make living in a tunus in a tunect an affordable housing option compared to the current living cost in Rotterdam, see Section 5.1.

A slight variation on the second scenario could be that the community is the overarching party and that every individual household pays to the communal account.

Other stakeholders that can be involved are the city of Rotterdam and innovative tech companies. The first has an interest in providing a lenient policy regarding rooftop villages as it will benefit from more green energy and green roofs that go against the hardening of the city. The latter can see their new technologies used in real systems. When these technologies are green they often go together with local or governmental grants. TripleSolar for example claims that for a $6\ kW$ heat pump, 2800 € is awarded.

6

ethical intermezzo

While designing a new type of living space - living in networks on roofs - one must take a step back now and then, to evaluate the ethical implications of what is created. Regarding tunus and tunect, there are several, wide topics that will be discussed here: civic spirit, comfort, consciousness, and privacy.

6.1. civic spirit

When moving from a regular house to a tiny house, many will feel like they are making concessions and are giving up some of their luxuries or necessities. In some ways, they are less storage space, often rural locations, and sometimes bare electricity, heat, and water supplies. Especially the earlier experience of someone, i.e. their references, are crucial. As Nobel laureate Daniel Kahneman describes in his book, Thinking, Fast and Slow, even when an outcome is good of itself, someone's references can severely influence the way this outcome is perceived (Kahneman, 2011). This means that there is no objective way to quantify such feelings. At this stage, the aim is to convince people to come to live in a tunus, by making it both comfortable, sustainable, and affordable. However, the question of how many will be willing to move to a tunus remains unanswered.

6.2. comfort

As tunus is designed to be comfortable and to increase accessibility, this entails two unwanted byproducts.

Comfort can drastically change the audience of certain living spaces. This in turn has an influence on the financial accessibility, as opposed to the comfortable-living accessibility. A comparison can be made with the influence of elevators in 19th and 20th century Paris. The lowest floors used to be reserved for the rich, as only poor people were willing to go up four, five, or even six floors worth of stairs. The maiden rooms, *chambres de bonnes* were occupied by servants and other household staff. Elevators changed architectural layouts completely as they were able to combine beauty with comfort and ease with a view. The *chambres de bonnes* had changed from maiden rooms to rooms with beautiful views of the city (Ayers, 2004). The last thing tunect was designed for is luxury. The project aims at luring people into what is a valuable idea and lifestyle and making it and increasing accessibility while doing it. Legislative action is required before introducing such tiny-roof-communities to an open market to protect its identity, that is sobriety and not affluence.

Secondly, there is the fundamental question of whether such comfort is really needed and even ethical: in the same way that regularly taking the plane can be regarded as an extravaganza. Why spend energy heating up a tunus, when the person inside could just take another sweater? Is the smart control that regulates the temperature to the inhabitant's preference, not an excessive luxury?

The first question is addressed with a combination of two things. On one hand, this comfort might be exactly what will convince some people to turn to a tiny house, which is already a step in the right direction regardless of whether they prefer the thermostat to be higher or to wear an extra sweater. On the other hand, this is behaviour that can evolve as it is susceptible to one's personal circle: people can easily decide to one day put the thermostat lower when they hear their friends do it. So the ideal scenario would be that people get persuaded by the prospect of having a warm tiny house and that later their neighbours' influence prompts them to grab that extra sweater and turn the thermostat down.

The smart control can be substantiated with numbers: smart control for lighting in common areas can reduce usage by 40% (Bhati et al., 2017) and smart heating control systems, like tado, claim to reduce energy use for heating by 31% (Tado, n.d.). So essentially the smart control's luxuriousness goes hand in hand with increased efficiency, rendering it a desirable addition to tunus.

6.3. consciousness

Making tunus accessible and comfortable can be detrimental to the third pillar of tunus: consciousness or the principle of downsizing consumption. When it becomes easy and cheap to turn the thermostat higher, take a longer shower, or leave the lights on when you are not in the room, people stop being aware of what needs to happen to make this possible. Even worse, is when users cease to appreciate these systems. This negligence will lead to ever more consumption which is precisely what tiny-house-living is supposed to prevent.

To solve this, inspiration is lent from the principle of exoskeletons: "In architectural and engineering applications, [...] it is a construction approach that places key components of a building on the exterior of the structure" (DesigningBuildings, 2020). By placing the structural elements of a building on the outside, they become visible for the world to see. Such visibility makes for a consciousness of its existence. Applying this principle for tunus would mean that the visibility of the existing technology is maximised.

Several suggestions to achieve this goal can be made.

- Using glass for parts of the central hub: inhabitants will be able to see the heat and electricity batteries, filtering systems, etc.
- When there is no practical reason to hide electricity cables or heat/water pipes, make them very visible in an appealing way.
- The installation compartment of tunus can be closed off with a glass plate.

This visibility is crucial, as the smart control strategy seeks and searches for the most efficient mode of operation within a system. The control strategy, based on artificial intelligence, operates within the given boundaries of the sketched system. Never will it question the stated boundaries, let alone the workings of the system. It is, therefore, crucial to be watchful and to prevent that the control strategy starts enforcing negative behaviour, just because it is efficient.

6.4. privacy

Privacy is a burning topic that is extremely relevant, with a new revelation or scandal happening almost every week. Fortunately, tunus and tunect are not built around a business model that demands the selling of data. The users are the customers, which is not the case for most social media platforms, where users are the product. This creates a community in which technology can serve its intended purpose.

Software that is made for the purpose of control, smart or basic, should enable the user to decide how much data they want to be registered and how they want this data to be used. Placing the hardware of these systems in the central hub is also a simple way to keep the systems local.

The main tools that are used for control - i.e. sensors - will also be incorporated according to the inhabitants' preferences. If you do not want something monitored - think about the temperature at different key points or the presence of people in a tunus - the sensor that does this is either not installed or disabled. One of the few exceptions that are standard and continuously active will be the sensors that drive the lampposts of tunect. Fortunately, they are very unintrusive and not personal.

6.5. sharing

The discussions above, all treated the interaction and relations between the inhabitants and tunus or tunect. But that does not stroke with the first pillar of the research. The interactions between the inhabitants themselves are just as important and can also lead to friction.

”Sharing is caring” as the saying goes. This implies a deeply rooted essence for sharing. So what happens when there is not enough of a shared feature - say electricity? And if this scarcity is caused by one specific person? Or if one person in tunect excessively uses the washing machines?

For these questions - and countless others - a renewed social contract must be defined that can be given structure using the smart control and the tunect app. A first step is tracking usage, which already prevents any disputes regarding facts. The next step is working out a set of rules that all inhabitants agree with. This rule-set can be customised to the users: students will, for example, prefer a different rule-set than other groups of people. Enforcing these rules will be a challenge but part of an ethical study on its own. An option, however, could be to introduce some kind of competition and reward system that encourages people to comply with the agreements.

7

recommendations

A recurring theme during the process of the project were the many encounters with ideas, additions, and inspiration. Unfortunately, the available time, size of the team, and circumstances do not allow for every one of these to be treated extensively. Fortunately, however, they were documented every time, to prevent them from being lost. They are given here and the hope is that some of these recommendations will be pursued one day, by the authors of this report, or by future tiny researchers.

7.1. housing compatibility

The hexagonal shape lends itself to a great variety of advantages. The hexagon only truly shows its power and potential when working in groups. The hexagon is the best shape to stack into each other without losing surface area. This has great potential in a future society where public and private space becomes a scarcity. Space optimisation could be done as visible in Fig. 7.1 This prominent and promising feature of the hexagon is important to research in the future. How can tuni be connected to each other in a modular way? How can the size and number of tightly connected tuni be predetermined with algorithms? How many tightly connected tuni can be viable for household usage? This also becomes interesting when considering tunus for families of more than two persons.

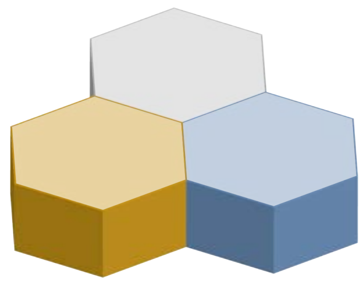


Figure 7.1: Tightly connected tuni

7.2. roof layout

The shape, form, and size of a tunus are important. If a tight connection can exist, how and why? Just as important is the shaping of tunect and the community around it. Immense potential could be gained from smart positioning of houses and grid appliances. Shaping the community is key in realising the ideas that tunus and tunect try to achieve. The layout is bound to restrictions such as roof size, but Fig. 7.2 shows a fragment of the great number of possibilities lying ahead.

