METABOLIC

New strategies for

Smart Integrated Decentralised Energy Systems

CREDITS

AUTHOR:

Florijn **de Graaf**, Spectral
florijn@spectral.energy

GRAPHIC DESIGN:

Marta **Sierra Garcia,** Metabolic

RESEARCH CONSORTIUM:

METABOLIC SPECTRAL DE CEUVEL vereniging Aardehuis Fraunhofer

SPECIAL THANKS TO:

Philip **Gladek,** Spectral
Wouter **de Graaf,** Aardehuizen
Chandar **van der Zande,** De Ceuvel

Project number: TESI117006
Project title: Nieuwe strategieën voor slimme integrale decentrale energiesystemen
Project lead: Eva Gladek, Metabolic
Project period: 01-07-2017 through 01-07-2018

Netherlands Enterprise Agency

This project is executed with a subsidy from the Dutch Ministry of Economic Affairs, National arrangements EZ-subsidies, Topsector Energy executed by the Netherlands Enterprise Agency

INDEX

EXECUTIVE SUMMARY

Transitioning our linear, carbon-based economy into a circular, renewable energy-based economy is without a doubt the single biggest challenge of our time. The energy sector plays a crucial role in tackling this challenge. For this reason, the Dutch government has decided to quintuple renewable power generation by 2030. It is a daunting task that requires radical new ways of thinking about our energy system architecture.

Thanks to recent developments in renewable energy technologies such as batteries, heat pumps and solar panels, it is now possible to produce, convert and store energy locally. As a result, a promising new concept has emerged in which energy flows can be balanced at the distribution system level in so-called microgrids. These microgrids have the potential to significantly contribute to the resilience and flexibility of our energy system, as they can facilitate the large-scale rollout of intermittent renewable energy technologies without requiring expensive infrastructure upgrades.

As part of the system integration studies programme of the Topsector Energie of the Netherlands Enterprise Agency, the goal of this report is to find out what the potential is for Smart Integrated Decentralised Energy (SIDE) systems, a highly sustainable and resilient subset of microgrids, to contribute to the renewable energy transition by increasing the flexibility of the energy system from the bottom-up.

This was done by looking at, and improving on, the techno-economic performance of four different cases that currently represent the state-of-the-art of decentralised renewable energy systems: the Aardehuizen, De Ceuvel, Schoonschip and Republica Papaverweg. Using both real-world data from the Aardehuizen and De Ceuvel, and detailed design criteria for Schoonschip and Republica Papaverweg, a detailed overview of their performance could be attained.

Central to their performance assessment are four key performance indicators: local renewable energy production, self-consumption, capital investment and payback period. In order to find their respective values, an elaborate Energy System Model was developed, that is able to simulate the energy flows of the four cases considered all the way down to the house level on an hourly basis. This made it possible to gain insight into all the different system interactions and to combine them into a holistic overview.

The obtained results are promising, although they vary widely for each scenario. The resulting techno-economic performances of 9 different scenarios do not show a single optimal configuration. Rather, a number of best practices have become clear that can be used for the future development of the next generation of SIDE systems. In the most optimal case (Aardehuizen scenario 3), combining these best practices results in a techno-economically feasible system that is nearly completely (89%) self-sufficient - a major increase from its already good baseline performance (32%).

Although there are still plenty of technical, economic and legal barriers to overcome, the rapidly declining costs of decentralised renewable energy technologies combined with an increasingly favourable political climate will lay the foundation for the development of the next generation of SIDE systems.

Ultimately, SIDE systems represent a decentralised design philosophy that has the potential to radically alter the shape of our energy system system architecture. The local integration of heat and power systems not only allows for high efficiencies, resilience, and flexibility, it also requires new models of ownership and ways of thinking about urban planning and governance. This type of disruptive thinking might be just what is needed in the race to transform our energy system and meet our climate targets.

"We cannot solve our problems with the same thinking we used when we created them."

– Albert Einstein

INTRODUCTION

Aerial view of De Ceuvel and Amsterdam-Noord

THE ENERGY TRANSITION

The Dutch government has set ambitious goals to transform the national energy system. By 2030, it aims to have achieved a 20% share of renewable energy sources (RES) and a share of 51% (of which 46% solar PV and wind) of electrical renewable energy sources (RES-E).[1]

Achieving these targets is no small feat. In 2017, the share of wind energy of Total Primary Energy Supply (TPES) is 1,66%, and the share of solar power of TPES is 0,37%.[2] With electricity supply making up 19% of TPES, this results in a RES-E share of wind and solar PV of 10,7%. Therefore, reaching a 46% share by 2030 requires a growth rate of at least 13% per year if electricity demand were to remain stable (which it will not).

Sustaining such a growth rate is a daunting task, as the widespread implementation of wind and solar PV poses serious challenges to the stable operation of the grid. The intermittent electricity generation inherent to solar PV and wind leads to more variability, steeper ramping requirements, and less room for baseload.

In addition, the electrification of the heat and transport sectors - an essential requirement for a successful renewable energy transition - will lead to a very significant increase in both peak demand and total electricity demand.

Furthermore, wind and solar generation is often spread out over many small power plants (e.g. rooftop solar), instead of a single large scale plant. The decentralised deployment of renewable technologies requires a shift in the power system architecture from the traditional centralised model towards a decentralised model.

All these developments put tremendous stress on the energy suppliers and system operators that are responsible for balancing supply and demand. As such, they require massive and costly adaptations to the energy infrastructure, while the utilisation of assets (e.g. transmission lines and existing power plants) is expected to reduce from 55% to 35% by 2035.[3] The transition also brings along the need for complex new control, market and ownership models, as well as the need for new regulations to facilitate these models.

In order to meet the Dutch climate targets for 2050 (80-95% reduction of CO_2 levels compared to 1990), "pretty much all available reduction options and potentials will have to be deployed." [1]

LOCAL ENERGY COMMUNITIES

One of these reduction options is the decision of the European Union to help facilitate the creation of local energy communities. By bringing citizens together in local energy cooperatives, they can help drive the energy transition by improving competition, providing local investment and increasing renewable energy production. By 2050, almost half of all EU households will be producing renewable energy, of which more than a third is participating in a local energy community.[4]

EU Clean Energy Package

Article 16: Local energy communities

1. Member States shall ensure that local energy communities:

   a. are entitled to own, establish, or lease community networks and to autonomously manage them;

   b. can access all organised markets either directly or through aggregators or suppliers in a non-discriminatory manner;

   c. benefit from a non-discriminatory treatment with regard to their activities, rights and obligations as final customers, generators, distribution system operators or aggregators;

   d. are subject to fair, proportionate and transparent procedures and cost reflective charges.

Despite the recent gesture of the EU to support local energy communities, these communities still face significant market and regulatory barriers that are not well understood, or acknowledged by national energy regulators. Hence, there is a large gap between the current situation and the desired implementation and enforcement of EU rules that will allow these energy communities to engage in market participation. In order for local energy communities to thrive, there needs to be a level playing field and active monitoring and enforcement of EU rules so that prosumer rights are protected and discrimination is prevented.

[1] Schoots, K., Hekkenberg, M., & Hammingh, P. (2017) Nationale Energieverkenning (2017)
[2] https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83140NED/table?ts=1531680603278
[3] N. Hatziargyrio, J. P. Lopes, C. Moreire, A. Dimeas, D. Papadaskalopoulos (2015) Microgrids: Enhancing the resilience of the European megagrid
[4] CE Delft (2016). The Potential of Energy Citizens in the European Union

MICROGRIDS

Recent technological developments have put forward several interesting opportunities that can enable us to overcome some of the challenges of the renewable energy transition. Along with wind and solar PV, a promising new set of decentralised technologies has emerged. Examples of these technologies include - but are not limited to - heat pumps, batteries, district heating, micro CHP's and fuel cells. Combining these technologies into local, integrated heat and power networks opens up many possibilities for exploiting technical and economical synergies, while increasing the resilience and sustainability of our energy system from the bottom up.

Hence, a solution to many of the renewable energy transition challenges is the development of *microgrids*: decentralised energy grids that can balance supply and demand locally through the utilisation of distributed energy resources. A microgrid is created by transforming a local distribution grid from a passive to an active network. This means that power is flowing both in and out of the system, and that it is controlled locally, which is what distinguishes a microgrid from distribution grids with local generation.

A microgrid provides benefits to multiple stakeholders. For the end users, it ensures a stable energy supply with higher power quality, and potentially a lower price. The utility companies benefit from added flexibility, congestion relief and increased power quality, as well as providing network support in times of stress by aiding restoration after faults. The owner of the microgrid (which can be the end consumers, utility company, or a third party) can reap the economic benefits of selling energy. Finally, there is the system-level benefit of increased energy efficiency as a result of reduced transmission and distribution losses.

For these reasons, "Microgrids have been identified as a key component of the renewable energy transition for improving power reliability and quality, and increasing system energy efficiency."[5]

For all their potential benefits, the challenges facing microgrids are immense. From a technical perspective, the system integration of many components requires advanced design, operation and control architecture. Equally important are the economic challenges; current market conditions prevent the implementation of microgrids through a lack of liquidity in the power market. Moreover, there are various laws and regulations that prevent the implementation of solutions that make sense from a technical perspective.

"Microgrids have been identified as a key component of the renewable energy transition."[5]

Overcoming these challenges will require close cooperation between end users, utility companies, lawmakers and energy companies. The first step towards the widespread implementation of microgrids is to recognise their potential to play a key role in the energy transition.

SIDE SYSTEMS

As part of the *Topsector Energie Systeemintegratie Programme*, the focus of this report's analysis is to see how the flexibility of the national energy system can be increased so that a larger share of renewable energy production can be achieved. The flexibility challenge posed by the large-scale deployment of intermittent renewable energy sources is extremely complex and multifaceted. It should therefore be addressed from both the top-down and the bottom-up. In this report, however, we will purely focus on the local level.

This report will build on the knowledge obtained from several state-of-the-art microgrid pilot projects that focus on sustainability, self-sufficiency and smart energy management. To distinguish this

SIDE-system definition

A SIDE System is defined as a highly self-sufficient and sustainable microgrid, characterised by a high degree of integration between heat and power technologies, resulting in a flexible and resilient energy system at the local level.

- **Smart:** managed intelligently through a local energy management system.
- **Integrated:** maximising synergies between all components.
- **Decentralised:** the system operates at the local level and has a clear system boundary.
- **Energy:** heat and power systems powered by sustainable technologies.

Note: a SIDE system is not necessarily an off-grid energy system. It can still be connected to the main grid. In fact, only 1 out of 9 scenarios considered in this report has no grid-connection.

[5] D. Pudjianto, D. Pudjianto, C. Ramsay, C. Ramsay, G. Strbac, and G. Strbac, "Virtual power plant and system integration of distributed energy resources," Renew. Power Gener. IET, vol. 1, no. 1, pp. 10–16, 2007.

SIDE system components:

- Solar PV panels
- Solar thermal panels
- Wind turbines
- Heat pumps
- Batteries
- Hot water tanks
- Combined Heat & Power (CHP)
- District heating network
- Electric vehicles
- Seasonal Thermal Energy Storage (STES)
- Fuel cells
- Electrolysers
- Electric boilers
- Electric heating (e.g. infrared panels)
- Biodigesters
- Biomass heating stoves
- Cooling systems
- Heat recovery ventilation

Figure 1: Example of a SIDE system

special category of microgrids, they will be defined from now on as a *Smart Integrated Decentralised Energy system*, or SIDE system.

A SIDE system is characterised by a high degree of system integration of various renewable energy technologies. Although there is no clear threshold defined that determines the minimum number of components that constitute a SIDE system, as we will come to see, a SIDE system entails more than just a few solar panels and a heat pump (the current state-of-the-art for renewable energy systems).

At the root of each SIDE system is a holistic design philosophy, aimed at exploiting as many synergies as possible between components. For instance, a solar PV/heat pump combination can be used to convert excess PV power into heat, which can then be stored in a hot water tank that provides heat during the rest of the day. Pairing solar PV with a combined heat and power (CHP) unit enables energy generation in both summer and winter. This helps alleviate the seasonal variability on the grid, especially when the heat pump can be reversed in order to provide solar-powered cooling in summer.

As a rule of thumb, the higher the number of featured technologies within a SIDE system, the greater the potential for exploiting synergies becomes. On the other hand, the higher the number of components, the more complex the integration becomes. Therefore, to fully utilize their potential, it is crucial that the perceived complexity of SIDE systems is reduced through comprehensive design guides and easily accessible information on best practices.

METHOD

Aerial view of Buiksloterham. Bottom right: the first jetties for the Schoonschip site.

GOAL

The goal of this report is to generate knowledge on the potential for SIDE systems to help improve the flexibility of the energy system. This is done by determining the technical, economic and legal feasibility of SIDE systems for different existing use cases. The knowledge gained through analyzing their performance is used for improving their design, in order to come up with the most self-sufficient and economically feasible SIDE system solutions. Ultimately, this knowledge will assist new initiatives in the development of integrated energy systems at the neighbourhood level, in order to help strengthening the energy system from the bottom up.

RESEARCH QUESTIONS

Technical:

What is the maximum local production and self-consumption for various SIDE system configurations and how can this be maximised?

Increasing the self-consumption of a system means that produced energy is distributed locally instead of being fed into the grid. This is generally the equivalent to having a highly flexible system, which in turn creates resilience, not only for the SIDE system itself, but also for the main grid. Self-consumption is therefore the most important technical parameter that will be assessed for each case.

Economic

What is the optimal capital investment and payback period for various SIDE system configurations (compared to a traditional system) and how can this be minimised?

SIDE systems are more expensive to build, but tend to have very low operating costs (except for maintenance). At some point in time, the costs for a traditional system will have exceeded the cost of a SIDE system, but how long will this take? The payback period is the most telling parameter for the economic performance of each SIDE system.

Legal

Which barriers prevent the realisation of techno-economic optimal SIDE system configurations and how can they be removed?

SIDE systems are a new and unconventional approach to the construction of local energy systems. In a SIDE system, the consumer becomes the producer, without having the legal status of an energy retailer, which is tied to numerous laws and rules. Finding new ways to facilitate the decentralised production and distribution of energy is crucial to the successful deployment of SIDE systems.

USE CASES

In order to gain realistic insights into the feasibility of various SIDE system configurations, it was decided to focus on existing or soon-to-be-realised use cases that already feature an innovative microgrid. The four use cases are:

- **Aardehuizen:** a self-sufficient ecovillage consisting of 23 earthship-type houses, Olst
- **De Ceuvel:** a former shipyard turned cleantech playground, Buiksloterham, Amsterdam-Noord.
- **Schoonschip:** Europe's most sustainable floating neighbourhood, Buiksloterham, Amsterdam-Noord
- **Republica papaverweg:** a highly circular mixed area development, Buiksloterham, Amsterdam-Noord

Of these four cases, the Aardehuizen and De Ceuvel have already been realised. Due to their experimental nature, both cases were equipped with sensors that have been gathering real-world data on the performance of their systems. This data was used as input for the model used to simulate the performance for each SIDE system.

Figure 2: The locations of the 4 cases considered in this report.

Buiksloterham

Three out of four cases considered in this report are located in Buiksloterham, and not without reason. Buiksloterham is a former industrial area in Amsterdam-Noord that is in full transition towards a highly circular area where life, work and recreation will fuse together harmoniously. Within Amsterdam, Buiksloterham is a rare case: though it has been treated as a functionally peripheral district because of its industrial past, it is located just five minutes from the old center of Amsterdam across the IJ river. Moreover, as housing prices in Amsterdam continue to rise, thereby putting enormous pressure on the housing market, Buiksloterham is expected to play an important role in the urban expansion of Amsterdam. The long-expected finalisation of the Noord-Zuidlijn has put Buiksloterham in a more prominent position that is already attracting many investors and people looking for houses. Unlike most other centrally-located neighborhoods, Buiksloterham is a comparative blank slate with many empty plots and almost no monumental buildings. This status creates space and flexibility for new development. Buiksloterham is therefore in a unique position to serve as both a living test bed and catalyst for Amsterdam's broader transition to becoming a circular, smart, and resilient/adaptive city.

THE MODEL

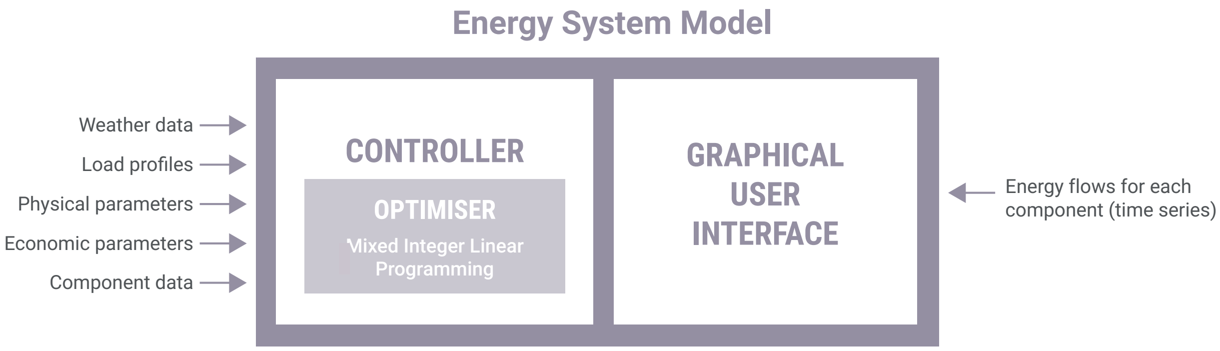


Figure 3: Schematic diagram of the Energy System Model.

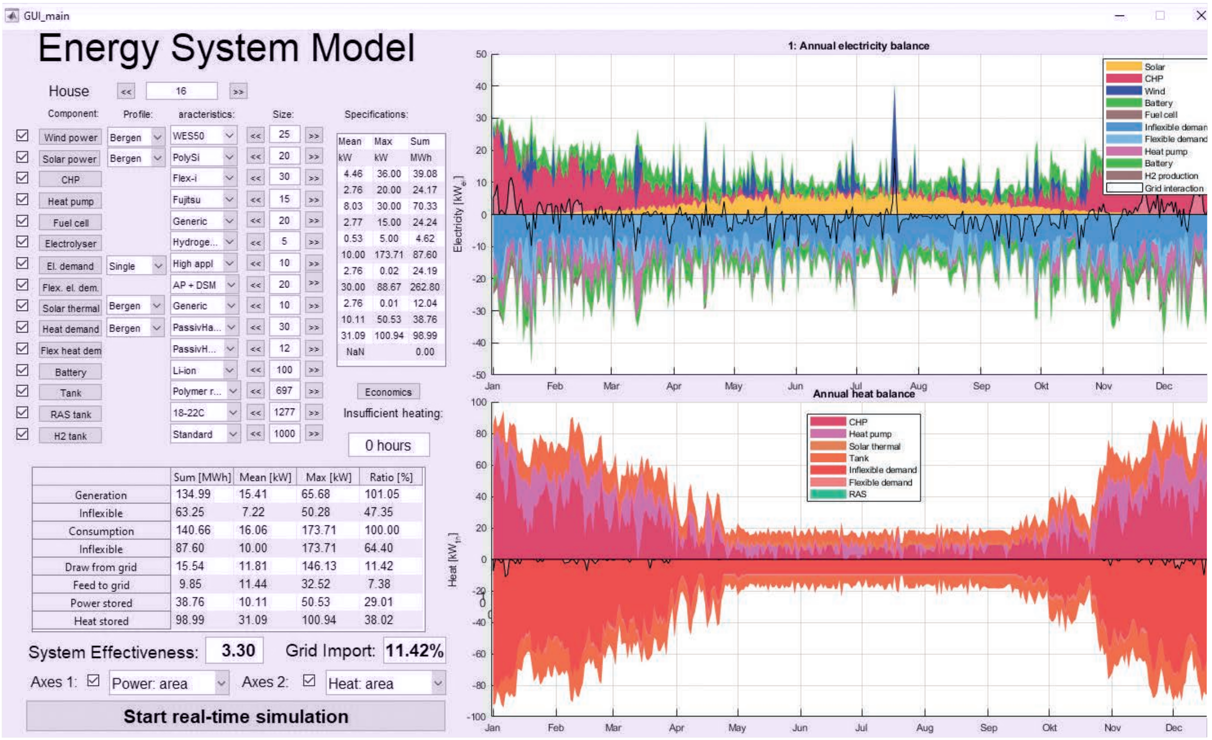


Figure 4: Example of the Graphical User Interface (GUI) of the Energy System Model.

A numerical model was developed in MATLAB to simulate the performance of the various SIDE systems. It is able to simulate the hourly energy flows for every component within a SIDE system, using input data such as load profiles and weather data.

At the core of the model is an optimiser module, which decides when each of the flexible loads is turned on or off. Given a set of constraints and decision variables, it uses mixed integer linear programming (MILP) to optimise the energy flows with respect to self consumption and economic cost. This is done at a house level initially, after which the results are collected for the individual dwellings. These results are then aggregated at the neighbourhood level so that a second optimisation run can be done at the neighbourhood level. Although this optimisation strategy may not necessarily perform optimally on a neighbourhood level, it closely represents the common real-world control architecture of a multi-agent system. The results of the optimisation can therefore be assumed to closely match that of a real-world energy management system.

The large amounts of data generated using this model are visualised in a Graphical User Interface using energy flow and balance diagrams. The relative size of each energy flow is clearly visible from these diagrams, allowing one to quickly see which processes dominate the total system interaction, both per house and for the system as a whole.

ASSESSING THE RESULTS: FOUR KPIs

Besides the detailed energy flow visualisations, there are four KPIs that define the technical and economic performance of each SIDE system. Each of these KPIs will be converted into a single grade ranging from 0 to 10 using the following formulae:

1. **Energy production vs. consumption:** How energy neutral is the system?

$$Grade_{prod} = \frac{\text{Total production [MWh]}}{\text{Total consumption [MWh]}} \cdot 10$$

2. **Self-sufficiency:** What percentage of consumed energy is produced locally?

$$Grade_{sc} = \frac{\text{Total self-consumption [MWh]}}{\text{Total consumption [MWh]}}$$

3. **Capital Investment:** How expensive is the system to build?

$$Grade_{CAPEX} = 10 - \frac{CAPEX_{current}\text{ [EUR]}}{CAPEX_{traditional}\text{ [EUR]}} \cdot 10$$

4. **Payback Period:** How long does it take for the system to be cheaper than a traditional system?

$$Grade_{PBP} = 10 - \frac{\text{PBP [Years]}}{2}$$

These four parameters will be combined into overall grade for the performance of the SIDE system, which is the weighted average of the four grades.

ASSUMPTIONS & IMPORTANT NOTES

Technical:

- The controller in the energy system model assumes a perfect forecast for inflexible energy supply and demand. In other words, it is known precisely how much solar or wind power will be produced at all times.
- Flexible energy supply and demand is optimally scheduled using Mixed Integer Linear Programming (MILP), assuming perfect forecast and no time-horizon. In reality, there is more uncertainty leading to suboptimal control, although the presence of buffering capacity (i.e. batteries and hot water tanks) diminishes this effect.
- All components are modelled as static blocks, i.e. there is no state-dependent operation: a battery, for instance, will always have the same round trip efficiency regardless of its state of charge.
- No heat losses are assumed in the hot water tank or distribution network.
- An electric vehicle consumes 1 kWh every 5 kilometres.
- The CHP's and heat pumps can be operated down to 40% of their maximum capacity.
- The fuel-source for the CHP is biomass in the form of wood chips obtained using sustainable forestry.
- Grootverbruiker = large consumer.
- Kleinverbruiker = small consumer.
- No flexibility scheduling of home appliances (e.g. fridge, washing machine, dishwasher) is taken into account.
- Real-world data was gathered for the electricity consumption and production of the Aardehuizen and De Ceuvel by equipping smart meters with sensors. This data was then transformed to an hourly resolution for each house/boat.
- Missing profile data includes the heat demand profiles for all cases except De Ceuvel, and all data for the two cases that have yet to be realised: Schoonschip and Republica Papaverweg. To model their inflexible energy production and demand, profile data from Alliander was used for the household electricity consumption. For the heat demand hourly load profiles were simulated using DesignBuilder software and normalised to the expected total heat demand from the EPC reports.
- The resulting profile data represents one year's worth of data only. In reality, production and demand profiles will vary from year to year, resulting in different outcomes of the simulations. Although this variance is not considered in this report, extensive tweaking of parameters has revealed that the influence of varying external factors only results in marginal difference in system control and performance. It is therefore not expected that increasing the timeframe will greatly improve results.

Economic:

- The time horizon for the economic analyses is 20 years.
- The "economic point of view" for all cases except Republica Papaverweg is that of a cooperatively owned energy system, meaning all private costs, revenues, subsidies, etc., are aggregated at a neighbourhood level. Individual differences are therefore not considered.
- For Republica Papaverweg the economic point of view is that of the project developer/ESCo.
- For cases that make use of the experimenteerregeling, it was assumed that the microgrids are a single legal entity behind a single meter connection.
- The price for gas heating, adjusted for boiler efficiency (90%), is 6,82 cts/kWh.
- Interest rates on capital investment are not considered:
- Energy price fluctuations are not considered.
- Energie Investerings Aftrek (EIA) is not considered.
- Vermindering energiebelasting is not considered.
- The cost of an energy management system is not considered.
- Electric car investment and maintenance is not considered, since it is assumed to be equal for electric vehicles (EV's) and internal combustion engine vehicles (ICEV's).
- Replacement costs have been normalised over the lifetime of the components. So, if a battery lasts 10 years, it will be replaced once during the 20 year time period under consideration. The replacement cost is equally distributed over that 20 year time period, instead of being added stepwise.
- Also, if the lifetime of a component exceeds 20 years, its remaining value is subtracted from the operational cost, potentially turning the operational cost negative.
- Similarly, the SDE+ subsidy has been normalised over the 20-year time period.
- Behind a single grootverbruiker connection, 10m of cabling per house is assumed.
- Grid take-in costs from components other than baseload are counted towards the cost of the respective components, not towards the grid connection costs.
- Revenue is strictly taken to be revenue from grid feed-in, not from otherwise saved costs.
- Traditional cases are assumed to have a 3x25A kleinverbruiker grid connection with net-metering and a kleinverbruiker gas connection between 400 and 4000 m^3 gas per year.
- Levelized Cost Of Energy (LCOE): average cost of energy over a period of 20 years.
- The LCOE for grid power is more expensive than the electricity price as a result of connection costs (transport, measurment, etc.).
- Self-produced electricity used for the operation of heating equipment and electric vehicles is not counted towards their operational expenditure.

THE AARDEHUIZEN

INTRODUCTION

The Aardehuizen is a small neighbourhood of 23 houses situated in the rural eastern part of the Netherlands. The houses were finished in 2015 after several years of collective construction. They were adapted from the traditional 1970's Earthship design of architect Michael Reynolds.

By using mostly recycled, locally sourced and low-impact construction materials, the Earthship design focuses on minimising the ecological footprint of its inhabitants. In addition to minimising the footprint of the construction of the houses, there are various systems in place aimed at maximising the self-sufficiency, of its inhabitants.

The low-impact, eco-friendly and community-minded philosophy underpinning the realisation of the Aardehuis project is markedly different from conventional housing projects. Its successful realisation makes the Aardehuizen a one-of-a-kind innovative housing project, from which many lessons can be learned for future housing developments.

Collectief Particulier Ondernemerschap

Due to this unique alternative approach, quite a few legal loopholes and exemptions had to be either found or created.

Despite these legal barriers, there was one legal construction that was crucial to the success of the project, and that is the option for Dutch citizens to form a "collectief particulier ondernemerschap", or CPO. A CPO is a form of social development in which the residents collectively act as the client for their housing development project.

United in the CPO, the future inhabitants gain full ownership of the land, as well as full responsibility over the design and construction of the buildings. By teaming up with a construction manager, architect and contractor of their choice, the future residents not only cut costs by an estimated 10-20%, they also gain a large degree of control over important design decisions in order to meet their demands and desires.

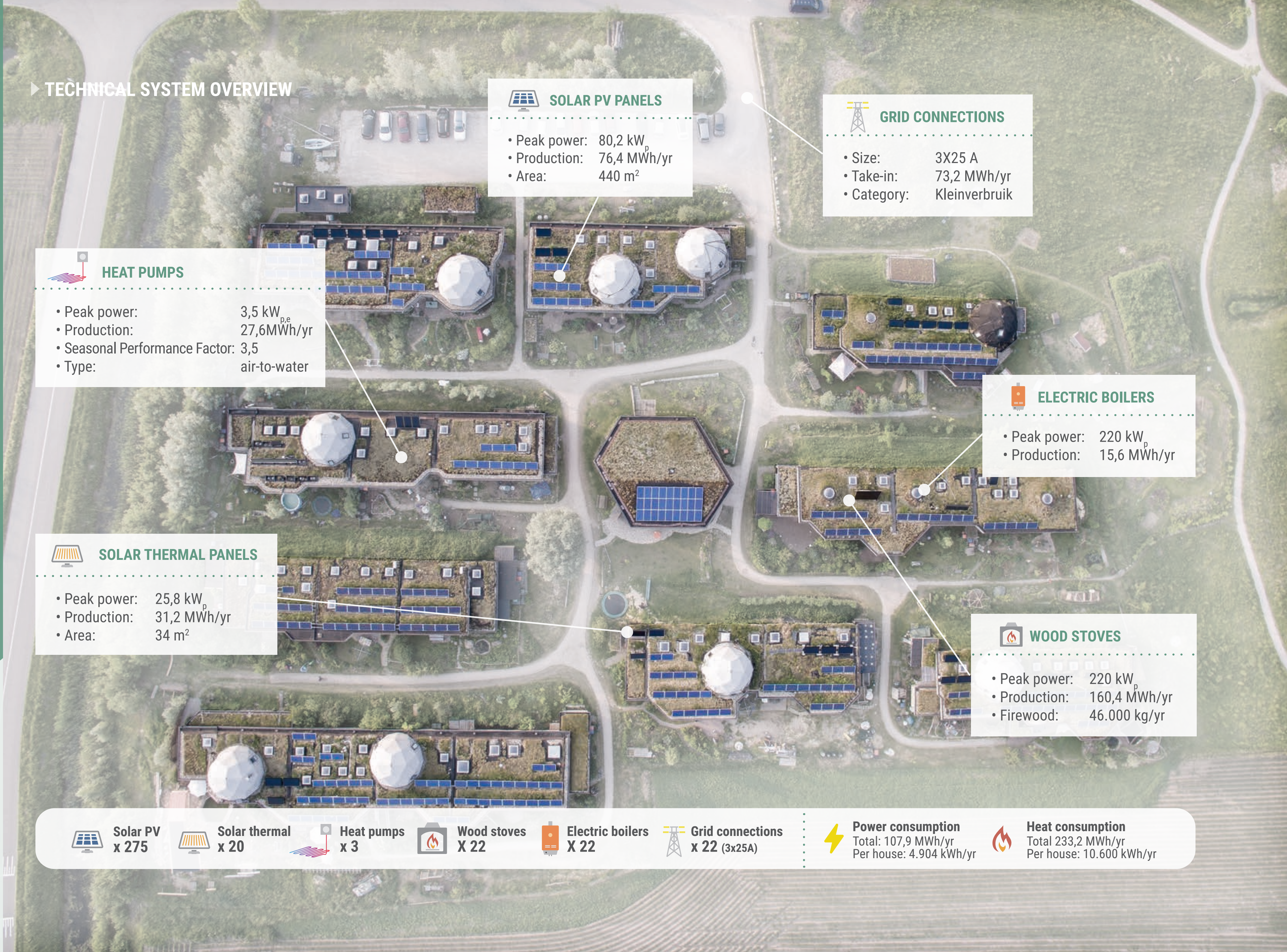
Sociocracy

Navigating the complex maze of information, rules and corresponding decisions requires a high degree of responsibility from the citizens within the CPO. The high-stakes, intensive cooperation requires a solid social framework that is capable of effectively settling disputes.

In the case of the Aardehuizen, any disagreements were solved according to sociocratic principles. Sociocracy is a decision making method based on the values of equality and effectivity. It is a consensus-based system in which the organisation is split into different circles, each with their own specific responsibilities.

The distribution of leadership combined with transparent communication and a focus on equivalence results in an effective and socially cohesive method of self-governance. Contrary to democracy, sociocracy is a structure in which no individual or groups of individuals is left out or overruled; making it an ideal method for large, complex, and cooperative projects such as Aardehuizen.

