Development of a generic assessment framework to evaluate decentralized water-energy nexus systems in neighborhoods

Case study City Nieuwegein

Master of Science
Master thesis

The cover shows a preliminary design of City Nieuwegein, the case study location. The image was retrieved from https://rijnboutt.nl/ (accessed July 6, 2022).

Development of generic assessment framework to evaluate decentralized water-energy nexus systems in neighborhoods

Case study City Nieuwegein

By

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In partial fulfillment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology,

Project duration:	March 2022 – March, 2023	
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Acknowledgment

First of all, I want to especially thank Els as my daily supervisor for always giving me well-reasoned feedback, supporting me to work with the Power-to-X model, asking critical questions, and for the quick responses when I had questions. And not to mention, a special thanks to KWR as I had the privilege to do a collaborative thesis between TU Delft and KWR. I would also like to thank Jan Peter, and Edo for providing me with valuable tips, feedback, and suggestions throughout the development of my thesis. It has been a period in which I could learn more about this research topic.

I am grateful for all the input I have been able to receive within KWR. With thanks to Marcel, I quickly came to the decision to use City Nieuwegein as the case study. In addition, he also gave me the contacts that allowed me to conduct interviews with stakeholders that are involved in this project. To everyone who was involved during these interviews, thank you very much for the interesting conversations and input. Furthermore, I would like to thank Dimitrios who helped me using the UWOT model. The same goes for Mirjam who shared the SIMDEUM model with me and explained how it could be used. Besides I want to thank at the team Energy and Circular Systems and of course the people other teams for their feedback.

At last (but not least), I would like to thank my family and friends throughout this process for their support.

Ruben van den Berg, Ruben van den
Leiden, 1 March 2023

Summary

The pressure on water and energy resources, along with the transition towards new infrastructure, requires an integrated approach to achieve future-proof concepts. A nexus approach can contribute to this by including the interaction between water and energy. This is also known as a water-energy nexus (WEN). Both the water- and energy systems form essential pillars for the functioning of urban areas that cannot be seen as separate elements. Furthermore, when considering decentralization as an 'infrastructure pathway', new solutions can be considered where more resources (e.g., rainwater and solar energy) are locally used. Figure 1 illustrates the difference between a centralized (left Sankey diagram) towards are more decentralized (right Sankey diagram) scenario for the water system. When using decentralization technologies (e.g., rainwater harvesting, greywater recycling and local hydrogen production), it is possible to make a transition from a linear towards a more circular water- and energy system, or decentralized WEN system. Therefore, the circular economy principle was used as a baseline for this research, as it becomes possible to include both water and energy as important resources. There are currently various assessment frameworks that facilitate the decision-making process for different infrastructure pathways. However, it was found that these frameworks do generally not evaluation indicator that go in line with a circular economy approach, such as resource recovery, self-sufficiency and integrality.

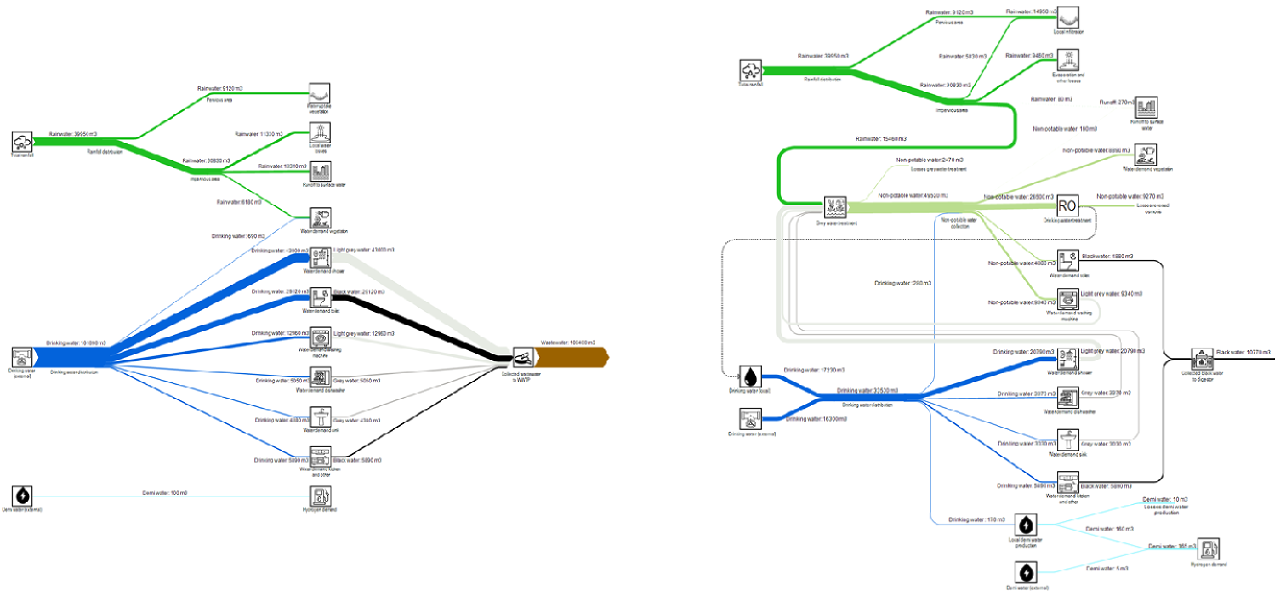

Figure 1: Example of a centralized versus a more decentralized water system

This research presents a six-step generic assessment framework (Figure 2) that can be used to evaluate different decentralized WEN systems. The first step ('case study selection') was formed to give the opportunity in setting up the research scope. It has the possibility to either select one neighborhood as a study case of multiple depending on the research objectives. After that comes a modular step ('design of scenarios') where it is possible to include different innovative technologies that are relevant for a more decentralized WEN system. The water- and energy balance can be modeled in the third step, providing insight into the (re)use of water- and energy sources on different temporal scales (yearly, monthly, and hourly). Subsequently, the generic assessment framework contains 13 evaluation indicators that are divided into four themes: (1) *water system*, (2) *value for people*, (3) *energy system,* and (4) *general characteristics*. The last step includes stakeholder perspectives to prioritize and weigh the indicators.

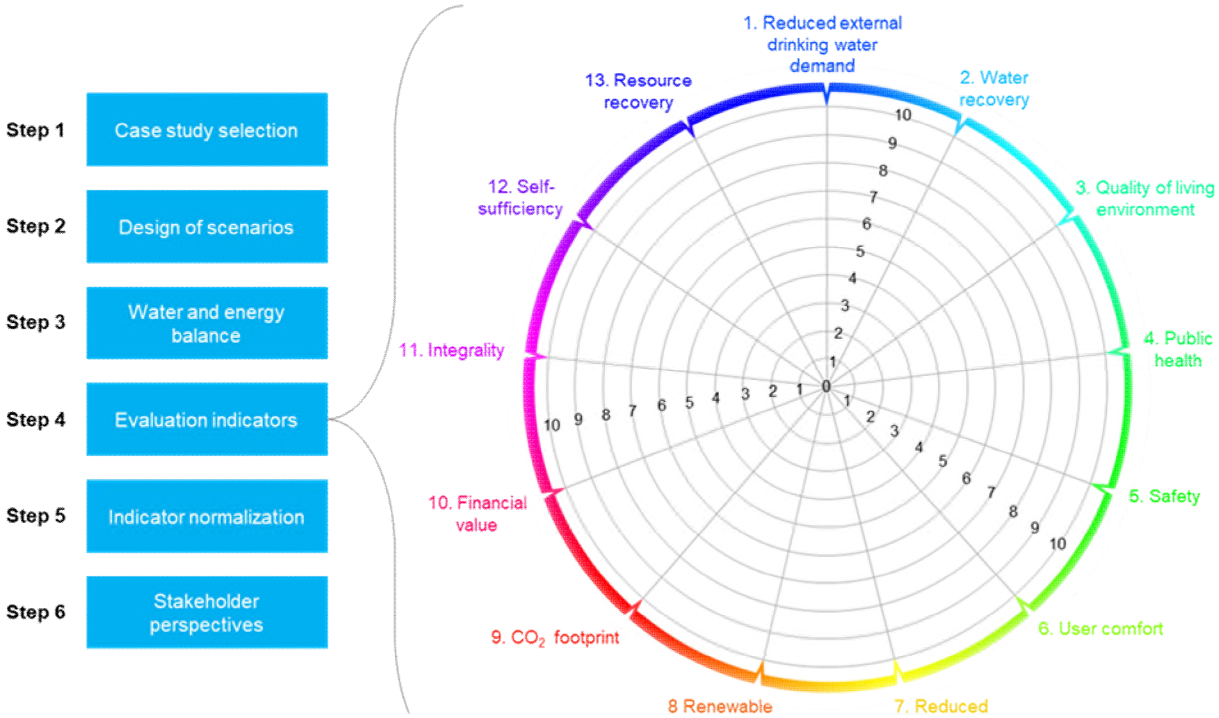

Figure 2: Summary figure of generic assessment framework

A modern Dutch neighborhood with a high building density (*City Nieuwegein*) was used as a case study to demonstrate the generic assessment framework. Four scenarios were designed (*reference*, *improved centralized*, *hybrid,* and *almost decentralized*) to assess the impact of a neighborhood with more decentralized WEN systems. The case study results showed that more decentralization strategies improved most indicator scores. Using different decentralized WEN systems (rainwater harvesting, greywater recycling, aquifer thermal energy storage, hydrogen conversion/storage, e.g.) increases the collection and storage of local water- and energy resources. Depending on the degree of decentralized WEN systems, 53-84% of the (drinking) water demand and 60-73% of the energy demand was covered by local water- and energy resources. It was found that neighborhoods with more decentralization strategies have a higher complexity (e.g., more required monitoring and spatial limitations) in implementation. Moreover, the investment- and maintenance costs can be up to 51% higher compared to a neighborhood with minimal decentralized WEN systems. However, the outcomes of the six stakeholder perspectives, used for this case study, showed that the scenario with the highest level of decentralization was, in all cases, preferred. Most evaluation indicators with a high prioritization (*reduced external drinking water demand*, *quality of living environment*, *safety, e.g.*) had higher scores for scenarios for more decentralized WEN systems. This ultimately outweighed the three indicators (*public health*, *user comfort,* and *financial value*), which scored lower for neighborhoods with more decentralization technologies.

The results of the case study showed that the generic assessment framework can be used to evaluate different decentralized WEN systems. The 13 evaluation indicators followed the circular economy principle as this favors future-proof concepts. Besides, the generic assessment framework included stakeholder perspectives so that it can facilitate the decision-making process of stakeholders. This framework can be further improved by including multi-objective optimization resulting in more scenarios that can be simulated. At last, more research is required for some qualitative indicators (e.g., user comfort and integrality) that improves evaluating the different scenarios.