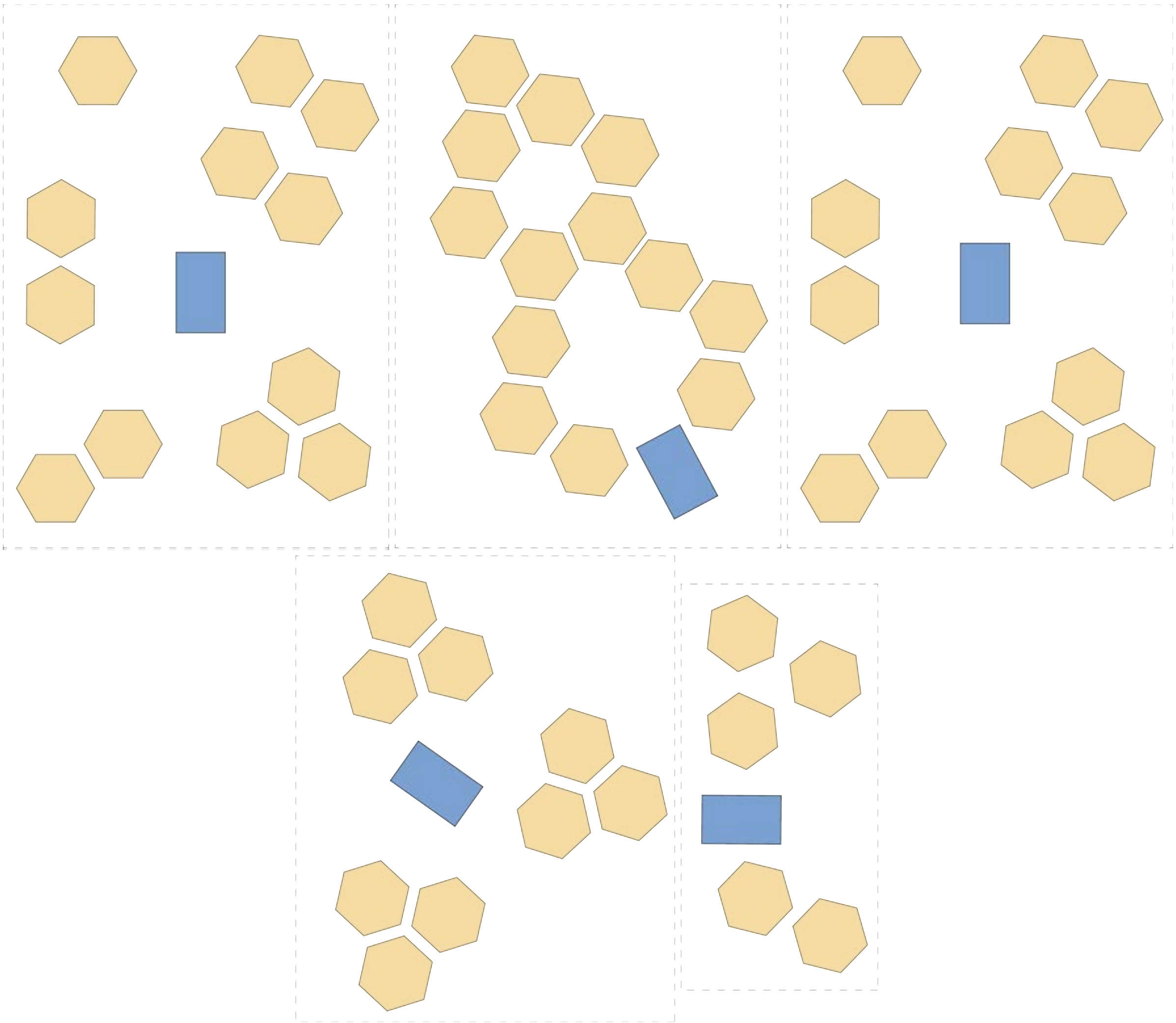


Figure 7.2: Roof layouts

7.3. sustainability

Sustainability is one of the four pillars this project is built upon. Throughout the process, decisions for materials and technologies have been made with a strong focus on circularity and ecology. However, many technologies come with implications for the environment. For example, end of life options for PVT panels and wind turbines and the rare materials used to produce them compromises the sustainability of the total design.

A life-cycle assessment should be done, to map the impact of tunus and tunect. This method includes all stages in the life cycle and consumer behaviour. It will reveal what aspects of the design need reconsideration to become truly sustainable.

7.4. electricity

With the existing technologies, already used in tunect, more can be achieved than what is presently the case. The PVT and PV panel installations can be customised to tunus, increasing efficiency, and bettering cost and appeal. The roofs of the tunus tiny houses could also be covered with PV panels entirely, instead of being sized according to demand. Doing this would raise electricity production to approximately 270% of demand. The surplus can then be provided back to the electricity grid, as a sustainable part of the energy mix. This concept could even be expanded to the point that the generation of tunect provides all of the demand of the host building. Parts of the roof that are used neither for living space nor for technological purposes could also be filled up with extra PV panels.

Interesting technologies that can be added as they mature are the Battolyser, by Battolyser BV, and the PowerWindow, by PHYSEE. The former is a combination of an electrochemical battery and a hydrogen storage installation: it operates as a battery until it is fully charged, the chemical process then starts producing hydrogen that can be captured and stored for later use (Battolyser B.V., 2019). The PowerWindow is a concept where incoming light of invisible - for humans - light is bounced to the sides of the window and then turned into electricity. In 18 months, these systems would be able to reach efficiencies up to 20% of that of regular PV panels, as was explained telephonically by engineers at PHYSEE, the producer of these PowerWindows (PHYSEE, 2020).

7.5. heat

7.5.1. heat battery efficiency

Defining the total amount of energy needed to always keep the inlet temperature of the heat battery at $80°C$ is difficult due to an immense lack of data. In the cooperation with "Dakdorpen" in a pilot series, through monitoring with sensors, the most important data can be determined. The frequency, temperature and flow rate of the heat provided to the battery can then be used to calculate the additional energy required for keeping the inlet flow at $80°C$.

7.5.2. storage

In this research, TNO's heat battery was selected. In future markets, provided a larger market competition on heat batteries is available, it could be feasible to look at other salts and phase changing materials with a lower phase change temperature, excluding the additional heating step from the PVT panel to the battery. This would result in a more efficient heat storage solution.

7.5.3. waste water heat recovery

The WWHR described in Section 4.4.4 was not viable on a small scale. An alternative would be to offer these solutions grid-scaled, centralising grey water waste and thus the heat recovery. This heat could then be directly used to heat the central battery or can be redirected via the control system to the present heating needs. Calculations should be done about the grid-scaled loss of heat but could decrease heat consumption significantly.
As hot grey water passes cold incoming tap water destined for the boiler, it is important to look at how these pipes are connected to one another. It is clear from Equation C.19 that the convection has the greatest influence on the total heat loss of Q. In this setup as is visible in Fig. 7.3, a h_0 of $200\ \frac{W}{m^2*K}$ was taken. This is retrieved from (Mills, 2014) as the value of forced convection of moderate speed air passing over the cylinder. If the grey wastewater plumbing would be installed as Fig. 7.3, it would cause a forced convection of a moderate flow of water, this has a h_0 value of $3000\ \frac{W}{m^2*K}$ and would result in a Q of $5728\ J$. This is a remarkably higher value and would result in a much more efficient heat transfer system. The setup itself will not be further discussed. In further research, it should be noted that investing resources in designing an adequate wastewater plumbing system is beneficial.

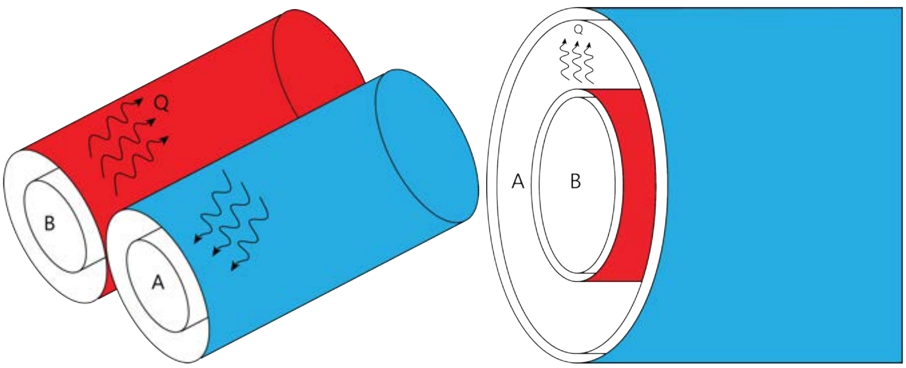


Figure 7.3: Left to right: parallel plumbing, concentric plumbing

7.5.4. panel positioning

Heat production could be optimised by researching PVT panel positioning on the roof. Simulating the heat production using solar data-sets, to identify what places on the roof generate remarkably more energy and anticipating this data, could increase heat production enormously. This way, non-roof-shaded areas can be utilised to the fullest and storage facilities can be placed at spots on the roof that have no heat-production-value.

7.5.5. case studies

Besides improvements for the design, an interesting path to move forward with is to take the designs and go make them.

dakdorpen

One option for this is building it on the roof of Dakdorpen, namely *De Kroon*. They are planning on having a pilot project and implementing parts of the designs of tunus and tunect would serve as great proofs-of-concept.

Samenwerking

Samenwerking is a housing corporation that would be interested in implementing the concept of tunect. They would like to see it realised in Vlaardingen between buildings, so not on a roof. From a technical point of view, there is little that forces tunect to be on a roof, so this could also be a useful next step.