TECHNICAL SYSTEM OVERVIEW



SOLAR PV PANELS

- Peak power: 80,2 kW_p
- Production: 76,4 MWh/yr
- Area: 440 m^2

GRID CONNECTIONS

- Size: 3X25 A
- Take-in: 73,2 MWh/yr
- Category: Kleinverbruik

HEAT PUMPS

- Peak power: 3,5 $kW_{p,e}$
- Production: 27,6MWh/yr
- Seasonal Performance Factor: 3,5
- Type: air-to-water

ELECTRIC BOILERS

- Peak power: 220 kW_p
- Production: 15,6 MWh/yr

SOLAR THERMAL PANELS

- Peak power: 25,8 kW_p
- Production: 31,2 MWh/yr
- Area: 34 m^2

WOOD STOVES

- Peak power: 220 kW_p
- Production: 160,4 MWh/yr
- Firewood: 46.000 kg/yr

Solar PV x 275 | Solar thermal x 20 | Heat pumps x 3 | Wood stoves X 22 | Electric boilers X 22 | Grid connections x 22 (3x25A)

Power consumption
Total: 107,9 MWh/yr
Per house: 4.904 kWh/yr

Heat consumption
Total 233,2 MWh/yr
Per house: 10.600 kWh/yr

SCENARIO 1: LOW-TECH MEETS HIGH-TECH

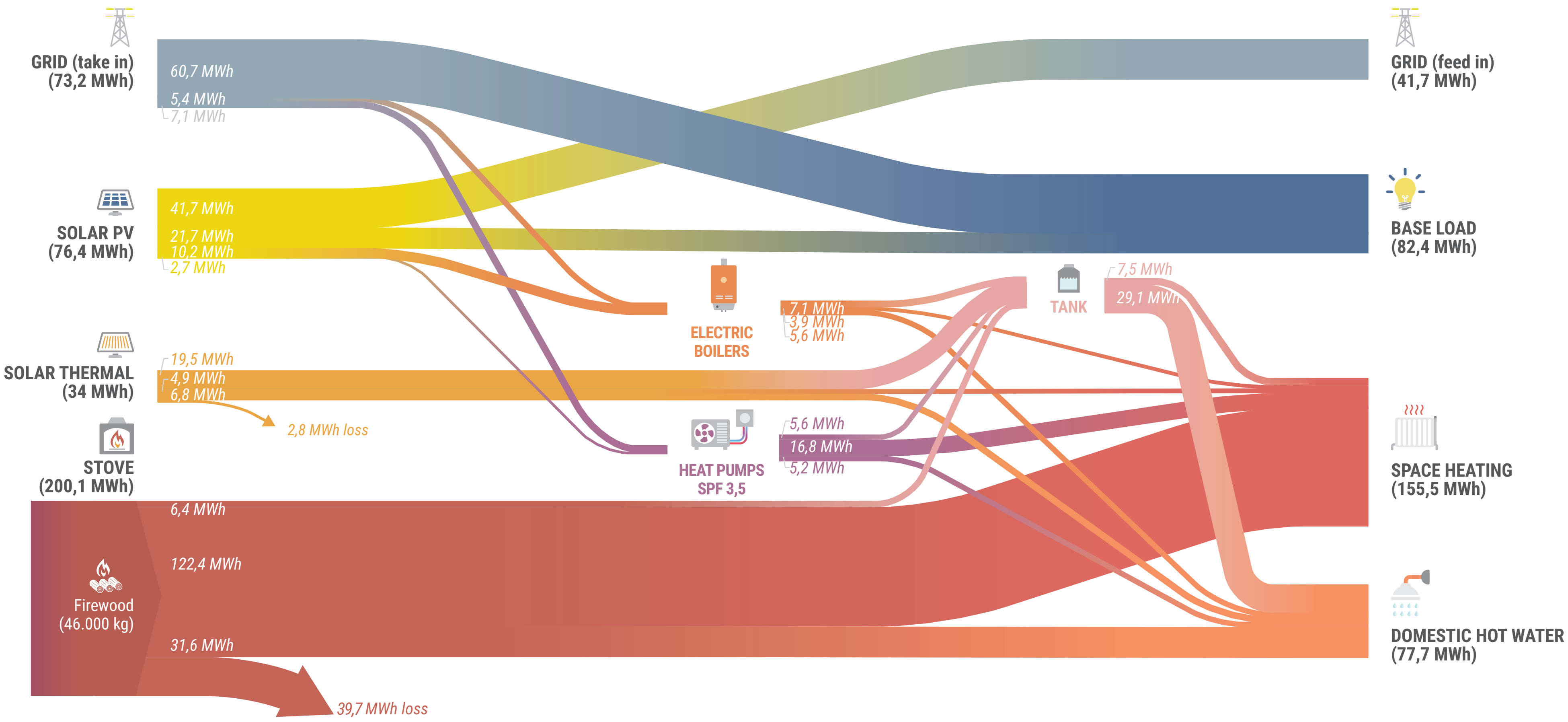
Following the design principles of self-sufficiency and eco-friendliness, the Aardehuizen's current energy system is based on passive-solar principles to reduce heat load, solar collector plates and stove-heating to provide the remaining heat demand, and solar PV to provide electricity. On top of that, each resident was free to choose and design their own house interior, floor plan and energy system configuration.

As a result of this freedom, some residents have chosen to opt for a more high-tech energy system. Examples of technologies present within these upgraded energy systems are: air-to-water heat pumps, underfloor heating, and specialised pellet stoves that include a heat exchanger for DHW. Since most houses do not own a heat pump, and the solar thermal collectors do not provide enough heating in winter, electric boilers have been installed in every house to provide backup DHW heating.

A special type of wood stove with high thermal mass ensures the smooth and constant delivery of heat. A combustion chamber burns the wood at very high temperatures in order to ensure full combustion takes place at high efficiency. In addition, an inbuilt heat exchanger supplies hot water to the thermal buffer vat, which can be used at a later time for showering or underfloor heating.

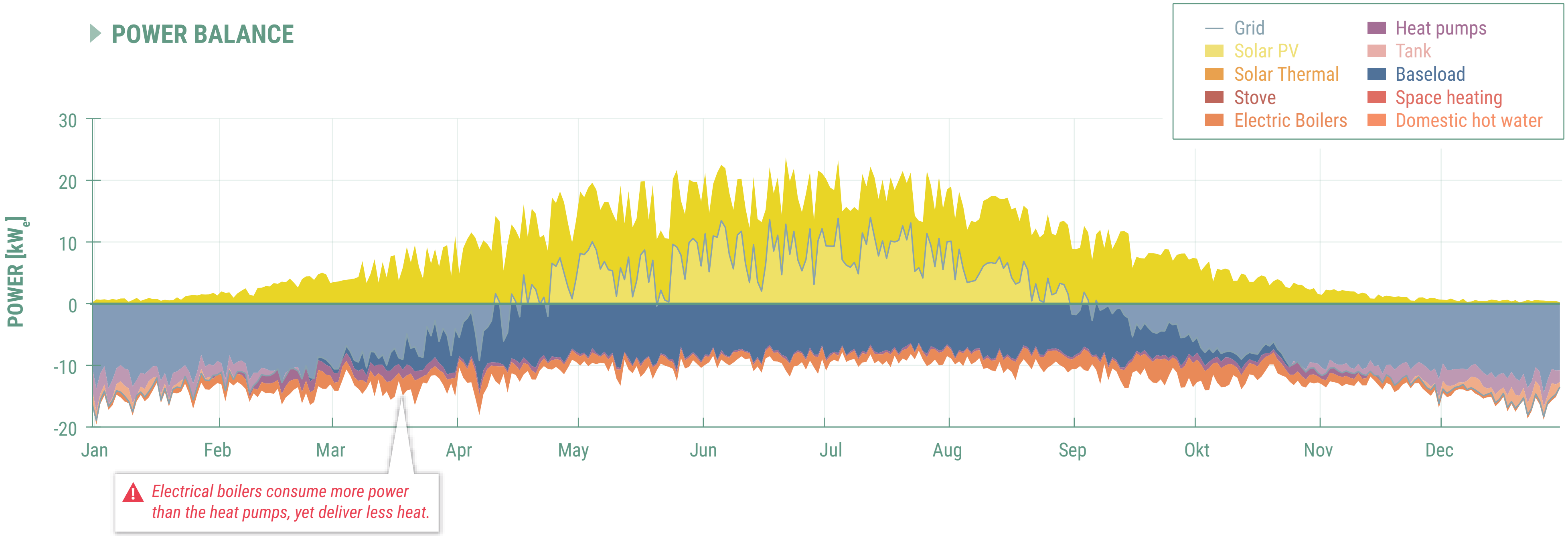
ENERGY FLOWS

ANNUAL ENERGY FLOWS

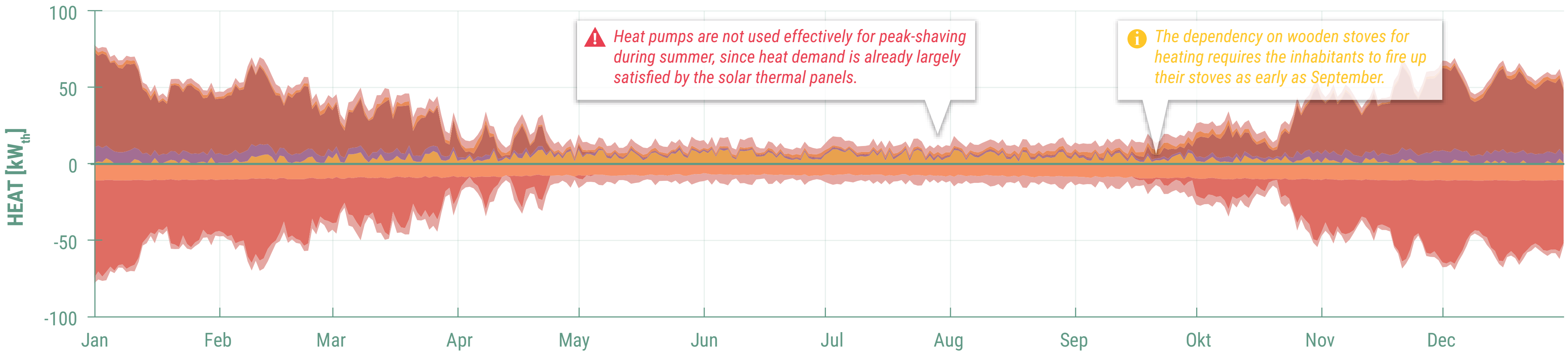


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

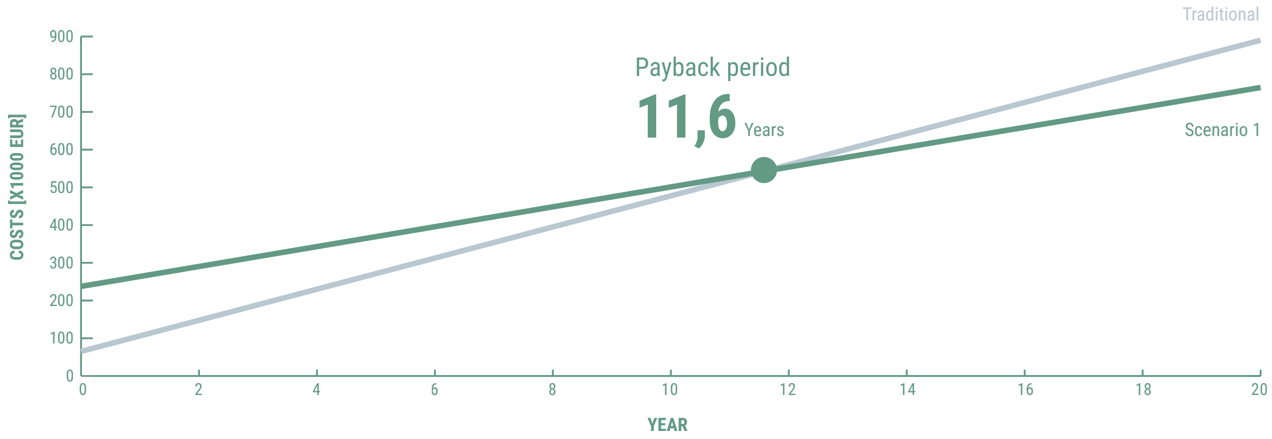


ECONOMIC ANALYSIS

Although a larger investment is required, the current energy system of the Aardehuizen is significantly cheaper in the long run than a conventional grid powered energy system, primarily for the power system.

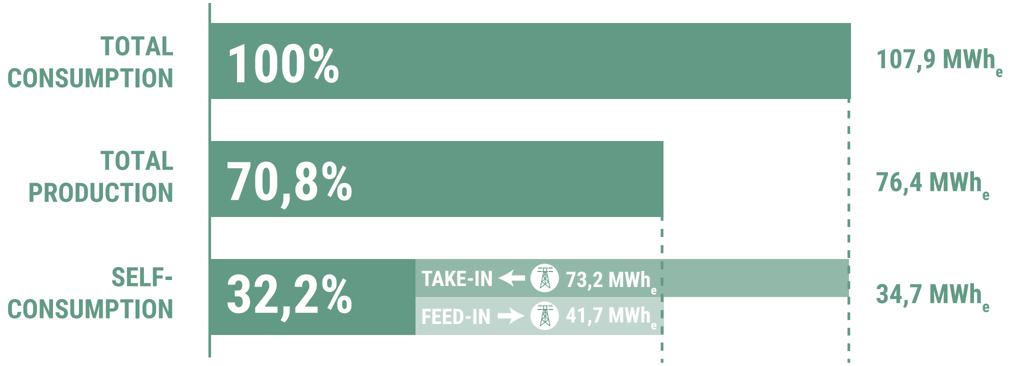
- The overall cost for electricity is significantly cheaper due to the large amount of solar panels in combination with net-metering.
- The overall cost for heating is slightly cheaper due to the low heating cost for solar thermal panels.
- The heating cost for the heat pumps is equal to the traditional case.
- Despite significant investment costs, the heating cost for the stove is equal to the traditional case due to a low price of firewood.
- Electric boilers raise the heating cost, although significant self-consumption diminishes this effect.

TOTAL SYSTEM COST

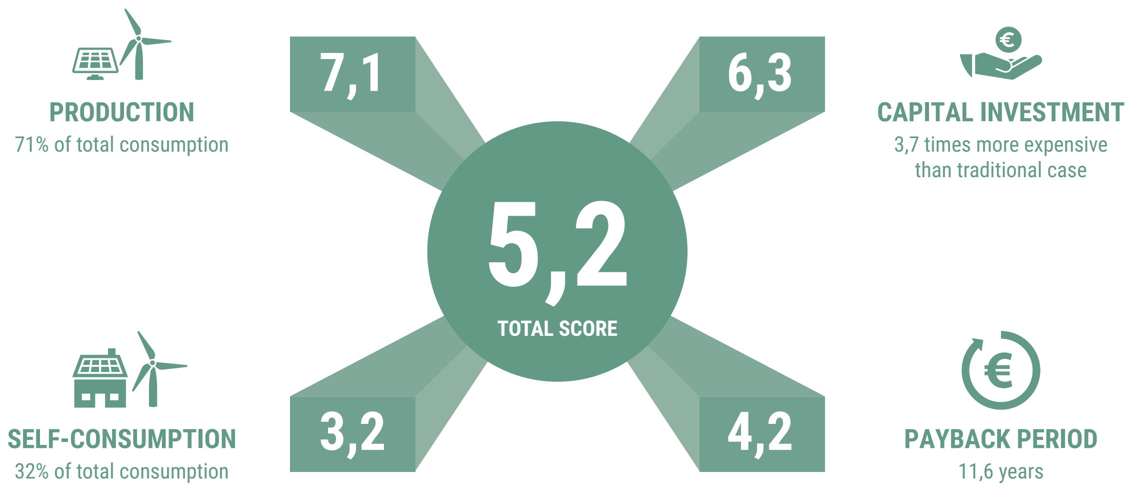


LEVELISED COST OF ENERGY

TOTAL PRODUCTION AND CONSUMPTION



OVERALL GRADE

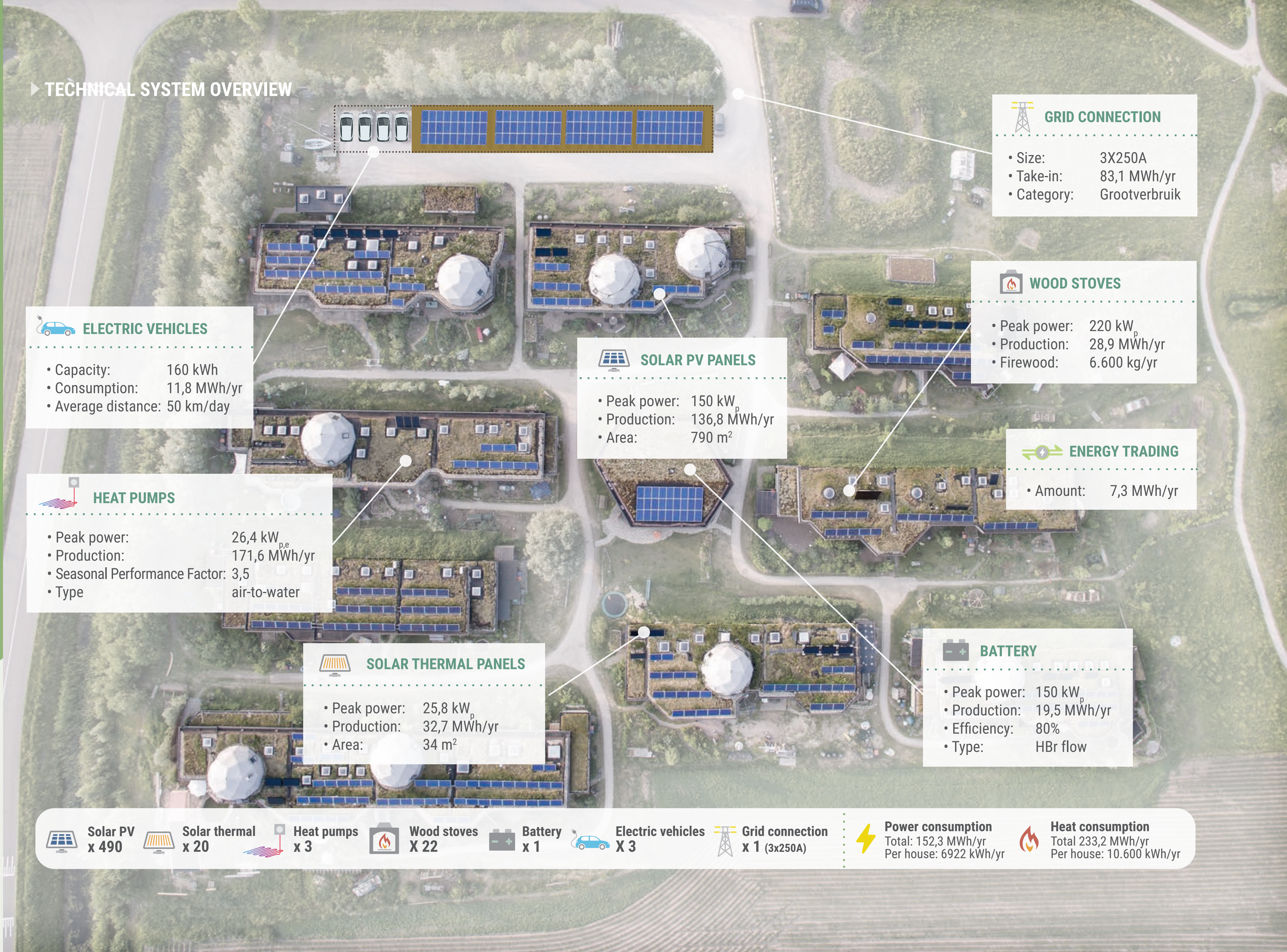


CONCLUSION

The low-tech philosophy that underpins the current energy system of the Aardehuizen results in a highly independent energy system, with a decent technical performance and acceptable economics. Being one of the first neighbourhoods within the Netherlands to step away from gas, they are able to get significant returns on their primarily biomass-based heating system. Although some clever design features have been incorporated into the design (such as wood stoves with heat exchangers), the technical performance of the Aardehuizen's current energy system still leaves much to be desired from a SIDE system point of view.

- The Aardehuizen can be considered a successful pilot project for self-sufficient neighbourhoods, yet there is much that can be improved, e.g. self-consumption of produced power.
- The economic performance is acceptable as a result of operational costs of the energy system being not too high thanks to net-metering and the low price of firewood.
- There is a lack of overall system integration due to the individualistic energy systems, resulting in a self-consumption of a meager 32%.
- Wood stoves require high inputs of biomass. Although they allow for a gas-less heating system, there is no guarantee that the biomass is obtained in a sustainable manner.

TECHNICAL SYSTEM OVERVIEW



GRID CONNECTION

- Size: 3X250A
- Take-in: 83,1 MWh/yr
- Category: Grootverbruik

WOOD STOVES

- Peak power: 220 kW_p
- Production: 28,9 MWh/yr
- Firewood: 6.600 kg/yr

ELECTRIC VEHICLES

- Capacity: 160 kWh
- Consumption: 11,8 MWh/yr
- Average distance: 50 km/day

SOLAR PV PANELS

- Peak power: 150 kW_p
- Production: 136,8 MWh/yr
- Area: 790 m^2

ENERGY TRADING

- Amount: 7,3 MWh/yr

HEAT PUMPS

- Peak power: 26,4 $kW_{p,e}$
- Production: 171,6 MWh/yr
- Seasonal Performance Factor: 3,5
- Type air-to-water

SOLAR THERMAL PANELS

- Peak power: 25,8 kW_p
- Production: 32,7 MWh/yr
- Area: 34 m^2

BATTERY

- Peak power: 150 kW_p
- Production: 19,5 MWh/yr
- Efficiency: 80%
- Type: HBr flow

Solar PV x 490 | Solar thermal x 20 | Heat pumps x 3 | Wood stoves X 22 | Battery x 1 | Electric vehicles X 3 | Grid connection x 1 (3x250A)

Power consumption
Total: 152,3 MWh/yr
Per house: 6922 kWh/yr

Heat consumption
Total 233,2 MWh/yr
Per house: 10.600 kWh/yr

SCENARIO 2: A SMARTER GRID

The residents of the Aardehuizen are aware of the fact that despite their great efforts, they have not yet managed to become completely energy neutral. Achieving self-sufficiency is an ongoing quest for them.

As part of the Clean Tech Energy Crossing, they have the ambition to create a local smart-grid within their community. Together with Saxion University of Applied Sciences, Zuyd University of Applied Sciences, Vonk Energie, Elestor, Dr. Ten, Energy Exchange Enablers (EXE) and GPX Energiebank, they are looking into behind-the-meter energy trading, as well as installing a community battery to increase self-consumption. The current proposal is to install smart meters in each home to monitor the consumption and production in order to determine the optimum battery size. If everything goes according to plan, the battery will be installed in the summer of 2018 (supplied by either Dr. Ten or Elestor).

The business case for the battery is mainly dependent on the possibility of lowering the connection size from 3x250A (grootverbruiker) to 3x80A (kleinverbruiker). In addition, they are also discussing the possibility of implementing flexible tariffs together with the energy provider Vonk Energie, which will allow for flexibility trading. Unlocking the flexibility of electrical devices such as heat pumps, electric boilers and EV's will be done using EXE's Demand-Side Management software.

Proposed changes from scenario 1:

- **Active monitoring** through the installation of smart meters.
- **Single grid connection** (experimenteerregeling) with local energy trading.[6]
- **Community battery system.**
- **Additional heat pumps** (one 1,2 $kW_{p,e}$ air-to-water for each house).
- **Demand-Side Management** of those heat pumps.
- **Flexibility trading** (not taken into account in this analysis).
- **Local energy trading.**
- **EV-charging poles** for a Tesla Model X and two Nissan leafs.

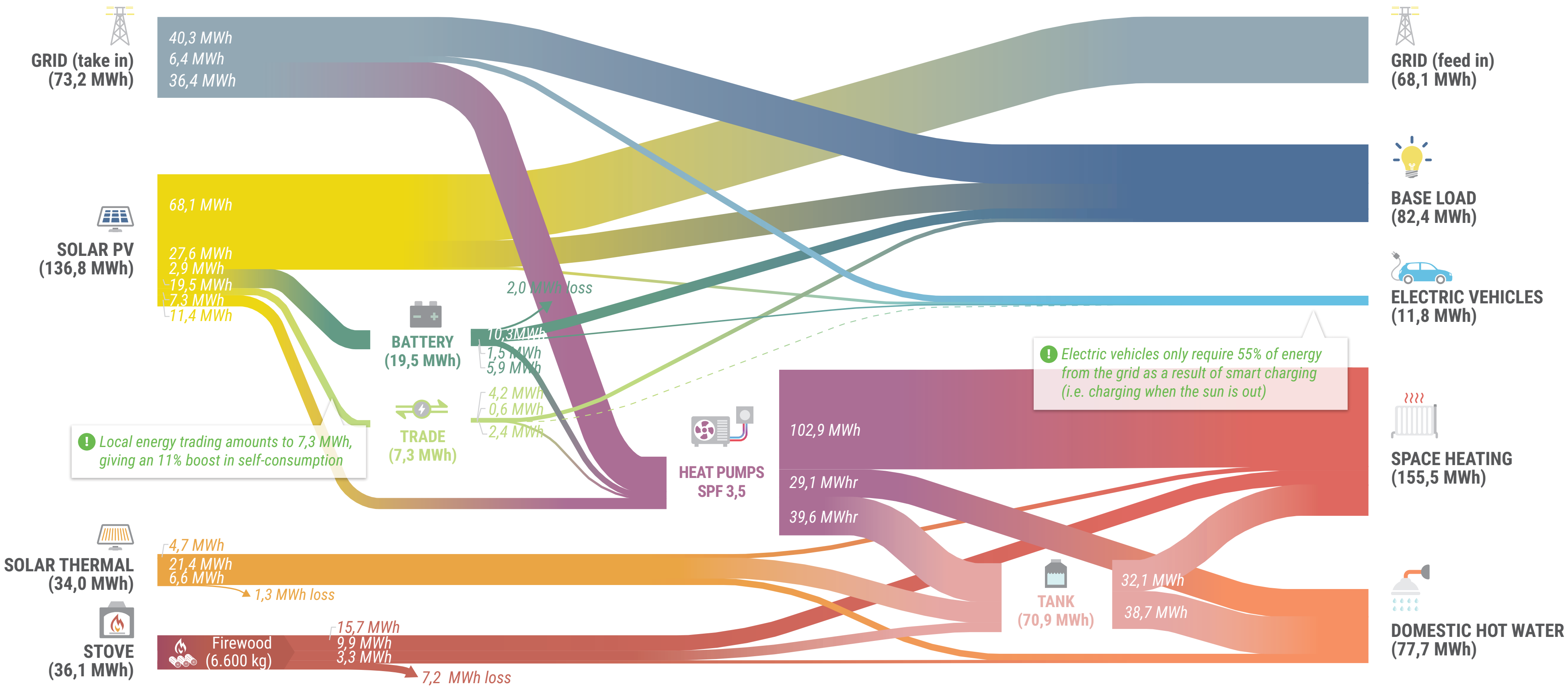
Experimenteerregeling

The "regeling experimenten elektriciteitswet", or experimenteerregeling, allows cooperations to deviate from the "Elektriciteitswet 1998".[7] It is meant to stimulate the decentralised production of renewable energy, by allowing cooperations to manage their own production, distribution and consumption of locally produced power, as if they were behind a single meter connection. The experimenteerregeling is still somewhat of a legal grey area, as the Belastingdienst still requires each house to maintain its individual connection for taxation reasons.

For scenario 2 and 3, it is assumed that the Aardehuizen are a single legal entity with a single connection to the main grid. Although this assumption may not comply with the legal reality, it makes sense from a technical point of view, as it allows for tax-free energy trading and management within the neighbourhood.

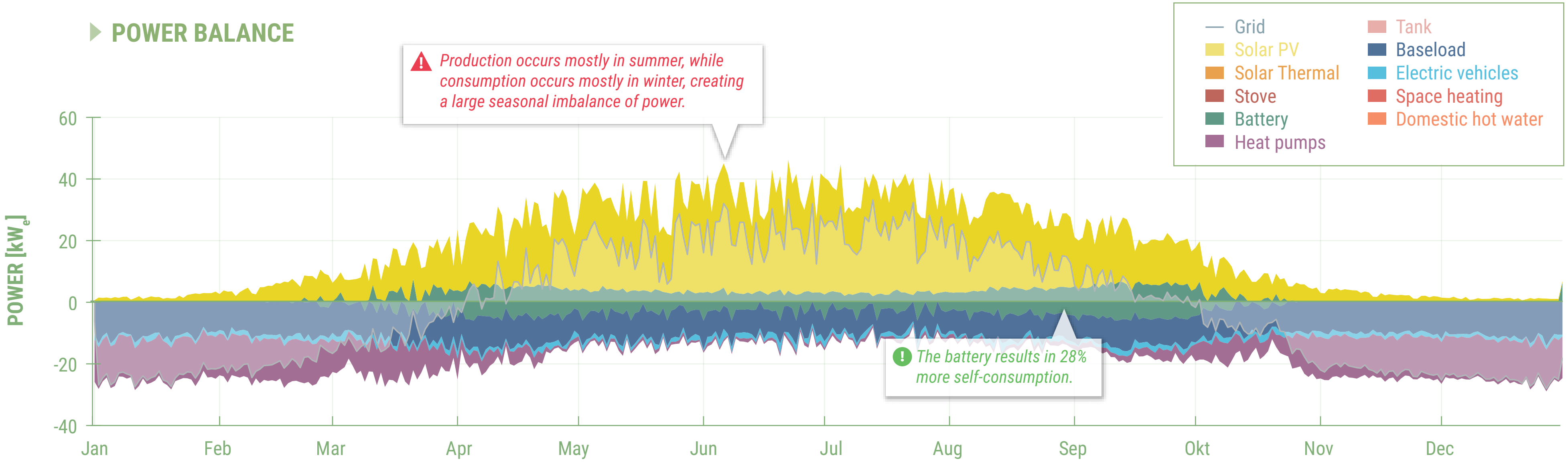
[6] https://www.rvo.nl/sites/default/files/2016/11/Samenvatting%20Aardehuizen.pdf
[7] https://www.rvo.nl/subsidies-regelingen/experimenten-elektriciteitswet

ENERGY FLOWS

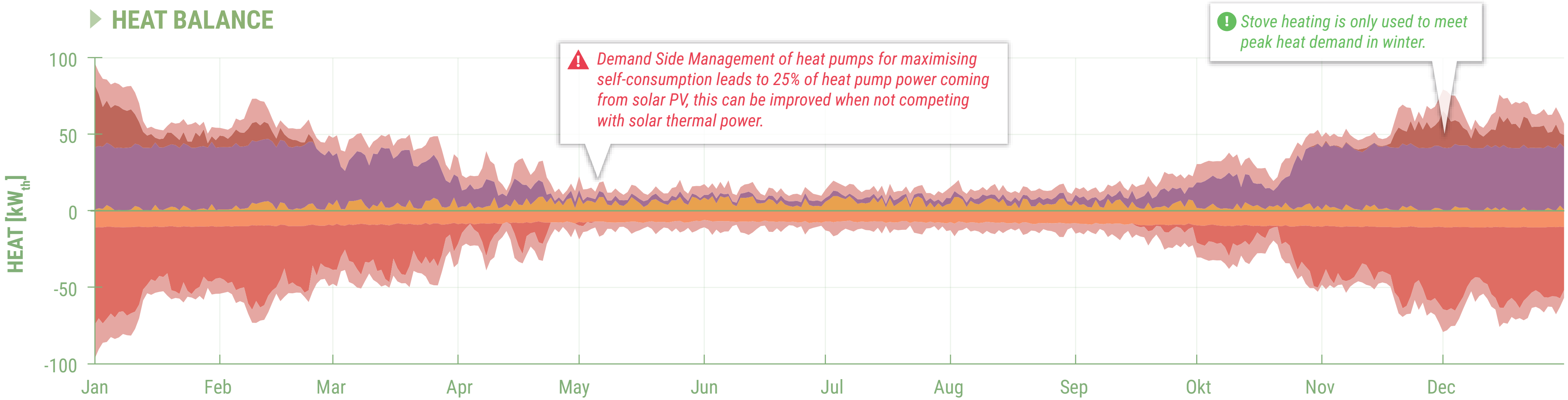


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

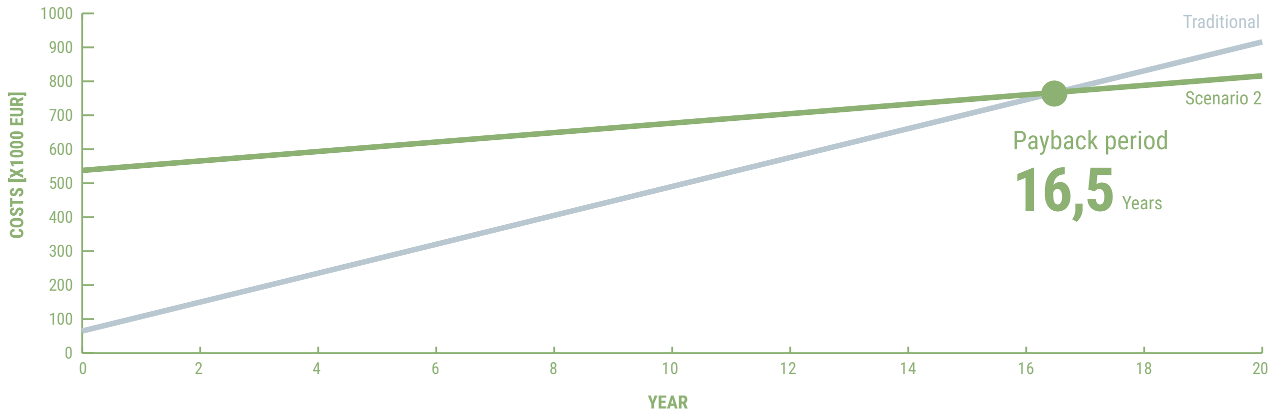


ECONOMIC ANALYSIS

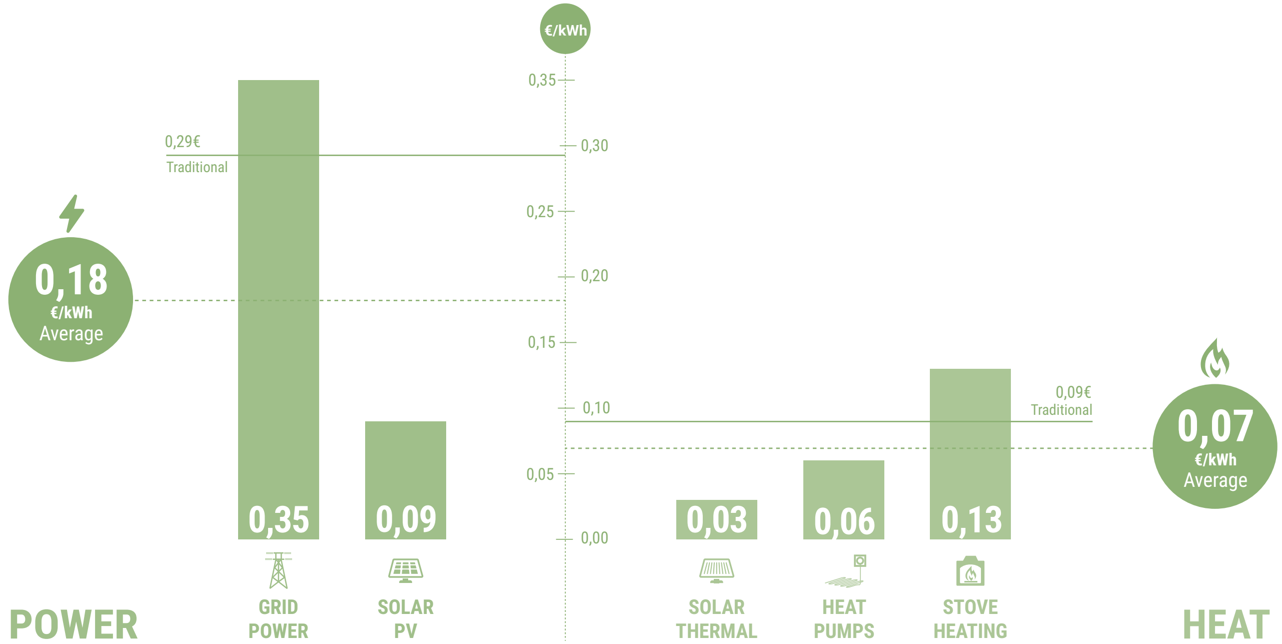
Although the proposed smart-grid upgrade is in many aspects an extension of the first scenario, it is not an improvement in economic terms as a result of high capital investments and inefficient utilisation of assets. Switching from mostly firewood as a heat source towards heat pumps in combination with solar PV results in 30% lower annual operating costs making this system cheaper in the long run than both the traditional case and scenario 1.