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List of abbreviations

ASHP	Air-sourced heat pump
ATES	Aquifer thermal energy storage
BENG	Almost energy neutral building
BW	Blackwater
CAPEX	Capital expenditures
CHP	Combined heat power
COP	Coefficient of performance
DMW	Demi water
DW	Drinking water
DWTP	Drinking water treatment plant
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FEW	Food-energy-water
GHG	Greenhouse gas
GSHP	Ground-sourced heat pump
GW	Greywater
GWR	Greywater recycling
HHV	Higher heating value
KNMI	Royal Dutch Meteorological Institute
KPI	Key performance indicator
LCA	Life cycle analysis
LGW	Light-greywater
MCA	Multi-criteria analysis
NPW	Non-potable water
OM	Operation and maintenance
PV	Photovoltaic
QMRA	Quantitative microbial risk assessment
RO	Reverse osmosis
RQ	Research question
RWH	Rainwater harvesting
RWHS	Rainwater harvesting system
SDG	Sustainable development goal
SIMDEUM	SIMulation of water Demand
UHI	Urban heat island
UWOT	Urban Water Optioneering Tool
WEN	Water energy nexuss
WiCE	Water in the Circular Economy
WW	Wastewater
WWTP	Wastewater treatment plant

List of symbols

Name	Description	Units
a	Scenario	-
$A_{blue-green}$	Total blue-green spaces	m^2
c_n	Level of acceptance	-
$CAPEX$	Capital expenditures	EUR/year
D_1	Comprehensiveness dimension	-
D_2	Integration dimension	-
D_3	Governance dimension	-
d_n	Customer perspective fixed share	%
$DW_{benchmark}$	Drinking water demand benchmark	m^3/year
$DW_{t,0}$	No external drinking water demand	-
$DW_{external}$	External drinking water demand	m^3/year
$E_{grid,export}$	Surplus energy to grid	MWh/year
$E_{produced,local}$	Locally produced renewable energy	MWh/year
$E_{t,0}$	No external energy demand	-
$E_{benchmark}$	Energy demand benchmark	MWh/year
E_{total}	Total energy demand	MWh/year
Eco	CO_2 footprint individual system element	tonnes CO_2/year
ET	Evapotranspiration	mm/day
i	System element CO_2 footprint	-
j	System element financial value	-
L	Lifetime system element	Years
m	Number of indicators	-
n	Total number of system elements	-
$n_{residences}$	Number of residences	-
$N_{residents}$	Number of residents	-
OM	Operation and maintenance	EUR/year
$Q_{benchmark}^{runoff}$	Runoff benchmark situation	m^3/day
Q_{loss}	Water treatment loss	m^3/year
Q_{runoff}	Runoff to surface water	m^3/year
$Q_{scenario}^{runoff}$	Runoff specific scenario	m^3/day
Q_{ww}	Wastewater discharge	m^3/year
R	Incoming rainfall	mm/hour, mm/day or m^3/year
r	Discount rate	%
R_{net}	Net incoming rainfall	mm/hour
RR_{COD}	Resource recovery COD compounds	tonnes/year
RR_N	Resource recovery nitrogen compounds	tonnes/year
RR_P	Resource recovery phosphorus compounds	tonnes/year
$RR_{potential}$	Resource recovery potential	tonnes/year
s	Stakeholder	-
SC	Yearly system costs	EUR/year
t	Timesteps	Hours or days
t_{end}	End growing season	Day
t_{start}	Start growing season	Day
v_m	Normalized indicator score	-
$V_{normalized}$	Total normalized scenario score	-
V_s	Total weighted stakeholder score	-
$veg(t)$	Vegetational water demand	mm/day

w_m	Weighted indicator score per stakeholder	-
x_1	Reduced external drinking water demand indicator	m^3/year
x_2	Water recovery indicator	%
x_3	Quality of living environment indicator	m^2/house
x_4	Public health indicator	-
x_5	Safety indicator	%
x_6	User comfort indicator	-
x_7	Reduced external energy demand	MWh/year
x_8	Local renewable energy use indicator	%
x_9	CO_2 footprint indicator	tonnes CO_2/year
x_{10}	Financial value indicator	EUR/person/year
x_{11}	Integrality indicator	-
x_{12}	Self-sufficiency indicator	%
x_{13}	Resource recovery indicator	%
x_m	Relative indicator score	-
$x_{m,max}$	Maximum indicator score	-
$x_{m,min}$	Minimum indicator score	-
X	System element amount	-
X_m	Points given to indicator from stakeholder	-
α	Capital recovery	-
β	Correction factor plant type	-
γ	Difference normalized and weighted score	%
Δ_r	Incoming rainfall correction	mm/hour

1. Introduction

1.1. Background and problem statement

Urban areas across the globe often experience versatile challenges in the provision of water and energy, which are expected to increase even further in the future [1]–[5]. One of these challenges is the predicted growth of the global population, which is likely to be 9.7 billion in 2050 [6]. This will result in a higher demand for vital resources such as drinking water (DW) and energy [7]. In addition, urban areas need to become more sustainable, not only to withstand but also to minimize the effects of climate change [8]–[10]. A crucial action to accomplish this, is the reduction of the carbon footprint. Therefore, the current fossil-dependent energy system should be transformed into a renewable energy-based system [11]. The potential of renewable energy sources, such as solar and wind power are often spatially and temporally dependent, resulting in a disbalance between the overall energy supply and demand [11]. In addition to reducing the carbon footprint, the total water and energy footprint should also be diminished. Water and energy systems are broadly interlinked and are recognized as essential pillars for the functionality of urban areas [2]. This mutual relation between water and energy systems can be defined as a water-energy nexus (WEN) highlighting the interlinkages between the water and energy systems [12]. For instance, water infrastructure highly depends on energy with around 2-3% of the global energy production that is used for DW production, distribution and sanitation purposes [5], [13]. Another example is a common interest in the subsurface. Drinking water companies rely on groundwater as a freshwater resource, whereas the subsurface can also be used to create an aquifer thzzermal energy storage (ATES) system that stores heated water [11]. It is necessary to consider its correlation, as this adds more value to the use of limited water and energy resources [5].

Up until the end of the 20th century, the energy sector would take the availability of water resources for granted and the same would apply for the water sector concerning energy [14]. Since then, the need for a water-nexus approach has been increasingly recognized by policymakers as more awareness has been created through published research, among others [14], [15]. With such an approach, new infrastructure can be developed where the use of local water and energy resources are optimized, and the dependency on external resources is reduced. This principle also known as decentralization [12], [16]. An example of a decentralized energy system is the use of photovoltaic (PV) panels on rooftops for solar energy production combined with a battery to store surplus energy [11]. Rainwater harvesting on the other hand, can be identified as a decentralized water system where rainwater is collected and used as an alternative water resource instead of DW [17]. A WEN approach that incorporates decentralized water and energy systems can contribute in creating multi-sectoral solutions.

Developing sustainable urban areas, such as neighborhoods, goes beyond only reducing the water and energy footprint. A neighborhood should also be safe and livable for their inhabitants and environment. A safe DW and sanitation system is crucial for public health as this drastically reduces exposure to contaminants [18], [19]. Having a secure and reliable system depends on both the local and surrounding infrastructure that are interconnected. The requisite for this is a well-functioning waste management system, operating to ensure that harmful substances such as microplastics and medicines do not contaminate the environment [20]. The possibility to separate highly polluted wastewater (WW), such as blackwater (BW) containing urine and feces, can be an effective way of improving the total resource recovery and reducing the environmental impact [19]. In addition, separating and collecting BW in combination with organic (kitchen) waste offers opportunities for decentralized digestion and conversion to biogas. Another aspect of having a safe and livable neighborhood is incorporating enough green spaces. This can contribute to a better living environment as it will improve the biodiversity [21], reduce the urban heat island (UHI) effects [22], and it will lead to more pervious areas that reduces the rainfall runoff [23]. The social acceptance of a neighborhood concept should also be considered, allowing residents to live appropriate without having to make drastic changes in their habits [24].

Policy integration by decision-makers is considered a necessary solution that enforces sustainable neighborhoods [8], [25]. While the public sector often includes these development goals in the decision-making process, this is rarely included in urban development projects financed by private developers and investors [8]. An important reason for this impediment is the lack of direct financial benefits for a private investor [8]. Adaptation measures, such as improving the quality of the living environment, are often considered a side effect and not a goal [8]. Private investors expect financial benefits from urban development projects, but also like to improve its corporate and technological image [8]. To stimulate private sector mainstreaming, Dutch municipalities already use a mix of policy instruments, such as mobility, climate adaptation, and biodiversity [26]. A gap in the literature is that these policy instruments are often not effective and therefore, are not frequently used, hindering the implementation of integrated solutions that lead to sustainable neighborhoods [26].

New water and energy infrastructure strategies should contribute to the development of multi-sectoral solutions [25], [27]. This could result in a more effective policy integration than a traditional method, which mainly focuses on the value of an individual sector [28]. However, identifying the best solution to these complex problems and challenges remains difficult. One way to approach this integral assessment is by means of a framework that can assess different multi-sectoral solutions. Many indicators are already defined and used in performance measurement systems, or frameworks, to compare different strategies and solutions, such as quality of living, waste management, and water consumption [29]. It is often experienced that these frameworks are usually not applicable to evaluate different concepts [29], [30]. Current assessment frameworks generally focus on either the water or energy system. When taking the circular economy principle as a baseline, it becomes possible to include both water and energy as important resources [31]. However, there are currently no assessment frameworks that use this circular economy principle on a neighborhood scale. This brings forward the following problem statement:

Although there are already existing frameworks as a tool to facilitate the decision-making process of stakeholders, there is no framework available with a high applicability that would allow to assess different strategies of decentralized water-energy nexus systems in neighborhoods.

1.2. Approach

This paragraph comprises the research objective and its (sub-)research questions that have been defined based on the problem statement. In addition, an overview of the report structure will be illustrated.

1.2.1. Objective and main research question

This research focuses on creating a framework with a high 'applicability'. This implies that an assessment framework can be used to assess the performance of different decentralized strategies for a WEN system in a neighborhood. Decentralized strategies can have an important role in creating multi-sectoral solutions that could result in a reduced water and energy demand. This framework should also include indicators that goes beyond assessing the performance of the water and energy footprint such as safety, livability, and the quality of the living environment. In addition, it has also been mentioned in the problem statement that a framework should facilitate the decision-making process of the stakeholders. This has resulted in a general research objective:

Develop a generic assessment framework to evaluate the performance of different decentralized water-energy nexus systems in a neighborhood which can be used in the decision-making process of stakeholders to select the most favorable concept.

The problem statement from contained two elements focusing on (1) how different decentralized WEN systems can be evaluated and (2) how this can be used in the decision-making process of stakeholders. Based on these research objectives, the following main research question (RQ) has been formulated:

How can the impact of different decentralized strategies for a water-energy nexus system in a neighborhood be assessed, thereby incorporating the decision-making process of stakeholders?

To answer the main research question, it is essential to first determine what elements are necessary to develop a framework that can be used to assess different decentralized strategies, or scenarios. These scenarios will be formed by incorporating innovative water and energy technologies that are relevant for decentralized WEN systems. To keep this assessment manageable, the research will be specified with a pre-defined scope. Depending on the chosen scope, the boundaries can generally be set on a (larger) regional scale, or they can be set on a (smaller) domestic scale. For this research, the boundaries will be delineated on a neighborhood scale in the Netherlands. One of the benefits of using this as a scope is that the temporal fluctuations for both demand and supply of the water and energy systems are less extreme and more predictable compared to a domestic scale with high variations [32]. This could also be applicable on a city level, however this adds more complexity in acquiring a complete overview of the overall functionality of the water and energy system. In addition to the complexity and predictability of the demand and supply by using domestic scale, a neighborhood scale creates more opportunities for application of decentralized solutions.

The steps needed to answer the main research question will become clear with the sub-research questions that have been defined. In the next section, the sub-research questions together with the report structure will be explained.

1.2.2. Sub-research questions and report structure

The sub-research questions provides guidance for this research and forms the basis for this research methodology and the report structure.

- ***(1A) What innovative water and energy technologies can be used in a neighborhood that are relevant for decentralized water-energy nexus systems?***
  There are different innovative water- and energy technologies that can be used in a neighborhood. A literature study should provide more insight in terms of the strengths and weaknesses of these innovations. With this knowledge, it is possible to integrate these technologies into different decentralized WEN systems which is relevant for the continuation of this research.

- ***(1B) How does a generic assessment framework look like that allows to evaluate different decentralized water-energy nexus systems and includes the stakeholder perspectives?***
  The objective is to develop a generic framework that consists of relevant evaluation indicators to compare different decentralized WEN systems, or scenarios, for a selected neighborhood. In addition, this generic framework should include the perspectives from different stakeholders which would be necessary for the decision making process. A literature review will be done that provides insight in the available assessment tools.

- ***(1C) How do different degrees of decentralized water-energy nexus systems impact the performance of a neighborhood?***
  The developed framework provides a tool to assess the different decentralized WEN systems. In this way, it is possible to explore whether or not decentralization has a positive impact on aspects such as water and energy demand, resource recovery and self-sufficiency.

- ***(1D) How does the perception of stakeholders impact the assessment of different decentralized water-energy nexus systems?***
  The stakeholder perspectives provide insight into the importance of the different evaluation indicators that have been defined for the framework. By conducting interviews with stakeholders, it is possible to draw conclusions on how their perspectives can be incorporated in the decision-making process.

The report structure (Figure 3) can be divided into six main components. The problem statement and research set-up has already been elaborated (Chapter 1). The second part of the report is the literature review which can be found in Chapter 0. The literature review will be used the answer the first sub-research question (*1A*) by evaluating different innovative water and energy technologies. In addition, the literature review will also cover different assessment tools that are part of the second sub-research question (*1B*). Chapter 3 will provide the materials and methods to develop the generic assessment framework in order to answer the second sub-research question (*1B*). In Chapter 0, a case study was selected for the generic assessment framework. The results present answers to the last two sub-research questions (*1C* and *1D*). The discussion will be provided in Chapter 5. At last, the conclusions and recommendations can be found in Chapter 6 which addresses the main research question.