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A

tunus

A.1. design exploration

Experimentation with sketching, maquettes and CAD drawings led to different concepts that were tested and evaluated. The figures underneath show some of the results.

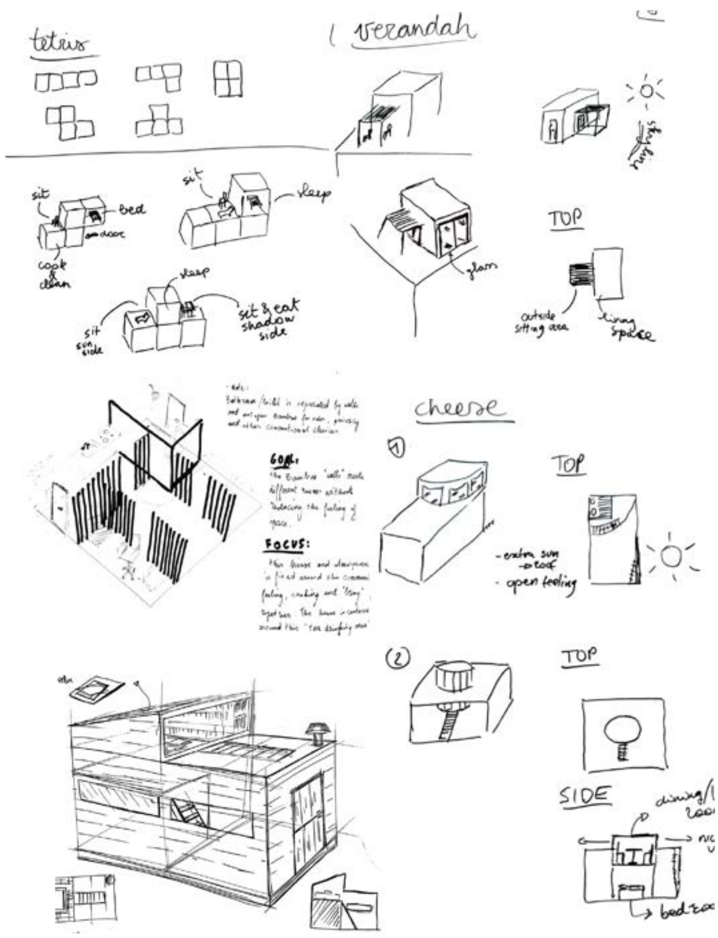

Figure A.1: design sketching

Figure A.2: design exploration Archineering

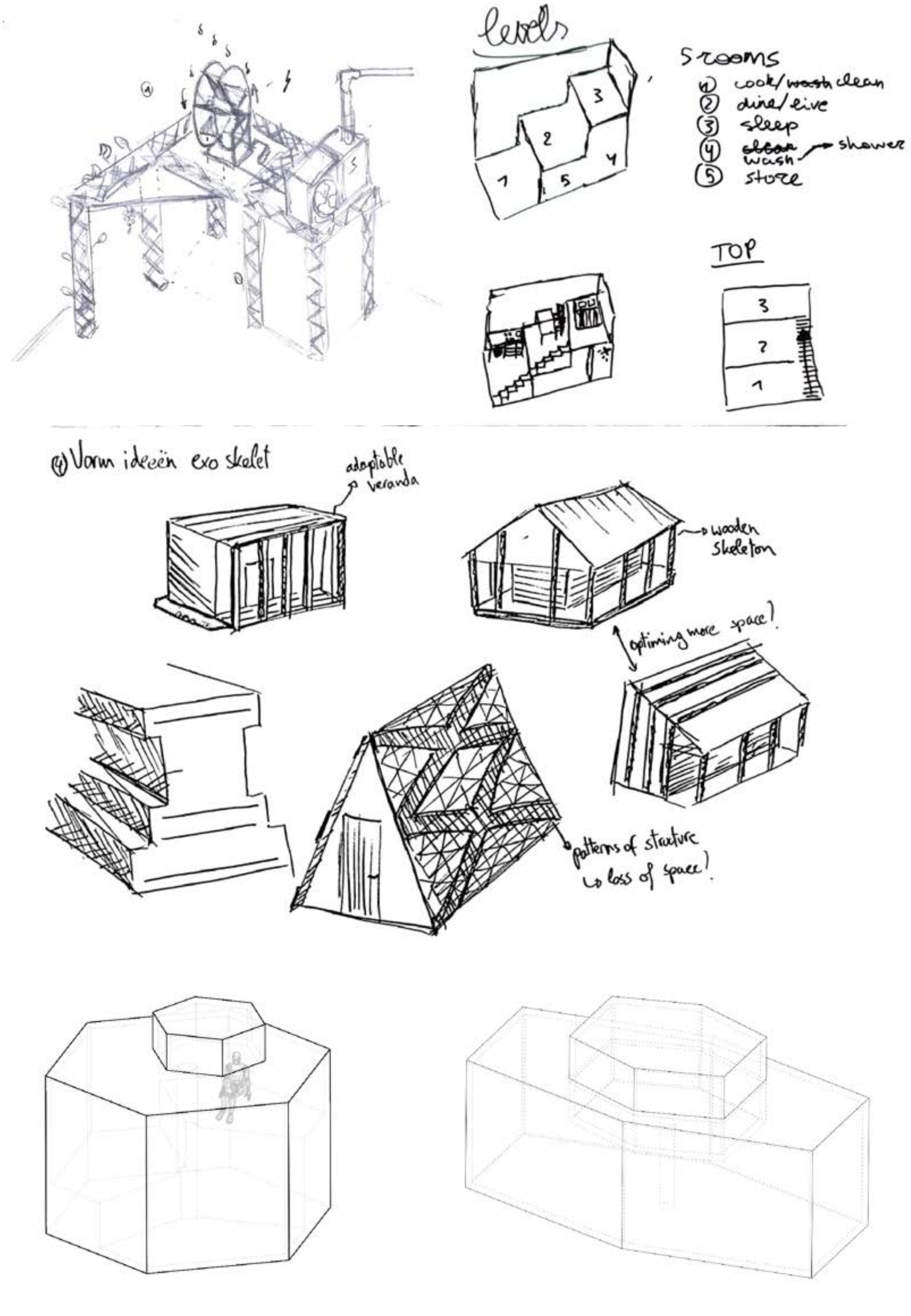

Figure A.3: design sketching

A.2. material properties

Typical use		LVL 48 P Beam	LVL 32 P Stud	LVL 36 C Panel	LVL 25 C Panel
Characteristic strength values, N/mm²					
Bending strength edgewise, h = 300 mm	$f_{m,0,edge,k}$	44	27	32	20
Bending strength flatwise	$f_{m,0,flat,k}$	48	32	36	25
Bending strength flatwise perpendicular to grain	$f_{m,90,flat,k}$	-	-	8	-
Compression parallel to grain	$f_{c,0,k}$	29	21	21	15
Compression perpendicular to grain edgewise	$f_{c,90,edge,k}$	6	4	9	8
Tension parallel to grain	$f_{t,0,k}$	35	22	22	15
Shear edgewise parallel to grain	$f_{v,edge,0,k}$	4,2	3,2	4,5	3,6
Shear flatwise parallel to grain	$f_{v,flat,0,k}$	2,3	2,0	1,3	1,1
Size effect parameter	s, [-]	0,15	0,15	0,15	0,15
Mean stiffness values, N/mm²					
Modulus of elasticity parallel to grain	$E_{0,mean}$	13800	9600	10500	7200
Modulus of elasticity perpendicular to grain in flatwise bending	$E_{m,90,mean}$	-	-	2000	-
Shear modulus edgewise	$G_{0,edge,mean}$	600	500	600	500
Density, kg/m³					
Mean value	ρ_{mean}	510	440	510	440
Characteristic value	ρ_k	480	410	480	410

Table 1.12. Basic mechanical properties of common structural wood products.

Typical use		Sawn timber C18 (EN 338:2016) Beam / stud	Glulam GL24h (EN 14080:2013) Beam	Spruce plywood 21 mm [17] Panel
Characteristic strength values, N/mm²				
Bending strength	$f_{m,0,k}$	18	24	20,6
Bending strength flatwise perpendicular to grain	$f_{m,90,flat,k}$	-	-	12,8
Compression perpendicular to grain	$f_{c,90,k}$	2,2	2,5	-
Shear parallel to grain	$f_{v,k}$	3,4	3,5	3,5
Mean stiffness values, N/mm²				
Modulus of elasticity parallel to grain	$E_{0,mean}$	9000	11500	8230
Modulus of elasticity perpendicular to grain in bending	$E_{m,90,mean}$	-	-	3770
Density, kg/m³				
Mean value	ρ_{mean}	380	420	460
Characteristic value	ρ_k	320	385	400

Figure A.4: mechanical properties of common LVL strength classes (Hakkarainen et al., 2020)

A.3. beam deflection

The reduction described in Section 3.3.3 offers the ease of using the following formula:

$$\delta = \frac{5 * q * l^4}{384 * E * I} \tag{A.1}$$

It is used to calculate the maximum deflection of the beam, with δ being the maximum deflection, I the moment of inertia of the beam, L the length of the beam, and E the elastic modulus of the pine wood. Since the roof girder is placed under an angle it should be disbanded, and the horizontal value should be used as the length l in Equation A.1 as the maximum deflection is calculated at a perpendicular relation between load and girder.