- Due to the high amount of PV feed-in, a kleinverbruikers connection is not possible. The additional cost is 847,50 EUR/yr.
- Although more PV power is fed in than in scenario 1, the absence of net-metering results in less feed-in revenue, and thus a lower profitability per kWh than in scenario 1.
- Still, overall electricity costs have dropped from 22 cts /kWh to 18 cts/kWh, due to both reduced grid dependency and the lower electricity costs for grootverbruikers.
- Battery savings do not outweigh its cost, even if it could be used to reduce the connection size.
- The higher investment costs for the stoves combined with much lower usage than in scenario 1 lead to high costs for stove heating.
- The 3 electric vehicles result in 6.195 EUR/yr in fuel savings.
- Using heat pumps as primary heat source reduces their heating cost from 9 cts/kWh to 7 cts/kWh (compared to scenario 1).
- As a result, total heating cost is reduced from 8 cts/kWh to 7 cts/kWh (compared to scenario 1).

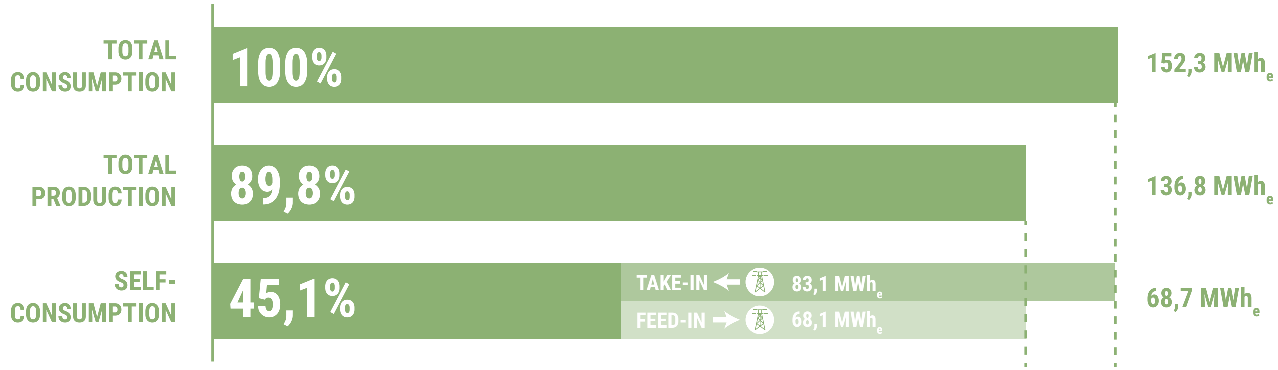
TOTAL SYSTEM COST



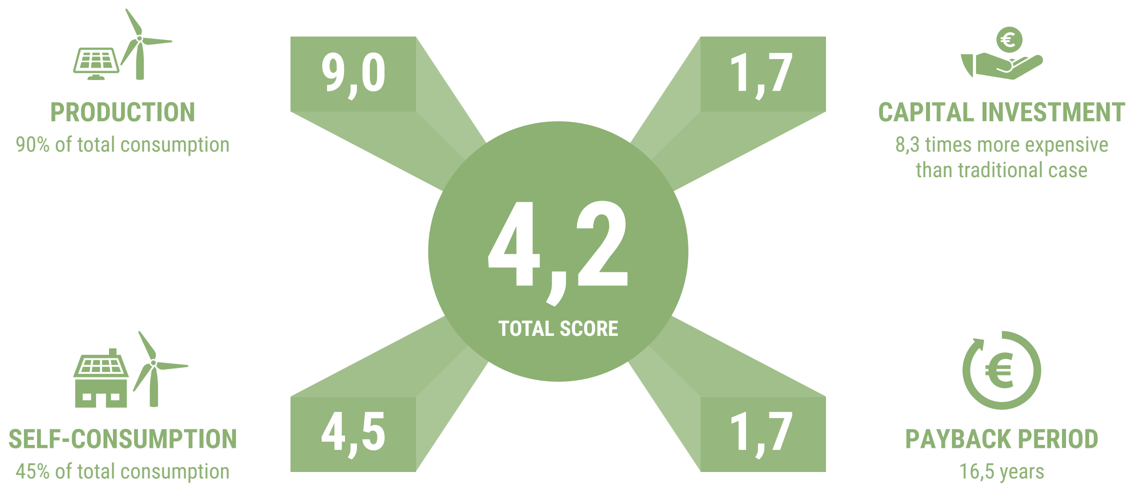
LEVELISED COST OF ENERGY



TOTAL PRODUCTION AND CONSUMPTION



OVERALL GRADE

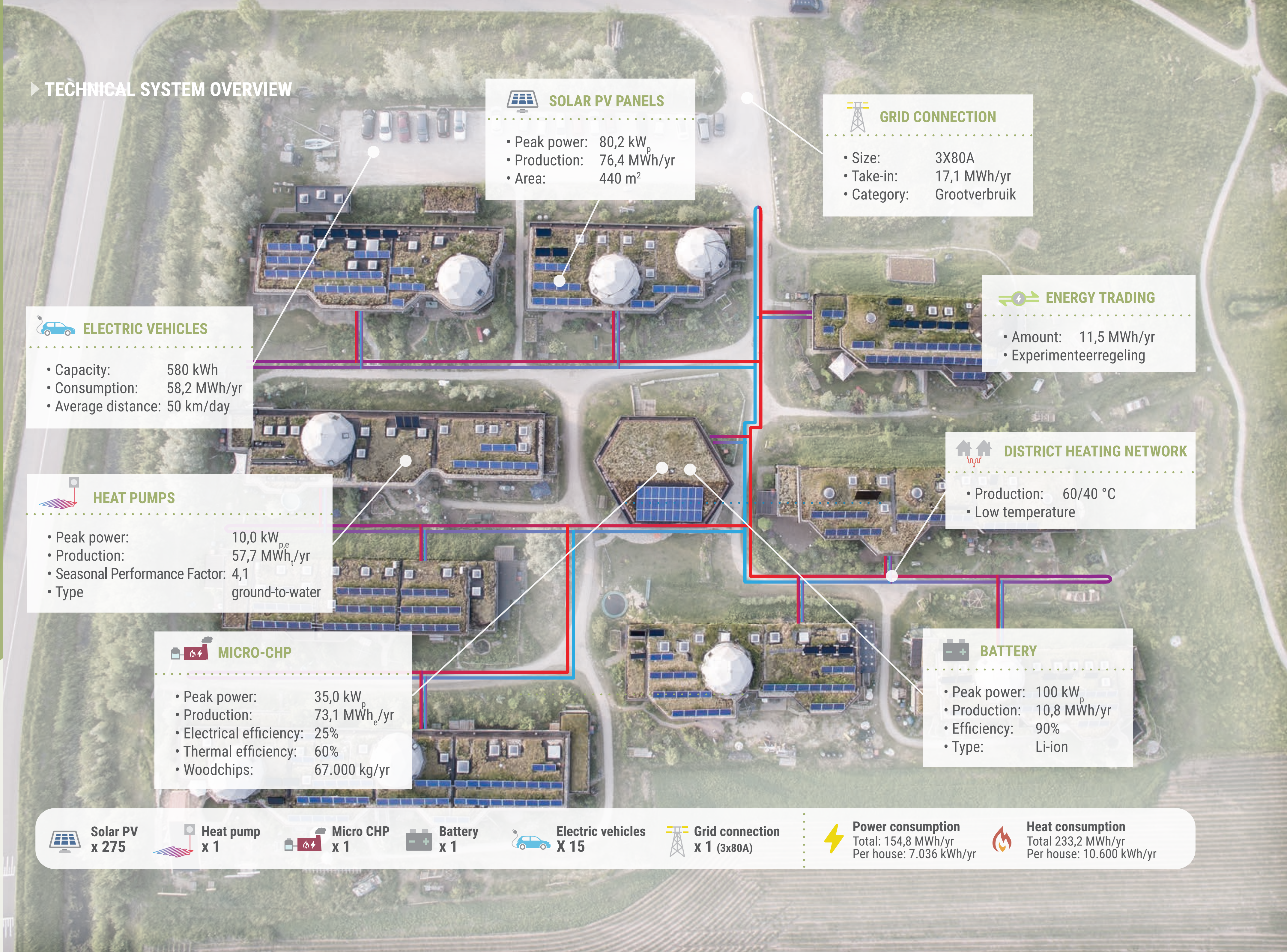


CONCLUSION

The proposed smart-grid upgrade for the Aardehuizen is a step forward towards becoming a more energy efficient and self-sufficient neighbourhood. Although it is a step in the right direction, the proposed smart-grid upgrade falls short of its ambition to make the energy system of the Aardehuizen an attractive upgrade, both in terms of self-sufficiency and economic feasibility. The main reasons for this are:

1. The overall self-consumption percentage for scenario 2 has increased only slightly compared to scenario 1, despite many expensive system upgrades. The root cause underlying this lack of self-consumption increase is the seasonal imbalance between PV power production in summer and heat pump power consumption in winter.
2. The battery system is not able to balance this seasonal imbalance, since it operates on a daily, not seasonal, timescale. Combined with the fact that the battery system is also not able to peak-shave sufficiently in order to reduce the connection size, the business-case for this battery is non-existent.
3. The experimenteerregeling that allows the residents to become a grootverbruiker does not provide any benefit in this case, for several reasons:
   - The feed-in tariff for grootverbruikers (0,11 EUR/kWh with SDE+) yields less benefit than net-metering (0,22 EUR/kWh).
   - The meters required for metering the 22 individual PV installations (“brutoproductiemeters”) are too costly to install (226,67 EUR per meter) and to operate (192 EUR/yr per meter) to make an attractive business-case.
   - The battery is unable to peak-shave enough electricity to reduce the connection size and corresponding costs.

TECHNICAL SYSTEM OVERVIEW



SOLAR PV PANELS

- Peak power: 80,2 kW_p
- Production: 76,4 MWh/yr
- Area: 440 m^2

GRID CONNECTION

- Size: 3X80A
- Take-in: 17,1 MWh/yr
- Category: Grootverbruik

ENERGY TRADING

- Amount: 11,5 MWh/yr
- Experimenteerregeling

ELECTRIC VEHICLES

- Capacity: 580 kWh
- Consumption: 58,2 MWh/yr
- Average distance: 50 km/day

DISTRICT HEATING NETWORK

- Production: 60/40 °C
- Low temperature

HEAT PUMPS

- Peak power: 10,0 $kW_{p,e}$
- Production: 57,7 MWh_t/yr
- Seasonal Performance Factor: 4,1
- Type ground-to-water

MICRO-CHP

- Peak power: 35,0 kW_p
- Production: 73,1 MWh_e/yr
- Electrical efficiency: 25%
- Thermal efficiency: 60%
- Woodchips: 67.000 kg/yr

BATTERY

- Peak power: 100 kW_p
- Production: 10,8 MWh/yr
- Efficiency: 90%
- Type: Li-ion

Solar PV x 275 | Heat pump x 1 | Micro CHP x 1 | Battery x 1 | Electric vehicles X 15 | Grid connection x 1 (3x80A)

Power consumption
Total: 154,8 MWh/yr
Per house: 7.036 kWh/yr

Heat consumption
Total 233,2 MWh/yr
Per house: 10.600 kWh/yr

SCENARIO 3: GRASSROOTS REDESIGN

For the third scenario, total design freedom was assumed for the energy system. This allows for a design that incorporates the lessons learned from scenario 1 and 2. The main challenges to overcome are:

- Addressing the seasonal imbalance of power.
- Reducing the connection costs by limiting peak power to 50 kW.
- Minimising total grid feed-in and take-in.

The chosen strategy for overcoming these challenges is as follows:

- Limit inflexible PV production to not exceed 50 kW connection capacity.
- Increase flexibility by increasing the amount of electric vehicles.
- Add a micro-CHP unit to provide electricity in winter.
- Centralise heat production via a district heating network.

Electric vehicles

One of the main design considerations for this scenario is to create a realistic and future-proof self-sufficient microgrid. It can be realistically expected that electric vehicles will dominate the future of automotive transportation, which is why the total amount of electric vehicles present in this scenario has been increased from 3 to 15.

Micro-CHP

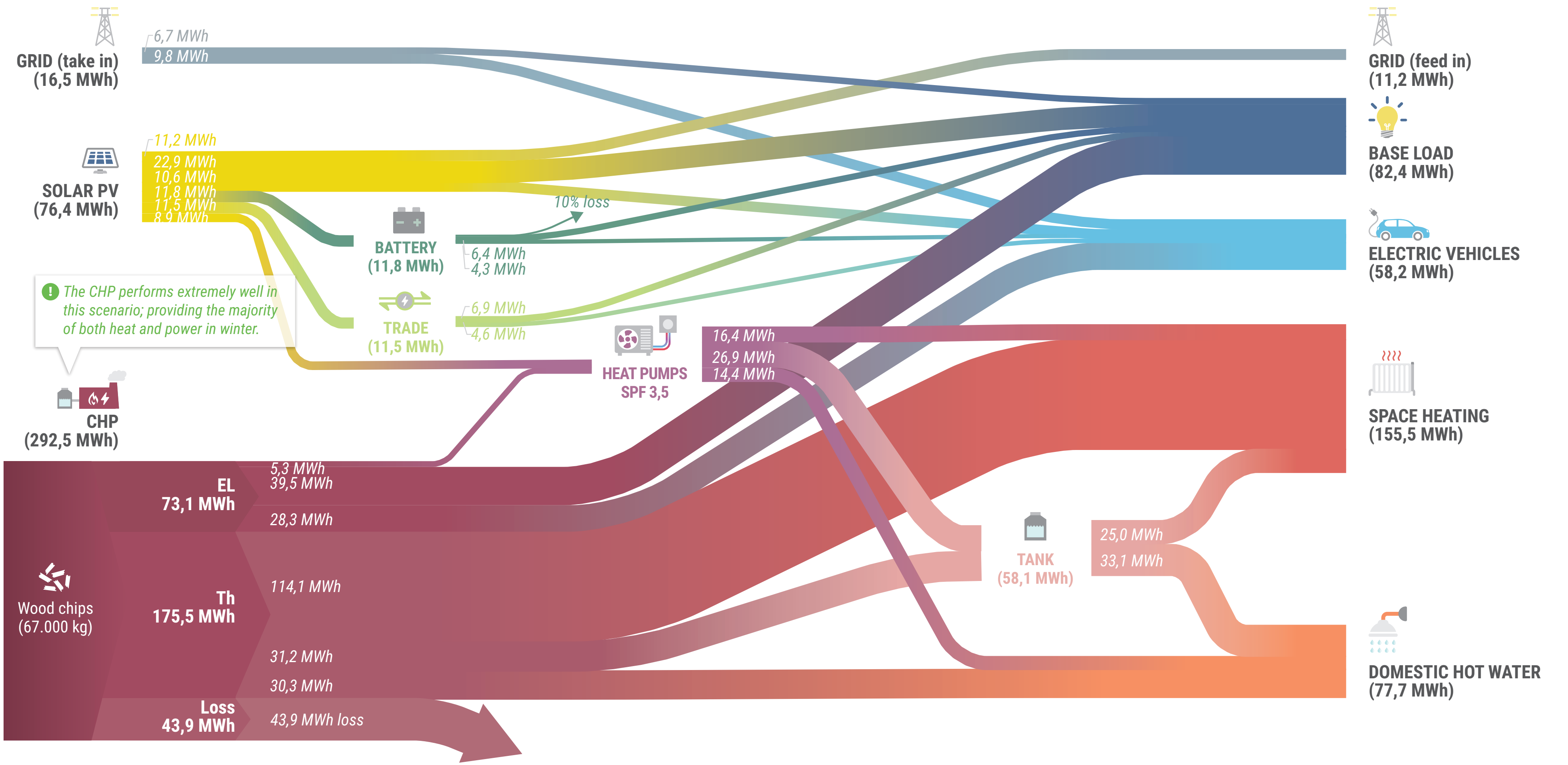
The proposed scenario hinges heavily on the presence of a CHP (Combined Heat & Power) unit, a machine that generates both heat and electricity by burning fuel. Although CHPs are mainly found in multi-MW industrial power plants connected to large district heating networks, there is a new class of micro-CHP (<100 kW) systems emerging for residential applications.

For this scenario, a 35 $kW_{p,e}$ micro-CHP running on wood chips was selected, with an electrical efficiency of 25% This is significantly less than than advanced industrial-scale CHPs (55%), making the business-case highly dependent on economical and technical circumstances. It is assumed that a 5,4 cts/kWh SDE+ subsidy can be arranged for the CHP.

District heating

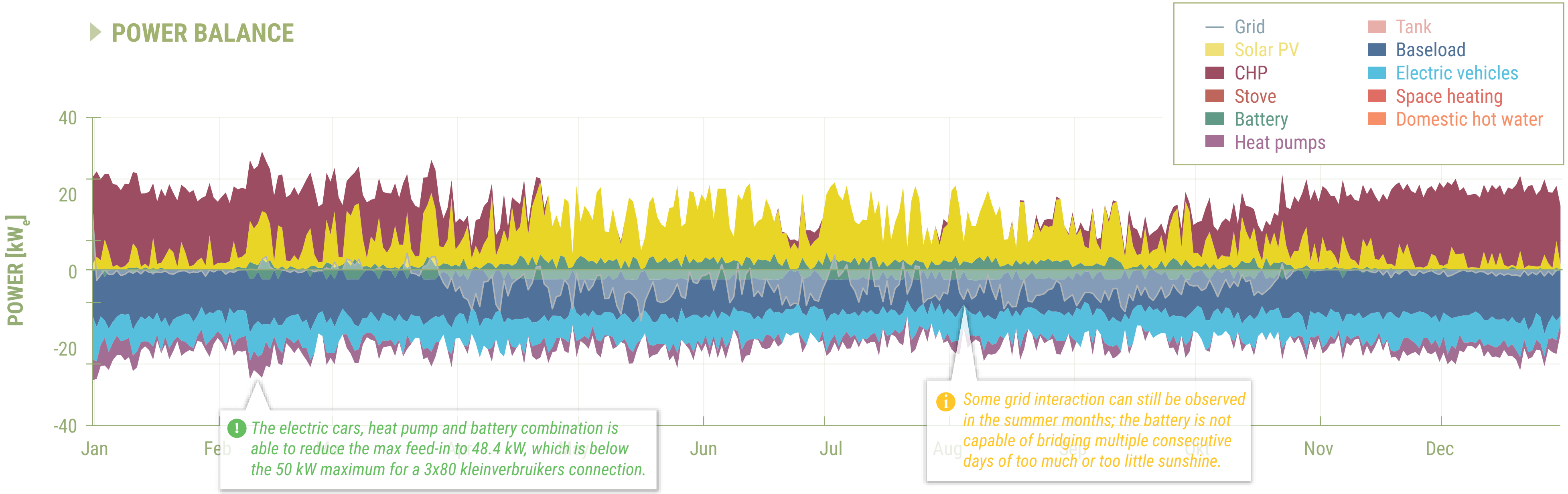
The centralised production of heat from the heat pump and CHP requires a local distribution network to deliver the heat to the houses. This is done via an insulated closed-loop pipe network that connects to residential district heating substations. These substations feature a heat exchanger, control valve, a heat meter and various sensors for temperature and pressure. Heat is transferred from the district heating network to the local residential heating system at a temperature of 60 °C - making it a low temperature district heating network. The low temperature was chosen to allow for the heat pump to run at the optimal efficiency, while the temperature is still high enough to deliver domestic hot water.

ENERGY FLOWS

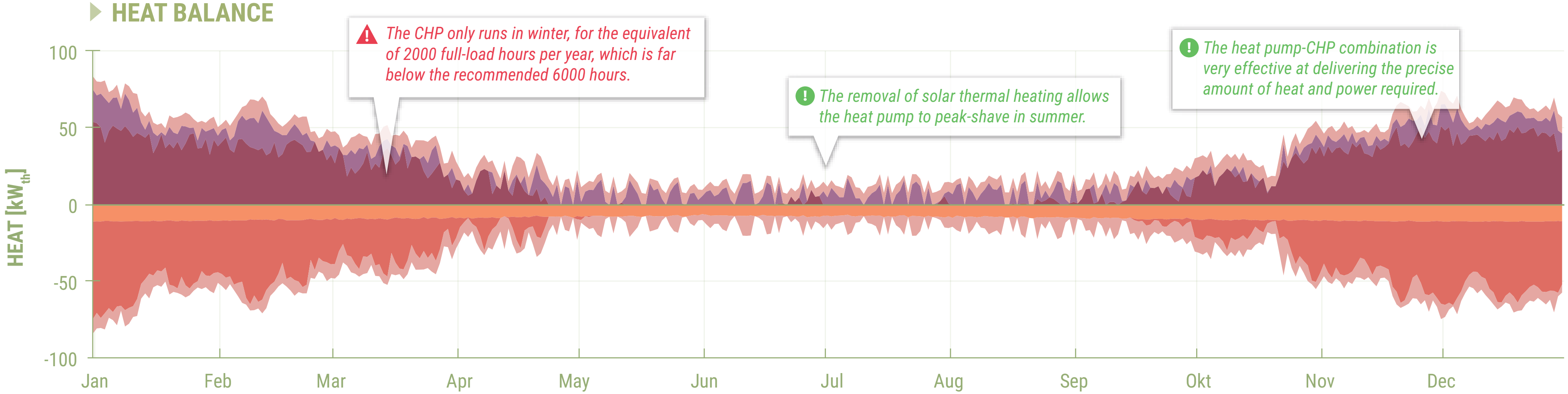


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

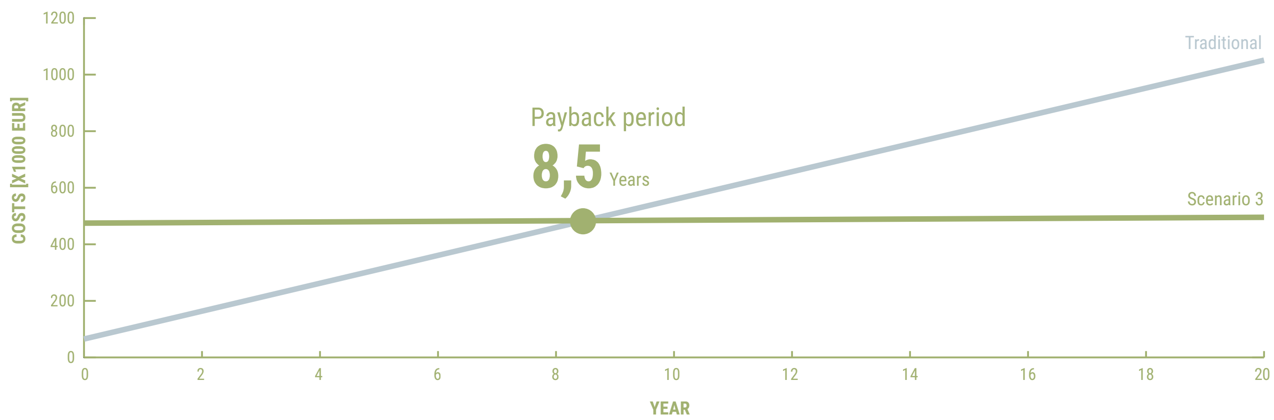


ECONOMIC ANALYSIS

The business-case for scenario 3 is the best of all scenarios, with the lowest power costs (14 cts/ kWh) and the fastest payback period. There are several reasons for this outcome:

- The peak power in scenario 3 is less than the grootverbruikers threshold, allowing the residents to save costs on the connection size (847,50 EUR/yr), as well as eliminating the need for brutoproductiemeters (4.986 EUR investment and 4.224 EUR/yr annual costs).
- The kleinverbruikers connection allows for net-metering up to 10.000 kWh/yr (a feed-in tariff of 8 cts/ kWh was assumed after that). The yearly feed-in of 11.200 kWh barely exceeds the threshold of 10.000kWh, making the PV system very profitable.
- Despite a high capital investment and maintenance cost, the CHP breaks even due to low fuel cost, even without subsidy. The total subsidy for the CHP amounts to 268,00 EUR, which has a very high positive impact on the business case.
- Less than 20% of EV power is drawn from the grid, resulting in 6.600 EUR in annual savings or 440 EUR per car.
- Scaling advantages for the centralised heat pump and CHP lower their capital expenditure per kWpth, making the system less expensive than scenario 2.
- The lack of power flows across the grid connection make it relatively expensive, since the transport and measuring costs are dominating the power costs. If a 3x80 A connection were not possible, the average cost for grid power would have increased to 0,56 EUR/kWh.

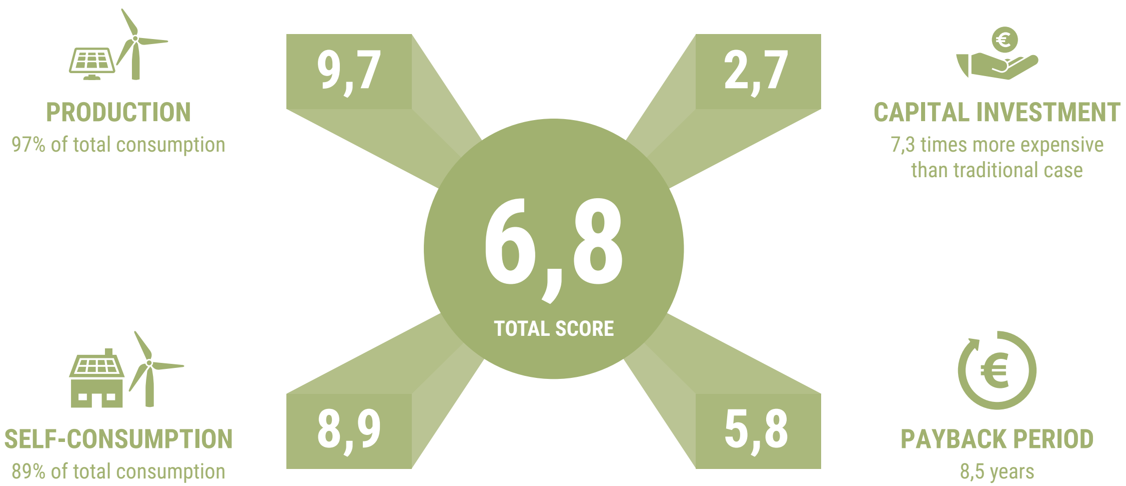
TOTAL SYSTEM COST



LEVELISED COST OF ENERGY

TOTAL PRODUCTION AND CONSUMPTION

OVERALL GRADE



CONCLUSION

A high degree of sustainable self-sufficiency combined with low operating costs make scenario 3 the best option out of all scenarios considered. Not only is it the most profitable and self-sufficient scenario of all cases considered, it is also the the most flexible and resilient.

- The system only requires 17,1 MWh of grid electricity per year to run, or only 11% of total consumption, making it nearly fully autonomous.
- The CHP plus heat pump combination solve the issue of seasonal imbalance as it provides both heat and power in winter with a high degree of flexibility.
- Although an external fuel source (woodchips) is required to operate the CHP, the consumption of biomass is only 50% higher than in scenario 1 (with far less grid dependency).
- The high degree of flexibility is not only effective at local balancing, it can also be used to help balance the main grid. For instance, the CHP could be operated for more hours per year, making it relatively cheaper, while also providing electricity to nearby neighbourhoods
- The impact of having a large electric car fleet in this scenario is an asset rather than a burden, as it provides a high volume for flexibility, while not exceeding peak power capacity.
- The experimenteerregeling provides significant benefit in for this scenario, as opposed to scenario 2, since a kleinverbruikers connection can be operated.

DE CEUVEL

INTRODUCTION

De Ceuvel is an award-winning, sustainable planned workplace for creative and social enterprises on a former shipyard on the Johan van Hasselt kanaal off the river IJ in Amsterdam North. In 2012, the land was secured for a 10-year lease from the Municipality of Amsterdam after a group of architects won a tender to turn the site into a regenerative urban oasis.

The former industrial plot is home to a thriving community of entrepreneurs and artists. What was once a shipyard has now been transformed into one of the most unique urban experiments in Europe. De Ceuvel was built, piece by piece, by a large group of passionate entrepreneurs and volunteers, using mostly recycled materials. Everybody involved has lended a hand to build Amsterdam's first circular office park. The plot now hosts several creative workspaces, a cultural venue, a sustainable café, spaces to rent, and a floating bed & breakfast.

Cleantech playground

Through experimentation, De Ceuvel aims to become as energy self-sufficient as possible, while simultaneously processing its waste in new innovative ways. De Ceuvel is not only a “forbidden garden” which will leave behind cleaner soil, but also a playground for sustainable technologies. This “Cleantech Playground” is a testing site for clean technology in the built environment. It aims to advance sustainable building technology and find ways to accelerate the transition of cities towards circular and sustainable urban metabolisms. Old houseboats have been placed on heavily polluted soil, workspaces have been fitted with clean technologies, connected by a winding jetty. Around the houseboats phyto-remediating plants work to clean the soil. By recycling entire buildings, cleaning the soil with plants, and using low-cost clean technologies to improve the sustainability of the development, De Ceuvel is a prime example of a creative, circular, urban community.

Notes

- Measured profile data was obtained for solar PV production, heat pump consumption and base load consumption for each boat during the period from 24-8-2017 to 11-5-2018.
- Missing profile data was extrapolated from the measured profile data. The resulting difference between the extrapolated profiles and the overall annual production and consumption smart meter data turned out to be less than 5%.
- No DHW usage was assumed due to De Ceuvel being a non-residential area. Any hot water demand for the cafe is included in its electricity consumption (electric heating).

TECHNICAL SYSTEM OVERVIEW

SOLAR PV PANELS

- Peak power: 42 kW_p
- Production: 26,5 MWh/yr
- Area: 240 m^2

WOOD STOVES

- Peak power: 15 kW_p
- Production: 8,7 MWh/yr
- Firewood: 2.500 kg/yr

HEAT PUMPS

- Peak power: 12 $kW_{p,e}$
- Production: 74,3 MWh/yr
- Seasonal Performance Factor: 4,3
- Type: air-to-air

ENERGY TRADING

- Blockchain- based
- Behind-the-meter
- Jouliette

ELECTRIC HEATING

- Peak power: 220 kW_p
- Production: 15,6 MWh/yr

GRID CONNECTION

- Size: 3x80A
- Take-in: 108,3 MWh/yr
- Category: Kleinzakelijk verbruik

Solar PV x 150

Heat pumps x 12

Wood stoves X 2

Electric heating X 6

Grid connection x1 (3x80A)

Power consumption
Total: 113,7 MWh/yr
Per boat: 6.317 kWh/yr

Heat consumption
Total 115,2 MWh/yr
Per boat: 6.400 kWh/yr

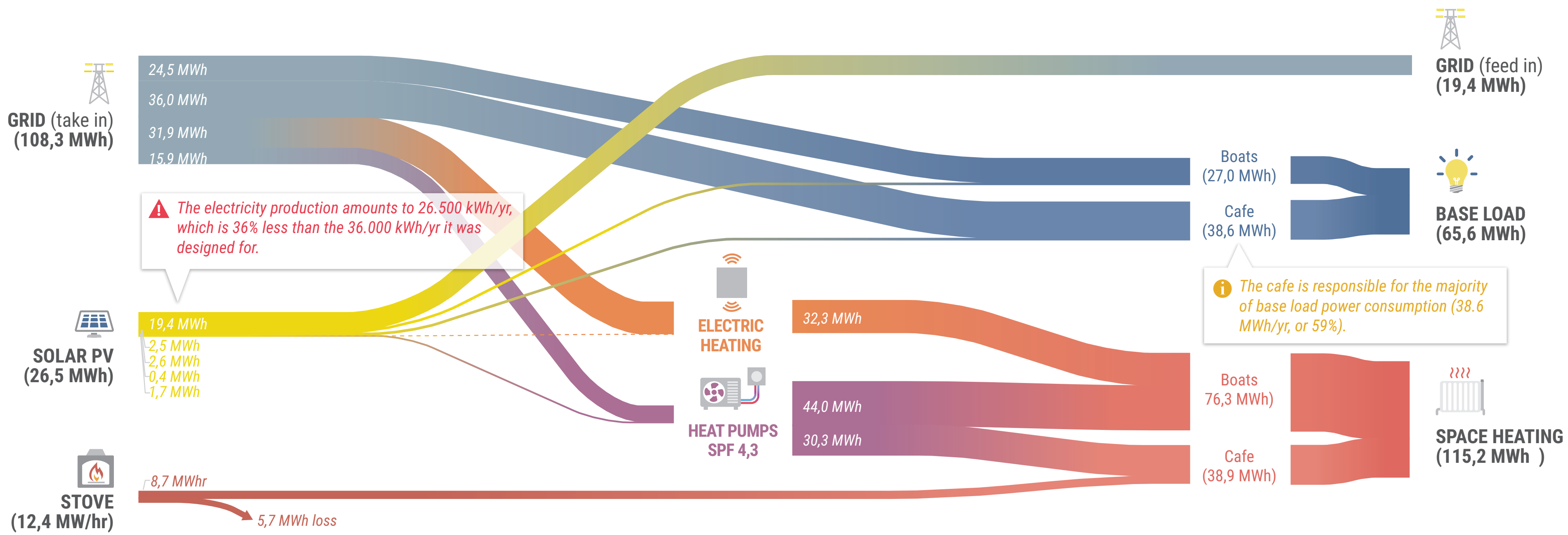
SCENARIO 1: ALL-ELECTRIC

In its search for gasless heating solutions, De Ceuvel has chosen to be an all-electric site (except for some stove heating in the cafe) through the use of solar panels, heat pumps and other innovative technologies:

- Over 150 Photovoltaïc (PV) panels generate power from the sun. The panels are installed on the majority of the office boats and have been designed to generate around 36.000 kWh of power annually. This covers the electricity demand of the heating systems, along with a part of the remaining electricity needs of the offices. The remaining energy demand is supplied by a green energy supplier.
- Each office boat has an air-to-air heat pump and a heat exchange ventilation system. The heat pump extracts heat from the surrounding air to heat up each boat. As warm air leaves the boat, over 60% of the heat is captured and circulated back inside. These simple technologies allow de Ceuvel to circumvent the need for a gas line and use renewable electricity to power a simple, low-cost option.
- Aside from renewable energy production, demand reduction has been a key focus of de Ceuvel. The boats have been retro-insulated to reach near-passive house standards, with increased daylighting and LEDs to reduce electricity demand. Each boat at de Ceuvel is equipped with sensors that measure temperature, humidity, energy consumption, production, and water usage.