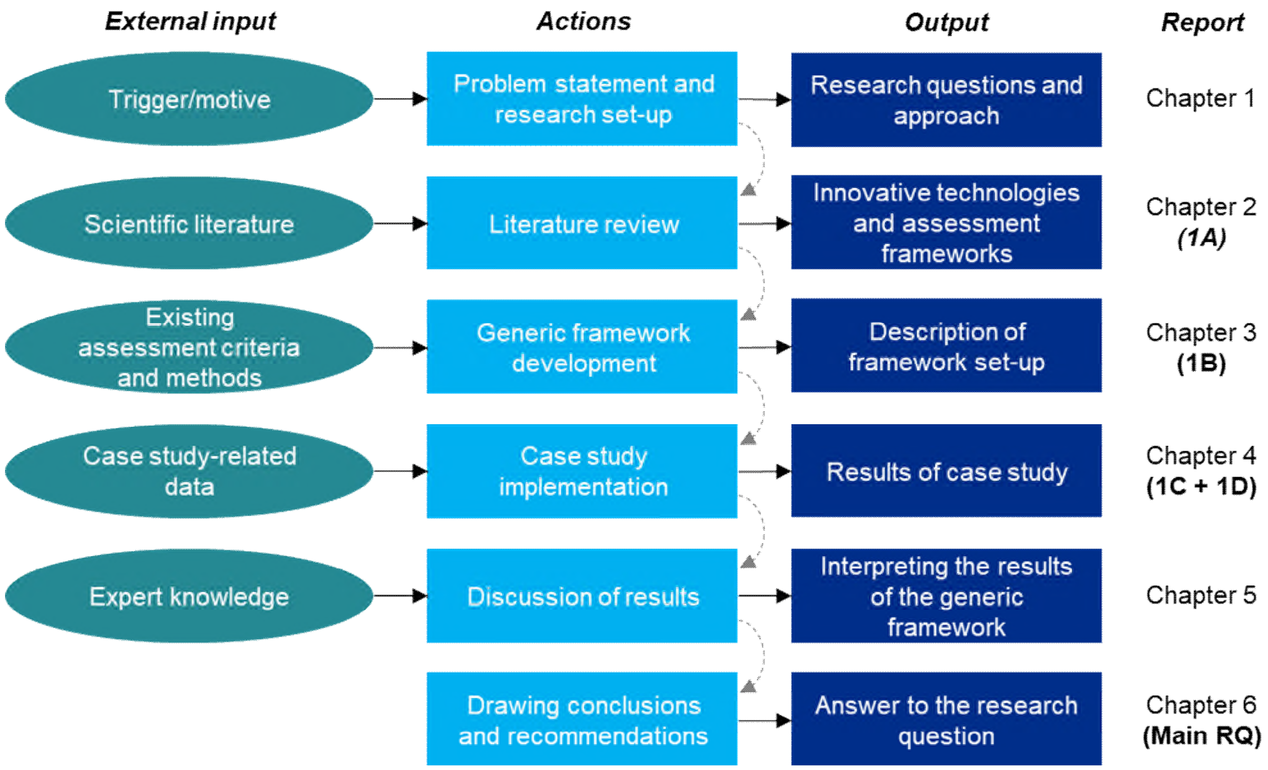


Figure 3: Report structure

2. Literature review

A literature review has been conducted to explore and compare decentralized WEN systems. The first part of the literature review describes innovative water and energy technologies that can be used in a neighborhood. This section will answer the first sub-research question (*1A*) formed earlier in this report. The second part describes different assessment frameworks that will be used as a reference to develop a generic assessment framework that can evaluate different decentralized WEN systems and includes the stakeholder perspectives.

2.1. Innovative water and energy technologies

This section will elaborate on innovative water- and energy technologies that can contribute to more decentralized water-energy-nexus systems. The first part describes different water-based technologies (section 2.1.1 to 2.1.5), whereas the second part focuses on energy-based technologies (section 2.1.6 to 2.1.8).

To start with, the different types of water sources that are frequently mentioned for these innovations will be elaborated. Water can originate from various sources with a variation in availability and quality (Table 1). The main water types or products can be divided into natural water sources, (non-) potable water, WW, and demi water.

Table 1: Definition of water types

Water types/products	Abbreviation	Characteristics (origin, quality, e.g.)
Rainwater	-	*Water originating from precipitation. The quality highly depends on the air quality and the characteristics of the runoff area* [33].
Surface water	-	*Water originating from the earth's surface, such as rivers, lakes, and oceans. The water quality highly depends on its origin* [34].
Groundwater	-	*Water stored in the subsurface can be used as a drinking water source. The quality highly depends on the soil properties (e.g., unconfined and confined aquifer).*
Non-potable water	***NPW***	*Water (also known as household water or 'huishoudwater' in Dutch) that can be used for vegetational water demand (irrigation) and non-potable water demand (toilet flushing and washing machine).*
Drinking water	***DW***	*Drinkable water that is purified with several treatment steps*
Light-greywater	***LGW***	*WW originating from showers and washing machines which are relatively low in pollution* [35].
Greywater	***GW***	*LGW together with WW originating from the dishwasher and sink which is more polluted than LGW but still reusable.*
Blackwater	***BW***	*WW originating from toilets and the kitchen sink is rich in nutrients and pollutants (bacteria, medicines, e.g.).*
Wastewater	***WW***	*This is the collection of all domestic WW, which is GW and BW.*
Demi water	***DMW***	*Water that can be used for high-quality purposes, such as the production of hydrogen*

2.1.1. Domestic water-(energy-)saving appliances

The literature often refers to the use of water-saving appliances that can have a positive impact on reducing the DW demand [36]–[39]. In practice, these technologies also influence the energy demand when considering the WEN. Reducing the DW demand and WW discharge results in lower energy demand for drinking water treatment plants (DWTPs) and WW treatment plants (WWTPs) [2], [40], [41]. Additionally, a higher energy recovery can be achieved with domestic water-energy-saving appliances. Examples of appliances are discussed below such as recirculating showers and vacuum toilets [19][30].

Recirculating shower

A recirculating shower can save more water and energy compared to conventional-, water-saving- and energy-saving showers. Water-saving showers differ from conventional showers as they have a shower head that reduces the water demand by 21% [30]. There are also energy-saving showers that use a heat exchanger to recover energy from collected water, saving between 57-64% energy depending on the initial DW temperature [42]. Using a heat exchanger would result in higher investment costs and requires more maintenance [42][43]. On the other hand, the payback period of a heat exchanger, which costs approximately €500, is between 4-13 years, depending on the number of occupants that use a heat exchanger [42]. In addition, the payback period could be reduced even further as it is based on previous electricity and gas tariffs of 0.23 €/kWh and 0.55 €/kWh, whereas this is currently 0.4 €/kWh and 1.45 €/kWh respectively [44]. With a recirculating shower, water is collected and treated directly for reuse, resulting in an even lower water demand of 71% [30] together with the energy-saving benefits.

Vacuum toilet

Compared to conventional and dual flush toilets (5-9 L water/flush), vacuum toilets (0.5-1.2 L water/flush) require much less water for flushing [30], [37], [45]. In addition, vacuum toilets are acknowledged as a technology that can contribute to better source separation that increases the recovery potential especially for BW [46]. Contrary, it was found that the anaerobic digestion of conventional and dual flush toilets have a higher methane recovery potential (48%) compared to vacuum toilets (34%) [45]. It appeared that a higher ammonia concentration, which can be found in the effluent of vacuum toilets, reduces the digestibility. However, if BW from a vacuum toilet is combined with kitchen waste, the energy recovery can increase by 104% [19]. Although vacuum toilets require more energy for flushing compared to conventional toilets, it does result in a positive energy recovery (+22.5 MJ/p/y), whereas centralized WWTPs require more energy for the treatment steps than it can recover (-107 MJ/p/y)[19]. Another downside of vacuum toilets is that they produce more noise than conventional toilets. Fortunately, vacuum toilet are generally accepted by customers due to the water- and energy-saving benefits and they have improved over the years in reducing the noise [30].

Remaining water-energy-saving appliances

Based on the average Dutch DW demand (119.2 L/p/d), approximately 28% of the total DW demand is used different than for toilet flushing and showering [47]. For this part, there are also noteworthy possibilities to reduce the overall water and energy demand. For example, eco-friendly dishwashers and washing machines have a lower water and energy demand than conventional appliances [48], [49]. Water-saving faucets can achieve over 50% of water savings and reduce energy demand for heating and pumping [50].

2.1.2. Rainwater harvesting

The process of collecting and storing rainwater is often referred to as rainwater harvesting (RWH) [12], [17], [33], [51]. One of the benefits of RWH is that it can be a solution to minimize the negative effects of urbanization (higher runoff) and climate change (more extreme rainfall events and droughts) [33][17]. The risk of urban flooding can be reduced because RWH systems can increase the total storage capacity and contribute to better stormwater management [2], [17]. In addition, using harvested rainwater as an alternative water source can reduce water stress in urban areas during droughts.

Rainwater is often considered a clean water source, which is available in high quantities and can be used for potable or non-potable purposes, such as toilet flushing and for washing machines [33]. Compared to surface water that might contain WWTP effluent (medicines, microbial contaminations, e.g.), rainwater would be more suitable for the production of DW [33]. However, the quality of rainwater is very variable and depends on different aspects. For instance, the surface type where the rainwater comes to runoff or the air quality affects the rainwater quality [34]. A first flush system could improve the harvested rainwater quality as the highest concentration of contaminants can be found in the initial runoff after a dry period [51]. Rainwater is typically harvested in ponds or storage tanks even though there is no consensus on whether or not storage tanks should be used [33][51]. One paper suggests that rainwater should be collected in ponds as rainwater tends to become anaerobic, which would deteriorate the water quality [33]. Another paper suggests the opposite, collected rainwater in closed tanks with absent natural light and under cool conditions decreases microbial concentrations by 70-90% after a storage time of 1 week [51].

The feasibility of RWH strongly depends on the quality and availability of rainwater. The storage tanks are often designed to have enough storage capacity to cover long dry periods (>4 weeks) [51]. In addition, it is also necessary that the storage capacity can collect multiple heavy rainfall events within 24 hours. The dimensions of the storage tanks that are required affect the total costs. In addition, the capacity of the purification systems for the production of DW should also be sufficient. Next to the costs of a rainwater harvesting system (RWHS), the environmental impact and energy demand are often used as indicators to assess the feasibility. A life cycle analysis (LCA) is a common tool to evaluate the environmental impact (climate change, human health, resource depletion, e.g.) of the different treatment processes that are required [4], [33], [37], [41]. Whether or not RWH is feasible as an alternative to centralized DWTP highly depends on the boundary conditions (yearly rainfall, DW demand, study case location, e.g.). The total reduction of DW demand highly varies from 26% [7] to 50% [33] or even up to 79% [17]. The literature didn't provide any examples of studies in which the DW demand could be totally provided by RWH [17]. Depending on the scope and the treatment steps used, RWH would either result in reduced energy demand of up to 20% [7] or increased energy demand by 0.9-2.3% [12]. The reduction in greenhouse gas (GHG) emissions varies from 0.14-1.38 kg CO_2/m^3 [17], [33]. However, other studies show that if purification installations for RHW are included, the environmental impact is not lower compared to a centralized situation. Finally , results on the financial feasibility also showed both viable and inviable outcomes [17], [33].

2.1.3. Wastewater recovery

Another water source that can be reused on a local level is greywater (GW). Approximately 70% of domestic WW can be categorized as GW [47]. Greywater recycling (GWR) is an innovative technology that recycles GW that is relatively low in pollution, such as the shower and washing machine [12]. With GWR, it is possible to reduce the DW demand from a centralized DWTP [12], [38], [52]. In practice, it is common to combine GWR and RWH to optimize the usage of local water sources [41], [52]–[54]. In contrast to a fluctuating availability of rainwater, GW supply is more constant with lower fluctuations in availability.

Separating WW into a GW and BW stream reduces the total amount of WW that needs to be transported to a WWTP. In addition, BW has a higher concentration of resources (phosphorus, nitrogen, biogas, e.g.) than 'regular' WW. This gives more opportunities to improve the recovery of these resources or to extract more contaminants that would otherwise end up in the environment [46]. However, GWR does require a more advanced separate drainage system, as this is essential to ensure that only GW is collected [55].