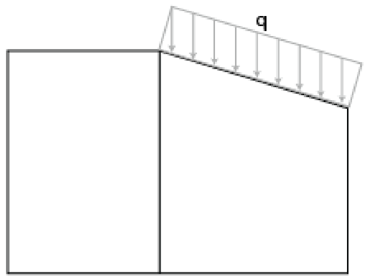

Figure A.5: Cross-section with supporting beams

$$I = \frac{1}{12} * b * h^3 = \frac{1}{12} * 0.045 * 0.24^3 = 51.84 * 10^{-6}\ kg * m^2 \tag{A.2}$$

$$E = 9.9\ GPa \tag{A.3}$$

$$l_x = 3.61\ m \frac{3.4\ m}{3.61\ m} = 3.4\ m \tag{A.4}$$

$$q = 650\ N \tag{A.5}$$

$$q_{surface} = q * A = 650\ N * 6.37\ m^2 = 612\ N/m^2 \tag{A.6}$$

$$q_{beam} = q_{surface}/l = 3.4 = 1217.8\ N/m \tag{A.7}$$

$$\delta = 4.13\ mm \tag{A.8}$$

Similar calculations can be done for the beam with length $3.58\ m$. Equation A.1 for the orange beams Fig. 3.13 of length $3.61\ m$ gives a δ of $4.13\ mm$, for the red beams of length $3.58\ m$ gives a δ of $5.65\ mm$. These values are within the ranges of rule of thumb used for roof girders where the border of the maximum deflection δ is determined at $0.004 * l$, with l the length of the girder.

A.4. water and waste

Attaining potable water is difficult and can be done in a variety of different methods.

The initial idea of making tunus completely off-grid led to the plan of catching and using rainwater. To this day most Dutch tiny house communities use a vessel of $1000\ l$ to catch rainwater, filter it using helophyte filters. For this research, adding an additional $1000\ l$ vessel critically increases the estimated weight per tunus and takes up limited volume. It was decided that using rainwater would not only significantly increase cost, but it would go beyond the purpose of a necessity for tunus.

Another way to attain this water is through dehumidifying the air with help of sunlight. Zero Mass Water is an interesting startup which does just that. (Source, n.d.). However, currently, this technology is too expensive and space-consuming for it to be used in tunus.

Grid-scaling the potable water consumption requires water passing through thorough filtering systems and need maintenance. As is described in Section 4.7.2 this technology does become viable the more tuni are connected. It is profitable if a large amount of water needs to be purified but for this project, it is disproportionately expensive.

dish washing machine

Nowadays, dishwashing machines are incredibly energy and water efficient, often using less water than doing the dishes by hand. However, research shows that when dishwashing by hand is done carefully in two tiles, one with hot water and one with cold water, and not letting the water run, the water consumption is less (Porras et al., 2020). This means that doing the dishes by hand is still better. Especially when taking into account that it does not use any electricity and it occupies less space in a tiny house which is profitable for tunus.

B

natural fibres as insulation

B.1. introduction

In a world where we, humans, are constantly trying to survive in the struggle for life, the well-being of our planet is essential. Consciously designing a sustainable and durable world is vital to maintain our prosperity. All industries and branches of society will have to contribute to this fundamental shift away from linearity and towards circularity. From the concrete streets to the vertical green city walls, construction and building sectors play a key role in this transition. The thermal regulation of this industry relies on one crucial part of the build-up, insulation. The further we progress, the more we realise the need insulate, for it is the most basic and important step of energy-efficient buildings. The need and way to insulate is centralised one step at a time, for every technology a renewable block is added and every day a greener future is in sight. Now, more than ever, the necessity of natural fibres and their functionality in the insulating world increases.

This essay tries to explore the possibilities, the effect and the future of natural fibre insulation in buildings. This work focuses on what is but more importantly, what could be.

The essay will commence with an introductory part specifying what kind of natural fibres is of interest to this research. Afterwards, an analysis of the current landscape is given, ranging from the production to the current end-of-life cycle. Followed by this, the focus will shift from now to tomorrow. This will discuss the circular future and how natural fibres play a role in this transition. The conclusion will summarise the essay from scope to specification, from linear to circular, from yesterday to tomorrow.

B.2. literature study

In this chapter, extensive research is done on the business-as-usual of natural fibres. First, the scope will narrow down the research. After that, the life cycle chain will be discussed from production to end-of-life.

B.2.1. scope

The use of natural fibres goes back more than 10,000 years. First, for textiles and reinforced pottery, but later, embedded in industrial materials, for many other applications (Mwaikambo, 2006). Due to the industrial development of mankind, the diversity of materials has increased by a factor of a thousand since 1800, largely neglecting these natural fibres. However, in recent years there has been a renewed interest in the natural fibres of yesteryear. The Kyoto Protocol (1997) and the Paris Agreements (2015) are consequences of the increasing awareness of climate change. These agreements demand innovative and sustainable solutions to install a balanced symbiosis between human progress and planet Earth. In this quest for renewable resources, natural fibres are possibly the answer for their synthetic counterparts, carbon and glass.

Natural fibres can originate from an animal, plant or mineral. Fig. B.1 shows a scheme of the different categories and types. Cotton has the highest production volume worldwide, but its application

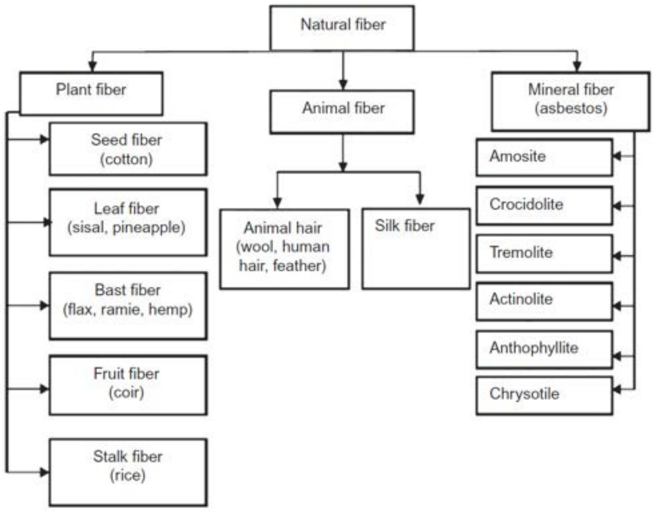

Figure B.1: Natural Fibre Classification

is not located in the built environment. For thermal insulation, the bast fibres -especially jute, hemp, kenaf and flax- are considered most important. These are found in the stems of dicotyledons (plants with two seed leaves cotyledons) and known to have high strength and lightweight potential (de Beus et al., 2019). The benefits and disadvantages will be discussed in more detail further on. Sisal, coir, abaca and ramie are other cellulosic based fibres that are used in the insulation industry, but to a lesser extent. (de Beus et al., 2019) (United Nations, 2008).

B.2.2. production and use

origin of bast fibres

The four most common bast fibres are produced in various places in the world, depending on their ideal climate. Jute currently has the highest production volume and is made from plants of the genus Corchorus, which grow in China, India and Bangladesh. This crop has high socio-economic importance in these regions as roughly 12 million farming families depend on it ("Woodhead Publishing Series in Textiles", 2012). Similarly, the growth of hemp and kenaf mostly takes place in Central Asia. Kenaf is especially interesting in Malaysia as the climate there makes enables two harvests per year (van Dam, 2008). The fourth most conventional bast fibre, flax, is most prominent in Europe. It lost some of its dominance as a resource when cotton started taking over the textile industry in the late eighteenth century, but it is still extensively produced in France, the UK, the Netherlands and Belgium. Other producing countries of flax are Belarus, Ukraine, and China ("Woodhead Publishing Series in Textiles", 2012) (van Dam, 2008). In general, the fibre manufacturers look for cheap-labour countries, as the whole production process can be quite labour intensive.

production of bast fibres

The plants of the bast fibres are mostly annual. To become useful fibres they go through a process of cultivation, harvest, and retting, after which they are transported, processed, and used as products (de Beus et al., 2019). The growth will require water and mostly non-organic fertilizers, depending on the location and farmer. When ready, the plants are collected and go through the retting process to separate the fibres from the stem. The more traditional way works with water, by putting the collected crops in water or by letting dew do the work and leaving them on the field for some weeks. The pectin structures connecting the fibres to the plant is slowly softened and degraded. Water-retting will give purer fibres, but also produces wastewater, unlike dew-retting which delivers a more polluted product. Nowadays, also chemical alternatives exist for retting ("Woodhead Publishing Series in Textiles", 2012). Other than retting, the fibre separation can also be done mechanically which delivers low-purity fibres or the separation can happen manually. The production scale that is required, however, makes this economically infeasible (Sadrmanesh & Chen, 2018). The annually produced volume of bast fibres has not increased as much as cotton and synthetic fibres in the last fifty years. Nonetheless, it takes about 2 million hectares of land for agriculture (flax: 220 000 hectares, hemp: 80 000 hectares, jute: 1.6 million hectares, kenaf: 50 000 hectares). Not all produced bast fibres are used in the insulation industry, they know many other applications as well. For example, 10,000 – 15,000 tonnes of flax and hemp, comprising 0.5% of the total European insulation market, are used as insulation material, but they are also very popular in the automotive industry (de Beus et al., 2019).