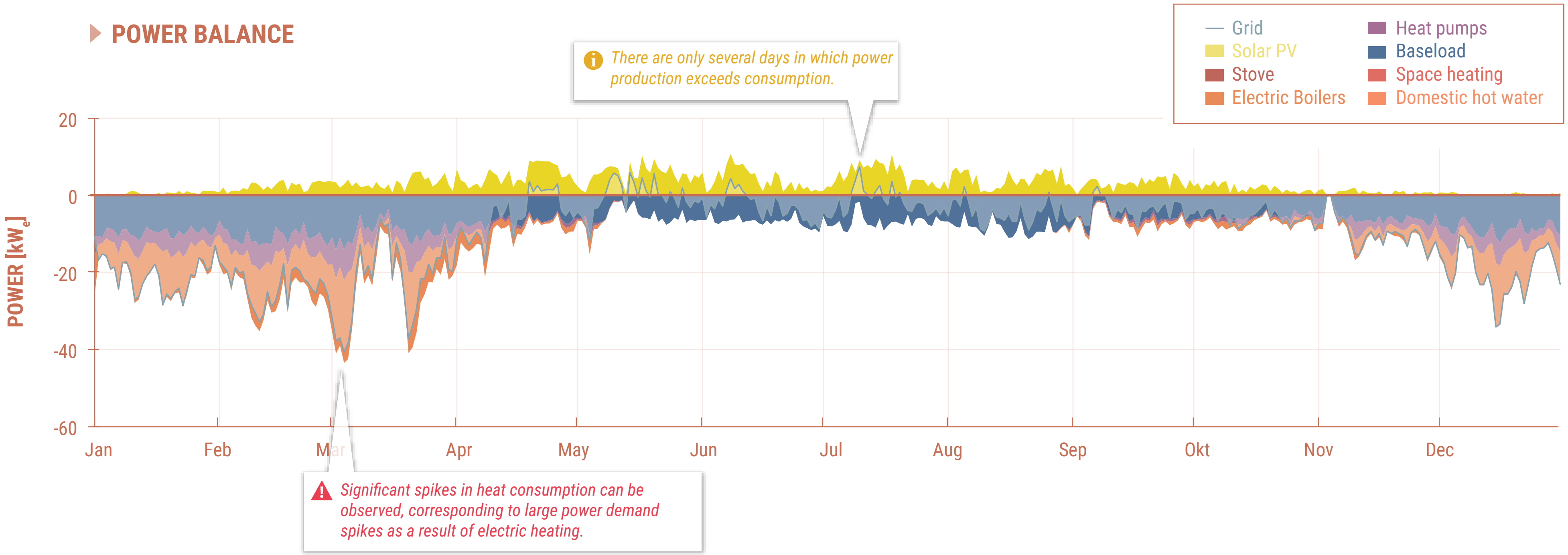
The workspaces at De Ceuvel consist of recycled old boats that have been hoisted onto land, after which they were retrofitted with insulation and environmentally friendly systems. Examples of these systems include composting toilets, helophyte filters and heat pumps.

ENERGY FLOWS

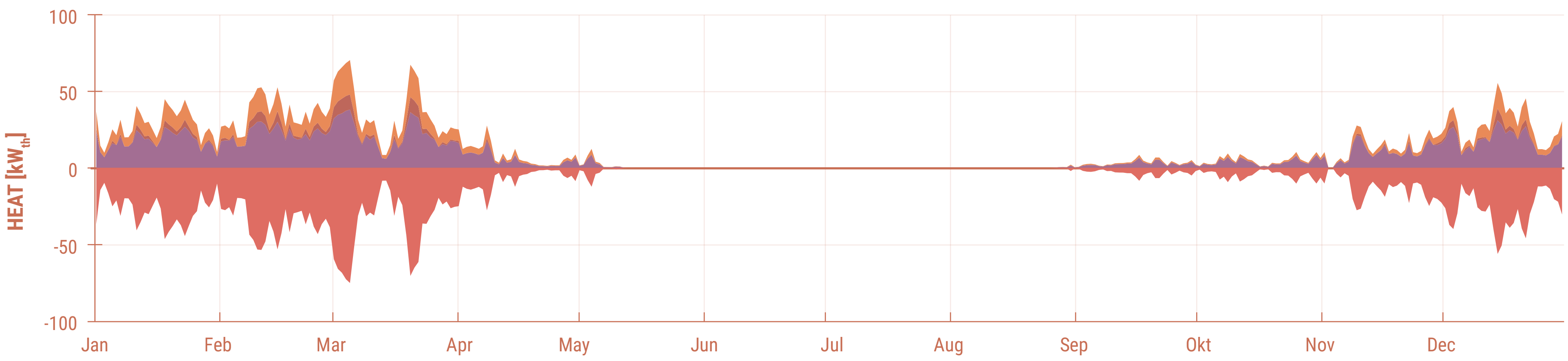


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

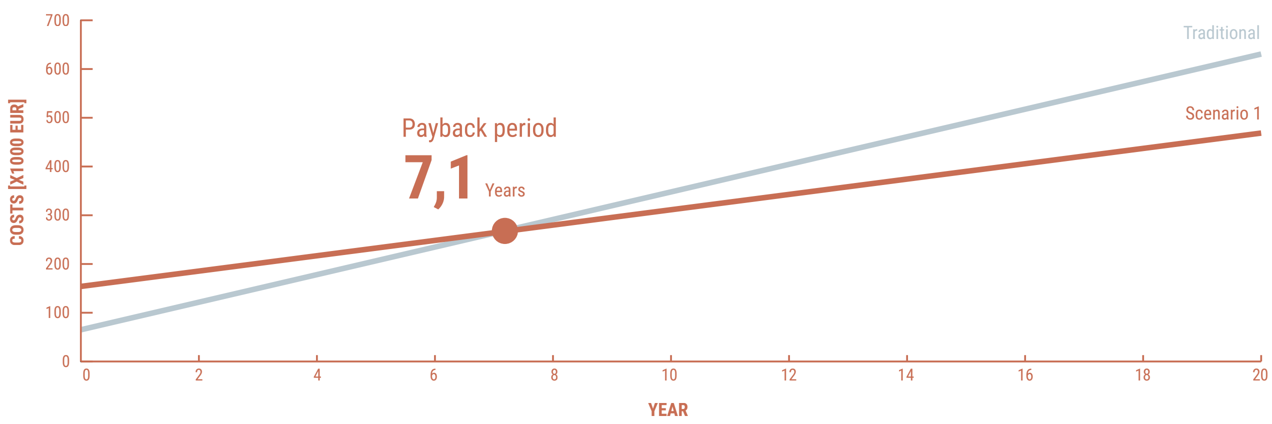


ECONOMIC ANALYSIS

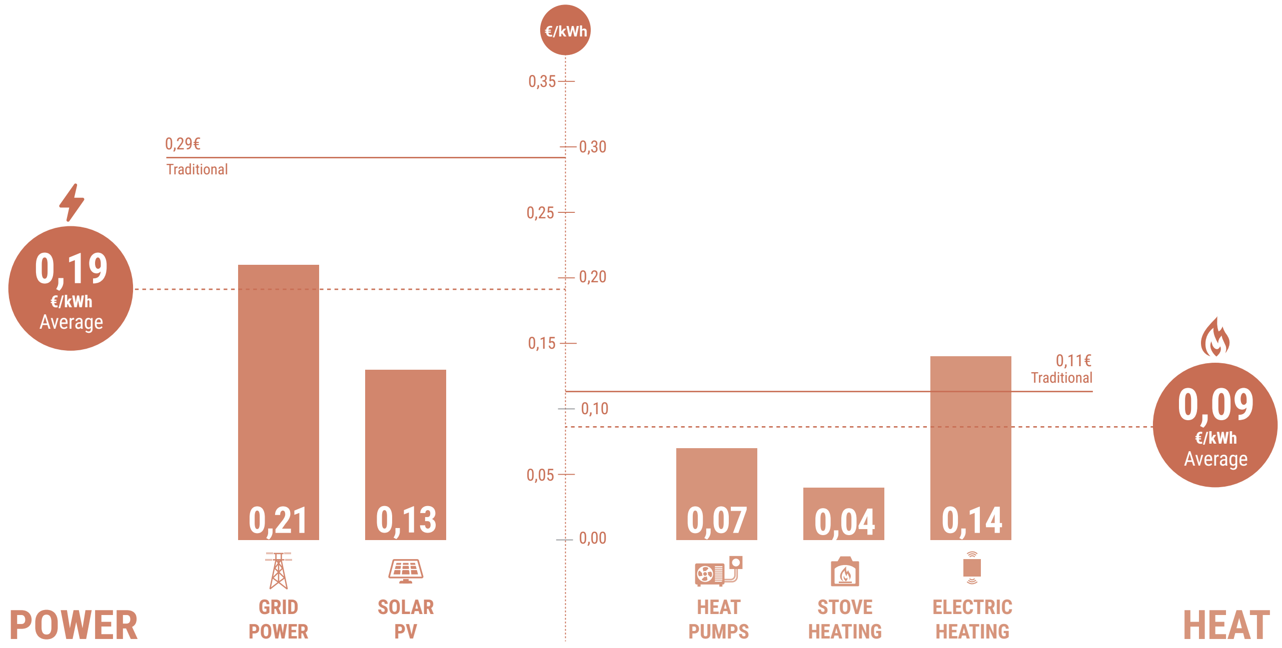
With a fast payback period of less than 6 years compared to a traditional gas-based heating system, the business case for the current energy system of De Ceuvel is clear. There is room for improvement, however.

- The air-source heat pumps running mostly (for 90%) on grid electricity are similar in overall cost to a traditional gas-based heating system.
- A high percentage of solar PV feed-in makes their profitability highly dependent on the height of the feed-in tariff. Fortunately, the combination of net-metering for the first 10 MWh and an 8 cts/kWh feed-in tariff after that make for a profitable business-case.
- Electric heating is expensive and has a negative effect on the business case.

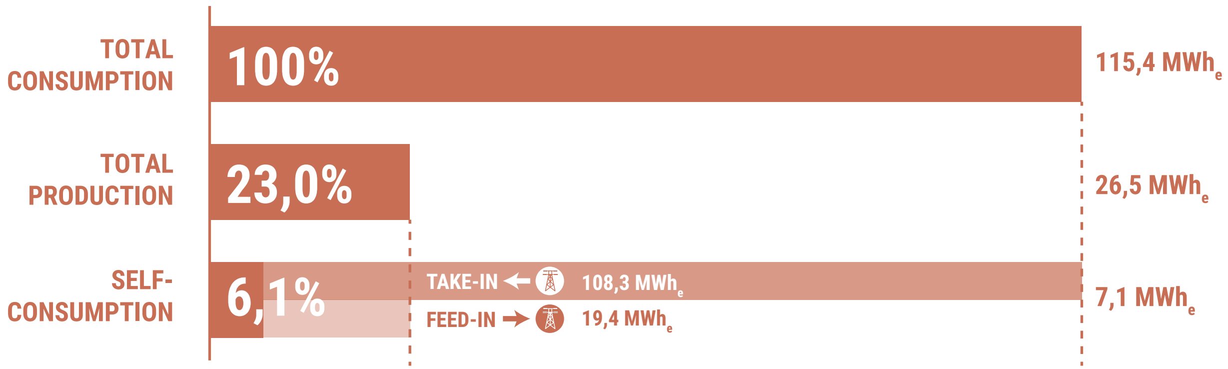
TOTAL SYSTEM COST



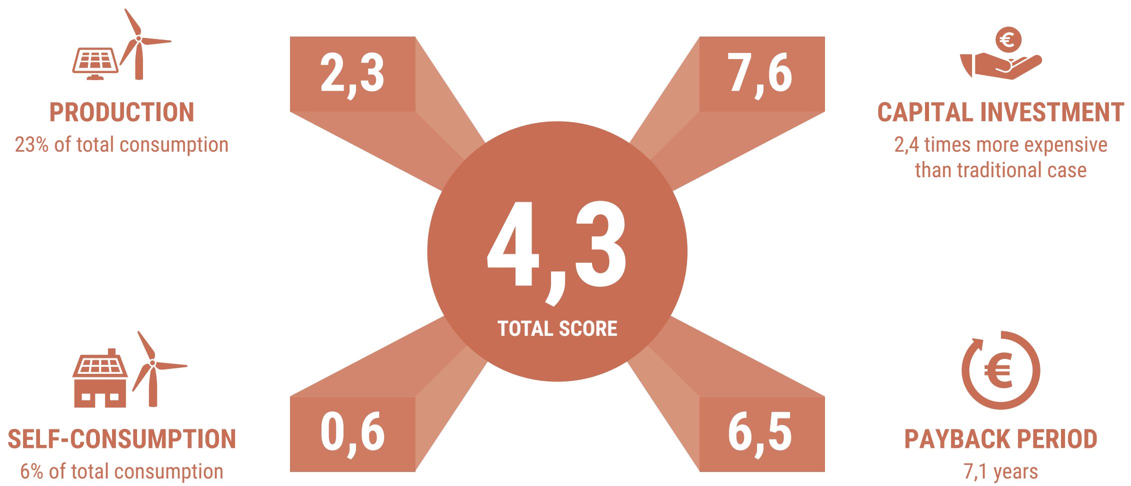
LEVELISED COST OF ENERGY



TOTAL PRODUCTION AND CONSUMPTION



OVERALL GRADE



CONCLUSION

De Ceuvel only partly succeeds in its ambition to showcase an innovative sustainable alternative to traditional gas-based energy systems. The all-electric approach based on solar panels and heat pumps makes sense from both an ecological and economical point of view, although its technical performance with regards to flexibility and self-consumption leaves much to be desired.

- The total power production (26,5 MWh/yr) is only 23% of total power consumption (113,7 MWh/yr), mostly due to poor solar panel performance (possibly due to shadows) and high energy demand of the cafe.
- Even though office hours tend to coincide with solar PV production, the percentage of self-consumed PV power is low at only 27%. An explanation for this is that the air-to-air heat pumps and electric heating have very little flexibility since they do not store the heat in a hot water tank for usage at a later time.
- The current system is highly dependent on grid energy, with 93,8% of power drawn from the grid, due to the large seasonal imbalance of power production and consumption
- With a payback period of less than 6 years, an overall power cost of 18 cts/kWh (compared to 29 cts/kWh traditionally) and an overall heating cost of 9 cts/kWh (compared to 11 cts/kWh traditionally), the business case for De Ceuvel's current energy system is self-evident.
- Overall self-consumption is very low due to a high seasonal imbalance of power production and consumption.

TECHNICAL SYSTEM OVERVIEW

CAFÉ DE CEUVEL

SOLAR PV PANELS

- Peak power: 73,2 kW_p
- Production: 53,0 MWh/yr
- Area: 420 m^2

WIND TURBINE

- Capacity: 50 kWh
- Consumption: 49,7 MWh/yr
- Seasonal Performance Factor: 4,3

HEAT PUMPS

- Peak power: 18 $kW_{p,e}$
- Production: 105,3 MWh/yr
- Seasonal Performance Factor: 4,2
- Type: air-to-air

ENERGY TRADING

- Blockchain- based
- Behind-the-meter
- Jouliette

BATTERY

- Capacity: 50 kWh
- Throughput: 7,5 MWh_e/yr
- Efficiency: 90%
- Type Li-ion

BIOGAS BOAT

- Biodigester + storage
- Production: 9,9 MWh/yr
- Organic wate: 6-10.000 kg/yr

GRID CONNECTION

- Size: 3x250A
- Take-in 45,8 MWh/yr
- Category: Grootverbruik

ELECTRIC VEHICLES

- Capacity: 250 kW_p
- Consumption: 18,3 kW_p
- Average distance: 50 km/day

Solar PV **x 260**	**Wind turbine** **x 1**	**Battery** **x 1**	**Heat pumps** **x 18**	**Electric vehicles** **X 6**	**Grid connection** **x1 (3x250A)**	**Power consumption** Total: 108,6 MWh/yr Per boat: 6.033,3 kWh/yr	**Heat consumption** Total 115,2 MWh/yr Per boat: 6.400 kWh/yr

SCENARIO 2: ALL-ELECTRIC EXPANSION

The main goal for this scenario is to upgrade De Ceuvel's energy system in order to become more flexible and self-sufficient, while maintaining its all-electric philosophy. The main challenges to overcome are:

- Lack of sufficient power production.
- Seasonal imbalance of power production and consumption.
- Increasing self-consumption by adding flexibility.

Proposed changes from scenario 1:

- **Additional solar panels:** 31,2 kWp of additional solar panels will be installed in such a way that they are not obstructed by buildings or trees.
- **Battery system:** A 50 kWh Li-ion battery will help balance local energy flows, so that more power can be kept within the local grid.
- **Electric vehicles:** 5 electric vehicles parking spots will be created so that inhabitants and visitors can charge their EV's while at De Ceuvel.
- **Urban wind turbine.**
- **Blockhain-based energy trading.**
- **Biogas:** Organic waste will be recycled and converted to biogas in an on-site biodigester boat that will produce biogas for the cafe's cooking stoves.

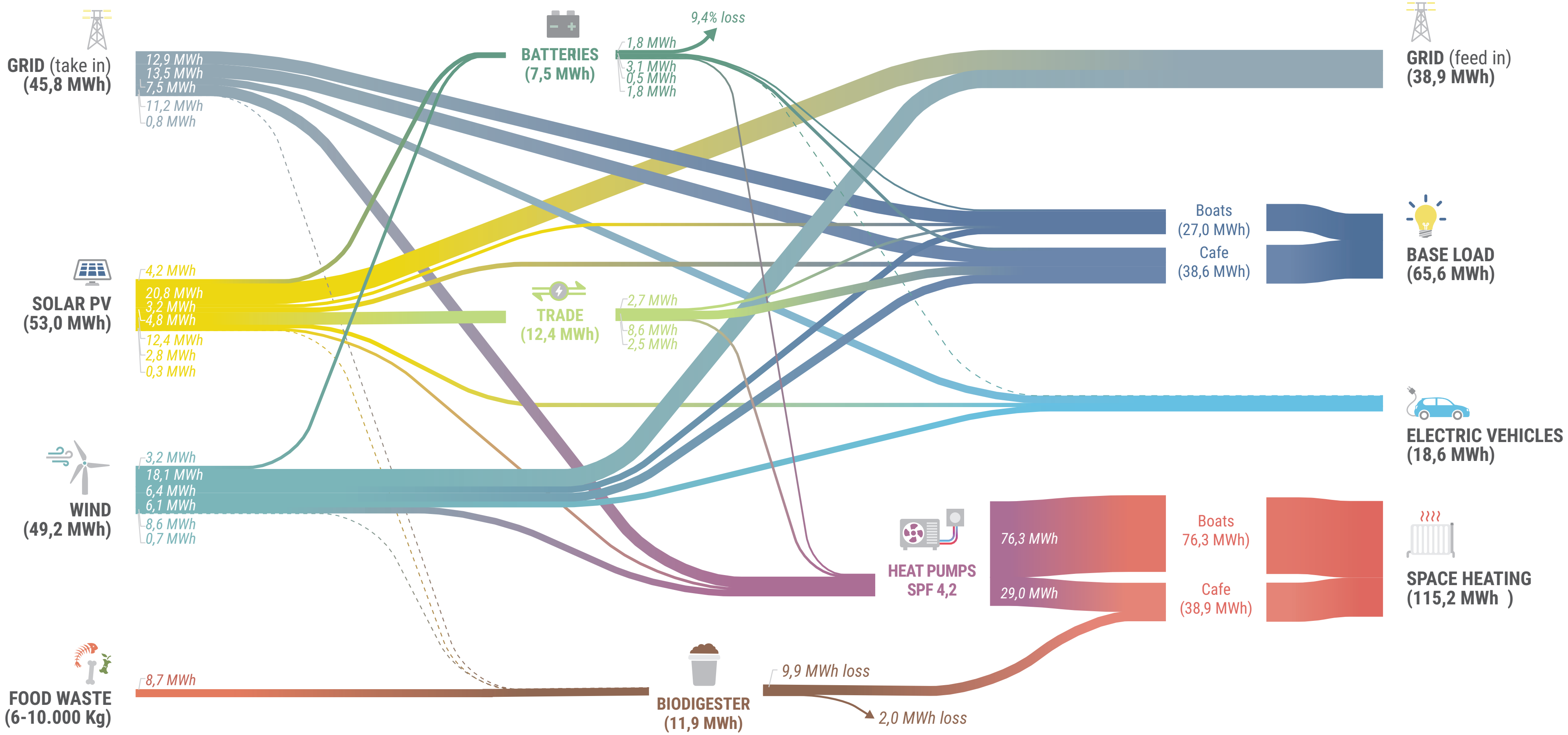
Urban Wind Turbine (UWT)

In order to produce more power without increasing the seasonal imbalance, a 50 kW horizontal-axis wind turbine (HAWT) is chosen to be installed at De Ceuvel for this scenario. A big advantage of wind power is that it tends to be windier in winter, thereby complementing the summer PV production. Although it is unusual for a wind turbine to be installed in urban areas, wind power can be a suitable option provided that there is sufficient wind to make a business case. Amsterdam is in a fairly windy area, and De Ceuvel is close to the IJ in Amsterdam-Noord, an area that already features an urban wind turbine, making this decision not entirely unrealistic.

Energy trading over the blockchain

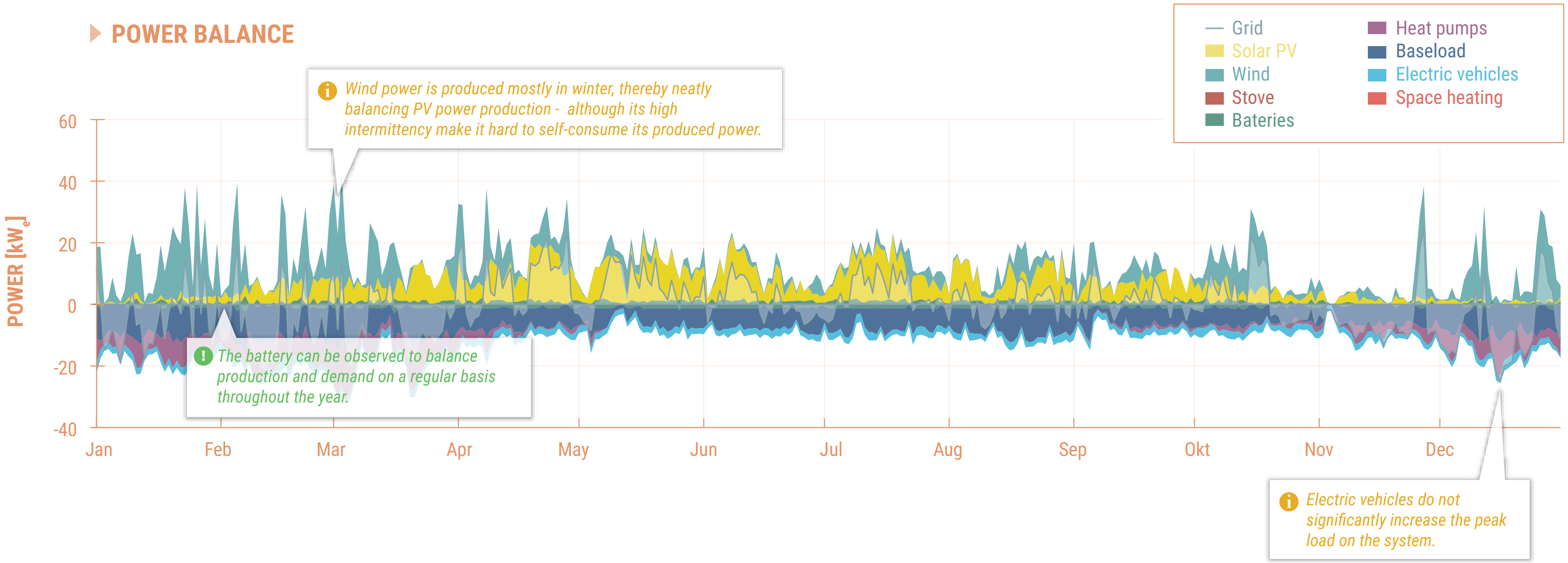
On 15 September 2017, Spectral (a spin-off of Metabolic) launched the Jouliette at De Ceuvel, a community in Amsterdam which has become a globally visible showcase for sustainable urban development. The Jouliette is a blockchain-based energy token that empowers individuals and communities to easily manage and share their locally produced renewable energy. In a process called minting, solar power produced on-site is converted into Jouliettes and distributed among users. Minting does not require the expenditure of energy to create new tokens, as opposed to mining (generally associated with cryptocurrencies such as Bitcoin). The goal of the pilot is to investigate whether blockchain technology can be harnessed to create greater social value and to support a bottom-up movement in our transition towards 100% renewable energy supply.

ENERGY FLOWS

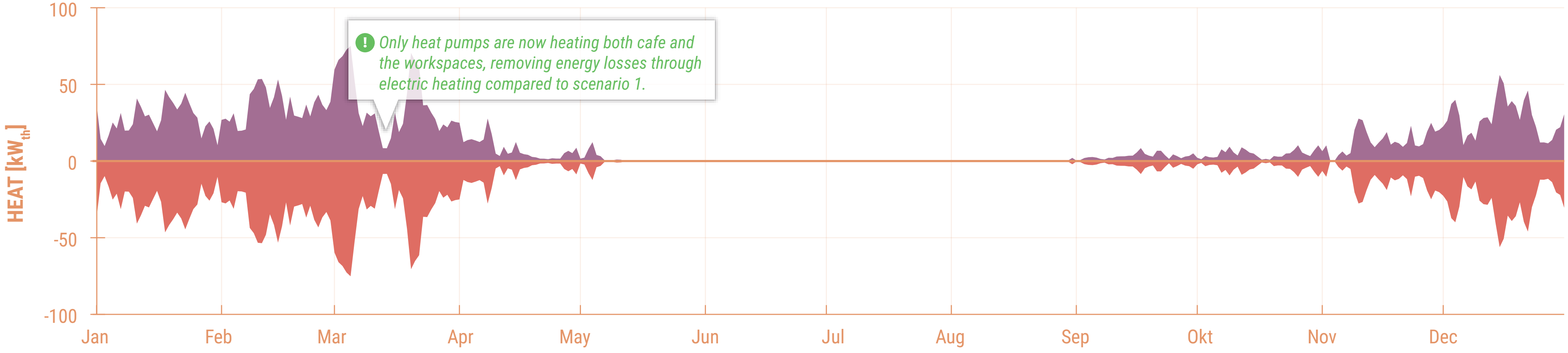


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

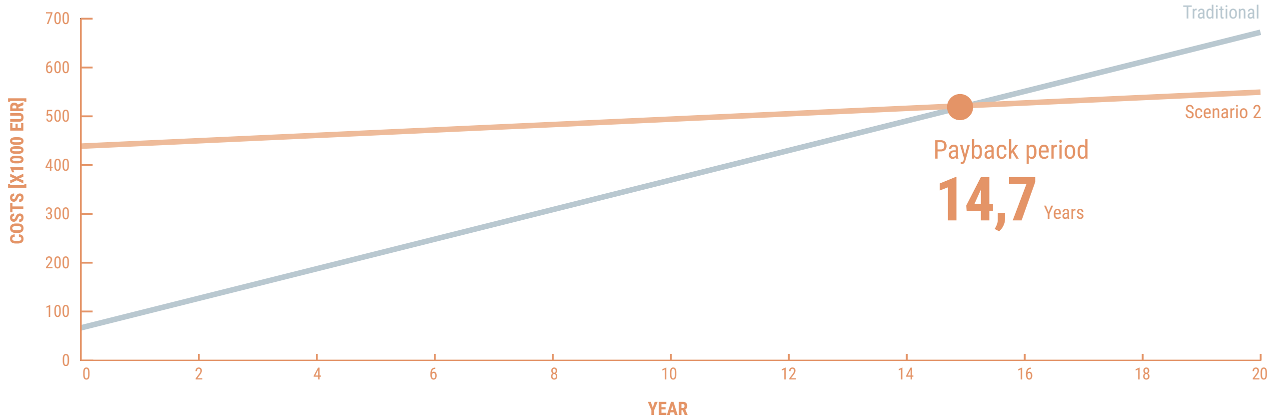


ECONOMIC ANALYSIS

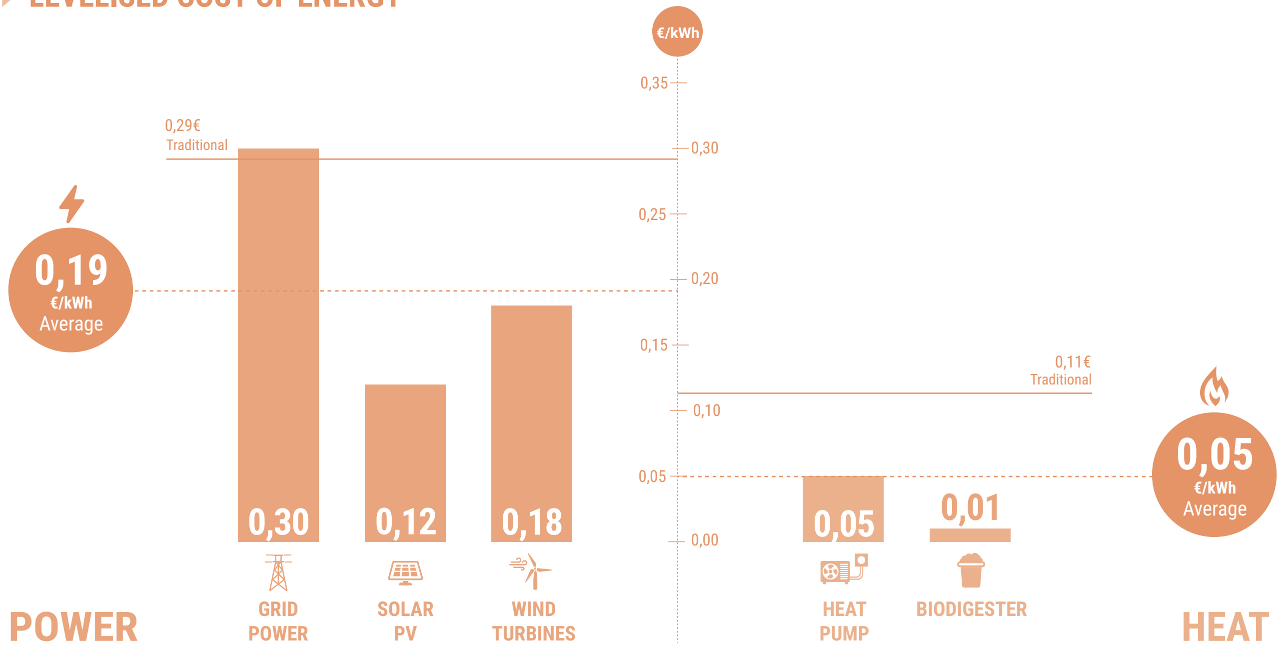
Despite an investment cost that is nearly 5 times higher than a traditional grid/gas-based energy system, the proposed all-electric upgrade manages to repay itself back in 15 years due to low operating costs.

- The installation of a wind turbine, additional solar panels, heat pumps and a battery system require a significant investment of roughly 300.000 EUR.
- The installation of a wind turbine and additional solar panels increase the peak power output of De Ceuvel so that it can no longer be kept under the 50 kW maximum for a kleinverbruiker. As a consequence, each PV system now needs its own brutoproductiemeter, adding significant costs.
- The wind turbine manages to break even over a 20-year period, although this is heavily dependent on actual wind speeds.
- A significant cost reduction in total heating cost from 9 cts/kWh in scenario 1 to 5 cts/kWh in scenario 2 is achieved by powering the heat pumps using locally produced energy.
- The battery has a negative effect on the business case, costing over twice as much as it reduces in savings.
- Charging electric vehicles with on-site produced solar and power instead of grid power, results in an annual savings of 1.188 EUR/yr, or 221,60 EUR/yr per parking spot.
- The total power cost has remained the same as scenario 1, while the heating cost has been reduced by 45% to 5 cts/kWh, resulting in low operational costs.