2.1.4. Blue-green infrastructure

Blue-green infrastructure can be used in urban areas for stormwater control and treatment of GW [4], [17], [38], [56], In addition, it can have a positive impact on biodiversity and reduces the urban heat island (UHI) effects [57]. Blue-green rooftops are an example of infrastructure that can result in these benefits [58]. Blue-green rooftops are designed to store rainwater that is being used for its vegetational water demand. The drawback of blue-green rooftops is that less rainwater can be harvest and used for domestic purposes (toilet flushing and washing machine).

Another green infrastructure example that can be used in urban areas are helophyte filters. Helophyte filters are used to improve the quality of rainwater and GW [56], [57], [59]. The concept is that polluted water is naturally purified by the micro-organisms (biofilter) that are present in the helophytes [57]. In general, these bacteria need oxygen to survive, but also use waste products from rainwater and WW as a source, that eventually can be converted into nutrients for the plants that on their part produce oxygen. This creates a natural purification method that doesn't need any additional resources. The purification efficiency is high, while the energy demand is low [59]. The treated water does not yet meet the standards that would allow it to use as DW, but it can be used for non-potable purposes or safely discharged to surface water [56]. A previous literature study found that the hydraulic loading rate can be around 500-800 $L/m^2/d$ with a high removal rate for organic matter (80%), nitrogen (60-80%), and suspended solids (>90%) [38].

2.1.5. Health implications on decentralized water systems

A sufficient purification system is required if rainwater and GW are harvested and treated for potable or non-potable purposes. With a quantitative microbial risk assessment (QMRA), it is possible to estimate the risk of infection after exposure to contaminants [53]. A Depending on the water appliance (toilet, shower, water tap, e.g.), potential health implications can occur from exposure to untreated rainwater or GW [53]. It was found that the inhalation of aerosols that contains Legionella pneumophila is the main risk of infection, which is above the Dutch benchmark of 10^{-4} pppy (per person per year). In addition, cross connections between DW and collected GW or rainwater also lead to a high infection risk through drinking and showering. Since 2003, the Dutch drinking water law only allows rainwater to be used as an alternative water source besides DW for toilet flushing [33]. For the other domestic water demands, only DW is allowed. This is partly because in 2001, around 200 people got ill due to the cross-connection of drinking and non-potable water [18], [60].

There are existing decentralized treatment systems that produce DW from collected GW and rainwater [3], [12], [41]. Reverse osmosis (RO) is often used as a treatment process to produce safe DW [33], [52], [61]. As mentioned for RWH, the overall costs and feasibility of decentralized treatment systems depend on the scale that is being used [33]. Similarly to centralized treatment facilities, decentralized systems require careful monitoring and maintenance to ensure that the DW quality meets the regulations of the Dutch drinking water law [33].

2.1.6. Aquifer thermal energy storage

Aquifer thermal energy storage (ATES) is seen as a promising water-energy-nexus technology that can minimize or replace the use of fossil fuels and reduce CO_2 emission by 40-70% compared to conventional heating systems [11], [62], [63]. An ATES system, or open-loop system, can be used for seasonal storage of heat and cold in the subsurface through injection and extraction of groundwater [62]. An overview of an ATES system can be seen at Figure 4 which was used from Rostampour et al. (2019) [63]. In summer, the cold well is used for the cooling demand, and the warm well is recharged. The opposite happens in winter; the warm well is used for the heating demand, and the cold well is recharged with cold water. An ATES system typically operates with a separate heat and cold well ('doublet') [64]. The heat is generally transferred to a heat pump (section 2.1.7) with a heat exchanger [65]. The applicability of ATES systems depends on the hydrological conditions of an aquifer [62]. It should be considered that it is currently not allowed in the Netherlands to have an ATES system in a designated area that is protected for DW production [64]. Approximately 70% of ATES systems are used for public and commercial buildings, and the remaining 30% for modern residential and industrial buildings with good isolation [64]. In 2017, most of the ATES systems (85%) across the globe were operational in the Netherlands, with a total of 2,500 in 2017 [62]. This number has increased to over 3,000 ATES systems in the Netherlands in 2022 [64].

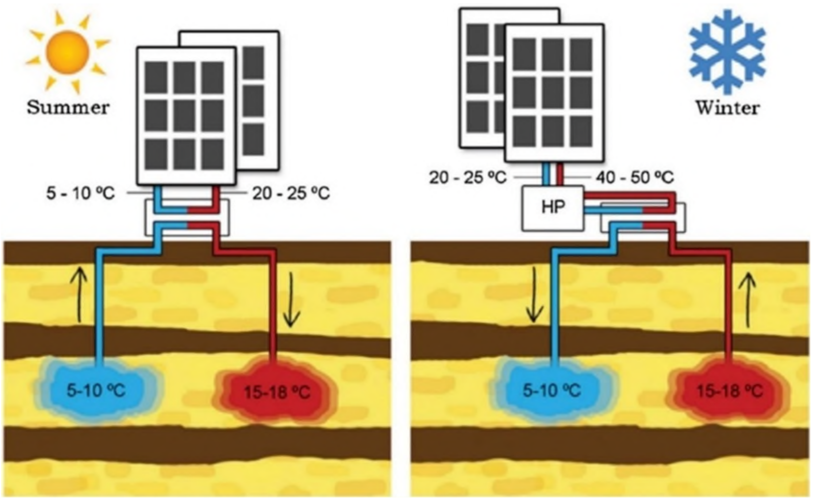


Figure 4: Principle of ATES system (Bloemendal et al., 2020)

2.1.7. Heat pumps

Heat pumps increase the water temperature, which is functional for heating buildings [64]. There are different types of heat pumps, such as ground-sourced heat pumps (GSHP) [66], air-sourced heat pumps (ASHP) [67], and water-sourced heat pumps [67]. A higher initial temperature of the heat source results in a higher coefficient of performance (COP) of the heat pump [67]. In other words, a higher COP indicates that less additional energy (electricity) is required to heat water to a fixed temperature. It was found that an ASHP is less efficient, especially during winter when the air temperature is low and the heating demand is high [67]. Heat pumps that are ground- or water-sourced generally function with more constant temperatures resulting in a 10-20% higher efficiency [66].

2.1.8. Battery and hydrogen energy storage

Both batteries and hydrogen conversion can be used as innovative technologies to store surplus energy and mitigate grid overvoltage [11], [68]–[70]. Due to the limited storage capacity and high capital costs for batteries [67], it is generally not a feasible technology for long-term (seasonal) storage. For long-term seasonal storage, other energy carriers are more feasible, such as hydrogen or heat (see section 2.1.6 about ATES systems). There are different pathways for using batteries as temporal energy storage. For example, batteries of electric vehicles (EVs) can potentially contribute to reducing grid overvoltage for both electricity import and export [11], [71]. EVs can be charged at periods when there is relatively much energy available (e.g., during the day with peaks of solar power), and the batteries can be used when there is not enough renewable energy available. Fuel cell electric vehicles (FCEV) can also be used for the same purposes [68]. An alternative is installing individual batteries that can only be used by a single household or collective batteries that are used on a larger scale [71].

In contrast to batteries, hydrogen storage is more applicable to use as an energy carrier for a more extended period [67]. An electrolyzer can produce hydrogen from demi water and electricity, and a fuel cell converts hydrogen back into electricity. However, the overall efficiency of approximately 45% for the production (80%)[72] and conversion (60%)[72] of hydrogen is lower compared to the efficiency of batteries (90%)[67].

2.1.9. Summary on *innovative water and energy technologies*

There are different innovative water and energy technologies available that can be used as decentralized WEN systems. On a household scale, water-energy-saving appliances can reduce the overall water- and energy footprint. On a larger neighborhood scale, there are different possibilities for reusing local water resources, such as rainwater harvesting (RWH) and greywater recycling (GWR). With blue-green infrastructure, more water can be retained within the neighborhood, recovered water can be treated, and the overall biodiversity can be improved. A necessary condition for the implementation is that these decentralized systems are safe with little risk of exposure to pathogens. For the energy system, batteries and local hydrogen production can be used to store surplus renewable energy that can be used when the energy demand is higher than the local renewable energy use. At last, the literature shows that aquifer thermal energy storage (ATES) systems have a high potential to reduce GHG as this is an efficient technology for seasonal heat and cold storage.

2.2. Assessment frameworks

As mentioned in the problem statement (section 1.1), many indicators are already defined and used in assessment frameworks to compare different strategies. Still, it is often experienced that these frameworks are usually not applicable to evaluate and compare the different concepts [29]. This section will look at different assessment frameworks for decentralized WEN systems that have been developed.

2.2.1. Urban water cycle framework

To quantify the performance of decentralized water-focused systems, such as rainwater harvesting (RWH), greywater recycling (GWR), and sustainable urban drainage, a simulation-based framework (Figure 5) was developed by *Bouziotas et al. (2019)* [30]. This study found that there were few methods and tools to assess the performance of these decentralized solutions, especially for real cases. Therefore, stakeholders and decision-makers can use this simulation-based framework to evaluate modeled water concepts on a neighborhood scale. The results of the simulation-based framework can be used to assess the different scenarios on six Key Performance Indicators (KPIs). These KPIs focus on the reduction of DW demand and WW discharge. In addition, the achieved reduction of runoff is also an important indicator that evaluates the flood event reduction and how reliable a system operates concerning the continuous availability of water sources from RWH and GWR.

	KPI	Unit	Description	Stream
1	Achieved reduction in household consumption (RHC)	% of demand reduced	Tap-level WDM metric, reduction in water requested from households before RWH/GWR take place	DW—demands
2	Reduction in (clean) water requested from central service (RDW)	% of reduction of demand requested from central service	Measure of **system autonomy,** dependent on al techs in place (appliances, RWH, GWR)	DW—demands
3	Reduction in WW that leaves the system (RWW)	% of WW reduced	Measure of **system autonomy** or (vice versa) dependence on central services (sewer network)	Generated WW
4	Achieved runoff reduction (RAR)	% of runoff reduced (annual)	Measure of the SUPERLOCAL ability to **hold water**	Runoff
5	Achieved flood event reduction (RER)	% of event-based runoff reduced	Measure of the SUPERLOCAL ability to **mitigate flood peaks**	Runoff
6	System design reliability (REL)	% of time steps that the system operated well	How **reliable** different parts of the system are against inefficiency (storage full, overflow)	Runoff

Figure 5: Example of water cycle assessment framework (Bouziotas et al., 2019)

2.2.2. Environmental performance framework for buildings

Another framework (Figure 6), developed by the European Commission in 2017, focused on assessing the performance of environmental sustainability of European office and residential buildings [73]. This framework was developed to analyze the life cycle environmental impact and resource efficiency with six main themes on a building scale. The various indicators were developed to achieve a circular economy, reducing the greenhouse gasses (GHG) and to stimulate the renovation of existing buildings [74]. The method includes literature reviews, surveys/interviews and indicators for the evaluation and assessment of a building. To calculate these indicators, different Life Cycle Assessment (LCA) software tools and datasets were implemented to support this framework.