applications of bast fibres
Natural fibres know a wide variety of applications. They are most prominently used in the textile industry, for clothing and tapestry, and as composites. Food bags, ropes and car upholstery are other well-known uses. The wide range of possibilities when looking into natural fibres is strongly related to a wide range of different values for material properties. These properties determine a major part of their applications in different industries. For the thermal insulation industry, it is most important to primarily look into the thermal conductivity of these materials, which is dependent on the thermal resistance and the thermal transmittance. Secondly, their surface emissivity should be considered, which is the effectiveness of emitting radiation and finally, the fire resistance should be determined. The thermal conductivity usually has values of about 0.019 W/mK to 0.046 W/mK, but it should be as low as possible, just like the surface emissivity (Power, n.d.). The bast fibres can conform to these standards. The air in the void spaces in between the fibres also decreases the conductivity. However, they also have some drawbacks as insulation material. Often they are bundled or combined with other materials, which makes recycling more challenging. In terms of quality, ensuring a standard value is difficult as naturally grown products can vary batch-to-batch. Finally, it is often necessary to add fire retardants and other substances to moisture or fogging. This also complexifies recycling and increases the ecological footprint of the bast fibres (Bhattacharyya et al., 2015).

The use of natural fibres, more specifically bast fibres, is inseparable from the use of bast fibre composites. A great part of material science research is striving for the ideal material. It is a constant search for the best properties in all conditions as every situation poses a different set of requirements. That search can be done by testing and researching the properties of current materials, but even more importantly, by creating new ones. Cross-pollination may be the most adequate word to describe this field, not only in material sciences but in all aspects of society. The scientific world poses no exception to this. Combining strengths and reducing weaknesses is an inventive and so far successful way to create the perfect material, forged from imperfect ones.

environmental impact
At first sight, a lot of positive and ecological properties can be attributed to natural fibres. Overall, the required production energy is about 60% less than glass fibres. Next to this, their abundant availability, high strength and lightweight make bast fibres an ecologically favourable resource (Bhattacharyya et al., 2015). It is, however, important to keep the complete production chain in mind and consider the negative impacts as well. An extensive life-cycle assessment shows that the biggest pollution throughout the production cycle can be pinned down to the fertilization. The use of synthetic fertilizers and pesticides to enhance crop growth and protection has a pernicious effect on greenhouse gas emissions. They embody about half of the total ecological impact up until transport to secondary industry. The second biggest polluting factor is the water retting during the liberation process of the fibres. The amount of water used and useless fermented waste it produces are a thorn in the side of environmentalists (de Beus et al., 2019). Up until now, the cultivation has remained relatively traditional. The importance of labour has kept the energy requirements and use of agricultural machinery low. Nonetheless, with European countries in the lead, the industrialization of the production process is on its way. This shift can either introduce an opportunity for renewable resources or endanger the ecological advantages of bast fibres (van Dam, 2008).

We do see a trend of governments looking for sustainable alternatives and long-term solutions. The European Union has been giving non-food agriculture, hemp more specifically, increasing subsidies over the past years. These policies were implemented because of the strong competition with food and animal agriculture (“Record cultivation of industrial hemp in Europe in 2016 – Discover Natural Fibres Initiative”, 2016). For this reason, we ought to thoroughly consider the overall scarcity of farmland, as it can cause more deforestation if we are to upscale the production and use of natural fibres.

B.2.3. end-of-life

In this section, many aspects of the natural fibres' end-of-life (EOL) are discussed. The three ways of using natural fibre-based composites after EOL are treated. Then, we look at the legislative methods of the EU and their substantial impact on industries, such as the automotive industry. Further, the lag of fibre collection, as compared to ordinary waste collection, is examined. To conclude, the increasing quality standards, which discourage downcycling, are reviewed.

The end-of-life cycle of bast fibres is not only a case of pure fibres but is present in other, sometimes unexpected applications and materials too. This makes investigating the end-of-life of bast fibres a tedious and difficult task as there are many end-of-life cycles of these fibres to be found. One study of the KU Leuven (Bensadoun et al., 2016) researches the different end-of-life cycles for thermoplastics reinforced with flax fibres. It compares chemical- and mechanical recycling and incineration as possibilities for the above-mentioned composite. The study finds that chemical recycling is, in fact, the only feasible recycling that can be done with these composites since it is the only way to preserve the properties of the original material. In mechanical recycling, a lot of the fibres' properties and potency decrease. This is still an improvement on incineration but is nonetheless characterised as downcycling. In the end, incineration of these composites is also an acceptable alternative because of their high calorific value, as opposed to most other composites which have less embedded energy (Bensadoun et al., 2016).

One of the industries benefiting from this research is the automotive industry. As of September 2000, the European Union started a series of policies reducing the use of polluting fibres and processes in the automotive industry where these fibres were used for car upholstery and the composites for the frame and doors (Parliament, 2000) (Baltazar-Y-Jimenez & Sain, 2012). As Bensadouns research of the KU Leuven states: "Lately, the European Union's End of Life Vehicles Directive has stated that all vehicle constructors have to assure the re-usability and/or recyclability of the materials of new cars put on the market to a minimum of 85% of their total weight and the re-usability and/or recoverability up to 95% of the total weight"(Bensadoun, 2016, p.327). An existing and perfectly suitable alternative to synthetic and poorly recoverable fibres are these natural fibres and their composites. Bast fibre composites are currently known to be recyclable in contrast to their less ecological counterparts. The automotive industry is now in conflict between investing immense amounts of time, energy and resources on creating new technologies to recover these synthetic composites or switch to natural fibre composites. These may even still contain traces of polluted fibres, despite this, they are still very recoverable. It is obvious that switching to natural fibres is the most cost- and time-efficient option.

In the Netherlands, garbage collection companies, e.g. Avalex, are renewing their waste collection systems in order to recycle more. They start to differentiate between different types of recyclable and reusable waste streams and are thus increasingly contributing to a circular economy. This "modernisation plan" ("Publieks_brochure_Avalex_150316_spreads_LR.pdf", n.d.) aims to reduce the annual residual waste to 35 kg per person. This being waste that is neither recyclable nor reusable.

In the Delfland region, this new way of waste collection is working fairly well. In a collaboration between the private and governmental sector, an awareness campaign was constructed which aimed at improving consumer behaviour on waste collection ("Publieks_brochure_Avalex_150316_spreads_LR.pdf", n.d.). Judging from this 2019 communal survey ("New developments in waste management in the Netherlands", n.d.), Avalex, together with the community, has succeeded in bringing awareness to the citizens of the new rules and mechanisms of sorting. The majority indicated to have positive experiences with wanting to sort effectively. These are sanguine numbers that may be of precedential value to the future for other communities in the Netherlands. It should be noted that this survey was conducted in a smaller community. Consequently, these statements and findings cannot be blindly extrapolated to larger cities and other metropolitan areas.

Although most waste streams have transparent data about how much is collected, reused, recycled, or incinerated for textiles this information is hard to come by. Mainly due to the fact that textiles are not only collected by one company, nor is most waste but usually one company is responsible for the waste collection of the region. The textile waste collection is much more decentralised in that manner.

A lot of textile recycling happens in charity organisations, churches or by the "Salvation Army" ("End Of Waste Selection WasteStreams for EoW 13022009", n.d.). To counter this decentralisation, but more importantly to reduce recycling losses, the European Union launched "resyntex" in 2017. Resyntex is a European scale project which aims at centralising textile waste collection. Non-wearable and non-reusable textiles will be mechanically pre-treated and synthesized into end products such as bioethanol, PET granulate and peptide-modified phenol-formaldehyde resin ("PowerPoint Presentation", n.d.). Yet another initiative of the European Union towards a more circular and sustainable future.

Lately, market trends have been changing drastically. The increase in production efficiency is causing a steep increase in quality in the demand for natural fibres. Flax production plants, for example, are now facing major dilemmas. The latest demands in quality of the produced fibres are so high that producers have to choose between drastically increasing investments in technologies to be able to meet these high-labour quality demands or close down as a whole ("Woodhead Publishing Series in Textiles", 2012). At first sight, this quality increase is a production problem, but this is also an indication of the required standards of the recycling of the fibres. If production standards are set this high, it shows that to completely recycle the fibres without tending to downcycle the product, is a very cost and labour intensive process.

B.3. transition

With all the information gathered from chapter B.2 we can now make an assessment of the transition to a circular economy (CE) and what societal changes that would call for. Some visions should be clarified before commencing this chapter. We strongly believe in a circular economy. It is based on transparency, after all, how can we optimise and fully use most of the current resources without knowing their composition, purity and quantity. For too long, individual corporate interests have hoarded this information for solitary financial advantages. In a circular economy, societal interests are centralised including the candorness of companies towards one another to reduce personal revenue streams but increase public profit. We believe that we can extrapolate this transparency from private to public and between nations. In a circular economy, a European strategy is required and national interests should not conflict with the other Member States. The competition should be scaled much higher than mere nationality. Throughout this research, a lot of that transparency was missing, especially concerning specific non-governmental data like market prices and profit margins.