TOTAL SYSTEM COST

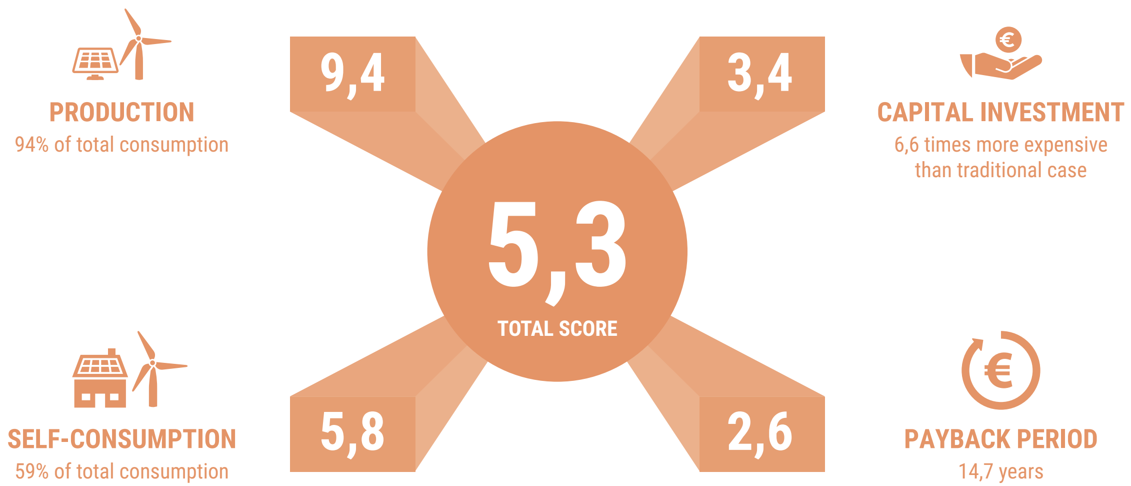


LEVELISED COST OF ENERGY



TOTAL PRODUCTION AND CONSUMPTION

OVERALL GRADE



CONCLUSION

The proposed all-electric upgrade to De Ceuvel performs very well from a technical perspective. It successfully manages to more than double the self-consumption of locally produced power (from 27% to 62,2%), while quadrupling the total power production (from 26,5 MWh/yr to 102,7 MWh/yr). From an economical perspective, the system has an acceptable performance. Despite high investment costs, low operating costs make this scenario the most attractive in the long run (15+ years).

- Wind turbines can alleviate the seasonal imbalance of solar power production somewhat, although their power output is intermittent with large spikes, making it difficult to retain the energy locally.
- The business case for the wind turbine is very context-specific. If the average wind speed were to increase by 1 m/s from 3,9 to 4,9 m/s, the wind turbine's energy output (and thus its revenue) would double.
- Trading energy locally using Jouliettes increases the self-consumption of the microgrid by 12,5 MWh, a better performance than most other cases for local energy trading. The reason behind this, is the large power consumption of the cafe, which can basically be used as an energy sink for overproduction.
- Electric vehicles perform well in this scenario; only drawing 40% of their energy from the grid. The two main reasons being that 1) cars being parked during working hours that coincide with solar PV production, and 2) cars can be charged in winter using wind energy, while simultaneously peak-shaving production spikes.
- The air-to-air heat pumps with heat recovery are energy efficient, but lack flexibility.

SCHOONSCHIP

Aerial view of the jetties for the Schoonschip site.

INTRODUCTION

Schoonschip will be a floating residential development of 46 households in Amsterdam-North. Its ambitious sustainability goals make it a daring attempt to re-imagine how cities function today and create a neighbourhood in harmony with the natural environment. The first floating houses are expected to be realised at the end of 2018, and by 2020, Europe's most sustainable floating neighbourhood is expected to become a reality.

Through an integrated design process, close cooperation with the community, and financial support from public and private partners, Schoonschip has developed into a groundbreaking concept for urban living that pushes many of the current boundaries of community governance, technology, architecture, and construction. Like De Ceuvel, Schoonschip is part of the Buiksloterham circulair manifesto, which aims to guide the development of the Buiksloterham region into a sustainable district based on circular design principles.

Social Structure

Schoonschip began as a foundation and was joined thereafter by a cooperative (CPO) of all the households, run by individual inhabitants of the neighbourhood. Similar to the Aardehuizen's sociocratic structure, working groups have been formed to research and implement themes such as mobility, communication, and building material selection.

Features

The site will harvest ambient water and energy, cycle nutrients locally, and create an environment that is supportive of biodiversity and human health and wellbeing. To reach these goals, the design process for Schoonschip is guided by a comprehensive sustainability masterplan with goals in nine key areas and means to achieve them through a combination of smart design and innovations in the field of technology, finance and governance.[8]

- An innovative smart-grid featuring solar panels, batteries and a customised energy management system developed by Grid-Friends.
- Gray water and black water will be flushed using vacuum toilets. Waternet will deliver the grey and black water to a bio-refinery, producing biogas.
- All homes will have a green roof covering at least one third of the roof's surface.
- Communal purchase of food, in order to minimize refuse and transportation, and to support local organic farmers.
- An efficient system for sharing 30 parking spaces and cars to the benefit of 46 households.
- A community center for meetings, yoga classes, film screenings, and other activities.

[8] Metabolic: Schoonschip sustainability masterplan

TECHNICAL SYSTEM OVERVIEW

SOLAR THERMAL PANELS

- Peak power: 64 kW_p
- Production: 64,5 kW_p
- Area: 96 m^2

GRID CONNECTIONS

- Size: 3x25A
- Take-in: 182,7 MWh/yr
- Category: Kleinverbruik

SOLAR PV PANELS

- Peak power: 150 kW_p
- Production: 127,3 MWh/yr
- Area: 827 m^2

ENERGY TRADING

- Blockchain- based
- Behind-the-meter
- Jouliette

BATTERIES

- Capacity: 294 $kWh_{p,e}$
- Throughput: 24,7 MWh/yr
- Efficiency: 90%
- Type: Li-ion

HEAT PUMPS

- Peak power: 46 $kW_{p,e}$
- Production: 366,4 MWh/yr
- Seasonal Performance Factor: 3,5
- Type: water-to-water

ELECTRIC BOILERS

- Peak power: 235 kW_p
- Production: 11,2 MWh/yr
- Included with heat pumps

Solar PV x 516	**Solar thermal** x 60	**Batteries** x 30	**Heat pumps** x 30	**Electric boilers** X 30	**Grid connections** x 46 (3x25A)	**Power consumption** Total: 252,6 MWh/yr Per boat: 5.941 kWh/yr	**Heat consumption** Total 402,6 MWh/yr Per boat: 8.752 kWh/yr

Source: Space and Matter

SCENARIO 1: SOLAR PV, HEAT PUMPS, AND BATTERIES

Schoonschip has the ambition to be one of the most sustainable and innovative neighbourhoods within Europe. Its buildings are designed for high energy efficiency, with a target Energie Prestatie Coefficient, or EPC, of 0. This means that the building-related net energy consumption is equal to zero. To meet this standard, a wide range of solutions will be implemented:

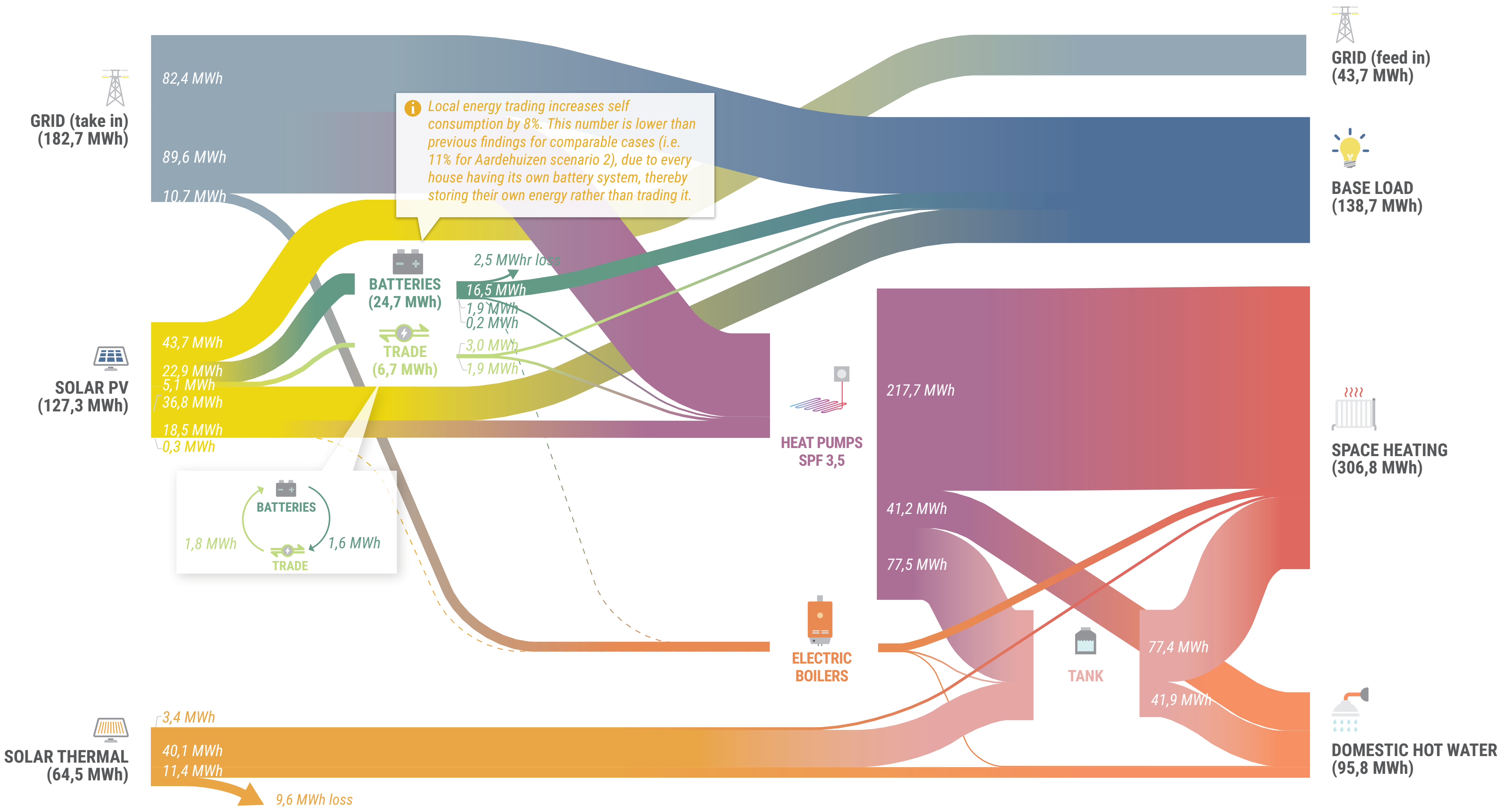
- The houses will be extremely well-insulated, initially designed to meet the PassivHaus standard of less than 15 kWh/m^2 of heat consumption per year (although later adjusted for EPC 0).
- The houses will not be connected to the natural gas grid.
- All houses are connected to a communal smart grid. This smart grid makes it possible to trade energy amongst the households. The blockchain-based energy trading token, Jouliette, will be used for this (just like at De Ceuvel).
- The 46 households will share only one connection to the main energy grid, through the experimenteerregeling.[9]
- Electricity is produced using solar panels.
- Every household has a battery in which excess energy can be stored.
- Both space heating and domestic hot water will be generated by water-to-water heat pumps that efficiently extract heat from the canal water.
- Additional heat will be generated by solar thermal panels installed on the roofs of the houses.
- All showers are equipped with installations that recover some of the otherwise lost heat.

Grid Friends

The energy system design of Schoonschip is not only focused on being energy-neutral, but also on paving the road towards the next generation of neighbourhood energy systems, or smart-grids. To meet this goal, a consortium called Grid-friends was formed. Grid-Friends is led by Centrum Wiskunde & Informatica (CWI) and includes the Fraunhofer Institute for Industrial Mathematics, Spectral, Evohaus, and the Schoonschip Foundation. The project is funded through the joint programming initiative ERA-Net Smart Grids Plus, with support from the European Union's Horizon 2020 research and innovation programme. Its goal is to develop and evaluate the coordination mechanisms and the technological platform for the energy cooperative, so that it can achieve a high-degree of self-sufficiency through shared exploitation of battery storage and other flexible resources. Research findings from the Grid-friend project will be used to further push cost efficiency when more cooperatives replicate and adopt its model in future scenarios.

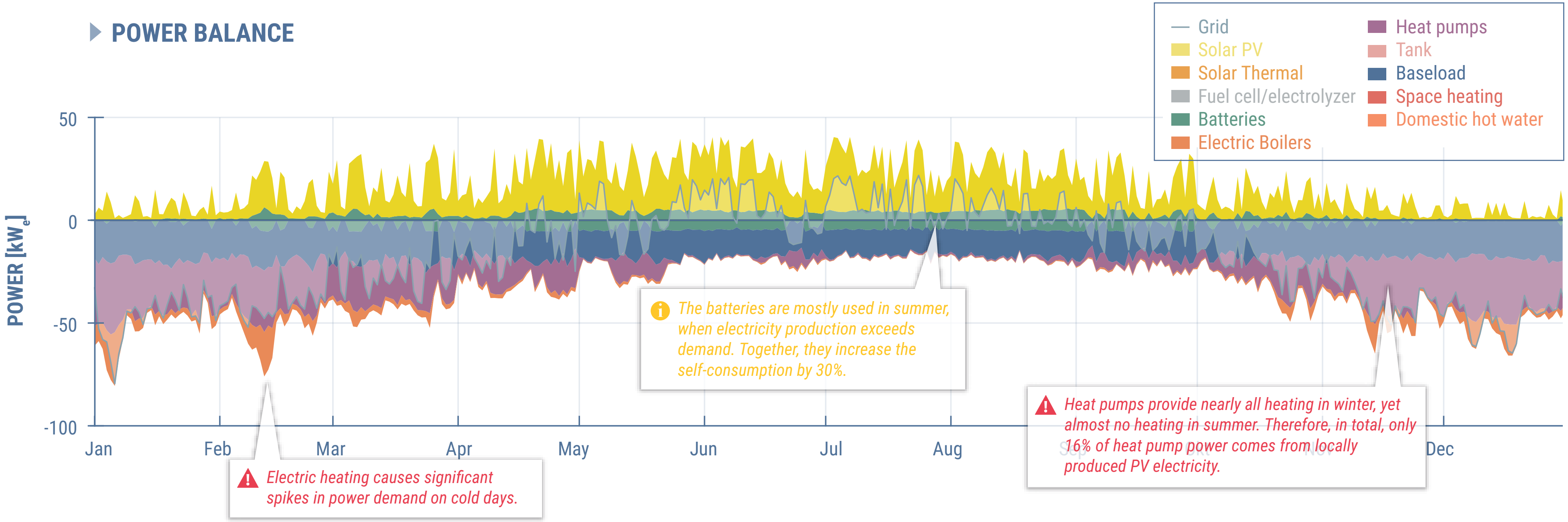
[9] https://www.rvo.nl/sites/default/files/2016/11/Samenvatting%20Schoonschip.pdf

ENERGY FLOWS

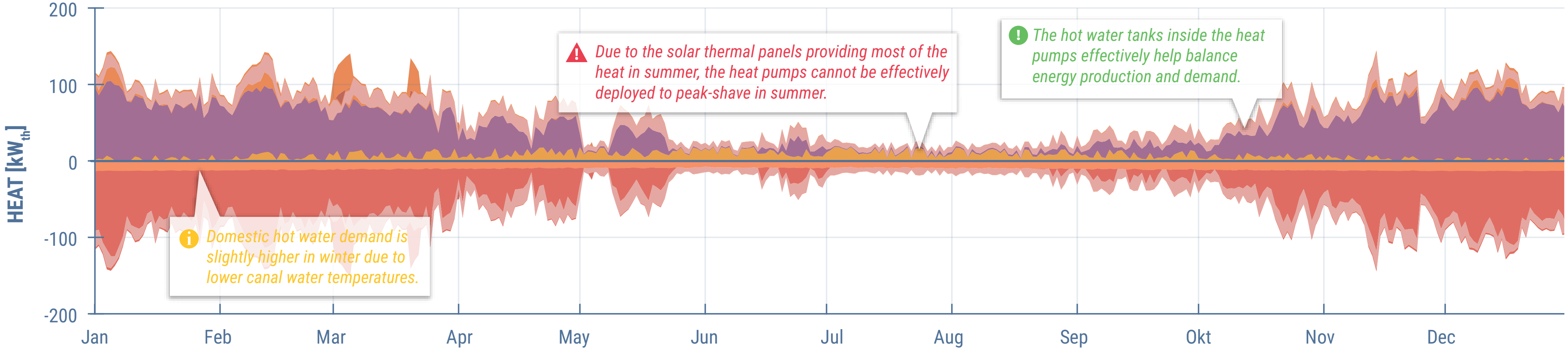


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

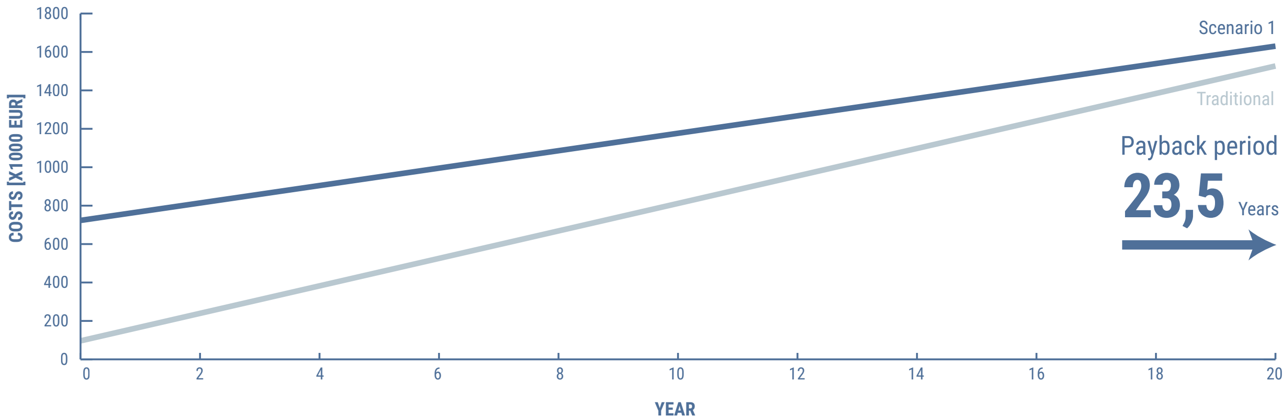


ECONOMIC ANALYSIS

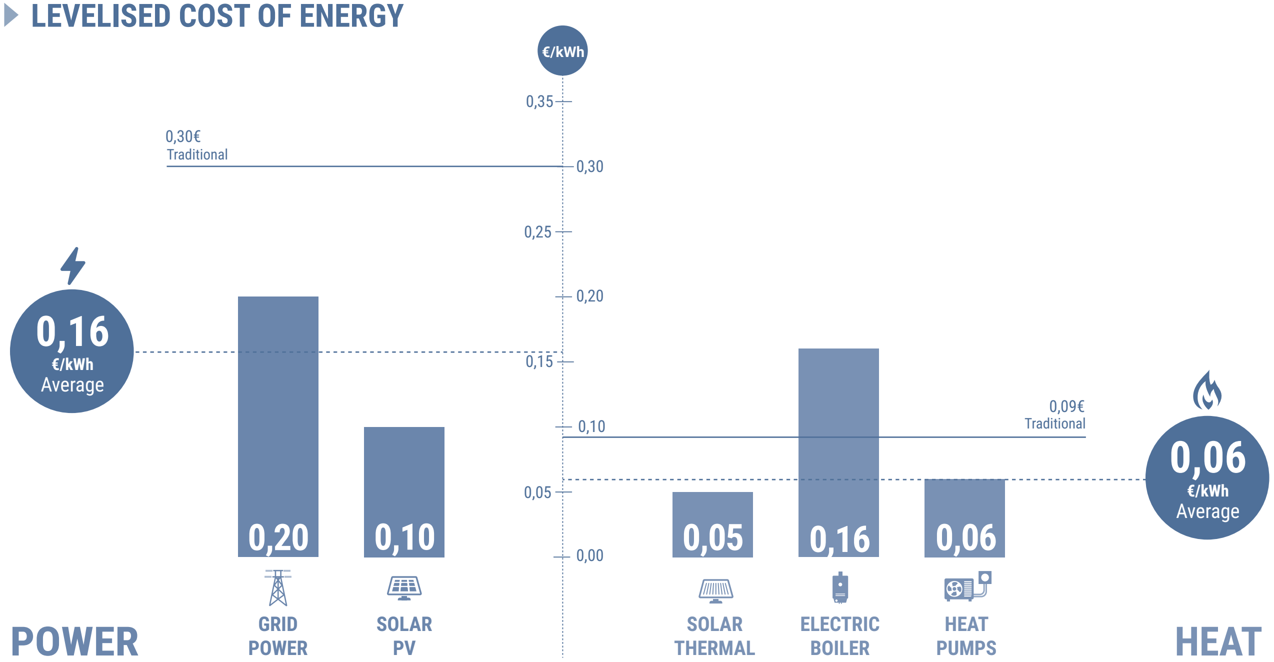
SS's main ambition is to be the most sustainable floating neighbourhood in Europe yet, such lofty ambitions also come with lofty costs. Compared to a traditional grid/gas-based energy system, the state-of-the-art smart-grid of Schoonschip requires a 7x higher capital investment. Unfortunately, the energy savings on the all-electric energy system are insufficiently capable of earning back its investment in a timely manner.

- The battery systems required to manage the electricity flows within the neighbourhood are very expensive compared to their economical benefits.
- The installation and upkeep of 46 brutoproductiemeters completely negate the SDE+ subsidy. Their 20-year total costs amounts to 187.000 EUR, whereas the SDE+ subsidy over that time period only amounts to 107.000 EUR.
- Despite this, the grootverbruikers connection does allow for a lower take-in energy price, making the overall business case for a grootverbruikers connection slightly better than for a kleinverbruikers connection.

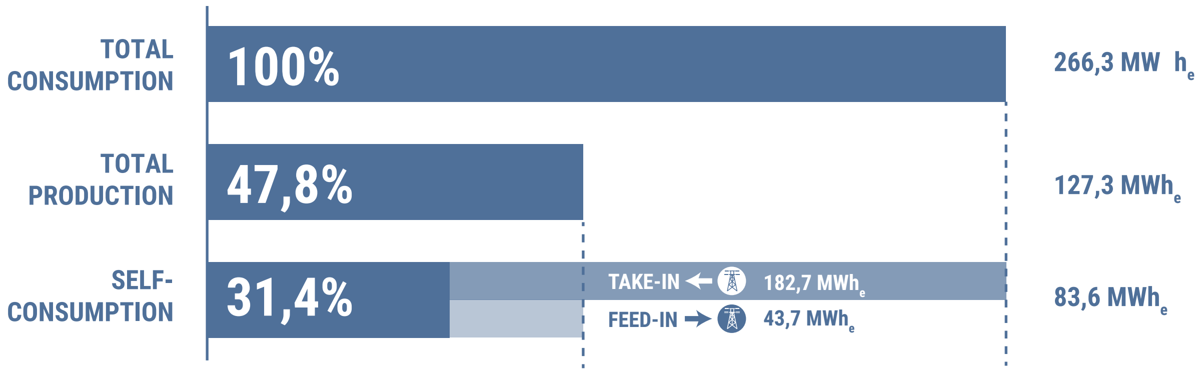
TOTAL SYSTEM COST



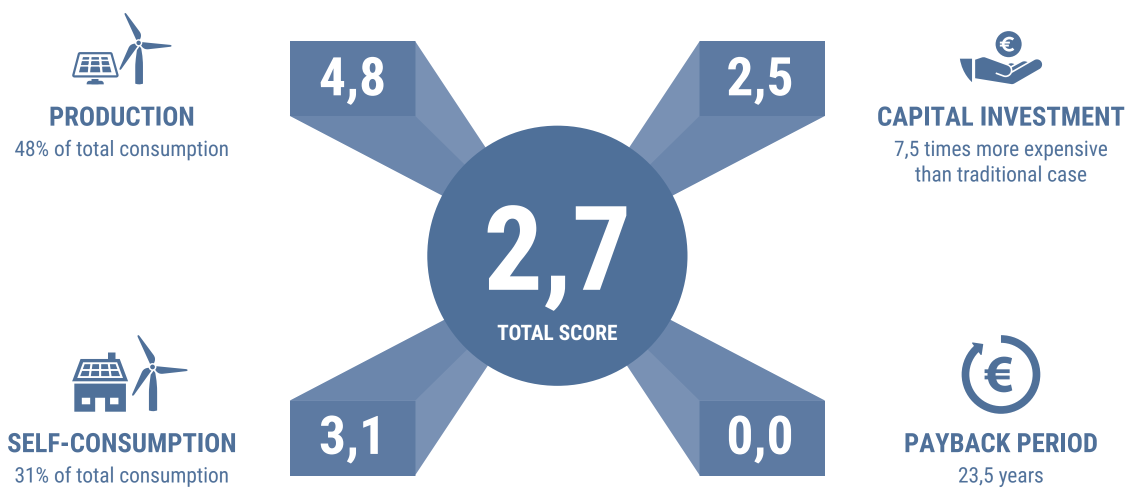
LEVELISED COST OF ENERGY



TOTAL PRODUCTION AND CONSUMPTION



OVERALL GRADE



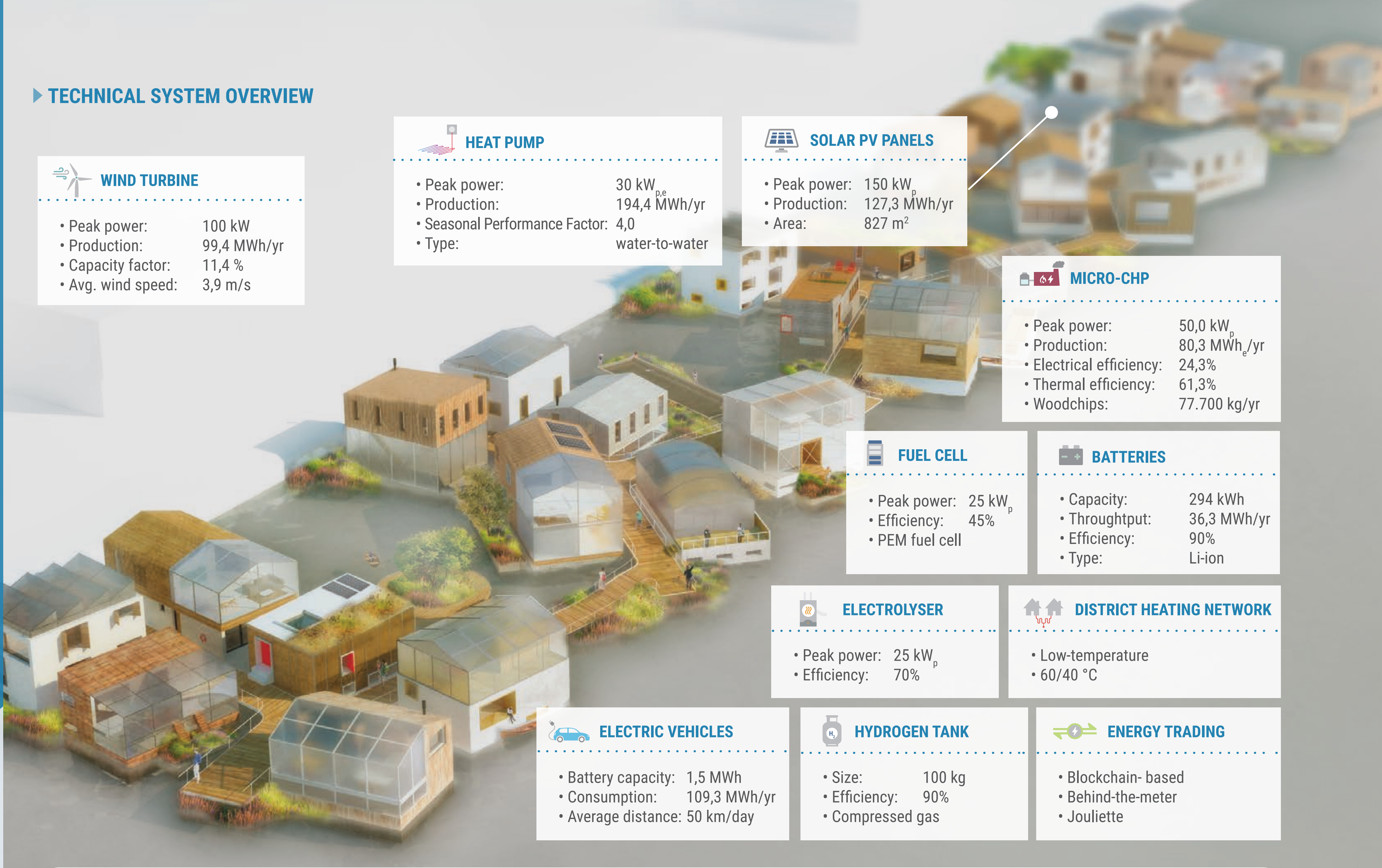
CONCLUSION

Once finalised, SS will have one of the most innovative smart-grids out there. By pushing the envelope in terms of energy efficiency, storage and production, it manages to retain most (65,7%) of its sustainably produced energy within the microgrid, which is significantly more than the other base scenarios (45% for Aardehuizen and 27% for De Ceuvel), due to the installation of battery systems and the blockchain-based local energy trading.

Nevertheless, Schoonschip falls short of its ambition to truly become energy neutral, as it still consumes twice as much power as it produces. Moreover, the current energy system design is too expensive to be realistically replicated for other urban area developments, although this may change in the future once regulation is changed and battery prices drop.

- Despite its net-zero-energy ambitions, Schoonschip only manages to produce 50% as much power as it consumes.
- Although the weighted average LCOE for both heat and power is cheaper than the traditional case, the peripheral equipment (i.e. battery system) makes the current energy system more expensive over a 20-year time period than a traditional grid/gas-based system.
- The households have chosen to each have their own heat pump and battery system. Both systems are rather expensive. A centralised solution could have been a better choice from an economical perspective.
- Given its focus on energy reticence, the installation of solar heating panels at Schoonschip seems a bit redundant. Since heat pumps and solar panels have already been incorporated in the design, it would have been a good opportunity to use the heat pump + solar PV combination to peak-shave electricity during summer and increase the self-consumption.

TECHNICAL SYSTEM OVERVIEW



WIND TURBINE

- Peak power: 100 kW
- Production: 99,4 MWh/yr
- Capacity factor: 11,4 %
- Avg. wind speed: 3,9 m/s

HEAT PUMP

- Peak power: 30 $kW_{p,e}$
- Production: 194,4 MWh/yr
- Seasonal Performance Factor: 4,0
- Type: water-to-water

SOLAR PV PANELS

- Peak power: 150 kW_p
- Production: 127,3 MWh/yr
- Area: 827 m^2

MICRO-CHP

- Peak power: 50,0 kW_p
- Production: 80,3 MWh_e/yr
- Electrical efficiency: 24,3%
- Thermal efficiency: 61,3%
- Woodchips: 77.700 kg/yr

FUEL CELL

- Peak power: 25 kW_p
- Efficiency: 45%
- PEM fuel cell

BATTERIES

- Capacity: 294 kWh
- Throughput: 36,3 MWh/yr
- Efficiency: 90%
- Type: Li-ion

ELECTROLYSER

- Peak power: 25 kW_p
- Efficiency: 70%

DISTRICT HEATING NETWORK

- Low-temperature
- 60/40 °C

ELECTRIC VEHICLES

- Battery capacity: 1,5 MWh
- Consumption: 109,3 MWh/yr
- Average distance: 50 km/day

HYDROGEN TANK

- Size: 100 kg
- Efficiency: 90%
- Compressed gas

ENERGY TRADING

- Blockchain- based
- Behind-the-meter
- Jouliette

Solar PV x 516
Wind turbine x 1
Batteries x 30
Heat pump x 1
Micro CHP x 1
Electric vehicles x 30

Power consumption
Total: 307 MWh/yr
Per boat: 6.674 kWh/yr

Heat consumption
Total 402,6 MWh/yr
Per boat: 8.752 kWh/yr

Source: Space and Matter

SCENARIO 2: FULLY OFF-GRID FANTASY

In line with Schoonschip's forward-thinking design philosophy, the second scenario builds upon the first and focuses on becoming completely self-sufficient using state-of-the-art technology. By combining nearly every possible sustainable technology, this scenario aims to see whether complete energy autonomy can be achieved, and at what cost. Economical limitations have therefore taken a back seat in this scenario, in order to let the technologies perform without too many restrictions. Nevertheless, great care was taken in order to ensure a realistic outcome.

- A 100 kW wind turbine is added performing under the same conditions as the wind turbine in De Ceuvel scenario 2, in order to increase power production and counter the seasonal power imbalance.
- A 50 kW_e centralised CHP unit that can flexibly assist both heat and power production, especially in winter.
- A 30 kW_e centralised heat pump that will complement the CHP's power production.
- District heating to distribute the centrally produced heat.
- 30 electric vehicle parking spots.
- A full hydrogen system, including production, storage and conversion.