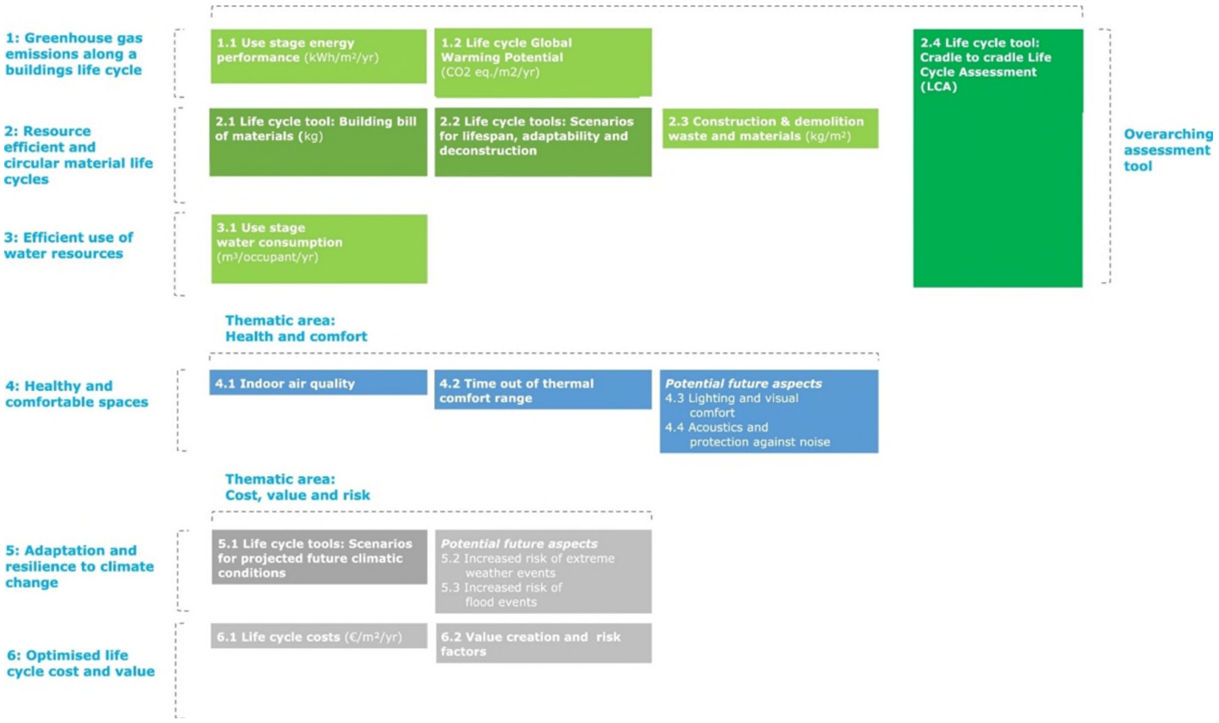


Figure 6: Example of environmental performance model for buildings (n.d., 2023)

2.2.3. Circular economy principle in the water cycle

A collaborative research program, ‘Water in the Circular Economy’ (WiCE), was formed by the Dutch water companies and other partners in de water cycle [75]. The goal was to contribute to social issues, such as the circular economy, climate adaptation, and the transition towards sustainable energy supply. With this research program, an assessment framework was formed that focused on three main themes (Figure 7): (1) *energy- and material flow*, (2) *value for people*, and (3) *system characteristics*. For all 16 indicators, a baseline measurement was performed to evaluate the water cycle's progress of the water companies over the years on a national level.

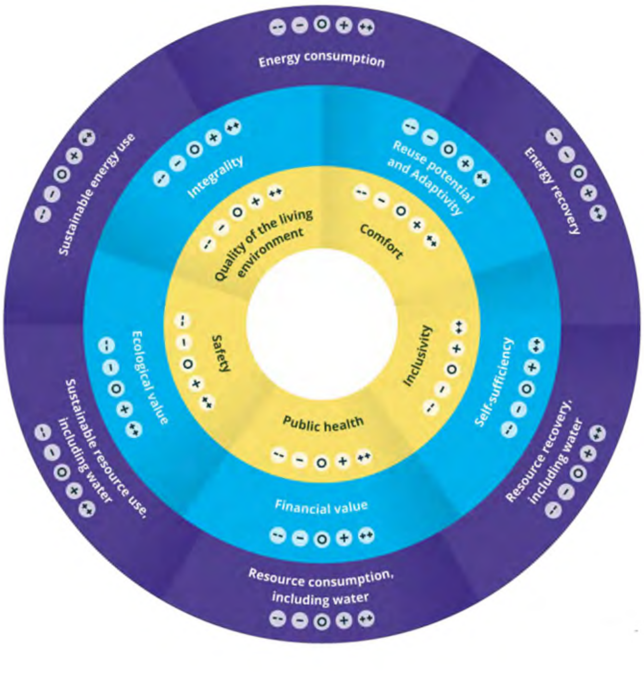


Figure 7: Overview of circular economy principle in water cycle (Segrave et al., 2020)

2.2.4. Integrative (modeling) framework

An integrative (modeling) framework was developed by *Valencia et al. (2022)* [4] to assess different food-energy-water (FEW) nexus concepts on a household scale. The integrative modeling framework (Figure 8) includes indicators such as the carbon-, water- and ecological footprint, food resilience and energy supply reliability. A Multi-criteria analysis (MCA) was included in this framework for the decision-making process. When applying a MCA, it is possible to get a specific weighing factor that allows to have a distinction between indicators with a lower/higher prioritization [4][1][76]. This is a common method for choosing the best-case scenario.

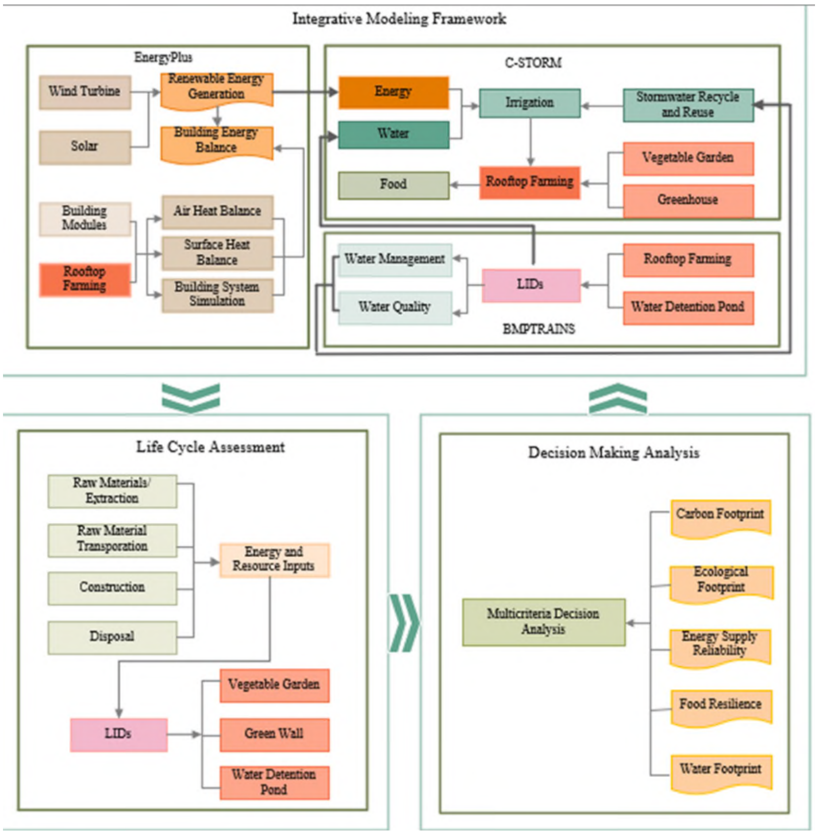


Figure 8: Example of integrative modeling framework (Valencia et al., 2022)

2.2.5. Summary on assessment frameworks

There are many frameworks with unique tools and methods (Table 2) to assess the performance of different water- and energy-based indicators, such as water- and energy footprint, recovery, sustainability, resilience and reliability. Besides, more general indicators are being used, such as public health, quality of living environment, user comfort, and safety. All frameworks have a specific research objective, which sometimes focuses on individual buildings, neighborhoods, or the entire water cycle of a country. For this research, a new assessment framework needs to be developed that is applicable on a neighborhood scale that includes decentralized WEN systems. The current assessment do not meet these indicators as it is either applicable on another scale or it doesn't focus both water and energy systems.

Table 2: Overview characteristics assessment frameworks

Assessment framework	Applicable scale	Indicator themes	Decision-making process
Urban water cycle framework	Neighborhood	Water system (e.g., water demand, wastewater discharge and reliability)	Individual scores per indicator
Environmental performance framework for building	Household	GHG emissions, material/resource use, health & comfort, adaptation & resilience to climate change and life cycle costs	Individual scores per indicator
Circular economy principle in the water cycle	National/regional	Energy & resources (e,g., energy demand and resource recovery), social characteristics (e.g., public health and comfort) and system characteristics (e.g., self-sufficiency and financial value)	Individual scores per indicator
Integrative modeling framework	Household	Carbon footprint, ecological footprint, water footprint, energy supply reliability and food resilience	Multi-criteria analysis

3. Materials and methods

In this chapter, the materials and methods that have been used for the development of the generic framework will be explained. The literature review already provided some examples of innovative water and energy technologies and assessment frameworks. For this research, a generic framework was created that consists of six steps (Figure 9). The generic framework was developed in such a way that it can be used by decision makers (e.g. municipalities and governments) and researchers to evaluate different decentralized WEN systems for future implementation. In the next sections, the origin of the different steps are explained.

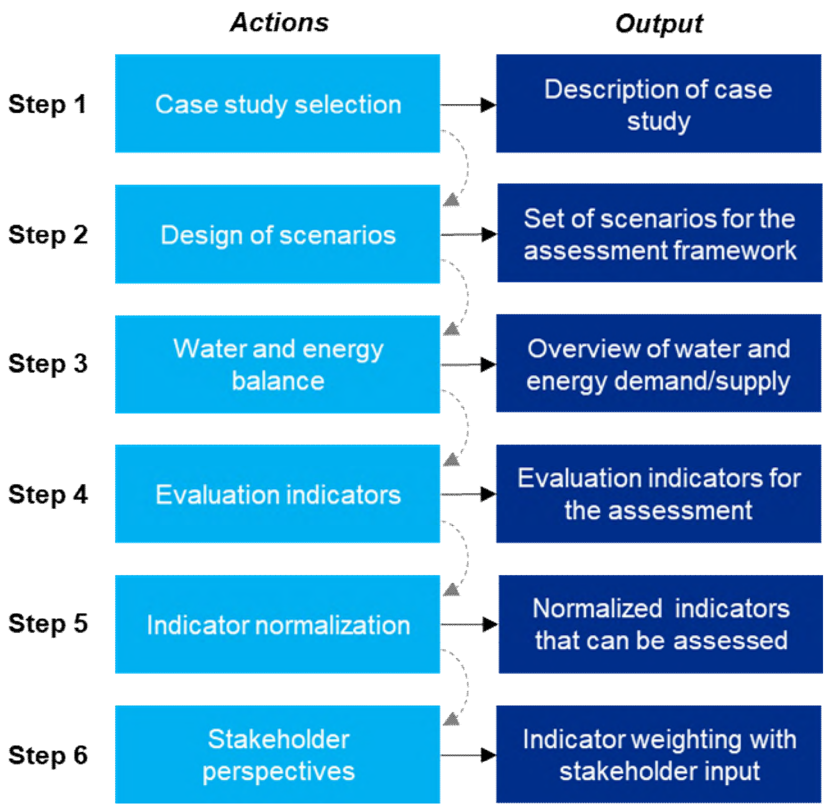


Figure 9: Main steps generic assessment framework

3.1. Step 1: Case study selection

The first step describes how one or multiple neighborhoods can be selected depending on the research objectives. With one neighborhood, or case study, it is possible to evaluate the impact of different innovative technologies. To assess the impact of different neighborhood characteristics (e.g., population and building density), it is possible to use multiple case studies. Studies that developed an assessment framework, often used a case study to show how an assessment framework can be implemented in practice [2], [4], [7], [30]. With a selected case study, the neighborhood characteristics would define the water and energy demand/supply to evaluate different decentralized WEN systems.

Spatial boundaries

The spatial boundaries are intended to assess the impact of decentralized WEN systems within the neighborhood. However, required water- and energy infrastructure outside the research scope will be included to make a fair comparison between scenarios with different dependencies on these ‘centralized’ systems.

Neighborhood area distribution

The neighborhood area can be divided into permeable and impermeable surfaces. Permeable surfaces can be used in different forms and allow rainwater to infiltrate into the subsurface. Green spaces typically have a high infiltration capacity. Permeable pavements can also be used with either porous material or nonporous segments that have gaps to increase the local infiltration rate compared to impermeable surfaces [77]. In addition, it is possible to define how much rainfall can be stored locally on impervious surfaces (rooftops, public spaces, e.g.) to reduce the initial runoff. Ultimately, the permeability and local storage capacity impacts the amount of rainwater that comes to runoff and can be collected with RWH systems.

Population and building density

For the case study selection, it is essential to define the number of inhabitants in the neighborhood. Based on the residential occupancy, the total number of residences can be defined together with the average housing area. These characteristics will determine how much water- and energy resources are required to meet the demands and how many resources are eventually returned.

Mobility characteristics

Mobility characteristics are relevant as this contributes to the overall demand for water- and energy resources. Therefore, it has to be determined how many parking spaces will be available and what type of vehicles will be used, such as electric vehicles (EVs), fuel cell electric vehicles (FCEVs) and (bio)fuel vehicles. Especially EVs and FCEVs impact the neighborhoods' water- and energy infrastructure. These vehicles can be reloaded or recharged partly or entirely with locally produced electricity and hydrogen, whereas (bio)fuel is only assumed to be available at external fuel stations. At last, the average distance a vehicle will drive in a year will determine how much energy is required for fueling.