B.3.1. homegrown

One way to start closing the circle and thus forming a circular economy is to start producing, recycling and reusing locally. If European Member States start developing a European market for the complete cycle of bast fibres, extra pollution, caused by transport and surplus regulations and policies regarding products that are imported from out the EU and thus taxed by the EU, can be disregarded.

Currently, 6% of the global production of bast fibres is stationed in Europe. This is a good beginning as this shows Europe is already heavily invested in local production. A big competitor in the field of fibre production is China. That is why in 2012 the EU set up "FIBRA". A project aimed at outlining a long term vision between the EU and China for the production of natural fibre crops intended for industrial products ("Final Report Summary - FIBRA (Fiber Crops as a Sustainable Source of Bio-based Materials for Industrial Products in Europe and China) | Report Summary | FIBRA | FP7 | CORDIS | European Commission", n.d.). This proves the EU has serious engagement and will be playing a role in this transition and has determined a vision to implement these fibres more and more in the economies and industries throughout the whole of Europe. Despite this effort, we do not think this is enough. As explained in chapter B.2.2 the vast majority of jute, kenaf and hemp production (jute accounting for more than half of the total production of bast fibres) are still produced in Central-Asia ("Natural Fibres and the World Economy – Discover Natural Fibres Initiative", n.d.). So even if Europe plays a key role in the production of flax, and an increasing amount in hemp ("Record cultivation of industrial hemp in Europe in 2016 – Discover Natural Fibres Initiative", 2016), importing massive amounts of bast fibres is still a necessity ("Civil Dialogue Group on Arable Crops", n.d.). In our opinion, the EU is already streamlining its future vision to one that strengthens the use of bast fibres but has not updated its production side of the equation.

Localising the production of natural fibres to be able to cope with European demands is part of the solutions but entails other global problems. We believe the future lies in greater scaled economies than national ones. A global economy may be a far-off dream but a European reinforced continental economy is certainly part of our suggestion. The free market is a complex concept and currently there are trade agreements with most Central-Asian countries to implement and tax these foreign products as they cross our borders. The taxation is necessary to not overflow current European markets with cheap foreign products and thus undermining the European economy. One example is the European trade agreement they made with Vietnam concerning tariff quotas to facilitate trade about these fibres ("EU-Vietnam trade and investment agreements - Trade - European Commission", n.d.) ("Civil Dialogue Group on Arable Crops", n.d.). In this globalising economy, we do not believe in protectionist visions and Colbertist political agendas, although a basic concept of taxation is necessary for the above-mentioned reasons. We also realise that increasing local production is accompanied by competition between locally grown products and imported ones. Growing locally means economic competition based on product origins but is a problem that is determined by political colour and its corresponding legislation. It is a variable vision that changes per direction. Our main issue lies in the social dilemma of aboriginal natural fibres. Currently, Bangladesh's jute production is rated at 4% of their Gross Domestic Product (GDP) and 4.07% of the country's national export earnings ("Woodhead Publishing Series in Textiles", 2012). European homegrown production would especially cost the work of millions of Central-Asian families. The change to a global service society is inevitable, it happened to Europe 200 years ago and similar trends are visible in current third-world countries and BRICS-countries today (Harari, 2015) ("BRICS BRASIL 2019 - What is BRICS?", n.d.). The leap to services is part of a country's growth ("Understanding services", n.d.), so investing in European fibre production means short-term unemployment and drop in export revenues for the involved non-EU countries but a long-term stimulation to a service-based economy. In the end, this service-based society especially benefits the population and economy of the involved countries themselves.

B.3.2. production optimisation

To achieve a circular economy, we ought to make changes on many different levels. Looking at the production chain up until transport, to the secondary industries, we see some valuable opportunities. The transport itself is done by ship and lorries, but will not be discussed extensively. It is of course an important factor in the transition to a circular economy, but it is also a sector that affects the complete trade industry and should be tackled globally. Hopefully, we will see a worldwide shift to renewable resources to fuel the vehicles of the future. For the bast fibres specifically, transport was not the biggest factor of pollution in the life cycle assessment. On top of this, they already do better in transport-related carbon emissions than their synthetic counterparts, because of their lightweight properties. More impactful change can be found in the cultivation and harvesting.

As time progresses, technology's importance increases in all parts of society. The agricultural sector is no exception. The complete mechanisation of the agricultural sector is a given, merely one with whom we have to deal and hopefully steer in a more sustainable future. With great machines come great carbon emissions. As such, it is crucial for the agricultural sector to take these emissions into account in the *greenification* and mitigation of its sector greenhouse gas emissions (Dyer & Desjardins, 2003), as this Canadian research concludes. The Canadian findings should be used in other worldwide agricultural sectors to cut down greenhouse gas emissions, especially in the life cycle of bast fibres.

Due to a great technological deficit, bast fibre harvesting has not yet reached its full potential. Harvesting processes, design of agricultural machinery and overall attention for the harvest optimisation in the agricultural sector could increase the current growing and reaping of bast fibres (Pari et al., 2015). Together with chapter B.3.1, we concluded that natural fibres should be enticed more in the future in Europe. Making them economically more attractive will not only make them able to compete with foreign products but will also increase profits in the sector. This profit will in its turn result in higher investments in harvesting technology since increasing efficiency in agriculture is economically feasible for both private and public interest. To speed up this *research and development* in efficiency, subsidies can also be rewarded to companies that show higher investment rates in innovative technologies and optimisation of resources.

The imminent increasing implementation of machinery due to technological development is equalled by the biological progress that is providing the tools for genetic manipulation. Synthetic fertilizers and agrochemicals are used during cultivation for crop protection and decease control. Like fossil fuels, however, they can have a harmful impact on the environment when left unregulated. Currently, they are responsible for the largest greenhouse gas emissions in the production process. To develop towards the circular economy goals it is necessary to use more sustainable resources, but also minimise the dependence on these resources. Exploiting a more traditional method, the farmers could leave the redundant crop waste and leaves on the fields to serve as natural fertilizers. This reduces resource dependence and in doing so uses waste as a resource for the next production cycle of the bast fibres (“Woodhead Publishing Series in Textiles”, 2012). This is a solution which is in line with the objectives of a circular economy, but it might not be enough to match the production volumes and speed that the future will require. An increasing interest in organic alternatives will, however, produce the research that is essential to find fertilizers that are applicable on a large scale without neglecting the ecological side of the story (Cervera-Mata et al., 2019).

Water retting is a technique that cannot be lacking in the optimisation of the production process. It is considered to be the purest fibre liberation technique. This does, however, require large amounts of water, which is left dirty and polluted afterwards, of an environmentally unacceptable quality (Mwaikambo, 2006). In an attempt to prevent waste and substantially reduce the use of water, it would be wise to invest money in research and improvement of the mechanical liberation techniques. These have great ecological potential and are already being used for the recycling of bast fibre composites in the automotive industry. This process does not allow the complete recovery of the fibre but makes a newly compounded composite from the shredded flakes. Currently, the mechanical liberation of both the first life cycle and the cycles that may follow is nowhere near the purity of water retting. Nevertheless, within the insulation industry, the recovery of the composites to reproduce insulation panels is deemed possible. The optimization of this technique is believed to make extraction of the bast fibres from other products possible, without losing the necessary quality for insulation (Bensadoun et al., 2016).

B.4. conclusion

We would like to conclude this essay with a concise summary of the future we want to be a part of. The future holds a lot of changes but for us, they are summable in two categories, change of notion and discrete changes. The change of notion is a global need for transparency. To wield a better future for all, public interests should be accounted for. As a community is only as strong as its weakest shackle, we should move forward together. Transparency ensures a faster transition and is overall a more balanced and coherent way to shape our society. Within that transparency, European strategies are our solutions to a European, thus also a regional, circular economy.

Specific changes shift our attention of the overarching structures to the single societal exchanges that should be made. Production of natural fibres should evolve to a local production scale where European demands are met by European supplies. The efficiency of the complete cycle of natural fibres should be increased, from harvest to incineration. Machinisation will be a key component of the future, the sooner the adaptation, the greater the long-term profit. Not only should there be a heavy investment in this machinisation, but it should also be paired with one that is based on the renewable energy sources and innovations of the future. The use of agrochemicals and non-organic fertilizers should be minimised during production phases. Moreover, the complete life-cycle of natural fibres should be shifted to a mechanical focus. As there is a high unharvested potential in the mechanical liberation of natural fibres in crops as well as their recyclage in their end-of-life waste handling.

We strongly believe that a warmer world should be for everyone. Natural fibres can create the basis of this future and we wish them a warm welcome.