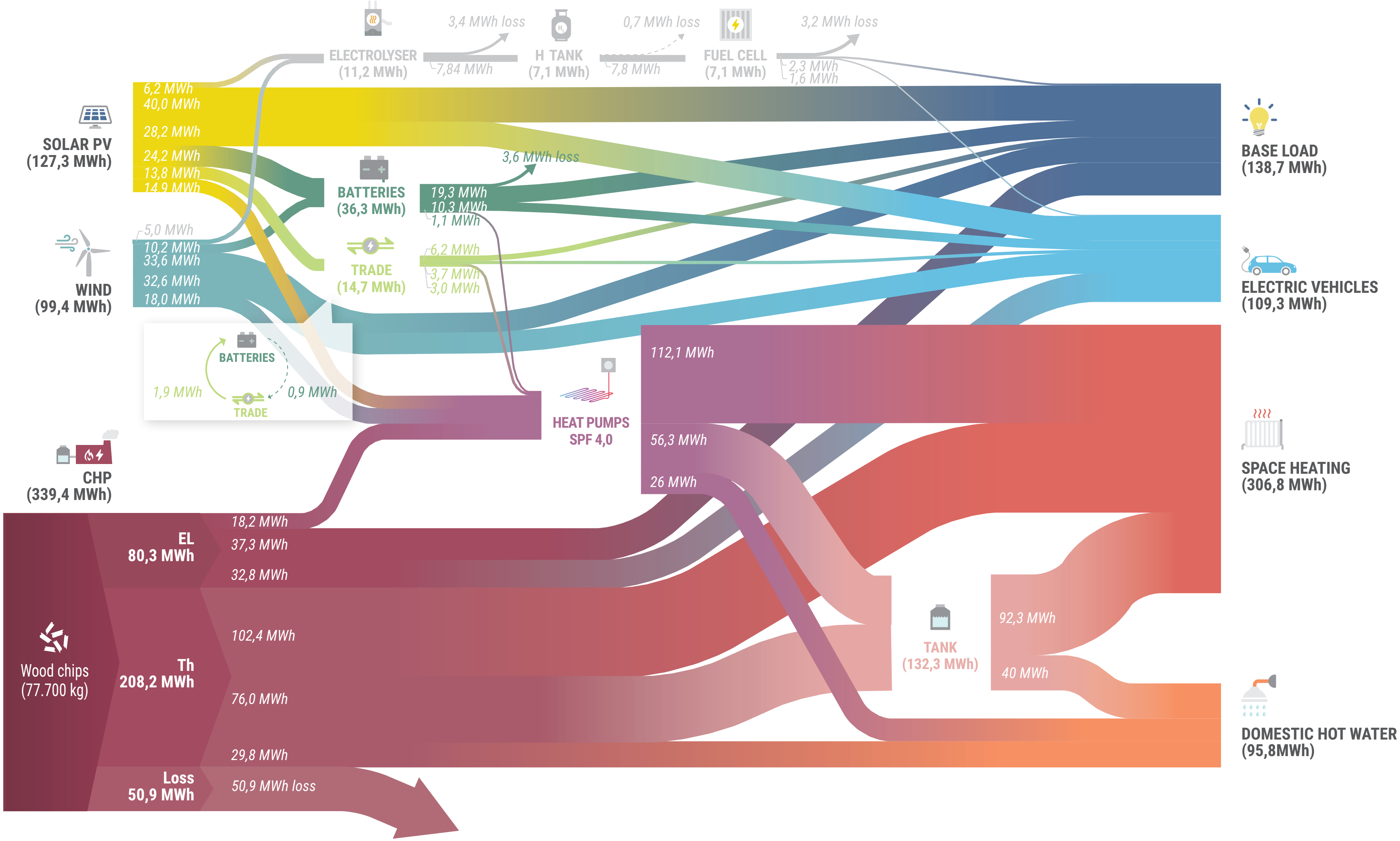
The hydrogen system

- Hydrogen is one of the most versatile sources of energy, capable of being used in a wide range of applications. Although the realistic large-scale implementation of hydrogen systems is still a long away into the future, the technical characteristics of a fullstack hydrogen system can provide the "missing link" in realising a fully autonomous, off-grid, renewable energy system.
- **Production:** The production of hydrogen is a convenient way to peakshave electricity generation spikes.
- **Storage:** Hydrogen can be used to store energy for long periods, potentially bridging seasonal energy imbalances. This perfectly complements the short-term storage batteries can provide.
- **Generation:** Fuel cells use hydrogen as a feedstock to produce electricity with no emissions or unwanted byproducts, and they can do so with a high degree of flexibility.

Expensive

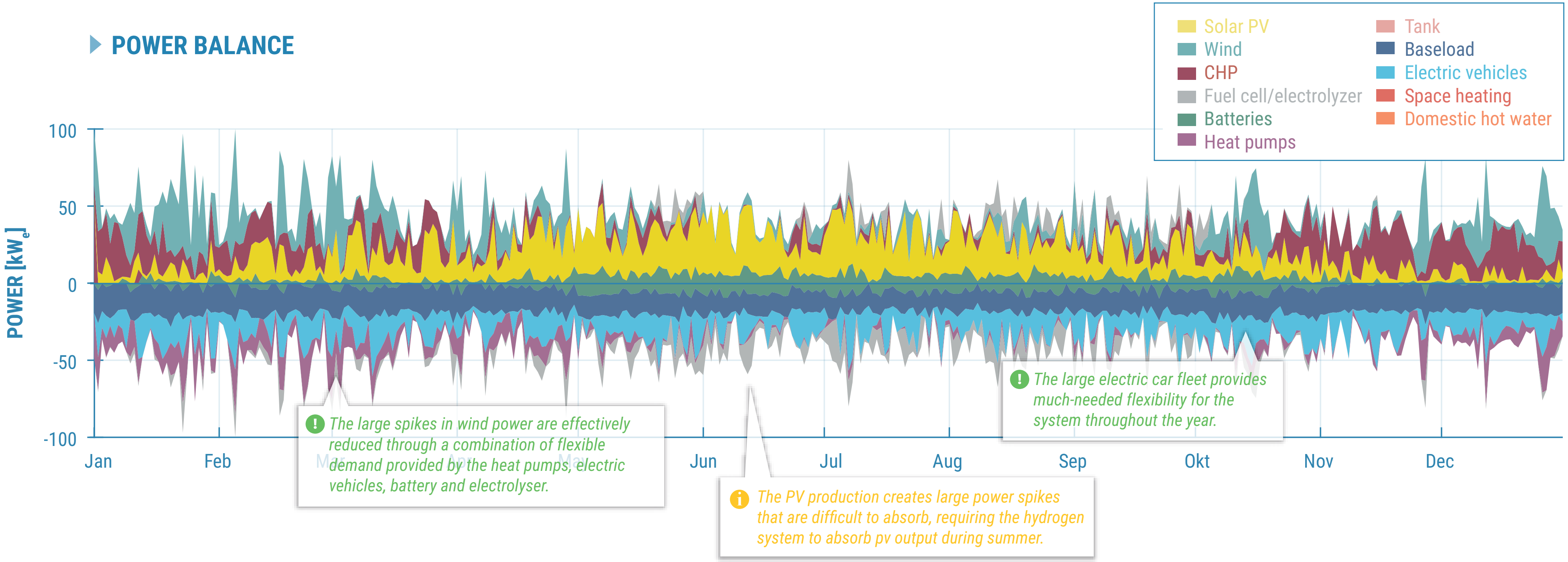
- Although hydrogen's versatility and complementary characteristics to the neighbourhood energy system make it an interesting choice from a technical perspective (flexibility, long-term storage, peak-shaving), installing a fullstack hydrogen system remains tricky from an economical perspective. Consensus on the exact numbers for the cost of the electrolyser, storage tanks and fuel cells is hard to find, as they differ per technology used and are dropping quickly in costs. The cost for the hydrogen system in this scenario should therefore be considered with a large degree of uncertainty.

ENERGY FLOWS

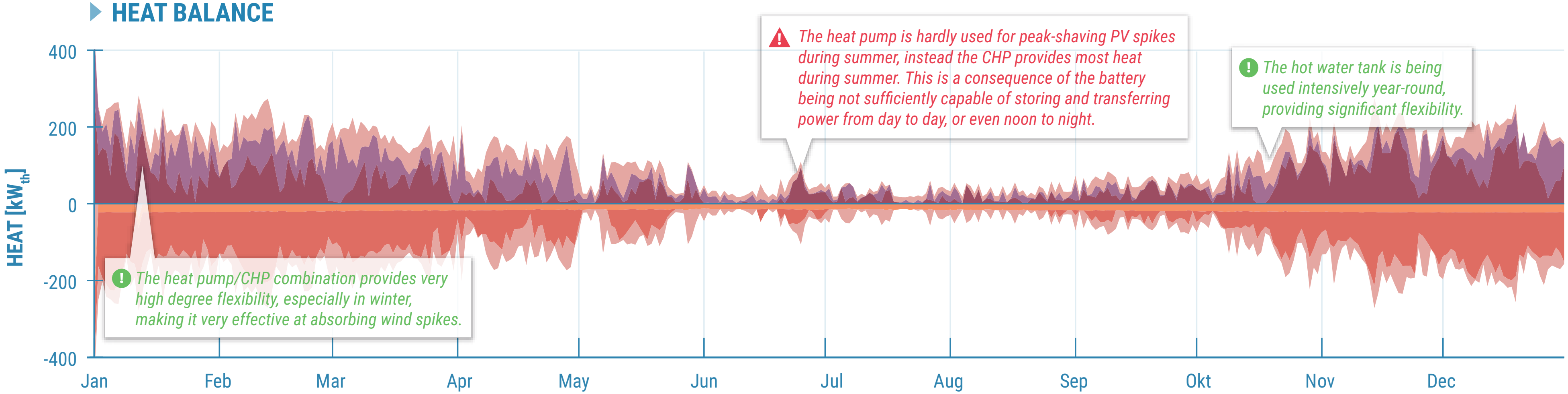


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

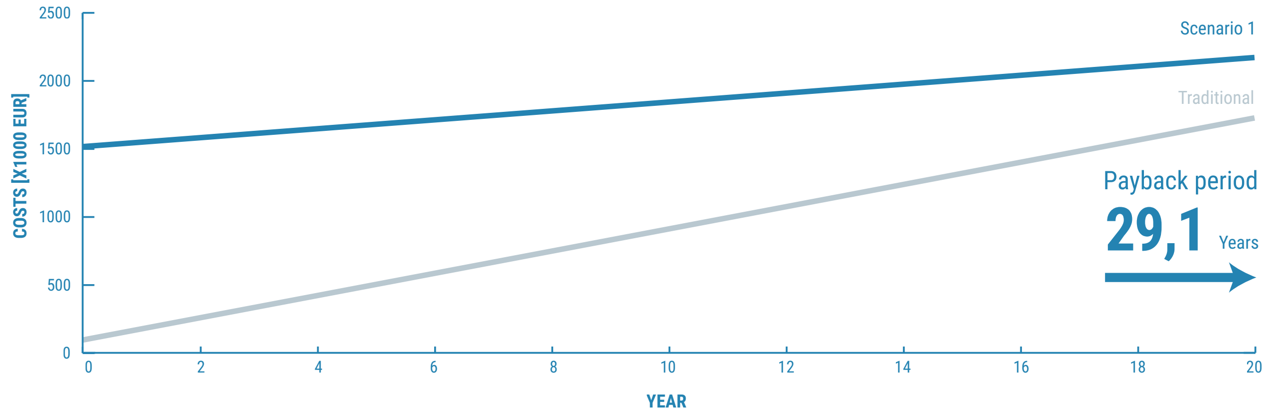


ECONOMIC ANALYSIS

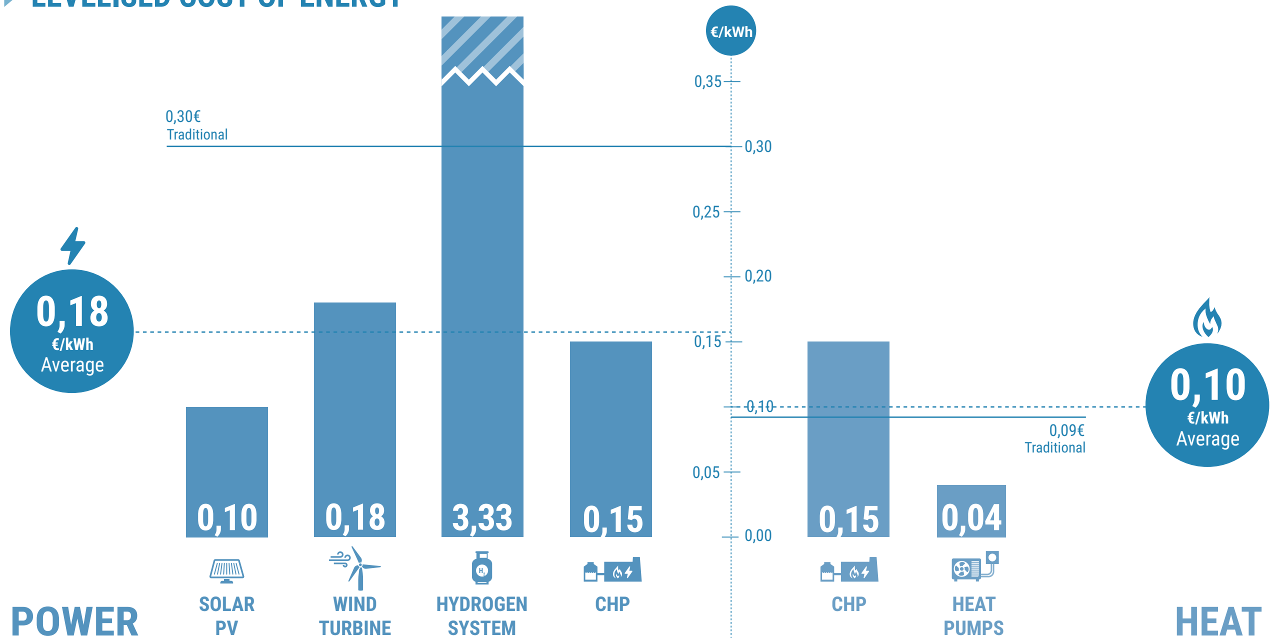
Unsurprisingly, the luxury of being able to go fully off-grid comes at a price. The proposed energy system in this scenario is extremely expensive to construct, as most of its costs have to be paid upfront. With a total capital expenditure of over 1.500.000 EUR, this system is more than 15x as expensive to realise than a traditional grid/gas-based energy system. On the flip side, the resulting energy system has low operational costs since all of its energy is produced on-site, resulting in a payback period of roughly 30 years. Although these numbers are not likely to impress any investors, it is not unthinkable that, given enough time, the expected rapid price drop of the system's components (e.g. batteries, fuel cells, solar panels) will allow for a positive business case in those cases where an off-grid energy system is a major boundary condition (for instance islands).

- A major advantage of this scenario is the complete lack of need for grid connection, saving 35.000 EUR/yr.
- The hydrogen system is essential for achieving that last 5% of self-sufficiency. Even though it is 18x more expensive per kWh of energy produced than the average production cost of power, the savings in terms of no longer needing a grid connection can potentially justify its investment.
- Interestingly, even though the system is extremely expensive, its average cost for power is lower than the traditional case. The reason that the system is still more expensive, is that it requires 222% more power to operate due to the electric vehicles and heat pumps.
- The cost for heating is nearly the same as in a traditional gas-based system: 10 vs. 9 cts/kWh.
- Electric vehicles can charge without any cost, resulting in over 15.000 EUR/yr in savings, or 500 EUR/yr per car.

TOTAL SYSTEM COST



LEVELISED COST OF ENERGY



TOTAL PRODUCTION AND CONSUMPTION

OVERALL GRADE

CONCLUSION

The high capital investments, technical complexity and lack of need for being off-grid, make this scenario a futuristic fantasy. Nevertheless, it is interesting to observe the many synergies between different system components, forming an integrated microgrid capable of functioning fully autonomously. It is a truly holistic system in which the whole outperforms the sum of its parts. While it is unrealistic to expect this system to be built anytime soon, it could potentially function as a blueprint for a fully sustainable off-grid microgrid for demonstrative purposes; e.g. a research-oriented living lab.

- The state-of-the-art system integration of a wide range of components creates a symbiotic synergy that allows for truly sustainable, off-grid living.
- High capital investments are offset by low operating costs, making the system profitable in the very long run (30+ years), at which point cheaper component replacements will have improved the business case.
- If the system were connected to a grid, it would be able to provide numerous flexibility services, such as peak-shaving, islanded-mode operation, congestion management and flexibility scheduling, potentially improving its business case.
- Unfortunately, the CHP is severely underutilised in this scenario, with a load factor of less than 10%, making its maintenance costs disproportionately big. If another heat demand source can be utilised (e.g. a nearby greenhouse or connection to a larger district heating network), its runtime can be increased in order to improve its economic efficiency.
- A possible workaround for needing a hydrogen system, is to simply allow the CHP to waste its heat while providing backup power demand during peaks, or to overdimension the wind and solar PV plants and curtail their production. Although this will reduce the overall efficiency of the system, it would probably be cheaper.

REPUBLICA PAPAVERWEG

Source: Marc Koehler Architects

INTRODUCTION

Republica Papaverweg is an upcoming area development in Amsterdam-Noord. It will consist of six building blocks, each with a different utility function. Three of the blocks will function as residential areas, one block as a hotel, and the remaining two blocks will be used as office spaces, including a cafe.

Following the design philosophy of other upcoming area developments in Amsterdam-Noord, Republica Papaverweg focuses on the densification of residential, commercial and office spaces in order to attain a certain critical mass at which these different functions blend seamlessly together. By allowing space for both large-scale architecture as well as small-scale developments, a unique blend of living, working and recreational spaces is expected to emerge, dubbed "The Creative Grid". In this Creative Grid, conventional top-down developments make way for a new style of bottom-up cooperative developments.

As a part of the Buiksloterham Circulair Masterplan, circularity is a key focus area of the design of Republica Papaverweg . In concrete terms, the following areas have specific design criteria for Republica Papaverweg to ensure a high degree of circularity:

Mobility

- 50% of the parking spaces ought to be destined for electric vehicles
- It should be possible to host an electric car sharing programme.
- Sufficient space for parking bikes is required.

Waste

- Organic waste should be collected and process into a nearby "resource station", where a biodigester transforms it into biogas.
- Material used for construction
- Strict criteria for the percentages of recycled or sustainable materials used

Resilience/versatility

- Make sure the buildings can perform various functions in case of a future shift in building use.

Water management

- Sufficient space for water management is important, it should be able to handle large rainstorms.
- The building should be able to handle droughts and heat stress.

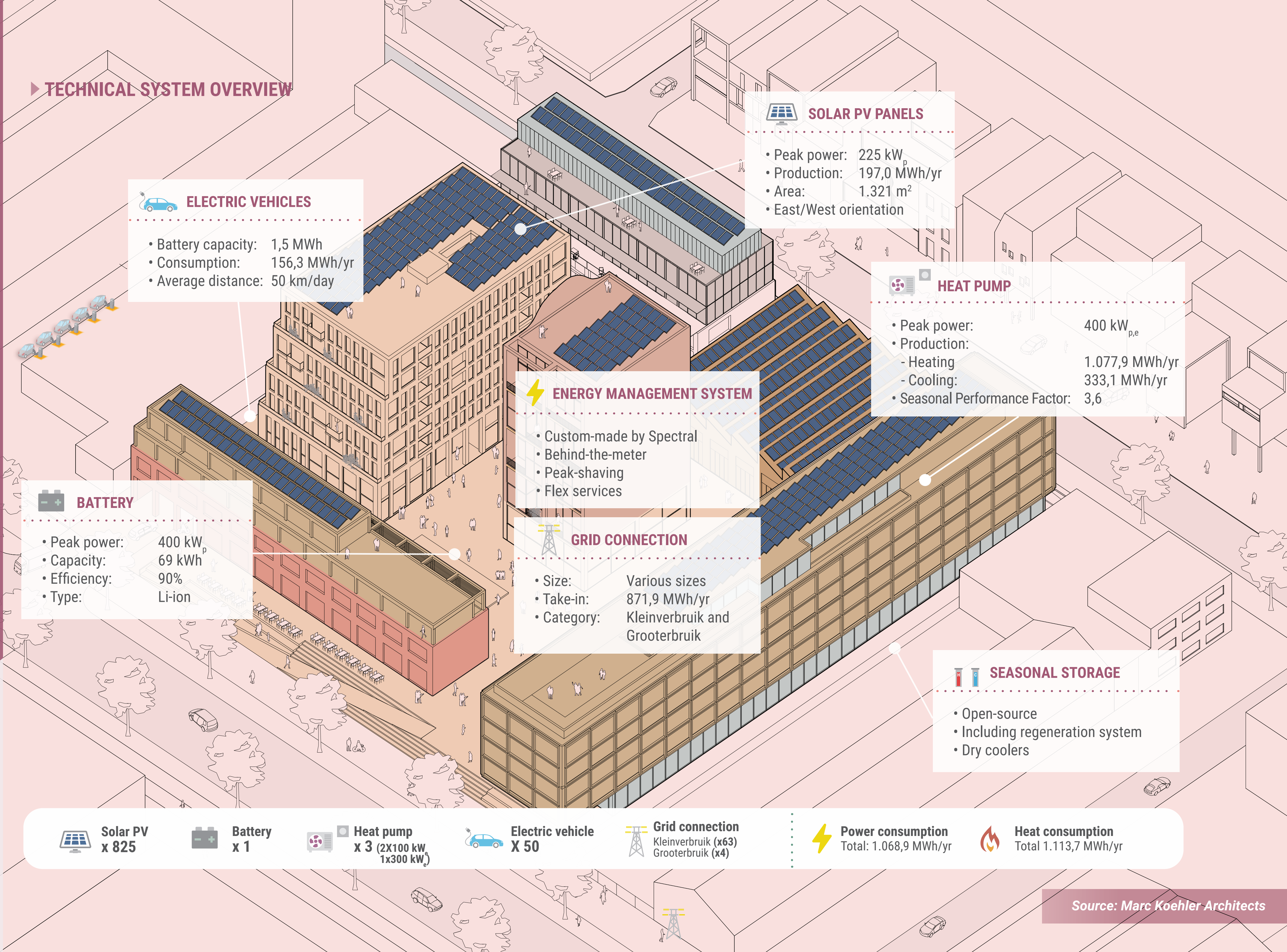
Green spaces

- The presence of green areas improves quality of life.
- Green roofs can reduce water peaks.

Energy

- An EPC of less than 0,15 is required.
- A smart-grid with energy storage will provide interesting insights.

TECHNICAL SYSTEM OVERVIEW



Source: Marc Koehler Architects

SCENARIO 1: SOLAR PV, EV'S, AND SEASONAL STORAGE

Republica Papaverweg has high ambitions for its energy system. Not only does the area development have to comply with Buiksloterham's strict building regulations, it also aims to push the envelope of building energy systems by incorporating a groundbreaking smart-grid into its design. Under the supervision of Spectral, an innovative new energy system will be realised that not only provides a high degree of sustainable energy production, but also integrates numerous innovative technologies. To achieve this goal, Republica Papaverweg has been granted a similar legal exemption to the cases discussed before, (the experimenteerregeling), allowing the microgrid to manage its production and distribution of energy as if it were a single entity. Spectral aims to utilise the experimenteerregeling in conjunction with a battery system in order to perform peak-shaving services and as backup power in case the main grid goes down.

In addition to the power system, the main heating system will comprise of two heat pumps attached to an underground aquifer thermal energy storage (ATES) system. To further improve the efficiency of the thermal energy system, a low temperature district heating network distributes the heat to the various demand locations. Special booster heat pumps will be installed for the residential areas that will top up the temperature to the required temperature required for space heating and domestic hot water. The showers in these apartments will be equipped with special heat exchanging pipes to recover heat.

ESCo model

Instead of owning the energy system collectively, like in previously considered cases, Republica Papaverweg 's energy system will be too complex for a cooperative to manage. The technical expertise required for the management and control of the energy systems will therefore be outsourced to an energy service company, or ESCo. An ESCo takes responsibility for the energy supply, with the goal of improving the quality of the energy system while reducing the risk for the building owner. An ESCo is oftentimes a consortium comprising a financer and a technical party, as is the case for Republica Papaverweg , where the system integrator Spectral joined forces with the traditional ESCo company Innax, to deliver an innovative integrated microgrid solution.

One of the most challenging aspects of Republica Papaverweg 's energy system is legislation. How do you distribute locally produced energy across multiple households that are free by law to choose their own energy supplier? That is, you cannot force the residents to choose the ESCo as their energy supplier. Although the ESCo is in a good position to undercut the market rates for electricity, and thereby becoming the preferred energy supplier for most residents, there are risks associated with it.

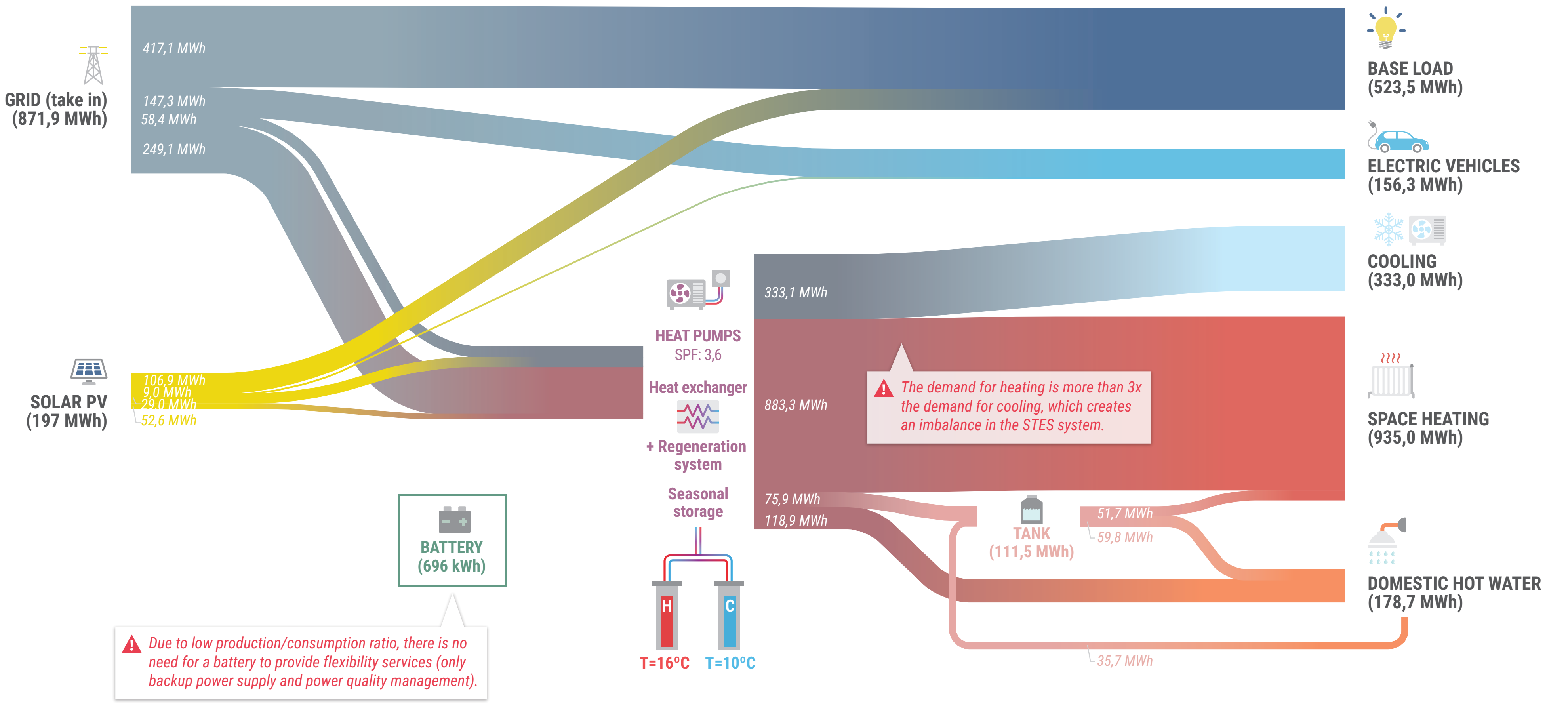
Seasonal Thermal Energy Storage (STES) system

The STES system at Republica Papaverweg will provide both heating during winter and cooling in summer, by storing excess heat or cold from its heating and cooling activities into an underground aquifer, to be used at a later time. The efficiency of an STES system can be very high, a seasonal performance factor (SPF) of over 5 is possible given that the system is properly controlled and that the heating and cooling demand are balanced.

The system used for Republica Papaverweg is an open system, meaning that the heat/cold is directly stored into the groundwater. The use of groundwater is not without complications. In dense urban areas with multiple wells, interference can occur when one building's heat well overlaps with another buildings cold well. This requires adequate urban planning (zoning of hot and cold wells) in order to prevent efficiency loss.

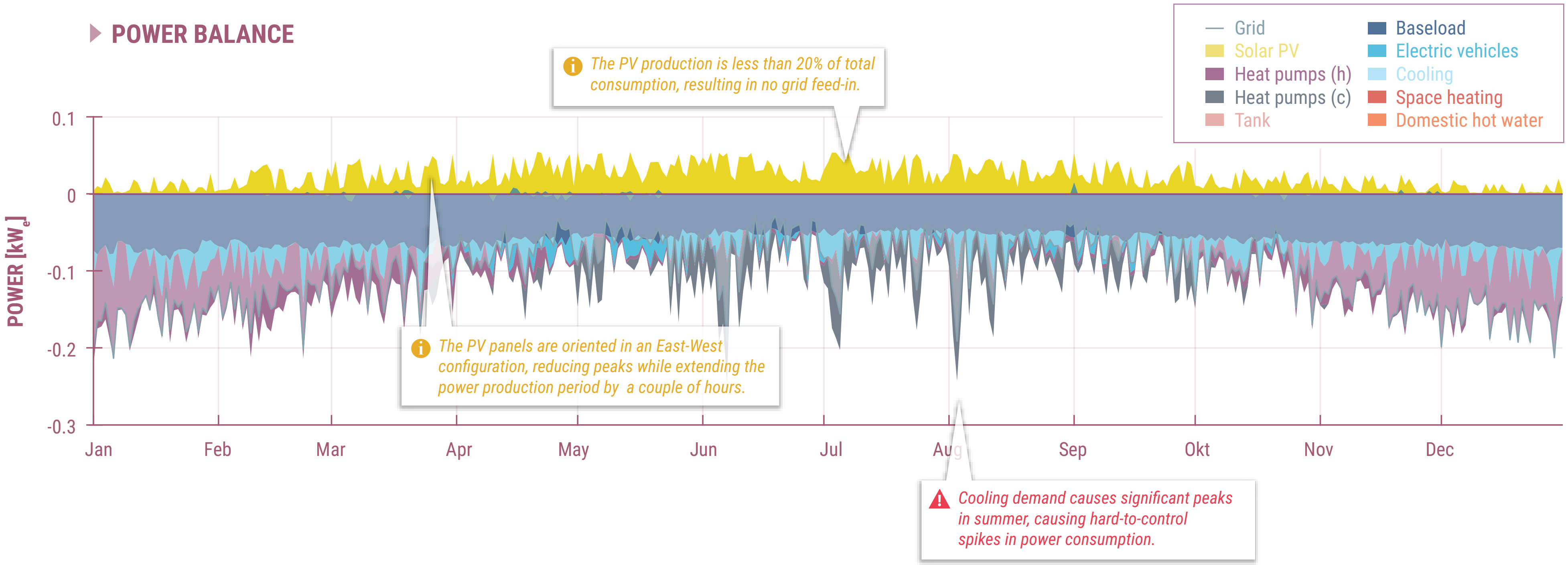
In addition, Dutch regulations require hot and cold wells to reach thermal equilibrium once every three years. Difficulties in estimating and balancing heat and cold demand of buildings have resulted in many STES systems to underperform. The solution used for this scenario, is to include a regeneration system to balance the overproduction of heat/cold using dry coolers, although this will lead to additional efficiency losses.

ENERGY FLOWS

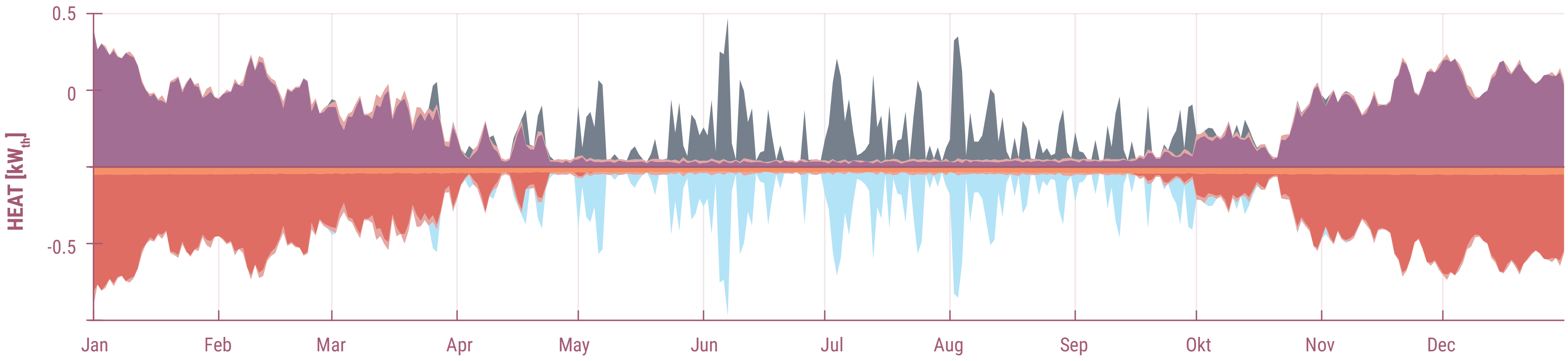


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

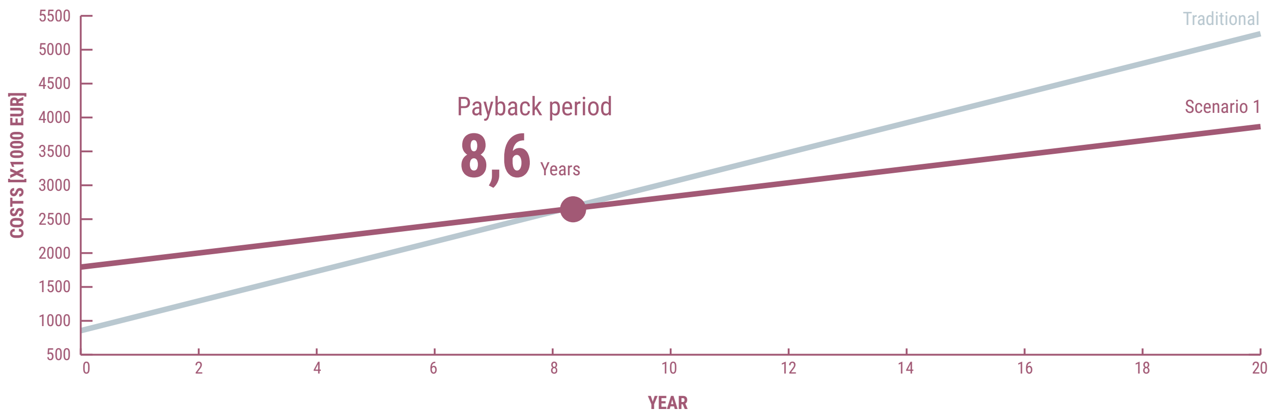


ECONOMIC ANALYSIS

The business case for Republica Papaverweg 's energy system is looking solid. The solar panels provide a significant reduction in annual power costs, while the STES system greatly diminishes the cost of heating. Overall, it is nearly twice as expensive as a traditional grid/gas-based system to build, but the reduced energy costs result in a payback period of within 10 years.