3.2. Step 2: Design of scenarios

After a neighborhood has been selected and defined, it is a common follow-up to design different scenarios based on the water and energy supply/demand (Figure 10) that applies [30], [46], [67], [78]. For each scenario, a decision can be made to what extent decentralized WEN systems will be used. Figure 10 gives an illustration of the different systems design characteristics and technology options that could be taken into account in the design process of the scenarios. For example, it is possible to incorporate rainwater harvesting systems (RWHs) that can collect and store runoff originating from *rainfall*. Optionally recycling (light-)greywater combines with RWH can be used to cover the *vegetational water demand* and *non-potable water demand*. Depending on the type of DWTP, it is possible to produce DW locally for the *drinking water demand*. The *WW discharge* can be separated, recovered and reused for different purposes such as GW recycling and biogas production. The *demi water and hydrogen demand* is primarily required for FCEVs. The *electricity demand* represents the total amount of electricity that is required for the household applications and EVs. The *heating and cooling demand* covers the total amount of energy that is required for the heating and cooling of residences. There are different energy carriers that can be used to store *surplus energy* such as batteries and the conversion to hydrogen.

Demand/supply	System design characteristics	Description
Rainfall	Rainwater harvesting system (RWHS)	The net incoming rainfall that can be harvested.
Vegetational water demand	Green spaces	The total vegetational water demand based on the total area of green spaces.
Non-potable water demand	Separated domestic distribution system	The presence of a domestic distribution system for toilet flushing and the washing machine.
Drinking water demand	Centralized DWTP and/or local DW production facility	The presence of a local drinking water production facility besides DW from a centralized DWTP.
Wastewater discharge	Sewage system, greywater recycling and/or blackwater treatment	The presence of centralized and/or decentralized wastewater treatment facilities.
Demi water and hydrogen demand	Hydrogen import and/or local demi water and hydrogen production	Imported demi water and hydrogen and/or a local electrolyser for hydrogen production.
Electricity demand	Grid connection, PV panels, fuel cell and/or biogas	Electricity supply from the grid and/or decentralized energy production.
Heating and cooling demand	Heat exchanger and/or heat pump	The presence of a heating/cooling network for seasonal heating and cooling demand.
Surplus energy (conversion/storage)	ATES system, battery and/or electrolyser	Decentralized conversion and storage of surplus energy from PV panels.

Figure 10: General water- and energy supply/demand for a neighborhood

3.3. Step 3: Water and energy balance

The next step of the generic assessment framework is setting up the water and energy balance. This would allow to quantify all the demands and supplies of the water and energy resources on a yearly average basis, but also at a smaller monthly/hourly temporal scale. It is a common step to determine what modeling tools and data are required to quantify and evaluate different scenarios that have been designed [11], [30], [46], [67]. The upcoming sub-sections provide an explanation what modeling tools and data can be gathered to come up with the water and energy balance which is based on Figure 10.

3.3.1. Modeling tools

This research uses different modeling tools to elaborate the water and energy balance for a certain scenario that has been designed. In practice, the outcomes of the water and energy balance are often represented in a Sankey diagram, for example in the study of van der Roest et al. (2021), to illustrate how the supplies and demands are processed for the water- and energy systems [1], [70], [79][67]. The Sankey diagrams will also be used to give a visual overview of the yearly water and energy balance. For all modeling tools, it was possible to use hourly time-steps which allows to process the hourly meteorological data (section 3.3.2).

SIMDEUM

To determine the hourly water- and energy demands/supplies of a neighborhood, a modeling tool was required that could generate these hourly patterns. Therefore, SIMDEUM (SIMulation of water Demand, and End-Use Model) was used which estimates the hourly water and energy (for warm tap water) demands/supplies for households [80]. This modeling tool has been used for multiple studies [32], [71], [79], [80]. The specific characteristics for this research (number of people per apartment, water demand per application, e.g.) will be used to generate an unique hourly patterns for a whole week.

UWOT

To quantify the water balance of a neighborhood, a modeling tools was required that could compute the different water demands and supplies. The UWOT (Urban Water Optioneering Tool) model was found to be a suitable modeling tool that could be used to determine the water balance for a neighborhood. The UWOT model has been used in practice and showed that it is possible to simulate an urban water cycle by modeling the rainfall runoff from different surface types, natural water losses (evaporation, infiltration, e.g.), water losses from treatment processes, individual water demands (drinking water, vegetation, demi water, e.g.), and WW collection/discharge [30].

Power-to-X

In addition to a water-based modeling tool, another modeling tool was required that focuses more on the energy balance of a neighborhood. Therefore, the Power-to-X model was found a suitable modeling tool for this research. The Power-to-X model has been used in different projects to simulate the water and energy balance that includes components such as heat, hydrogen, demi water and electricity [11], [67], [71], [79]. For these components it is possible to adjust technical (scale of system components), energetic (efficiency, conversion losses, e.g.) and economic (tariffs for electricity, hydrogen, e.g.) parameters. These parameters (input data) will be used together with scheduling strategies, the pre-defined priorities of the energy systems, to produce hourly results of the water and energy balance. This model allows to compute whether or not a certain scenario leads to CO_2 saving and a lower financial value. In addition, it is possible to incorporate the coupled groundwater flow model MODFLOW that simulates the heat injection, storage and extraction of the ATES system. This simulation can also be excluded which results in constant temperatures for the cold and warm aquifers.

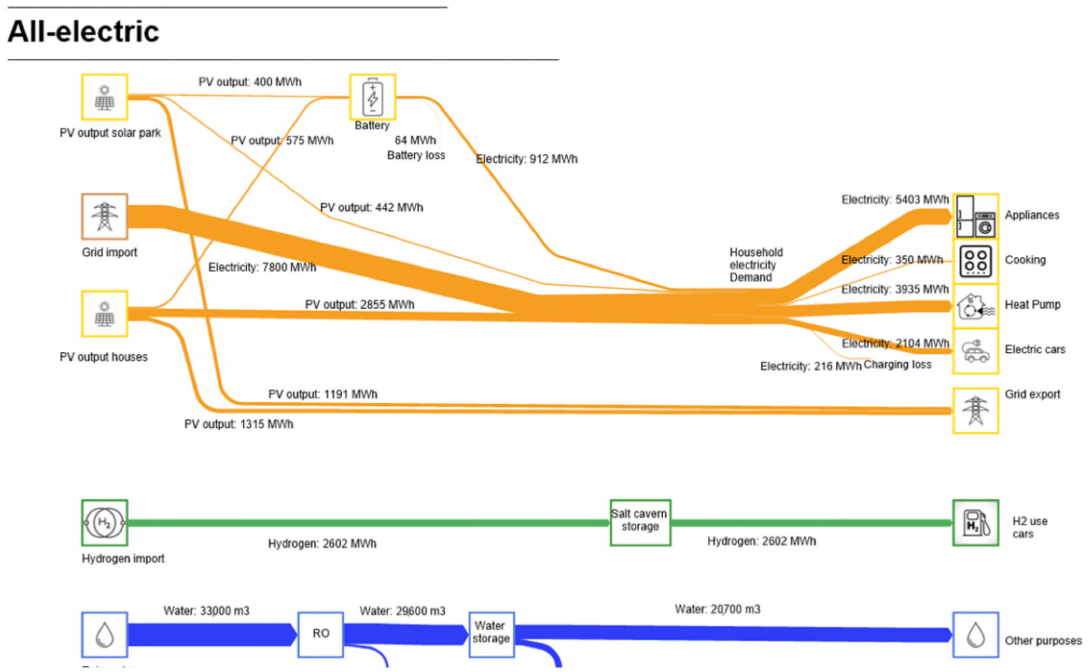


Figure 11: Example of Sankey diagram for a water- and energy system

3.3.2. Rainfall and other meteorological data

For a neighborhood in the Netherlands, meteorological data can be collected from the Royal Dutch Meteorological Institute (KNMI). In addition, the scenarios will also be assessed on a smaller temporal scale during extreme meteorological conditions.

Rainfall

Hourly rainfall time series can be collected from KNMI. The net rainfall that is collected will be determined for all types of surfaces by considering the specific runoff for a surface type and the collection of the first flush [33]. The net runoff is rainwater that can effectively be collected with relatively low pollution by separating it from the first flush [51]. It is assumed that there is a net runoff of 50% of rainfall on pavements [71]. A net runoff of 32% percent for blue-green rooftops will be assumed. For regular rooftops, a net runoff of 80% will be assumed. Rainfall in pervious areas will either evaporate or infiltrate locally. The net incoming rainfall can be computed with the following equation:

$$R_{net}(t) = \begin{cases} 0 & if\ R(t) \leq \Delta_r \\ R(t) - \Delta_r & otherwise \end{cases} \tag{1}$$

For this equation, R represents the incoming rainfall from KNMI and R_{net} the net incoming rainfall in mm/hour. The timesteps (t) will be expressed as hours. In addition, Δ_r represents the constant incoming rainfall correction in mm/hour for a specific runoff specific surface type. With this correction, the net incoming rainfall that comes to runoff includes the amount of rainwater that is intercepted. In other words, it is assumed that small rainfall events (< 1 mm/hour) will not by harvested.

Surface water temperature
Surface water will be used as an energy source for cold-warm aquifer storage. The surface water temperature (°C) determines how much additional energy is required to store heated water in the aquifer. The data from Rijkswaterstaat measures the surface water temperature of the nearby river Lekkanaal at a 10-minute time interval [81]. This data will be used for the Power-to-X model.

Solar irradiation
The solar irradiation (J/cm^2/hour) data from KNMI will determine how much solar power can be generated with the PV panels on rooftops and facades. The equations that are used to calculate the total solar power from PV panels can be found in the Power-to-X model [79].

3.3.3. Vegetational water demand

The additional vegetational water demand besides rainfall is approximately 600 mm for (public) green spaces during a growing season of around 180 days [71]. Green facades will have a vegetational water demand of 700 mm during a growing season of approximately 180 days [71]. It is assumed that the growing season is from April to September. The daily vegetational water demand is irregular as it depends on the difference between incoming rainfall and evapotranspiration. The vegetational water demand can be determined with the following equation:

$$veg(t) = \begin{cases} 0 & if\ R(t) \leq ET(t) \\ \beta * \left(R(t) - ET(t)\right) & if\ t_{start} \leq t \leq t_{end} \\ 0 & otherwise \end{cases} \tag{2}$$

The vegetational water demand veg equals the difference between daily incoming rainfall (R) and evapotranspiration (ET) in mm/day [26]. It is assumed that there is only a vegetational water demand if the daily evapotranspiration is higher than the incoming rainfall during the growing season (April-September). The timesteps of the vegetational water demand will be expressed as days from the first (t_{start}) to last (t_{end}) day of the growing season. To convert this to hourly data, it is assumed that the daily vegetational water demand is fulfilled at a fixed time (from 08:00 to 09:00). If there is not enough harvested rainwater and/or recycled GW available, it is possible to fulfill the vegetational water demand with DW. For this equation, β represents the correction factor for the specific plant type.

3.3.4. Drinking water and non-potable water demand (domestic water)

The domestic water demand is based on the daily average in the Netherlands which is 119.3 L/person/day [82]. This can be distributed into several household demands (Figure 12). Over 71.8% of the DW demand required for showering and toilet flushing. Approximately 17.9% of the water demand is needed for the washing machine and dishwasher. The remaining 10.3% is used for the sink, food preparation (kitchen) and others.