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C

tunect

C.1. table of tunus usage

Table C.1: Average electricity usage per day for a tunus

Item	Contribution	Wh/day
Dryer/Shaving machine	1%	50
Electronics	4%	200
Fridge	5%	250
Heating grid	35%	1700
Induction cooker	10%	480
Kettle	5%	250
Lighting	1%	50
Magnetron	3%	125
Others (e.g. Blender)	3%	125
Shower	18%	875
TV	5%	250
Vaccuum cleaner	1%	30
Ventilatie	10%	500
Total	**100%**	**4,885**

C.2. heat calculations

Calculating the energy demand is a necessary step in determining battery size, PVT panel surface coverage and implementing the necessary architectural changes they require. This heating data is scarce. This is due to the great variety in heating systems, resources and installations. Not all systems are measurable and those that are can be expressed and used differently. Some use the chemical potential of natural gas, others use the effective burnt quantities to express the necessity. The conversion from conventional oil and gas heated homes to electrical heating shined a lot of light on useful energy data. The search for scalding data is big and one that seems to be most effective when considering empirical data. The empirical data of actually consumed energy is most accurate and useful, it does not require knowledge of how this data was retrieved since the data speaks for itself. This empirical evidence is however absent in tiny house communities and tiny house builders. Tiny houses still heavily rely on fired stoves, gas heating and other not quite measurable heating techniques. Moreover, the tiny houses that use electrical heating, heavily rising at the moment, are not gathering data and sharing this publicly. The search for heating data of tiny houses is never-ending, assumptions have to be made.

C.2.1. boiler energy requirements calculations

Theoretically, daily hot water consumption should not exceed $25\ l$, this because of the very efficient shower described in Section 3.5.1. Taking into account that a reserve of warm water is comfortable a boiler of $40\ l$ is taken. For calculations, a household uses one $40\ l$ of heated water a day. In Fig. C.1 the heated water delivered by the heat battery will be heated electrically to meet energy demands. This hot water then passes through a heat exchanger inside the boiler, passing on its energy to the tap water in the boiler. The water to water heat exchanger has an efficiency factor of 0.95. To make sure enough energy is produced and stored, it is necessary to calculate the amount of complementary energy Q_in needed to cover this heating requirement. As can be seen in Table 4.4, for one tunus the heat battery can deliver a power of $1\ kW$. In order to determine the input, the output must be known. Energy losses in tubing and turns will be disregarded. The amount of daily energy required to heat the $40\ l$ boiler from $5°C$ to $60°C$ is then calculated by:

- $m = 40\ kg$
- $c = 4200\ \frac{J}{m*°C}$
- $T_{in} = 273$
- $T_{out} = 333$
- $\eta = 0.95$

$$Q_{out} = m * c * \Delta T = 40 * 4200 * 55 = 9.24\ MJ \approx 2.57\ kWh \quad \text{(C.1)}$$

$$Q_{in} = \frac{Q_{out}}{\eta} = \frac{2.57\ kWh}{0.95} = 2.71 kWh \quad \text{(C.2)}$$

The boiler needs $2.71\ kWh$ a day to provide for the house. Since this is a closed system, the required energy Q_{in} can easily be calculated by:

$$Q_{in} = 2.71\ kWh - 1\ kWh = 1.71 kWh \quad \text{(C.3)}$$

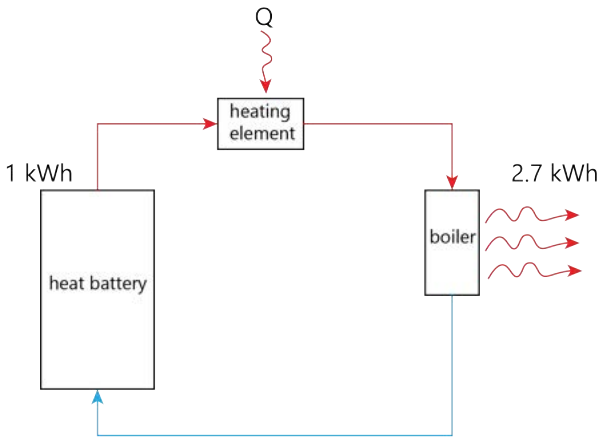

Figure C.1: Boiler energy demand

C.2.2. heat battery salt choice

TNO is not yet sure how many cycles such a household battery can run. They are currently testing a large version at a facility in Breda, still, they do not know how this salt cycles will react to household usage of continuously switching between charging and being charged, hydrating and dehydrating. The workings of the heat battery itself are outside the scope of this project, it was decided not to take this into account for realisability for heat storage of this project. Furthermore, throughout TNO's publications of their research, different salts and compositions were tested and stated as being the one chosen for the eventual product. In this report, the choice of salt was based on the meeting that was conducted with the chief engineer of the heat battery research and the information gained from that meeting.

C.2.3. battery size calculations

As is described in Section 4.4.1 the PVT panel provider, Triple solar uses minimum parameters to determine PVT panel quantity for clients. TNO also made assumptions about heat demand in households.

The assumptions of TNO and Triple solar will be used to determine the maximum heat demand of the tiny house. TNO states a regular household roughly consumes $108GJ = 30MWh$ in winter times, which is peak performance if the capacity covers the winter it should cover all seasons.

$$\frac{\text{energy demand}}{\text{time}} = \text{power}$$

$$\frac{30MWh}{3600s * 24 * 30.5 * 3} = 3795W \tag{C.4}$$

The assumption is made that, due to the relatively small volume, the power and size of the battery have a linear relation. Using the power found in Equation 4.6 and Equation C.4 the minimal size of a heat battery for one tunus can then easily be calculated by:

$$\frac{200l}{3795W} * 1155W = 60.87l \approx 60l \tag{C.5}$$

The linear factor 0.3044 derived by $\frac{Equation\ 4.6}{Equation\ C.4}$ is used to determine, power, price, capacity and total volume. Scaling this volume to tunect 12 tuni:

$$60.87l * 12 = 730.48 \approx 730l$$

In TNO's published presentation about their heat battery, scaling problems are only handled at higher volumes, they make distinction between $1000l$, $10000l$ and $100000l$ (Keizers, 2017), the $720l$ battery is still within the ranges of the $1000l$ battery thus the stated linear relation is maintained. The same accounts for the other specifications of the battery.

C.2.4. waste water heat recovery calculations

Table C.2: Flow velocities in water systems (Engineering Toolbox, 2003)

Application	Maximum Velocity	
	(m/s)	(ft/s)
General Water Service	$0.9 - 2.4$	$3 - 8$
Tap water (low noise)	$0.5 - 0.7$	$1.6 - 2.3$
Tap water	$1.0 - 2.5$	$3.3 - 8.2$
Cooling water	$1.5 - 2.5$	$4.9 - 8.2$
Suction boiler feed water	$0.5 - 1.0$	$1.6 - 3.3$
Discharge boiler feed water	$1.5 - 2.5$	$4.9 - 8.2$
Condensate	$1.0 - 2.0$	$3.3 - 6.5$
Process water	$1.5 - 3$	$5 - 10$
Pump discharge	$1.5 - 3$	$5 - 10$
Pump suction	$0.9 - 2.4$	$3 - 8$
Heating circulation	$1.0 - 3.0$	$3.3 - 9.8$

Water supply systems often exist out of copper tubing, for the scope of this research copper tubes will also be used to simulate the water supply. To determine the minimal diameter of the indoor tubing the maximal theoretical water usage per second should be calculated. The shower uses an initial flow rate of $35\ l/min$ and maximal tap water output $2\ l/min$. This translates to

$$35\ l/min \approx 0.58\ l/s \tag{C.6}$$

$$2\ l/min \approx 0.03\ l/s \tag{C.7}$$

$$0.58\ l/s + 0.03\ l/s = 0.61\ l/s \tag{C.8}$$

As can be derived from Equation C.8 and Table C.3 the copper tube size should have an outer diameter of $0.015\ m$.

Table C.3: Copper pipe size per flow rate (Engineering Toolbox, 2008)

Copper Pipe Size DN (mm)	Total Max. Demand (liter/s)	Max. Expected Demand (liter/s)
12	0.2	0.2
15	0.8	0.4
18	1.6	0.5
22	4.0	0.6
28	15	1.1
35	30	1.8
42	65	2.8
54	130	4.5

The speed rate of the incoming water stream can be derived from Table C.2 as "suction boiler feed water" and has an average value of $0.75\ m/s$ and will be called the water in tube A. The speed rate of the outgoing grey water stream has a maximal value of 0.6 ("Wastewater information", n.d.) for copper tubes. For the pipes a diameter of 25 mm is used. Forced convection will occur between both pipes. The pipes are inside a well-insulated system. First, the heat transfer coefficient h_c of forced convection occurring inside of the grey waste water tube, tube B, will be calculated. Calculations are done based on the findings of (Mills, 2014).