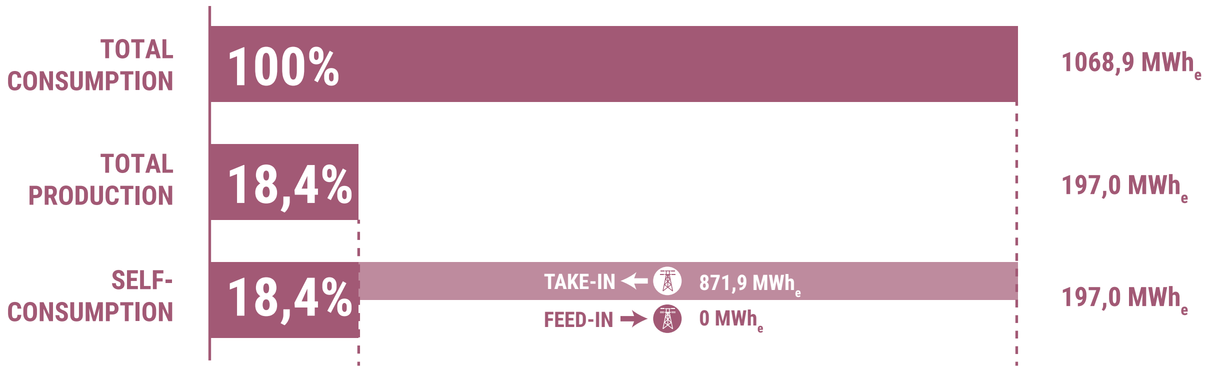
- The STES system, even though it performs suboptimally, results in a very low overall heating cost. At 4 cts/kWh, it is the lowest of all cases considered.
- The PV system not only saves grid power costs and taxes, it also receives an SDE+ for self-consumed power, making it extra profitable compared to a traditional system.
- Spectral analysed the business case for using the battery flexibility to provide flexibility services on the flex market, and came to the conclusion that 80.000 EUR/yr in revenue could be generated by providing this service, resulting in a payback period for the battery of less than 10 years. Market participation is not incorporated in the business case analysis here.

TOTAL SYSTEM COST

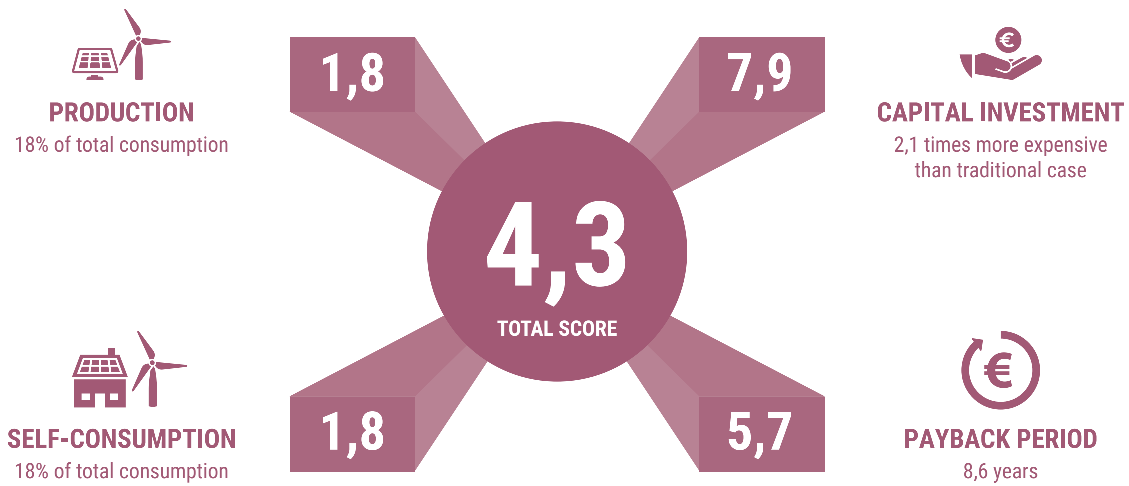


LEVELISED COST OF ENERGY

TOTAL PRODUCTION AND CONSUMPTION



OVERALL GRADE

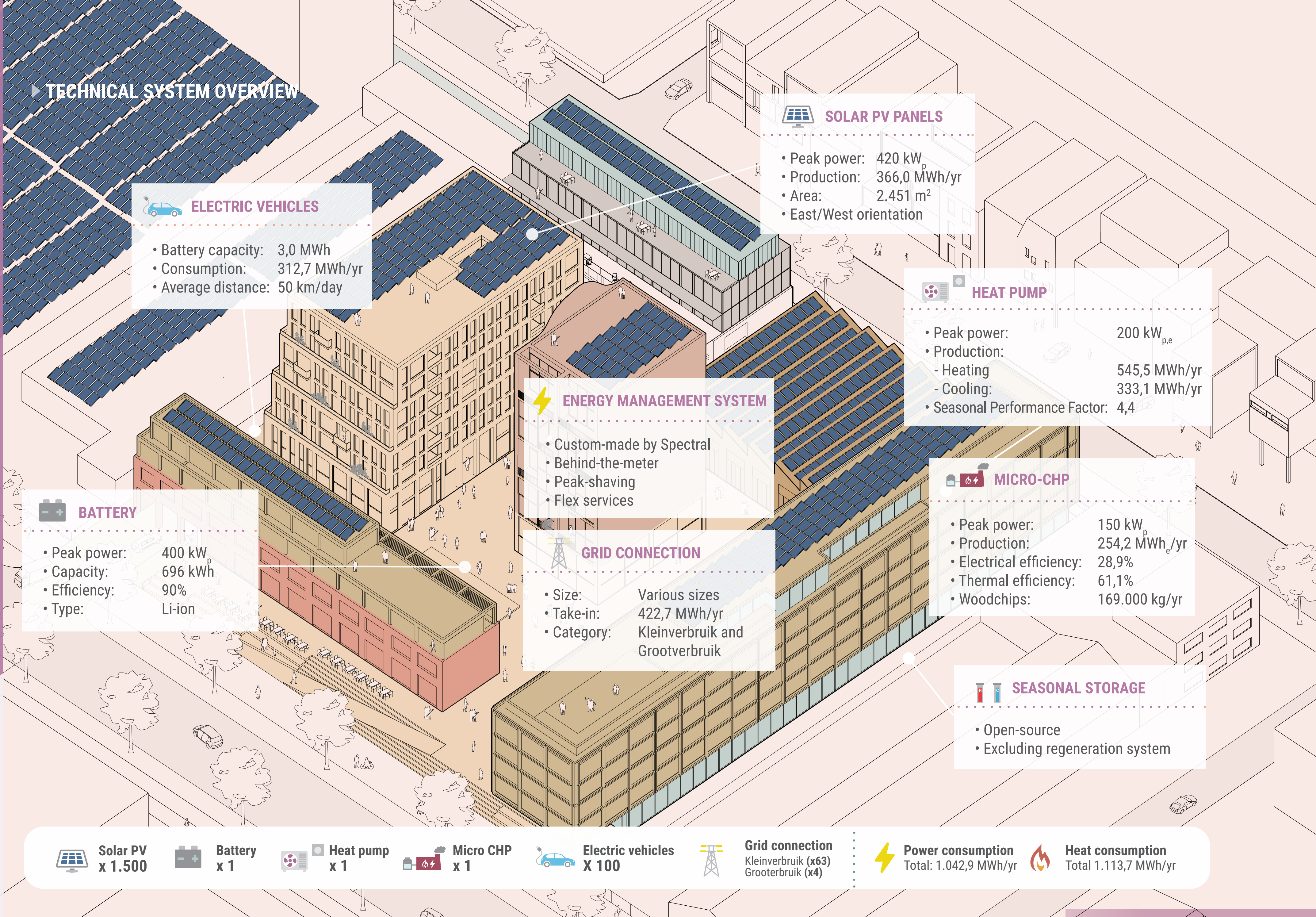


CONCLUSION

Once fully realised, Republica Papaverweg will feature one of the most advanced smart-grid systems in the Netherlands. Even though the energy system will not have more components than some of the other cases analysed in this report, the sheer scale of the proposed energy system requires many challenges to be overcome.

Republica Papaverweg will be a test case for trying out new market and ownership models. Its successful realisation will pave the roads towards a new way of developing integrated microgrids. All in all, the proposal for the energy system seems feasible from both a technical and economical point of view, although its self-sufficiency leaves much to be desired for a project with such high sustainability ambitions.

- The STES system provides efficient heating and cooling, although this efficiency could be higher if the system were balanced.
- The battery is currently underutilised, only performing backup power supply function and potentially some peak-shaving (although peak-shaving was not required for the current analysis).
- The amount of solar panels on the roof of the buildings is not enough to provide sufficient power to the complex. Only 18% of total power consumption is produced by the solar PV installation. Improving the amount of on-site renewable energy generation will require additional an area outside of the building area (which is allowed by the EPC norm).



Source: Marc Koehler Architects

SCENARIO 2: IMPROVED SMART-GRID

In trying to achieve its goal of becoming a highly innovative and sustainable energy system, the first scenario is plagued by low on-site energy production and an imbalanced STES system. The solution to these problems is simple on paper: increase the amount of energy production and improve the balance of the STES system by either reducing heat demand or providing an alternative heat source. In reality, there is simply not sufficient space to place more solar panels, and there are not too many sustainable alternatives to an already existing heat pump system.

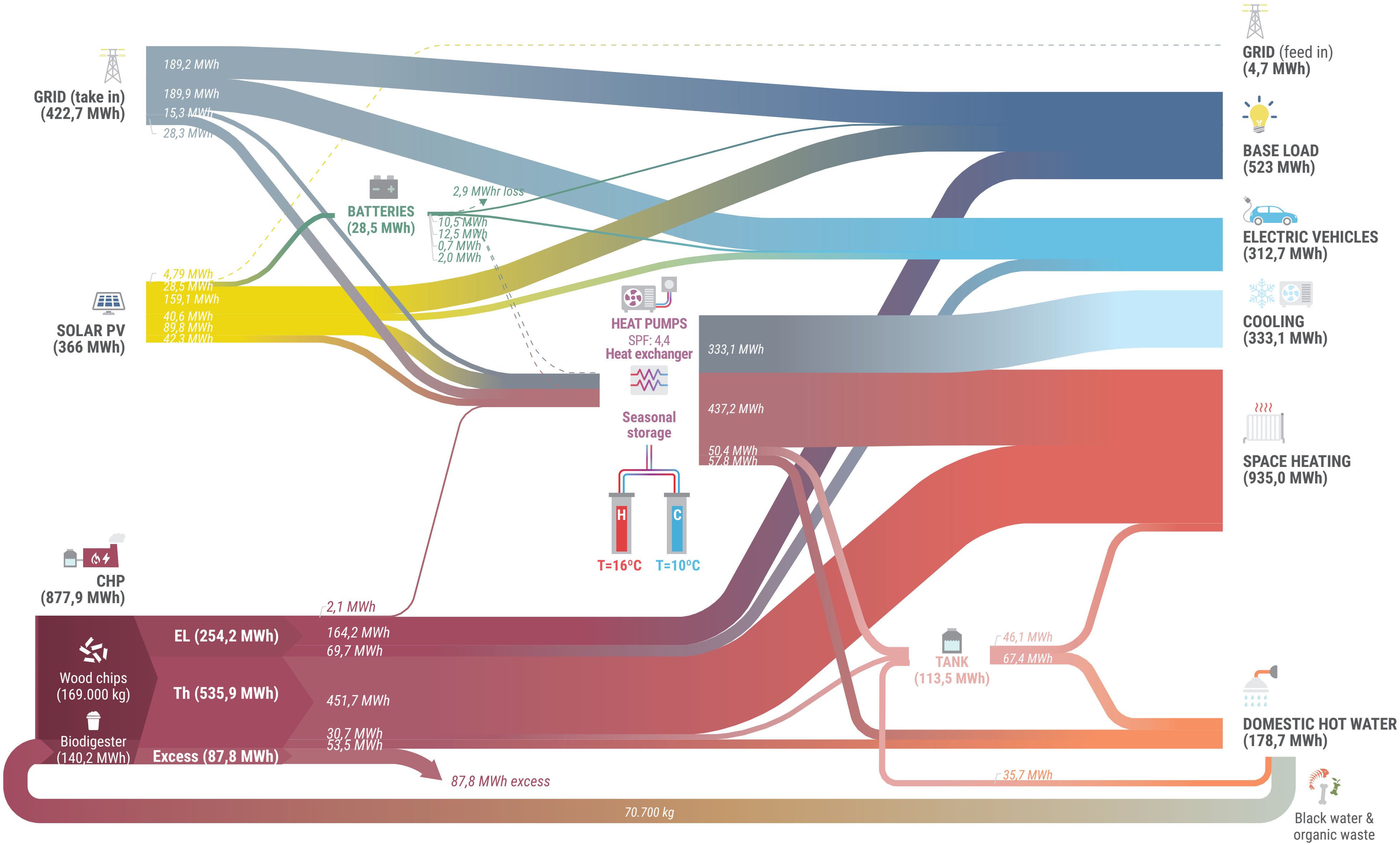
Fortunately, the EPC building norm allows for a certain area of energy production to be outside of the building site boundaries. For an EPC of 0,0, an additional 197 kW_p has to be installed. For this scenario it was assumed that those solar panels can be installed complying with EPC regulations in a nearby area, such as an undeveloped piece of land.

The imbalance in the STES system is caused by a surplus of heat demand, requiring dry coolers to regenerate the wells. This problem can be solved by either providing an alternative supply of heat, reducing the heat load, or increasing the cooling load of the system. Heat demand reduction through insulation is outside of the scope this research, and cooling demand increase is undesirable from an efficiency perspective. This leaves us with providing an alternative heating source. Since the imbalance of the STES system varies from year to year, the alternative heating source has to be able to adjust accordingly. This leaves us with two candidates: CHP and a city district heat connection. It was decided to opt for the CHP in order to also increase the local production of power.

The CHP system will be partially powered by biogas from a local organic waste treatment facility. This facility consists of a biodigester in which all the organic waste and black water (pumped through a vacuum system) from Republica Papaverweg and several other neighbouring complexes is collected. It is part of the local water utility's (Waternet) plan to experiment with decentralised sanitation, so that energy and nutrients can be recovered from waste streams.

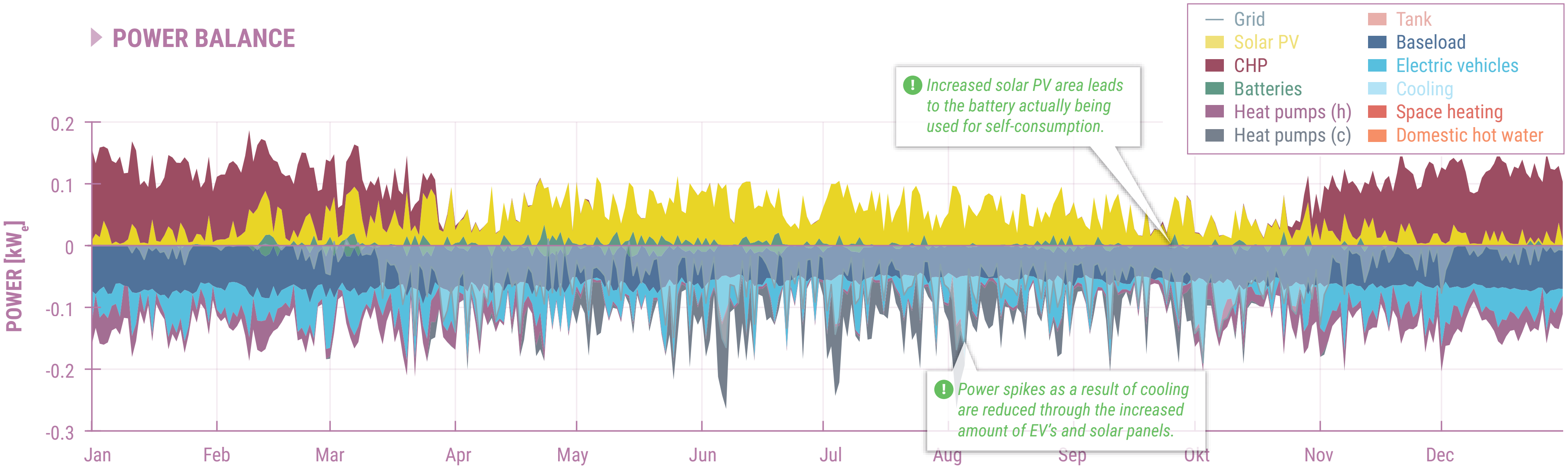
Finally, the electric car parking spots have been increased from 50 to 100 in order to increase the flexible loads within the system.

ENERGY FLOWS

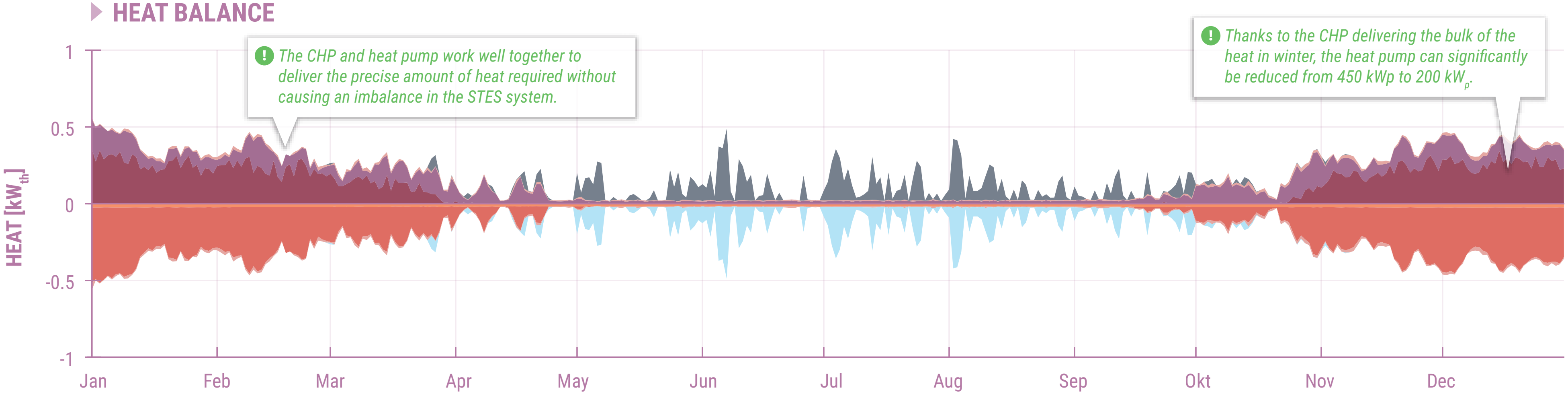


ENERGY BALANCES

POWER BALANCE



HEAT BALANCE

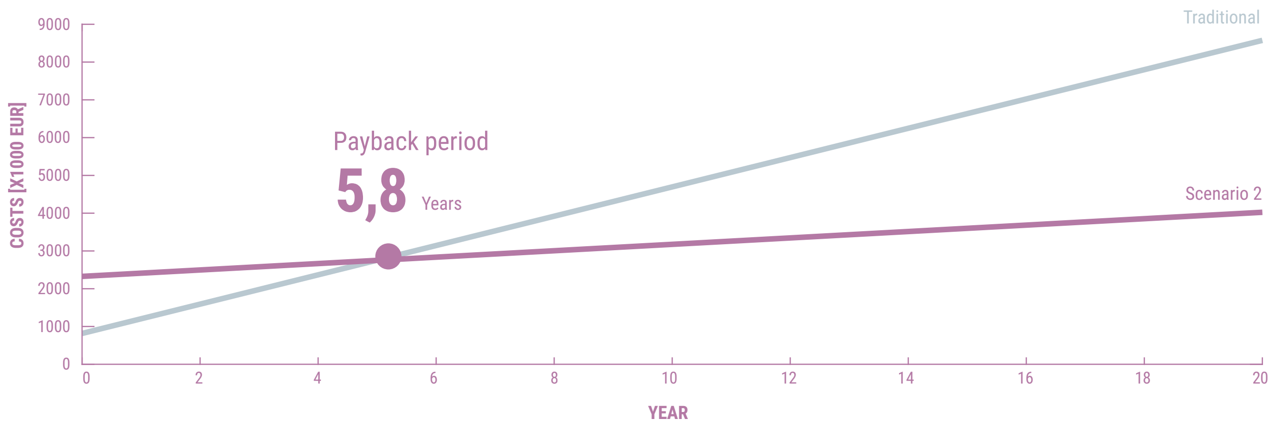


ECONOMIC ANALYSIS

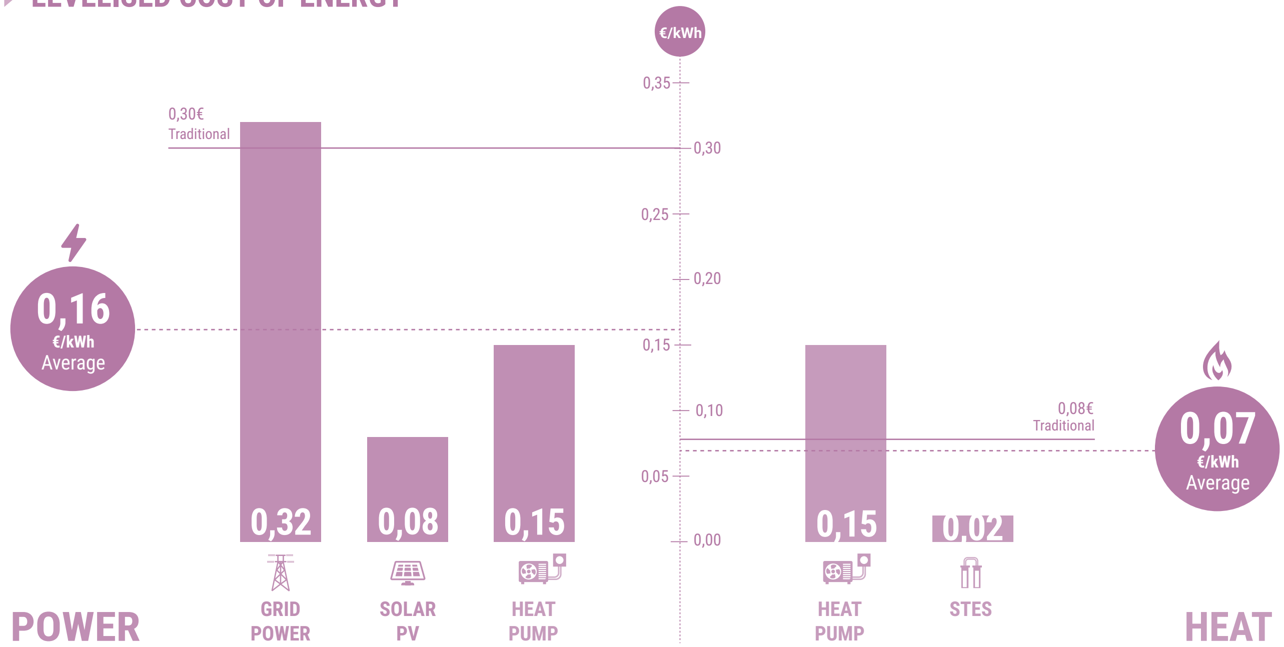
The improvements made for the second scenario of Republica Papaverweg substantially increase an already profitable business case. The addition of of extra on-site generation improves the synergies within the system, which result in a more cohesive system. The resulting improved utilisation of assets results in an economic gain as well, which make this scenario the second-most economically feasible scenario out of all scenarios considered.

- Additional solar panels reduce the grid dependency and corresponding costs.
- The heat pump for the STES system is now 44% of its original size, which greatly reduces the capital investment for the STES system.
- Thanks to an SDE+ subsidy amounting to over 40.000 EUR/yr, the CHP turns a profit of approximately 30.000 EUR/yr.
- The battery is no longer there for redundancy only, it actually helps increase the self-consumption, which results in a higher amount of PV savings.
- The LCOE for heat from the STES system is 0,02 EUR/kWh, the lowest heating cost of all components in all scenarios considered. This is only possible due to the synergies with the CHP system.

TOTAL SYSTEM COST

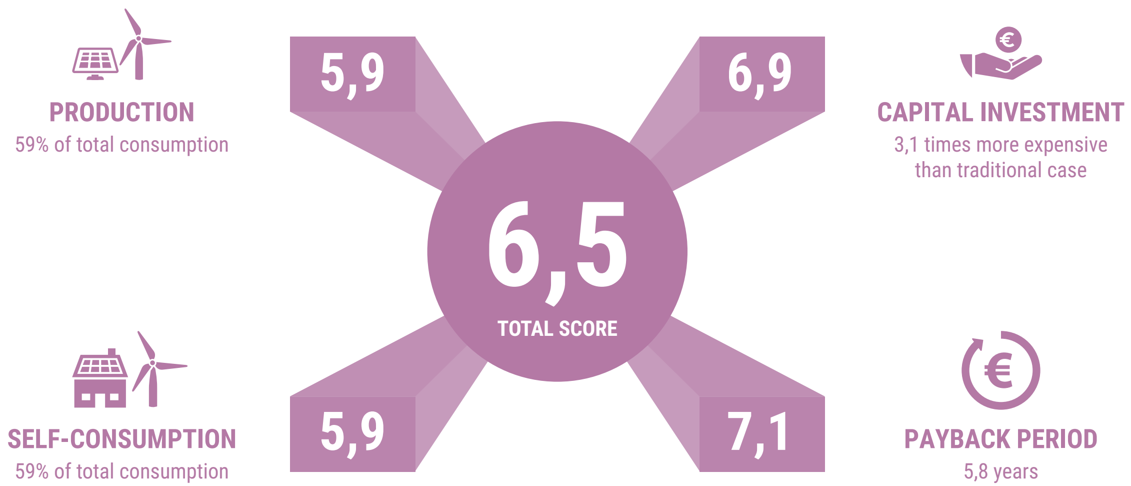


LEVELISED COST OF ENERGY



TOTAL PRODUCTION AND CONSUMPTION

OVERALL GRADE



CONCLUSION

The second iteration of Republica Papaverweg's SIDE system result in an energy system with a good all-round performance. A fast payback period combined with acceptable capital costs and an overall good technical performance make RP2 the most well-rounded and second-highest scoring scenario of all scenarios considered. Thanks to several key improvements it successfully manages to overcome most of the first scenario's downfalls: underutilisation of the battery, lack of renewable energy production and an imbalanced STES system.

As a result, the total share of local renewable power production has increased has increased from 18% of total consumption to 60% of total consumption. In the first scenario, the building complex barely manages to get an EPC of 0,4, the minimum legal requirement. Thanks to the addition of extra solar panels and a CHP, the EPC is now well beyond 0,0, which classifies it as an energy-positive building.

- Nearly all (99,2%) of the produced power is self-consumed.
- The building is well-prepared for the future, with its large amount of electric vehicle parking spots.
- The combination of extra EV parking spots and a CHP, make the smart grid experimentation potential even higher. They allow the ESCo to provide more flexibility and take bigger risks when engaging with the market, thereby improving their profit margins.
- Despite the STES system having the lowest heating costs of all scenarios considered (0,02 EUR/kWh), the overall heating cost is slightly more expensive than in scenario 1 (the cheapest of all), due to the higher CHP heating costs. Still, the total energy costs are lower.
- A nearby decentralised sanitation facility that produces biogas from black water and organic waste can provide 16% of the CHP's input needs.

DISCUSSION

GENERAL RESULTS

The four cases analysed in this report each represent the state-of-the-art in sustainable building technology within their respective context. The differences in boundary conditions, design philosophies and desired outcomes have resulted in a different SIDE system configuration for each case, and each corresponding scenario. Each SIDE system is therefore unique and has to be treated as such. There is no one-size-fits-all configuration when it come to SIDE systems. As a consequence, it is difficult to reach a clear overall verdict on the four defined KPIs; production, self-sufficiency, capital investment and payback period, as the nine scenarios considered in this report vary widely in their techno-economic performance. Some have great technical performance and poor economic performance, and vice versa.

Production

The wide variability is easily demonstrated when it comes to local power production, one of the four key performance indicators of this research. It ranges from 18% for RP1 to 100% for SS2, with an average of 67%. For each first scenario of the four cases, the average renewable power production only amounts to 41%. This shows that there is still a long way to go from the current state-of-the-art in neighbourhood sustainable energy systems, towards fully renewable building energy systems.

Self consumption

The variability is no different when it come to self-consumption, ranging from a meager 6,2% for DC1, to a full 100% for SS2, and everything in between. There is no clear correlation between the self-consumption ratio and the total amount of production or consumption: it all depends on the particular system configuration. One thing that can be said about the self-consumption, is that it is quite low for every first scenario of each case, ranging from 6,2% for DC1 to 33,1% for SS1, with an average of 21,3%.

Table 1: Overall grading for the nine different SIDE system scenarios.

GRADES	AH1	AH2	AH3	DC1	DC2	SS1	SS2	RP1	RP2	AVER-AGE
Production	7,1	9,0	9,7	2,3	9,5	5,0	10,0	1,8	6,0	6,7
Self-consumption	3,2	4,5	8,9	0,6	5,9	3,3	10,0	1,8	5,9	4,9
Capital investment	6,3	1,7	2,7	7,6	3,4	2,5	0,0	7,6	6,9	4,3
Payback period	4,2	1,7	5,8	6,5	2,6	0,0	0,0	5,7	6,5	3,7
Total	**5,2**	**4,2**	**6,8**	**4,3**	**5,3**	**2,7**	**5,0**	**4,3**	**6,3**	**4,9**

Table 2: Table: Self-consumption analysis for the nine different SIDE system scenarios. Unit: MWh

	AH1	AH2	AH3	DC1	DC2	SS1	SS2	RP1	RP2	AVER-AGE
Consumption	126,6	136,8	154,8	113,7	108,5	252,6	307	1068,9	1034,7	367,1
Production	76,4	152,3	149,5	26,5	102,7	127,3	307	197	620,2	195,4
Self-consumption	34,7	68,7	138,3	7,1	63,8	83,6	307	197	615,5	168,4
Grid take-in	91,9	68,1	16,5	106,6	44,7	169	0	871,9	419,2	198,7
Grid feed-in	41,7	83,6	11,2	19,4	38,9	43,7	0	0	4,7	27,0

Although achieving a 100% self sufficiency is not necessary when connected to the main grid, the self-consumption figure does represent an important aspect of a SIDE system: namely the flexibility and resilience that is inherent within it. SIDE systems with a high self-consumption percentage are not only able to manage their local energy flows in more optimal ways, resulting in both technical and economic advantages, they can also provide flexibility services outside of the confines of their neighbourhood. Although this has not been looked at in this study, it could potentially provide an interesting direction for further research.

Capital investment

Similarly, the economics of the considered SIDE systems vary widely from scenario to scenario. It is without exception, however, that SIDE systems are more expensive than traditional grid/gas-based systems, with the cheapest system considered (RP1) still being more than twice as expensive. The reasons for this are obvious: the investment for a SIDE system includes investing not only in distribution infrastructure (as in the traditional case), but also the production infrastructure. Since the SIDE systems for every case (except Republica Papaverweg) was assumed to be cooperatively financed, the capital investment is made by the same people who end up using the system. The high capital investments form a barrier for the realisation of SIDE systems, which is why alternative methods of financing ought to be considered.

One example of such an alternative is given by the ESCo model of Republica Papaverweg, in which the capital investments of the energy system are outsourced to an external party responsible for the reliable delivery of energy. This model could potentially allow for a more acceptable financial proposition for project developers and cooperatives interested in realising a SIDE system. Legally, this kind of financial structure does pose a certain risk, as an end-consumer of energy is, by law, free to choose its own energy supplier. It is therefore essential that each end-consumer within the SIDE system accepts the ESCo as its preferred energy supplier.

Payback Period

High capital investments are an inherent property of any SIDE system, but so are low operational costs. As a result of low marginal cost of renewable energy production, the payback periods range from 5 to more than 20 years. With an average payback period of 12,5 years, most SIDE system configurations will not be an attractive proposition for investors.

However, if the investors are, in fact, the end-consumers - as is the case with energy cooperatives - then higher payback periods could potentially pose less of a problem. After all, when buying a house, people tend to accept mortgage periods of 15 years and over. If the SIDE system can be included within the mortgage, then the additional costs on the mortgage payment are offset by the reduction in utility bills. Such a construction is cheaper on the whole, although potential homeowners may find it harder to get a larger mortgage arrangement. Perhaps a first few pilot projects can convince banks of the economic attractiveness of SIDE systems and help support energy cooperatives in their financial needs in the future.

On to a higher building standard

After analysing the four different scenarios, it becomes clear that the current standard of what entails a highly sustainable building energy system, the Energie Prestatie Coefficient (EPC), is not adequately equipped to facilitate the large scale rollout of intermittent renewable energy generation technologies. There is currently no consideration for the enormous additional strain that building energy technologies (e.g. heat pumps, electric vehicles and solar panels) put on the main grid. In order to prevent expensive infrastructure upgrades and to relieve the grid of increasingly volatile loads, building energy systems should aspire to address the issue of flexibility, by finding ways to intelligently reduce their imbalances.

As exemplified by the first scenario of every case, the current best practice is essentially characterised by two components: solar panels and heat pumps. Both have a negative effect on the flexibility within the grid, as both have a strong seasonal imbalance, with solar power also having a strong daily imbalance. The combined overproduction of solar power in summer combined with the demand increase in heat pump power, results in an amplified seasonal imbalance that puts extra strain on both the grid operators and energy suppliers. Overcoming the daily and seasonal imbalances associated with solar PV and heat pump installations can therefore be identified as the main hurdle for any SIDE system.

PERFORMANCE ASPECTS

Instead of trying to draw conclusions on the overall performance of widely dissimilar systems, it is better to step down a level and look at the various recurrent patterns of component interactions across the different scenarios:

Solar powered heating: essential but moderately effective

Solar panels in combination with heat pumps form the basis for every SIDE system. Unfortunately, the overlap between solar power production in summer and heat pump power consumption in winter is relatively small. Still, depending on the amount of solar power, around 10-30% of the heat pump power consumption can be derived from the sun for a heat pump-PV combination with no other form of heating (AH2, DC1, DC2, SS1, RP1), mostly in spring and autumn. It is important for these heat pumps to have access to a hot water tank so that they can store the heat produced during sunny times for use at a later time in the day. Air-to-water, ground-to-water and water-to-water heat pumps are therefore preferred over air-to-air heat pumps.