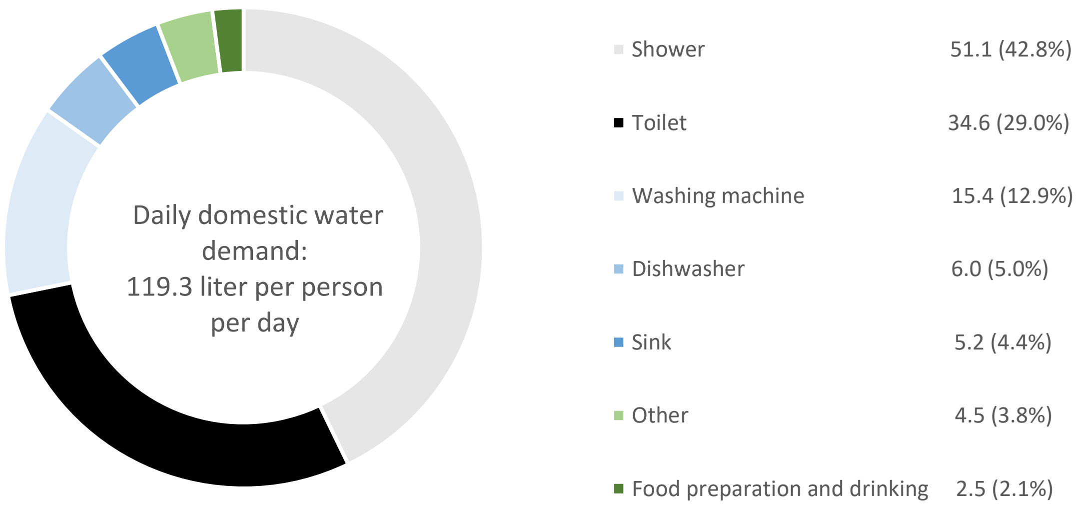


Figure 12: Daily domestic drinking water demand with water-energy-saving appliances

The domestic water demand for households in a Dutch neighborhood will be based on the different purposes (Table 3) for which DW can be used. In general, only DW is used to cover the domestic water demand. However, the literature study showed that it is possible to use non-potable water, also known as harvested rainwater and/or recycled (light-)greywater, as an alternative for toilet flushing and the washing machine. During the design of the scenarios, it is possible to determine whether or not non-potable water is being used.

Table 3: Assumed in- and outflow water quality

Domestic water demand types	Possible water sources	Outflowing water quality
Shower	Drinking water	Light-greywater
Toilet	Drinking water, rainwater and (light-)greywater	Blackwater
Washing machine	Drinking water, rainwater and (light-)greywater	Light-greywater
Dishwasher	Drinking water	Greywater
Sink	Drinking water	Greywater
Kitchen (food preparation and drinking)	Drinking water	Blackwater
Other	Drinking water	Greywater

The generic assessment framework the impact of a reduced external DW demand by implementing different water-energy-saving appliances. The DW savings are based on existing technologies from the literature review combined with pre-determined assumptions. During the design of the scenarios, it will be determined whether or not the water-energy-saving appliances are used. For a scenario that has many decentralized WEN systems, it is realistic that water-energy-saving appliances are incorporated.

Vacuum toilet
A vacuum toilet requires significantly less water (1L water/flush compared to a dual flush toilet (6L water/flush) [36]. On average, the daily water demand for toilet flushing would decrease 83 percent from 34.6 L/person/day to 5.8 L/person/day. In addition, a vacuum toilet can be used to separate more concentrated BW from other WW sources.

Recirculation shower

It is assumed that the water demand for a conventional shower is 51.1 L/person/day, with an average shower time of 9 minutes [83]. A recirculation shower will be considered as a water-energy-saving technology. The concept of a recirculation shower is that it reuses shower water after it is treated with a microfilter and UV filter. Additionally it is assumed that the shower time will decrease by one third to 6 minutes. Based on the average water demand of a recirculation shower, the water demand for showering is 24.7 L/person/day [84]. With a heat exchanger in a recirculating shower, less warm tap water is required, saving up to 500 kWh/year [85].

Washing machine

Modern washing machines can save more water and energy compared to older models. It is assumed that a water-energy-saving washing machine will reduce the water demand by 28% from 15.4 L/person/day to 11.1 L/person/day (to eco) [48]. It is assumed that this will reduce the energy demand, compared to a conventional washing machine, with 53 kWh/year, resulting in an energy demand of 62 kWh/year instead of 115 kWh/year [48].

Dishwasher

Eco-friendly dishwashers can save a lot of water and energy. It is assumed that a new dishwasher can save up to 50% of water resulting in a water demand of 4 L/person/day instead of the original 6 L/person/day [49]. It is assumed that this will reduce the energy demand, compared to a conventional dishwasher, with 72 kWh/year, resulting in an energy demand of 147 kWh/year instead of 219 kWh/year [49].

Water saving faucet

A water-saving faucet can reduce the water demand by up to 50% [86]. However, to avoid overestimations, as it is also a drinking source, it is assumed that water-saving faucets in (bathroom) sinks will reduce the water demand by 30%. This reduces the water demand for a sink from 5.2 L/person/day to 3.6 L/person/day.

In addition to the water-energy saving appliances, it is crucial to consider temporal fluctuations as this will change the daily DW demand. The index figures (Table 4) show that the DW demand is above average during the months April to July and less than average for the remaining months [82]. Compared to the average daily DW demand, the highest demand is in June (+6.4%) and the lowest demand is in December (-3.7%). The hourly variations of the DW demand will be determined with SIMDEUM (section 3.3.1).

Table 4: Index averay water supply per month (source: Vewin)

Month	**Index figures (2005-2019) [-]**
January	96.8
February	97.4
March	99.0
April	102.5
May	103.3
June	106.4
July	104.0
August	97.8
September	99.8
October	98.4
November	98.3
December	96.3
Total (average)	**100**

3.3.5. Wastewater discharge (water treatment parameters)

This sub-section describes essential water treatment parameters, such as water losses during treatment and energy demand for treatment and water distribution. This will give more insight with regards to the mean and maximum treatment capacity that is required for decentralized treatment facilities. The treatment capacity for 'centralized' treatment plants outside the neighborhood scope will not be considered.

Drinking water treatment plant

A centralized drinking water treatment plan (DWTP) produces DW that will be distributed to the consumer. A DWTP will be located outside of the neighborhood area and falls outside of the scope. For further research, it will be considered that the energy demand to produce and distribute DW from a DWTP is 0.50 kWh/m^3 [82].

Based on the literature, it is assumed that 65% of the (light-)greywater and rainwater can be recovered as DW through reversed osmosis (RO) [87][88]. Another case study assumed a recovery of 60-70%, which is in the same range [39]. This study used surface water instead of WW as a source to produce DW. Though, it did mention that these results can be used as a reference for DW production from WW [39]. For this treatment facility, the energy demand is assumed at 1 kWh/m^3 [58].

Wastewater treatment plant

A centralized wastewater treatment plant (WWTP) treats WW that is collected and distributed through a sewer system. A WWTP will be located outside of the neighborhood area and falls outside the scope. The energy demand to treat WW at a WWTP will be considered for further research. Based on existing literature, it is assumed that more concentrated WW will have a lower energy demand [19]. As a result, the energy demand for an *original centralized*-, *improved centralized*-, and *hybrid scenario* is 29.3 kWh/person/year, 23.2 kWh/person/year, and 11.7 kWh/person/year. A *decentralized scenario* will not have a sewer system to the WWTP.

Helophyte filter

A helophyte filter, with a hydraulic loading of 800 L/m^2/day [38], it is possible to purify rainwater and (light-)greywater that contains some pollution. Based on the literature, it is assumed that there is an average water loss of 5% for helophyte filters [54][38]. There is no additional energy demand besides the pumping system to transport purified water to the storage tank. The total surface area of the helophyte filter will be determined based on the peak flow during a heavy rainfall event. However, deciding whether or not there is enough space available falls outside of the scope of this project.

Blackwater digestor

BW contains organic matter, and in combination with kitchen waste, it can be treated anaerobically to recover energy in the form of methane. In total, 115.2 MJ/person/year (32 kWh/person/year) can be converted into electricity, and 169.2 MJ/person/year (47 kWh/person/year) as heat that is partly required for the production of biogas[1] with combined heat and power (CHP) [19]. By taking additional losses[2] into account, the net energy production is 81.7 MJ/person/year (22.7 kWh/person/year) as electricity and 89.2 MJ/person/year (24.8 kWh/person/year) as heat. In addition, it is important to address that local anaerobic treatment from a digestor has a higher energy recovery efficiency than a WWTP[3]. Energy from BW is being used to optimize overall energy balance and to become more self-sufficient.

Pumping system

Water will be distributed and drained with a pumping system. The energy demand for centralized DW and WW facilities has already been considered for a centralized DWTP and WWTP. For this

[1] Blackwater must be heated from 15-20 °C for optimal anaerobic treatment.
[2] A total of 14 MJ/person/year, 3.5 MJ/p/y, and 16 MJ/person/year of electricity are needed for vacuum transport, P removal, and N removal. A total of 80 MJ/person/year of heat is required for blackwater heating.
[3] A WWTP (sewage and treatment) has a net energy demand of 107 MJ/p/y with biogas production from sludge, while blackwater treatment produces excess energy [19].

research, the additional energy demand to transport collected water will be considered for the scenarios. It is assumed that no pumping capacity is required to collect rainwater and (light-) greywater as this will be transported through a gravity sewer system. To transport water to storage tanks and surface water, it is assumed that the energy demand is 0.05 kWh/m^3 based on the pump specification of the UWOT model. Treated water being transported to apartments will have a higher energy demand due to the water head. It is assumed that this will be 0.1 kWh/m^3 based on the pump specifications of the UWOT model.

3.3.6. Demi water and hydrogen demand

Hydrogen can be imported from a centralized production facility or it can be produced locally. For the production of hydrogen (H_2), it is essential to use very pure water, also known as demi water. With a reversed osmosis (RO) installation, it is possible to produce demi water. If DW is used for the production of demi water, it is assumed that there is a recovery of 95%. To produce 1 kg of hydrogen, 9 liters of demi water is required [11]. The higher heating value (HHV) of hydrogen is 39.4 kWh/kg H_2 [70]. For the water and balance, both imported as well as locally produced demi water and hydrogen will be considered.

3.3.7. Electricity, heating and cooling demand

Domestic energy demand and mobility will cover all energy demands that are required for residences.

Domestic energy demand

One of the domestic energy demand is the heating and cooling demand. This should be <65 kWh/m^2/year according to the BENG1 energy standards for newly built Dutch buildings [89]. Initially, the energy demand was 51 kWh/m^2/year for heating and 4.4 kWh/m^2/year [90]. However, it is advised for modern buildings that are highly isolated and use an ATES to use a cooling demand up to 17 kWh/m^2/year [90]. To ensure that the total heating and cooling demand was <65 kWh/m^2/year, it was assumed that there was a cooling demand of 14 kWh/m^2/year.

The energy demand for electrical household appliances is 2,000 kWh/year [44]. This also includes the energy demand for induction cooking, which is 175 kWh/year [91]. The energy demand for warm tap water is assumed to be 1,600 kWh/year [44]. With water-energy-saving appliances the initial energy demand for household appliances and warm tap water can be reduced to 1,875 kWh/year and 1,100 kWh/year respectively.

Mobility

Only the energy demand for electric vehicles (EVs) and fuel cell electric vehicles (FCEVs) will be considered for this study. It is assumed that all cars will drive on average 13,000 km/year [92]. For an EV, it is assumed that the energy demand is, on average, 15 kWh/100 km, according to the New European Driving Cycle (NEDC) [93]. The yearly energy demand for a single EV is 1,950 kWh. Based on existing literature, a FCEV needs 1 kg H_2/100 km [79]. On yearly basis, a FCEV needs 130 kg of hydrogen which can be produced with 1,170 liters of demi water. Based on the HHV of hydrogen (section 3.3.6), the yearly energy demand for a single FCEV is approximately 5,100 kWh.

3.4. Step 4: Evaluation indicators

The literature review on assessment frameworks showed different evaluation indicators that can be used. For this research, it was decided to use a multi-criteria analysis (MCA) that consists of relevant evaluation indicators, also expressed as indicators. A MCA is often used as an evaluation framework for the decision making process to compare and score different concepts by integrating the preferences of stakeholders [76]. Therefore, the fourth step of the generic assessment framework was to form different evaluation indicators.

As mentioned in the problem statement, there is no framework available with a high applicability and comparability that would allow to assess different strategies of decentralized WEN systems in neighborhoods. The report of Segrave et al. (2020) did provide an assessment framework for the water chain that consisted multiple indicators that are related to the circular economy principles

[75][31]. The 16 indicators that were used, could be divided among three main themes. Indicators related to *energy- and material flow* would focus on physical characteristics, such as the footprint/recovery of energy, water and other resources. The second theme, *value for people*, focusses on social-political characteristics such as public health, safety, comfort and quality of living environment. The last theme, *system characteristics*, focusses more on aspects, such as self-sufficiency, reusability, financial value, integrality and ecological value.