- $V_A = 0.75\ m/s$
- $V_B = 0.6\ m/s$
- $D_{in} = 0.0136\ m$
- $D_{ex} = 0.015\ m$
- $v = 0.4 * 10^{-6}\ m^2/s$
- $k_{\text{water}} = 0.67\ \frac{W}{m*K}$
- $P_r = 2.5$
- $k_{\text{pipe}} = 401\ \frac{W}{m*K}$ (Patterson & Miers, n.d.)
- $T_A = 278\ K$ (Agudelo-Vera et al., 2020)
- $T_B = 298\ k$
- $l = 3.5\ m$

First calculating the convective heat transfer coefficient h_i is determined by determining the Reynolds number Re.

$$R_e = \frac{V_B * D_B}{v} = \frac{0,6\ m/s * 0,015\ m}{0,4 * 10^{-6} m^2/s} = 20400 \tag{C.9}$$

$$R_c > 2300 \rightarrow \text{turbulent flow} \tag{C.10}$$

(C.11)

Nusselt number follows from Equation C.13:

$$Nu_D = 0.023 * Re^{0.8} * Pr^{0.4} = 0.023 * 20400^{0.8} * 2.5^{0.4} = 93 \tag{C.12}$$

$$h_i = \frac{Nu_d * k}{D_i n} = \frac{93 * 0.67\ \frac{W}{m*K}}{0.0136\ m} = 4583\ \frac{W}{m^2 * K} \tag{C.13}$$

Total heat loss over length l of tube:

$$Q = \frac{T_B - T_A}{R_{tot}} \tag{C.14}$$

$$R_{tot} = \frac{1}{h_i * A_i} + \frac{1}{k_{\text{pipe}} * s} + \frac{1}{h_0 * A_0} \tag{C.15}$$

Determining thermal resistance for the convection internally of tube B:

$$\frac{1}{h_i} = \frac{1}{h_i * *\pi * D_{in} * l} = \frac{1}{4583 * \pi * 0.0136 * 3.5} = 1.459 * 10^{-3}\ K/W \tag{C.16}$$

Determining thermal resistance for the conduction of tube B. In order to determine this, knowledge of a shape factor S should be taken. S depends on the form and dimensions of the tubes, in this case the internal and exterior diameter.

$$S = \frac{2 * \pi * l}{ln(\frac{D_{ex}}{D_{in}})} = \frac{2 * \pi * 3.5\ m}{ln(\frac{0.015\ m}{0.0136\ m})} = 224 \tag{C.17}$$

The thermal resistance is then easily calculated by:

$$\frac{1}{k_{\text{pipe}} * S} = \frac{1}{401\ \frac{W}{m*K} * 224} = 1.11 * 10^{-6}\ K/W \tag{C.18}$$

Determining thermal resistance for the convection externally of tube B:

$$\frac{1}{h_0 * A_0} = \frac{1}{h_0 * 2 * \pi * l * D_{ex}} = \frac{1}{200\ \frac{W}{m^2*K} * 2 * \pi * 3.5\ m * 0.015\ m} = 0.0303\ K/W \tag{C.19}$$

Substituting this back into Equation C.14 gives:

$$R_{tot} = 0.03179\ K/W \tag{C.20}$$

$$Q = \frac{298\ K - 278\ K}{0.03179\ K/W} = 630\ J \tag{C.21}$$

C.2.5. heat recovery unit refrigerator calculations

Research by Indian student teams, supervised by assistant professors from the Mechanical Engineering Departments of the Universities of Mumbai (Jadhav et al., 2014), Jaipur (L. Soni, 2016) and the Technological Institute of Sangli (Y.A.Patil & H.M.Dange, 2016) have tested and shown that cooling refrigerators with water, increased the overall coefficient of performance (COP) of the refrigerators and produced an advantageous amount of energy by warming up a water basin. Averaging the findings from the Indian studies on heat recovery units (HRU) on refrigerators to optimise efficiency and recover lost heat prompt following findings.

The studies show that the coefficient of performance (COP) of the refrigerators significantly increases when connected to an HRU. Conclusions vary between 2 and 4, with an original COP of 1 without the connected unit. The experiments indicate a rise in temperature from 32°C up to 45°C in eight hours of water basin of $100\ l$.

- Q = heat energy J
- P = rated power = $100\ W$
- P_r = returned power W
- m = mass = $100\ kg$
- c = specific heat capacity = $4200\ (\frac{J}{kg*K})$
- T_1 = $305\ K$
- T_2 = $318\ K$
- ΔT = change in temperature = $T_2 - T_1$ = $13\ K$
- t = time = $28800\ s$

$$Q = m * \Delta T * c = 100\ kg * 13\ K * 4200\ \frac{J}{kg * K} = 5.46 * 10^6\ J \tag{C.22}$$

$$P_r = \frac{Q}{t} = \frac{5.46 * 10^(6)\ J}{28800\ s} = 189.6\ W \tag{C.23}$$

This leads to COP of 1.9 derived by $\frac{100\ W}{189.6\ W}$. This COP indicates the power of the refrigerator including the HRU will be able to deliver for heat recovery. The deterministic value of this COP will be interpolated to the use of the prescribed refrigerator of tunus. The refrigerator used in the tunus tiny house has a rated power of $10.6\ W$.

$$10.6\ W * 1.9 = 20.14\ W \approx 20\ W \tag{C.24}$$

C.3. documentation on Triple Solar

For the Fig. C.2, Fig. C.3, and Fig. C.4 a design manual from Triple Solar was used. (Triple Solar BV, 2020)

Vuistregel transmissieverlies (indicatief)	*Eenheid*	**Type woning**
70	W/m²	Voor een redelijk goed geïsoleerd huis
60	W/m²	Voor een goed geïsoleerd huis jaren 80-90
50	W/m²	Voor een goed geïsoleerd huis vanaf jaren 90-00
40	W/m²	Voor een zeer goed geïsoleerd huis na 2000
35	W/m²	Voor een zeer goed geïsoleerd huis met WTW

Figure C.2: Rule of thumb for transmission losses

Afgifte vermogen warmtepomp	**Aantal m² warmtepomp panelen**	**Bijbehorend aantal panelen Model XL 2.0 m²**	**Bijbehorend aantal panelen Model L 1.65 m²**
3 kW	8	4	5
4,5 kW	12	6	7
6 kW	16	8	10
8 kW	22	11	13
10 kW	27	14	16
12 kW	32	16	19

Figure C.3: Amount of panels for power of heat pump

	Oriëntatie (afwijking in graden t.o.v. het zuiden)																		
	Zuid	Zuid-Oost Zuid-West								**Oost West**	Noord-Oost Noord-West								**Noord**
Dakhelling	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°
0°	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%
10°	93%	93%	93%	92%	92%	91%	90,0%	89%	88%	86%	85%	84%	83%	81%	81%	80,0%	79%	79%	79%
20°	97%	97%	97%	96%	95%	93%	91%	89%	87%	85%	82%	80,0%	77%	75%	73%	71%	70,0%	70,0%	70,0%
30°	100%	99%	99%	97%	96%	94%	91%	88%	85%	82%	79%	75%	72%	69%	66%	64%	62%	61%	61%
40°	100%	99%	99%	97%	95%	93%	90,0%	86%	83%	79%	75%	71%	67%	63%	59%	56%	54%	52%	52%
50°	98%	97%	96%	95%	93%	90,0%	87%	83%	79%	75%	70,0%	66%	61%	56%	52%	48%	45%	44%	43%
60°	94%	93%	92%	91%	88%	85%	82%	78%	74%	70,0%	65%	60,0%	55%	50,0%	46%	41%	38%	36%	35%
70°	88%	87%	86%	85%	82%	79%	76%	72%	68%	70,0%	58%	54%	49%	44%	39%	35%	32%	29%	28%
80°	80,0%	79%	78%	77%	75%	72%	68%	65%	61%	56%	51%	47%	42%	37%	33%	29%	26%	24%	23%
90°	69%	69%	69%	67%	65%	63%	60,0%	56%	53%	48%	44%	40,0%	35%	31%	27%	24%	21%	19%	18%

Platdak: ga uit van een hoek van 10°

Figure C.4: Percentage of maximal generation by PV's depending on orientation and roof angle

D

cost analysis

D.1. tunus costs

Table D.1: tunus cost details

product	**amount**	**price/unit**	**price**
PVT panels (Triple Solar, n.d.)	3.5 m^2	1,104.25 €/m^2	3,864.88 €
DucoBox Silent (Ventilatieland, n.d.)	1	182 €	182 €
EasyFit 50 'ZR' (DUCO, n.d.-b)	2 m	150 €/m	300 €
Upfallshower (Upfallshower, n.d.)	1	3,995 €	3,995 €
heater	1	200 €	200 €
water boiler (Boilermarkt, n.d.)	1	300 €	300 €
grants	**amount**	**price/unit**	**price**
PVT panels (Triple Solar, n.d.)	1.2 kW	466.66 €/kW	560 €
TOTAL			**8,281.88 €**

D.2. tunect costs

Table D.2: tunect cost details

product	**amount**	**price/unit**	**price**
VWT	4	3,000 €	12,000 €
lithium-ion batteries	12	5,000 €	60,000 €
salt heat battery	730 l	10 €/l	7,300 €
helofyte filter	2.4 m^2	2,000 €/m^2	4,800 €
grease trap	1	1,000 €	1,000 €
software development	100 hours	100 €/h	10,000 €
washing machines	4	800 €	3,200 €
variable	-	-	20,000 €
TOTAL			**118,300 €**