Table 3: Solar powered heat pump heating as a percentage of self-consumption and heat pump electricity consumption.

	SOLAR PV TO HP (MWh/yr)	SELF-CONSUMP. (%)	HP FRACTION (%)
AH1	2,7	7,78%	27,55%
AH2	16,8	24,45%	27,32%
AH3	8,9	6,44%	62,68%
DC1	1,7	23,94%	9,66%
DC2	4,8	7,52%	30,97%
SS1	22,6	27,03%	20,14%
SS2	17,9	5,83%	49,86%
RP1	29	14,72%	33,18%
RP2	42,3	6,87%	58,18%

The self-consumption increase that can be attributed to coupling a heat pump with a solar PV installation depends on the circumstances, such as the presence of other generation capacity (e.g. CHP or wind turbine). For the pure solar PV-heat pump cases (AH2, DC2, SS1), around 25% of self-consumption can be attributed to solar powered heat pump heating, given that their control is optimised for self-consumption through an energy management system.

Ultimately, a heat pump/solar PV combination is energy efficient and sustainable, but not sufficiently flexible.

Solar powered cooling: an excellent match

The possibility for peak-shaving solar power with the use of cooling systems is very attractive. After all, the demand for cooling is highest on warm, sunny days. Operating the cooling system in tandem with solar power production is, therefore, an obvious choice.

Table 4: Solar powered cooling as a percentage of self-consumption and heat pump electricity consumption.

	SOLAR PV TO HP (MWh/yr)	SELF-CONSUMP. (%)	COOLING POWER (%)
RP1	52,5	26,65%	47,34%
RP2	89,8	14,59%	85,44%

Only one case used a cooling system for their building: Republica Papaverweg. Its cooling system simply reverses the heat pump cycle to become a refrigeration cycle, distributing cold water from the seasonal storage throughout the building's network.

In both scenarios, solar power makes up a high percentage of cooling power. This would have been even more for the first scenario if the solar power would have been able to match peak cooling demand. When solar power peak capacity can meet the peak cooling demand, as is the case in scenario 2, the cooling system can operate almost completely on sustainable electricity.

The large overlap between solar power production and cooling demand make the solar PV - cooling combination an excellent choice. Not only does it allow the cooling system to operate nearly completely on renewable solar power, it also significantly increases the self-consumption (14-26% for RP), while reducing energy spikes.

Solar heating panels: ineffective with heat pump and solar PV

Solar heating panels may seem like an attractive option for producing hot water using solar energy. For SIDE systems, however, their use is quite ineffective. The reason being, that nearly every SIDE system will have at least a heat pump and a solar PV installation due to their excellent performance. If this combination is already present, it is more effective to produce heat using the solar powered heat pump, than it is to produce heat via solar heating panels. Even though solar heating panels can be over four times more efficient in terms of energy produced, the COP of a heat pump essentially brings the solar PV efficiency on par with that of a solar heating panel. In economic terms, there is not much of a difference. Add to that the fact that a heat pump can be used to peak-shave some of the solar power spikes, and it becomes clear why solar heating panels do not have a well-defined role to play in SIDE systems.

Urban wind power: effectiveness highly dependent on circumstances

Wind power is currently the largest source of renewable electricity in the Netherlands, with 6,95% of electricity consumption in 2016 generated from wind.[10] The majority of this power is generated in large scale wind farms, with roughly 70% of electricity generated on land and 30% at sea.[11] The market for small-scale wind power is very small compared to the bigger projects, with only 0,3% of wind power generation coming from turbines with an axle height <30m, but there is plenty of room for growth.

The case for small scale wind turbines in SIDE systems is highly dependent on a couple of factors. By far the most critical issue is that of location: the importance of having sufficient wind (>4,5 m/s preferably) resources in an area cannot be stressed enough. The difference between an average wind speed of 4 m/s and 5 m/s results is a factor 2 in energy output, due to the cubic relation between wind speed and energy output. Another important aspect is the local surroundings: urban environments generally do not have the space nor the wind speed to facilitate a wind turbine. On top

[10] http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=71227ned&D1=0,4-12&D2=a&D3=25-26&VW=T11
[11] http://statline.cbs.nl/statweb/publication/?dm=slnl&pa=82610ned

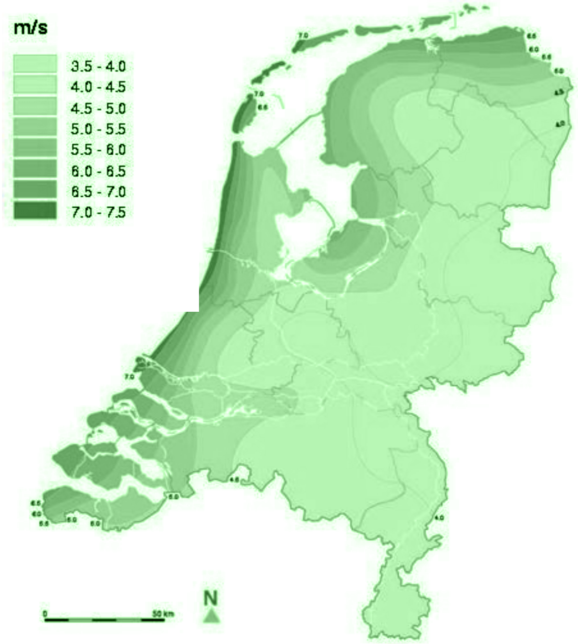


Figure 4: Wind speed in the Netherlands in meters per second at a height of 10m.

Table 5: Wind power production and self-consumption.

	WIND POWER (MWh/yr)	SELF-CONSUMP. (%)	PRODUCTION (%)
DC2	42,9	63%	47,91%
SS2	99,4	100%	32,38%

	CAPACITY (kWh)	THROUGHPUT (MWh/yr)	USAGE (cycles/yr)	SELF-CONSUMPTION INCREASE (%)	LEVELISED COST OF STORAGE (EUR/kWh)
AH2	150	19,5	216,67	14,20%	0,26
AH3	100	11,8	196,67	15,40%	0,28
DC2	50	7,5	250,00	9,90%	0,22
SS1	300	34,7	192,78	19,40%	0,29
SS2	300	36,3	201,67	16,00%	0,28
RP2	696	28,5	68,25	14,40%	0,81

Table 6: Battery performance statistics for the different scenarios assuming a 500 EUR/kWh battery price and a battery lifetime of 15 years.

of that, regulations restrict the placement of wind turbines in most urban areas. This mostly leaves rural and industrial areas with sufficient wind speed open to consideration for the placement of a wind turbine.

Given that these criteria are met, a wind turbine can prove to be a valuable asset for a SIDE system. Increased power output in winter due to high wind speeds nicely complements solar power output. Similarly, wind blowing at night can be used to charge electric vehicles, when solar power can not.

It is important to consider the variability and intermittency of wind power production, which results in a highly erratic production profile. A wind turbine is therefore best suited in SIDE systems with a high number of load balancing components, such as electric vehicles, heat pumps and batteries.

In the two cases considered that feature a wind turbine (DC2 and SS2), the wind turbine performs quite good. Even if we disregard the fully off-grid fantasy scenario that is SS2, the percentage of self-consumed wind power is 63%, which is significantly better than solar PV. With an average wind speed of 3,9 m/s for both cases, the levelised cost of wind power equals 0,18 EUR/kWh. Although this is cheaper than grid electricity, it takes over 15 years for the investment to pay itself off. Note that, if the wind speed were to be 1m/s higher, the wind turbine would pay off within 8 years.

Batteries: useful but still too expensive

Perhaps the most obvious way to increase the flexibility of an energy system is to add buffering capacity in the form of batteries. Older, yet well-matured battery technologies such as lead-acid batteries suffer from high (>30%) losses and are therefore too inefficient for intensive energy management. Li-ion batteries, with losses of only 10%, are becoming a more attractive option. The recent surge in electromobility has greatly reduced the cost for Li-ion batteries: over 70% since 2012.[12]

[12] https://www.pv-magazine.com/2017/08/03/lithium-ion-batteries-below-200kwh-by-2019-will-drive-rapid-storage-uptake-finds-ihs-markit/

Still, residential battery modules are too expensive in their current state. None of the scenarios considered manages to break even on its battery investment, even when assuming net-metering has been replaced by a feed-in tariff. The levelized cost of storage varies from 0,22 to 0,29 EUR/kWh,[13] which is significantly higher than the price of electricity. Depending on the height of the feed-in tariff (that will replace the current net-metering starting 2020), which is still a matter of uncertainty at the time of writing, another 70-90% decrease in battery costs is required for batteries to become an economically attractive option, when the difference between the electricity price and the feed-in price exceeds the Levelised Cost of Storage. With current cost reduction trends continuing, this price point will be reached somewhere before 2030.

The battery performance is fairly constant across the considered cases. Self-consumption increased between approximately 10-20%, depending on circumstances such as the presence of a wind turbine and the amount of solar PV compared to total consumption. The usage of the batteries is good for all cases except Republica Papaverweg: at approximately 200-250 cycles per year, the battery will make 3000-3750 cycles throughout its 15 year lifetime, which is roughly its cycle lifetime as well (3000-5000 cycles).

From a pure self-consumption point of view, batteries are moderately effective and still too costly. However, a battery can perform many other useful ancillary services to the microgrid that cannot be expressed in energy savings alone. Examples of such services include frequency regulation, power quality control, backup power supply and peak-shaving. Determining the values of these services is outside of the scope of this research, but could prove vital to the operation of not only the SIDE system itself, but also the grid at large. All in all, in due time, batteries will most likely prove themselves to be a vital part of any sufficiently advanced SIDE system.

	EV TOTAL (MWh)	SELF-CONSUMP. (%)	PV FRACTION (%)	WIND FRACTION (%)	CHP FRACTION (%)	EV FRACTION (%)	GRID FRACTION (%)
AH2	11,8	17,18%	33,05%	0,00%	0,00%	12,71%	54,24%
AH3	58,2	42,08%	26,12%	0,00%	48,63%	7,39%	17,87%
DC2	18,3	28,68%	22,95%	33,33%	0,00%	2,73%	40,98%
SS2	109,3	35,60%	30,74%	29,83%	30,01%	9,42%	0,00%
RP2	156,3	79,34%	5,76%	0,00%	0,0%	0,00%	94,24%
RP2	312,7	50,80%	12,98%	0,00%	22,29%	4,00%	60,3%

Table 7: Electric vehicle energy consumption as a percentage of self-consumption.

Electric vehicles: enormous challenge or big opportunity?

Electric vehicles will be a key ingredient of the smart grids of tomorrow. Their large energy consumption and high power spikes are both a challenge and an opportunity. Our current power infrastructure may not be sufficiently prepared for the increase in peak power demand. However, if their energy consumption can be intelligently controlled using smart charging software, as was done in the model used for this report, EV's can greatly increase local self-consumption, while simultaneously reducing peak demand.

Although solar power can be used to charge EV's during the day, most EV's will be charged primarily in the evening. A solar power system is therefore not fully equipped to provide most of the EV's charging needs, as exemplified by scenario AH2: more than 50% of power still has to come from the grid. However, in cases with additional sources of renewable power generation, the reliance on grid power is greatly diminished (AH3, DC2, SS2, RP2). All renewable generation technologies (solar PV, wind, and CHP), can provide between roughly 20-40% of EV's charging needs, depending on sizing and circumstances.

In any case, electric vehicles have a very positive effect on self-consumption, ranging from 17% to 79%, depending on the share of EV's and the specific SIDE system configuration. EV's therefore form an essential component of any sufficiently advanced SIDE system.

[13] Excluding Republica Papaverweg, whose battery is not designed for optimal self-consumption.

CHP's: extremely effective, but not without complications

CHP systems are a great way to produce electricity as a byproduct of heat production. CHP systems come in various shapes and sizes, mostly running on fossil fuel such as natural gas. Recent technological advancements in small-scale CHP units are creating a new opportunity for the decentralised deployment of CHP units. These systems do not necessarily have to run on fossil fuels, but can also run on biomass, which makes them an interesting choice for integration into SIDE systems.

Provided that there is sufficient infrastructure in place (i.e. a district heat network and technical space), a CHP unit is a great way to improve the technical performance of a SIDE system. The three best performing scenarios (AH3, SS2 and RP2) all feature a CHP. for a couple of reasons:

- CHPs are one of the very few technologies considered that can flexibly produce power
- CHPs are mostly used during winter for both heating and power, this gives a considerable boost to self consumption, and nicely complements the production of solar power in summer.
- CHPs combined with heat pumps combine to create a negative feedback control mechanism that can accurately match the exact amount of heat and power demand.
- The CHPs considered in this report are always paired with a district heating system that allows for efficient and flexible distribution.

Economically speaking, CHPs can be a good investment, given that certain criteria are met. Firstly, the margin between fuel cost and energy price (the spark spread) has to be great enough to ensure economic feasibility. Then there is the efficiency of the CHP itself, consisting of electrical and thermal efficiency. The higher the electrical efficiency, the better. Furthermore, the capital investment and maintenance costs are important economic considerations. Although CHPs are currently still prohibitively expensive for most scenarios, the prospects of rising electricity prices and stricter environmental regulations is expected to have a positive effect on the demand for CHPs.

Seasonal Thermal Energy Storage systems: effective despite difficulties

Storage of heat and cold in the ground using Seasonal Thermal Energy Storage (STES) systems is common practice in the Dutch utility building sector, and is gaining ground in the residential sector. However, the technology still needs maturing; as most systems currently in operation perform sub-optimal.

Common problems with STES systems include:

- Overdimensioning, leading to loss of efficiency as a result of narrow operating band.
- Pumps not properly selected to accommodate wide range of variable flow rates.
- Oversimplified usage design conditions, resulting in decreased operability.
- "Short-circuiting" of hot and cold well.
- Deviating return temperatures as a result of bad control system design.

The storage of heat and cold in the ground can be categorised in two systems: open and closed. Open systems make use of groundwater aquifers to store heat and cold. They are currently the standard within the Netherlands, although the use of groundwater is not without complications. In dense urban areas with multiple wells, interference can occur when one building's heat well overlaps with another buildings cold well. This requires adequate urban planning (zoning of hot and cold wells) in order to prevent efficiency loss. In addition, to protect the groundwater, Dutch regulations require hot and cold wells to reach thermal equilibrium once every three years. Difficulties in estimating and balancing heat and cold demand of buildings make it hard to follow these regulations.

Closed systems (featuring a closed ground-loop heat exchanger) are well suited in densely populated areas as they do not cause any groundwater interference issues (and therefore do not require a big zone). Although open systems perform better in theory, a well-designed closed system does not have to be inferior to an open system in practice. In addition, they have a long life expectancy and do not require maintenance. Outside of the Netherlands, closed systems have therefore already become the norm. Within the Netherlands, there is a shift noticeable towards closed systems, although it is currently limited to small-scale (<70 kW) installations.

The one case considered in this report with a STES system (RP1), is an open system in a populated area. The performance of the STES system of RP1 is fair, providing both heating and cooling with a seasonal performance factor (SPF) of 3,6. The imbalance of the system requires dry coolers to regenerate the wells, which results in inefficiencies. This is where the SIDE system philosophy comes in: integrating a STES system into SIDE systems can help balance the hot and cold wells so that the system is always balanced and running at maximum efficiency.

[14] Unica Ecopower (2013) Komt een WKO bij de dokter.

The benefit of integrating STES system with other components is exemplified in the RP2 scenario, where a CHP system complements the STES heat production. The resulting 22% increase in energy efficiency and the reduction in STES size decrease the levelised cost of energy for the STES system from 0,04 EUR/kWh to 0,02 EUR/kWh, the lowest cost of all cases considered. Hence, STES systems can play a key role in many SIDE systems.

District heating greatly improves system integration and efficiency

District heating networks can play an important role in the transition towards a sustainable energy system, given that the heat is produced in a sustainable manner. About 4% of the Dutch heat demand is currently supplied via district heating. In the coming decades, this can grow by a factor of 7, thereby helping our heating infrastructure move away from gas.[15] SIDE systems can help facilitate this growth by incorporating a district heating network.

The advantages of a district heating network within a SIDE system are numerous. District heating can play an important role in integrating the heat and power systems through a centralised heat pump and/or CHP. An added benefit is that this centralised production also results in a higher efficiency due to scaling advantages. Furthermore, Local distribution of heat has the distinct advantage that there are no 10-20% distribution losses associated with the delivery of energy. On top of that, the aggregation of the heat demand of individual dwellings results in a smoother heat demand profile, resulting in more buffering capacity, and thus a higher self consumption and resilience.

For these reasons it may come as no surprise, that the three scenarios scoring highest on self consumption (AH3, SS2 and RP2) have included a district heating network in their design. If the high investment costs of a district heating system can be overcome, a district heating network is an excellent addition to any SIDE system.

Hydrogen: inefficient and too expensive

High energy density combined with zero emissions have created the promising image of hydrogen as a clean alternative to fossil fuels. Hydrogen has several interesting properties that make it a unique sustainable contender for certain applications. Ongoing research into fuel cell, storage and electrolyser technology is consistently cutting the costs of these technologies, yet the question remains whether they will gain enough market traction to become an integral part of our energy system.

For SIDE system applications, hydrogen technology is still a faraway future fantasy. Although there are several key benefits of hydrogen technology that SIDE systems would benefit from, such as its capability to store large amounts of energy for long periods of time, having a fully operational hydrogen system is simply too inefficient to be realistic. The production, storage and conversion of hydrogen leads to over 70% of energy being lost in the process. On top of that, these systems are very expensive to build. The only case that considered a hydrogen system (SS2), resulted in a Levelised Cost of Energy of 3,33 EUR/kWh, or roughly 15-30x more expensive than the other renewable energy generation technologies.

Despite this, it is unfair to completely write off any hydrogen system. There are cases imaginable in which hydrogen will play a role, such as systems with high volumes of wind power curtailment, or systems that require longer-term energy storage. Small islands, for instance, could be an ideal entry market for a hydrogen system. In these cases, hydrogen could aid in realising a fully off-grid renewable energy microgrid.

Local energy trading: makes sense but is unnecessarily taxed

The current Dutch law requires taxes to be paid for every unit of energy that enters a dwelling. As a result, if two neighbouring households exchange energy, taxes have to be paid even though the total energy production in the system remains the same as when they had consumed the energy themselves. The current tax structure therefore disincentivises energy trading amongst neighbours, which has a negative effect on stimulating local energy

Table 8: Amount of energy traded as a percentage of production and self-consumption.

	ENERGY TRADED (MWh/yr)	PRODUCTION (%)	SELF-CONSUMP. (%)
AH2	7,30	4,79%	10,63%
AH3	11,50	7,69%	8,32%
DC2	12,40	12,07%	19,44%
SS1	6,70	5,26%	8,01%
SS2	14,70	4,79%	4,79%

[15] http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2017-toekomstbeeld-klimaatneutrale-warmtenetten-in-nederland-1926.pdf

balancing. This is a missed opportunity, since from a techno-economic stance it makes sense to allow small producers of energy to locally sell their energy. This will create a local market in which a price signal (local energy being cheaper than main grid energy) will incentivise the local exchange of energy.

The benefits of local energy trading on self-consumption are relatively small, yet noticeable. The amount of energy trade occuring in the considered scenarios depends on their specific circumstances. It varies between 4,79-12,07% of produced energy and 4.,9-19,44% of self-consumed energy (although it is generally less than 10% if De Ceuvel is counted as an outlier due to its power hogging cafe).

All in all, allowing tax-free local energy trading will have a positive effect on the flexibility of the energy system, given that the right technology and legal measures can be put in place (e.g. local energy price). Not only will prosumers benefit from increased revenue, it also helps to spread awareness of local power imbalances. This awareness can stimulate both producers and consumer of electricity to better match local supply and demand.

Local energy management systems

Any SIDE system is incomplete without an intelligent local energy management system (LEMS). Most of the previously discussed benefits of SIDE systems on grid flexibility and self-consumption can only be unlocked through the smart management of energy flows. Without it, an electric vehicle would simply charge whenever a certain simple condition was met, such as “charger plugged in”, regardless where the power is coming from at that moment, resulting in high peaks and large grid take-in. The same thing goes for many other components in a SIDE system: heat pumps, batteries, electric heating: all benefit from being locally managed by a LEMS.

The actual nature of how such a LEMS would look like depends on many complex design decisions that are outside of the scope of this report. However, the optimisation of power flows, local dispatch and power purchases of microgrids is extensively researched. Most control strategies can be categorised into two categories: centralised and decentralised control. Centralised control is used to coordinate storage devices, satisfy load requirements and minimise the total operating costs of the microgrid. In decentralised control, the distributed energy resources of the microgrid are controlled separately, with each component acting as its own agent for control, operation and monitoring, while also communicating with other agents. These systems are called Multi-Agent Systems (MAS).

Essentially, the issues of decentralised and centralised control boils down to the level at which the system is optimised. It is possible to optimise energy flows at the component level, house level, neighbourhood level, or even city level. The lower the level, the more detailed the system model can be, at the expense of missing out on potential synergies at a higher level. In addition, more agents are required which muddle the accuracy of higher level control. At higher levels, computational power becomes an issue. It is already extremely computationally expensive to optimise energy flows at the neighbourhood level in real-time with a 15 minute resolution. Increasing the scope of the managed energy system will always be a trade-off between the efficiency improvements that can be gained through improved modelling accuracy of lower level components and the efficiency improvement that can be gained through higher level synergies.

On top of the computational challenges that arise with the complex mathematics of multinodal energy systems, there is the overlying layer of transactional challenges that have to be overcome when transacting between multiple stakeholders that are tied to real-world laws and regulations. For instance, an energy management system might optimise for local self-consumption, which - although great from a technical and environmental perspective - results in high monetary losses due to energy taxes having to be paid for each kWh entering the meter. Incorporating these rules and laws into the management software is easier said than done, and begs the question whether the LEMS should change to math the laws, or whether the laws should change to better match the physical reality?

Ultimately, the issue of microgrid control is a complex one, but one that can be solved. The current state of microgrid control still has to go through puberty in order to reach full maturity, but promising new technological frameworks (e.g. USEF and blockchain technology) are being developed that can hopefully one day provide a universal framework for smart energy technologies. If the lessons learned from pilot microgrid projects (such as the ones regarded in this report) can be incorporated into new laws and regulations, it can speed up the process of rolling out LEMS to other cases.

CONCLUSIONS

By looking at four different cases, each with their own unique set of boundary conditions, a detailed overview of the performance of a set of widely different SIDE system configurations was constructed. Central to their performance assessment were four KPI's: production, self-consumption, capital investment and payback period.

Detailed analysis using a time-series simulation model revealed widely different outcomes for the four KPI's, both per case individually and across the cases themselves. This variability in outcomes makes it hard to generalise the conclusions. Still, it has become clear that there is a wide range of techno-economically feasible SIDE systems for an evenly wide range of use-cases. Although SIDE system configurations and performance are highly context-specific, residential neighbourhoods, office parks and mixed area developments can all benefit from the system integration that SIDE systems can offer.

The goal of this study was to investigate the feasibility for Smart Integrated Decentralised Energy (SIDE) systems to contribute to the resilience, flexibility and circularity of the Dutch national power system infrastructure, so that the ambitious renewable energy targets for 2030 can be met. The potential for SIDE systems to support the energy transition from the bottom-up is clear; some of the systems outlined in this report, such as Aardehuizen scenario 3, demonstrate an almost fully (89%) self-sufficient and techno-economically feasible energy system. It's highly synergetic local energy systems like these that can greatly improve the flexibility and resilience of our national energy system, without requiring expensive infrastructure upgrades.

The decentralisation of production and consumption of renewable energy allows for interesting new business cases that force us to rethink the way we structure, design and control our energy system. The line between producers and consumers of energy is blurring, as more and more people take matters into their own hands and form energy cooperatives that produce and distribute their own renewable energy. Ultimately, the bottom-up design philosophy that SIDE systems embody may prove to be an essential cornerstone on which to build our fully renewable energy system.

Takeaways

With the outcomes of the analysis of nine different scenarios, several conclusions, recommendations and best practices have been identified that can aid the development of the next generation of microgrids, i.e. SIDE systems. They are summarised below:

- Both **solar panels** and **heat pumps** are essential components to any SIDE system. They have good technical and economic performance and provide the basis for local heat and power production. A solar PV - heat pump combination can result in approximately 25% extra self-consumption of solar power, although it also results in high seasonal power imbalances
- **Solar power** performs very well in combination with **cooling systems**; reducing power peaks while increasing self-consumption.
- **Solar heating panels** become obsolete in the presence of a heat pump and solar panels, and therefore do not play a well-defined role in SIDE systems.
- **Urban wind turbines** can be a good option provided that the circumstances are right and there is local opposition. Their business case is highly dependent on wind speed, thereby excluding most urban locations.
- **Combined Heat & Power** units can be a very effective addition to a SIDE system as they flexibly provide heat and power at those times it's needed most (winter). However, they require active control and maintenance, as well as an external biomass source. On top of that, their business case is heavily reliant on subsidies.
- Based on energy storage alone, **batteries** are still a factor 3-10x too expensive to incorporate in SIDE systems economically, depending on the height of the feed-in tariff. However, their economic feasibility may increase if there is a need for other services the battery can provide, such as backup power supply, power quality management, or offering flexibility to the power market. By 2030, their business case should be solid.
- **Electric vehicles** are an essential component of any sufficiently advanced SIDE system, as they allow for substantial local energy management. Smart charging algorithms can greatly increase the self-consumption of renewable energy.
- **District heating** systems are a good choice for any SIDE system. They greatly improve the system integration, energy efficiency and overall flexibility of a SIDE system. High capital costs can be mitigated by the resulting scaling advantage of the heating systems.
- The difficulties surrounding traditional **Seasonal Thermal Energy Storage** systems can be mostly overcome through smart integration with other technologies. STES systems can therefore be a great addition to many SIDE systems.
- **Local energy trading** allows for a modest increase in self-consumption and can help incentivise smarter energy systems, provided that regulatory barriers can be overcome. Ideally, smart-grid technology will allow for a real-time local energy price, similar to the stock market. Local price signals will then help create a highly flexible system.
- Although **combinations** between two individual SIDE components tend to have modest synergies with one another, most components have synergies with multiple other components. These effects stack up to create a highly symbiotic energy system, as exemplified by the latest scenario of each case.
- Local **Energy Management Systems** are complex in nature and raise many important issues regarding our energy infrastructure and legal architecture. It is safe to say that LEMS technology is not yet mature. Hopefully the lessons learned from pilot projects such as the ones considered in this report can help LEMS technology get through puberty.
- **Hydrogen systems** (fuel cell, storage, electrolyser), despite some unique properties that can aid SIDE system performance, are too inefficient and expensive to be a realistic component of most SIDE systems, with the exception of off-grid cases (e.g. islands).
- The **experimenteerregeling** in its current state is still too restrictive to fully unlock the potential of SIDE systems. Ideally, the experimenteerregeling allows a microgrid to have a single connection, with every house or connection behind it aggregated into a single entity. Although difficult for tax reasons, it will improve local energy trading and help create more interesting business cases.
- The **brutoproductiemeters** required for the SDE+ subsidy have a severely negative effect on the business-case of microgrids with many different small-scale PV-owners such as the ones assessed in this report.

BIBLIOGRAPHY

- **Agentschap NL. (2013).** Warmte en koude in Nederland, 1–14.
- **Berenschot. (2015).** Advies aan de topsector energie.
- **Bouwmeester, H. T. W. (2013).** Wko 3x beter, 1–15.
- **Bracco, S., Delfino, F., Pampararo, F., Robba, M., & Rossi, M. (2012).** A system of systems model for the control of the University of Genoa Smart Polygeneration Microgrid. Proceedings - 2012 7th International Conference on System of Systems Engineering, SoSE 2012, 18, 7–12. http://doi.org/10.1109/SYSoSE.2012.6384186
- **C. Hugel (Delft University of Technology). (2018).** Flexibility services by a community microgrid. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:430ee1ce-9b68-47cb-ac0e-a67ba8b7a8f7?collection=education
- **CE Delft. (2017).** Socialiseren van netkosten van warmtenetten Gevolgen voor lasten huishoudens en economische argumenten, 1–49.
- **De Ceuvel. (2018).** Energie gebruik per boot op De Ceuvel.
- **DNV GL. (2015).** Routekaart Energieopslag, 1–120.
- **ECN. (2015).** Nationale Energieverkenning 2015. Ecn-O--14-036, 1–276. http://doi.org/ECN-O--16-035
- **Ecorys. (2017).** Investments in a renewables-only market, (September). Retrieved from http://www.ecorys.nl/news/ecorys-onderzoekt-marktmodel-een-volledig-duurzame-elektriciteitsmarkt
- **Elestor. (n.d.).** Waterstofbromide Flow Batterij Technologie, (c), 1–4. http://doi.org/10.15713/ins.mmj.3
- **Enexis Netbeheer. (2017).** Periodieke Aansluit- En Transporttarieven Elektriciteit, 1–2.
- **Entso-e. (2016).** Optimising Available Transmission Capacities for Trade While Ensuring System Security. Retrieved from https://www.entsoe.eu/Documents/entsoe_paper_Optimising_available_TRA_capacities_web (002).pdf
- **Gudmundsson, O., Thorsen, J. E., & Zhang, L. (2013).** Cost analysis of district heating compared to its competing technologies. WIT Transactions on Ecology and the Environment, 176, 107–118. http://doi.org/10.2495/ESUS130091
- **Hatziargyriou editor of compilation, N. (2014).** Microgrid : architectures and control.
- **Hedman, B., Wong, E., Darrow, K., & Hampson, A. (2012).** Combined Heat and Power : Policy Analysis and 2011 – 2030. Prepared for the California Energy Commission, (February). Retrieved from www.icfi.com/
- **Heimovaara, T. J., & Trcka, M. (2012).** Onderzoek criteria energiebalans WKO.
- **Hers, S., Rooijers, F., Afman, M., Croezen, H., & Cherif, S. (2016).** Markt en Flexibiliteit. Publicatienummer 16.3E90.35, 37.
- **Kleeens, O., Voor, R., & Nederland, O. (2014).** Status rapportage warmtepompen technologie en markt in Nederland. Rvo, RVO0921401/RPDUZA. Retrieved from https://www.rvo.nl/sites/default/files/2014/11/Definitief_Statusrapportage Warmtepompen.pdf
- **Metabolic. (2015).** Schoonschip sustainability masterplan.
- **Naumann, M., Karl, R. C., Truong, C. N., Jossen, A., & Hesse, H. C. (2015).** Lithium-ion battery cost analysis in PV-household application. Energy Procedia, 73, 37–47. http://doi.org/10.1016/j.egypro.2015.07.555
- **Nordman, R., Kleefkens, O., Riviere, P., Nowak, T., Zottl, A., Arzano-Daurelle, C., … Nordman, R. (2012).** SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector SEPEMO-Build: FINAL REPORT. Retrieved from https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/sepemo-build_final_report_sepemo_build_en.pdf
- **PBL. (2017).** Toekomstbeeld Klimaatneutrale Warmtenetten in Nederland. Uitgeverij PBL, 80. Retrieved from http://www.pbl.nl/publicaties/toekomstbeeld-klimaatneutrale-warmtenetten-in-nederland
- **Puylaert, H., & Puylaert, H. (n.d.).** Ruimtelijke kansen voor warmtenetten.
- **Quak, T., & Sinke, M. (2018).** E1A, 1–10.
- **REScoop. (2017).** What local energy communities need from the Clean Energy Package, 1–9. Retrieved from https://www.duurzameenergie.org/f/files/download/rescoop-position-paper-on-clean-energy-package-final.pdf
- **RVO. (n.d.).** Factsheet: WKO en warmtepompen, 5–8. Retrieved from https://www.rvo.nl/sites/default/files/2017/07/RVO.nl - Factsheet WKO en warmtepompen.pdf

- **Schepers, B., & Van, M. P. J. V. (2009).** Warmtenetten in Nederland. Overzicht van grootschalige en kleinschalige warmtenetten in Nederland, (09.3031.45). Retrieved from http://www.ce.nl/publicatie/warmtenetten_in_nederland/976

- **Schoots, K., Hekkenberg, M., & Hammingh, P. (2017).** Nationale Energieverkenning 2017. Energieonderzoek Centrum Nederland, 1–238. http://doi.org/ECN-O--16-035

- **Schreck, S. (2016).** Implementation and Analysis of a Rolling Horizon Approach for the Energy System Model REMix submitted by Sebastian Schreck.

- **Strbac, G., Hatziargyriou, N., Lopes, J. P., Moreira, C., Dimeas, A., & Papadaskalopoulos, D. (2015).** Microgrids: Enhancing the resilience of the European megagrid. IEEE Power and Energy Magazine, 13(3), 35–43. http://doi.org/10.1109/MPE.2015.2397336

- **Temmink, A. (n.d.).** STEG en WKK Beschouwingen, 1–293.

- **Unica Ecopower. (2013).** Komt een WKO bij de dokter.

NOMENCLATURE

CHP	Combined Heat & Power
COP	Coefficient of Performance
CPO	Collectief Particulier Ondernemerschap (Collective-Private Partnership)
DG	Distributed Generation
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand-Side Management
DSO	Distribution System Operator
EMS	Energy Management System
EPC	Energie Prestatie Coefficient (Energy Performance Coefficient)
ESCo	Energy Service Company
EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
HAWT	Horizontal Axis Wind Turbine
HEMS	Home Energy Management System
KPI	Key Performance Indicator
kWh	kilowatt hour
LCOE	Levelised Cost of Energy
LEMS	Local Energy Management System
MWh	Megawatt hour
PBP	Payback Period
PV	Photovoltaic
RES	Renewable Energy Sources
RES-E	Renewable Energy Sources: Electricity
SDE+	Stimulering Duurzame Energie (subsidy)
SPF	Seasonal Performance Factor
STES	Seasonal Thermal Energy Storage
TSO	Transmission System Operator
UWT	Urban Wind Turbine
VAWT	Vertical Axis Wind Turbine
VvE	Vereniging van Eigenaren (Association of Owners)

METABOLIC

+31 (0) 203690977
info@metabolic.nl
www.metabolic.nl

Meteorenweg 280M
1035RN Amsterdam
The Netherlands