These indicators focused on a national system level whereas the scope for this research is on a neighborhood level. Therefore, the indicators were reconsidered to make them more applicable for decentralized WEN systems in a neighborhood. For this research, 13 indicators were chosen (Figure 13) divided among 4 main themes: (1) *water system*, (2) *value for people*, (3) *energy system* and (4) *general characteristics*. Several methodologies were conducted to evaluate the different indicators. In general, the indicators will either be quantitatively or qualitatively evaluated. Quantifiable indicators can be evaluated with pre-determined modeling tools/method on which the score isn't given by the researcher or an external specialist. With a qualitative indicator on the other hand, input from literature is required for giving a score [29]. The indicators will be further described in the upcoming sub-sections.

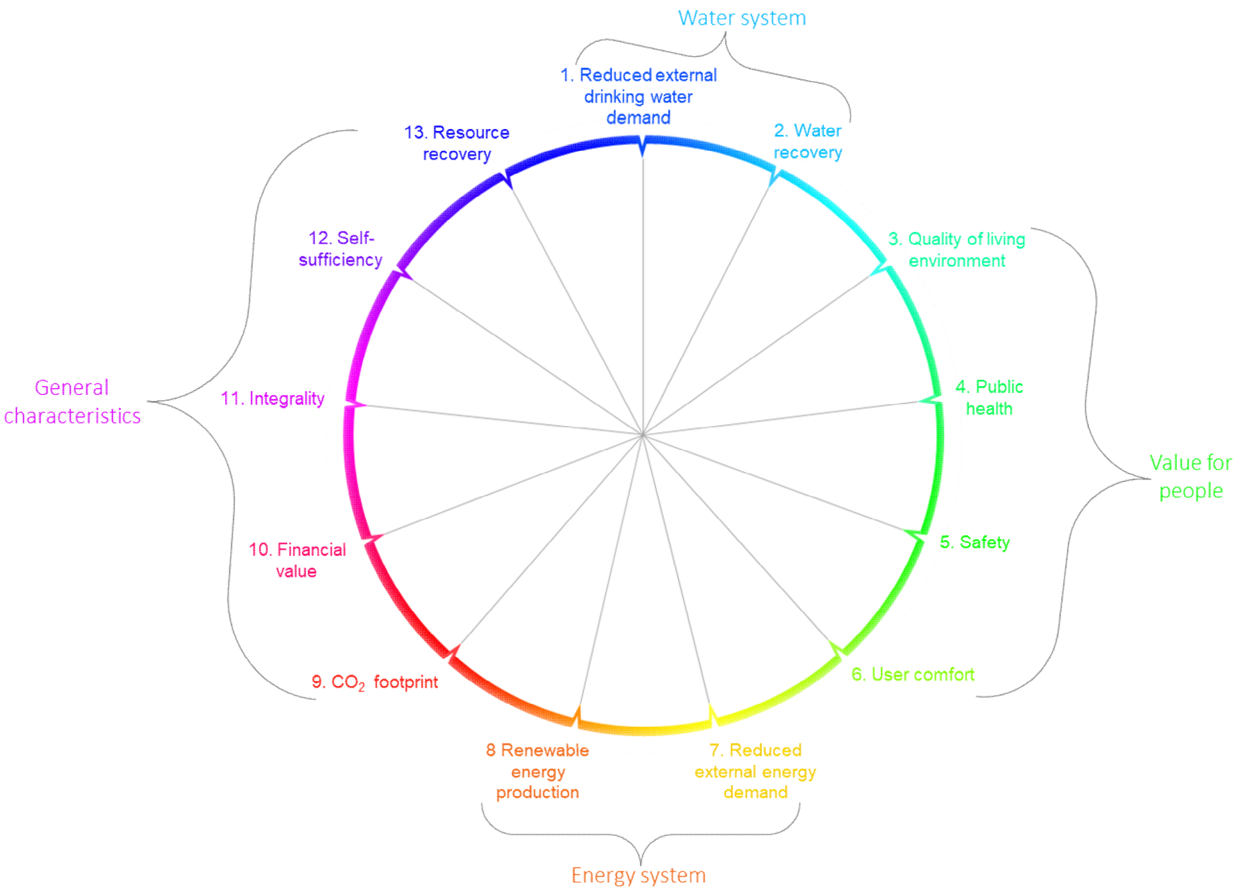


Figure 13: Overview of 13 evaluation indicators for generic assessment framework

3.4.1. Indicator 1: Reduced external drinking water demand

This indicator was formed to assess the dependency on DW from a centralized DWTP. This indicator was inspired on the study of Bouziotas et al. (2019) that used a 'Key Performance Indicator' (KPI) to measure water system autonomy of a neighborhood [30]. With the UWOT model (section 3.3.1), it was possible the assess the reduced external DW demand:

$$x_1(a) = \begin{cases} minimum\ score & if\ \mathrm{DW}_{benchmark} \leq DW_{external}(a) \\ \mathrm{DW}_{benchmark} - DW_{external}(a) & otherwise \end{cases} \tag{3}$$

The total reduced external DW demand (x_1) for a specific scenario (a) will be expressed in the units m^3/year. The maximum reduction of the external DW demand is based on the current DW consumption in the Netherlands 43.6 m^3/person/year (119.3 L/person/day) [82]. This will be used as the benchmark ($\mathrm{DW}_{benchmark}$) and compared with the actual external DW demand of a scenario ($DW_{external}$). A lower external DW demand will therefore result in a higher score. If the external DW demand ($DW_{external}$) is greater or equal than the benchmark ($\mathrm{DW}_{benchmark}$), a minimum score of 0 m^3/year will be given.

3.4.2. Indicator 2: Water recovery

The water recovery was defined as the total amount of available rainwater and WW that is recovered and reused within the neighborhood. The study of Bouziotas et al. (2019) used two separate indicators that evaluated the reduction of WW that leaves the system and the achieved runoff reduction [30]. This research has combined the recovery of rainwater and WW into one indictor as these aspects are both essential to measure the overall ability to recover and reuse water for a certain scenario. The total amount of water is recovered can be determined with the UWOT model (section 3.3.1):

$$x_2(a) = \left(1 - \frac{Q_{runoff}(a) + Q_{ww}(a) + \sum Q_{loss}(a)}{R + DW_{external}(a)}\right) * 100\% \tag{4}$$

The total water recovery (x_2) for a specific scenario (a) will be given in percentages. To compute the total water recovery, the total amount of water that enters the neighborhood must be defined. The main water resources are rainwater (R) and external DW supply $DW_{external}$. Water resources that leave the neighborhood are defined as runoff (Q_{runoff}), WW discharge (Q_{ww}) and water treatment losses (Q_{loss}) and given in m^3/year. A minimum score of 0% will be given if none of the available water is being recovered. A maximum water recovery of 100% will be given if all available water resources are collected and reused.

3.4.3. Indicator 3: Quality of living environment

The quality of living environment is an essential indicator that has a direct impact on the well-being and public health of residents [94]. A high quality of living environment is in this research defined as an area with enough access to blue and green spaces. This creates healthy and comfortable spaces with a good air quality, limited UHI effects and better protection against noise [73][95][96]. The indicator will be expressed as the total blue and green spaces per residence which was also used in a study of Bezemer and Visschedijk (2003) [97]:

$$x_3(a) = \begin{cases} maximum\ score & if\ x_3(a) \geq benchmark \\ \dfrac{A_{blue-green}(a)}{n_{residences}(a)} & otherwise \end{cases} \tag{5}$$

The quality living environment x_3 for a specific scenario (a) will be expressed as m^2/house. This can be computed by taking the total area of blue and green spaces ($A_{blue-green}$) in m^2 relative to the number of residences ($n_{residences}$). Based on existing research, it is advised to have at on average 75 m^2/residence of blue and green spaces in Dutch urban areas [97]. A 75 m^2/residence will be used as the benchmark as this would represent a high quality of living environment. A minimum score (0 m^2/house) will be given if there are no blue and green spaces present within the neighborhood. A maximum score (75 m^2/residence) will be given if the total area of blue and green spaces are equal or higher than the benchmark.

3.4.4. Indicator 4: Public health

The public health risks will be evaluated for each scenario by evaluating the potential dangers of reusing treated rainwater and GW. A Quantitative Microbiological Risk Assessment (QMRA) can be used to determine the risk of exposure to microorganisms [53]. The potential risks for each scenario will be based on studies from Kusumawardhana et al. (2021) and Roest et al. (2016) that performed a QMRA on decentralized water systems [53], [58]. Possible exposure routes are: inhalation through aerosolized non-potable water from toilet flushing and showering with non-potable water due to cross-connection between the rainwater/GW system and the DW system [53]. It is taken into consideration that the maximum chance of infection caused by pathogenic microorganisms, which is legally allowed in the Netherlands, is one infection per 10,000 persons per year (pppy) [53], [58]. This infection rate will be used as the benchmark. A score (Table 5) for public health (x_4) will be given on a qualitative basis. A minimum score of 0 [-] will be given if there are high health risks from an exposure route. If the possible health risks are equal or below the benchmark, maximum score of 10 [-] will be given.

Table 5: Qualitative evaluation format for public health indicator

Verbal Expressions	Score x_4 [-]	Context
No significant health risks	> 8.0	No additional measures are required as they would already meet the current standards.
Some health risks	6.0 – 8.0	There are some additional measures required to monitor potential exposure to pathogenic microorganisms.
Concerning health risks	4.0 – 6.0	Some concerning threats could result in exposure to pathogenic microorganisms. The water quality that is available within the apartments should be monitored actively.
High health risks	2.0 – 4.0	There are direct threats that will lead to exposure to pathogenic microorganisms. Additional treatment steps are required to prevent these health risks.
Very high health risks	< 2.0	A fundamental problem with the water system results in an unsafe water system. Another type of water system is required with no significant health risks.

3.4.5. Indicator 5: Safety

The level of safety will be determined by looking at the probability urban flooding that can arise. A rainwater harvesting system (RWHS) and blue-green spaces can minimize the negative effects of urban flooding [98]. The current Dutch standard is to have at least a buffer capacity 40-60 L/m^2 (40-60 mm of rainfall) [99]. The *safety* indicator will be measured by the achieved runoff reduction from an extreme rainfall event of >40 mm/day. The study of Bouziotas et al. (2019) was used as a reference that assessed the achieved runoff of a peak flood event [30]. The total buffer capacity would be optimized to reduce the overall runoff and prevent it from being over dimensioned that would result in a higher financial value (section 3.4.10). With the UWOT model, it is possible the determine the what extent a peak flood event is mitigated:

$$x_5(a) = \left(\frac{Q_{benchmark}^{runoff} - Q_{scenario}^{runoff}(a)}{Q_{benchmark}^{runoff}} \right) * 100\% \tag{6}$$

The safety indicator (x_5) for a specific scenario (a) will be expressed in percentages. To determine the maximum runoff reduction, the initial runoff during a flood event without any buffer capacity is used as the benchmark ($Q_{benchmark}^{runoff}$) and given in the units m^3/day. If the runoff of a certain scenario is similar to the benchmark because there is no buffer capacity, a minimum score of 0% will be given. A maximum score of 100% will be given if there is enough buffer capacity to mitigate runoff to nearby surface water.

3.4.6. Indicator 6: User comfort

The level of user comfort will be determined by the amount of unburdening, ease of use, and (customer) satisfaction for each scenario. This will be a qualitative assessment which is based on literature that indicates what residents experience as (un)comfortable. The study of Brouwer et al. (2019) held more than 30 interviews to determine the different customer perspectives in DW [24]. Research that looked into the acceptance of different decentralized WEN systems hasn't been found. Therefore, a study of Brouwer et al. (2019) was used that evaluated the tap water awareness on 9 different themes, such as caring for water and sense of responsibility [20]. The results of this study are based on approximately 1,000 online surveys, in the Netherlands, that were divided among the four customer perspectives:

Quality & health concerned (12.6%): Customers with this perspective have a personal focus on their health. This implies the DW quality or other aspects that can impact their health.

Aware & committed (32.7%): Customers with this perspective feel responsible for taking collective and individual actions that will have a (more) positive impact on the environment.

Egalitarian & solidary *(28.3%)*: Customers with this perspective experience great solidarity with the rest of society. They experience (drinking) water as a public that should be affordable and available for everybody.

Down to earth & confident (26.4%): Customers with this perspective are confident in the competence of the (drinking) water utilities and do not want to be bothered with new responsibilities.

Based on a meeting (S. Brouwer, personal communication, 5 September 2022) with the first author of the two mentioned papers, it was advised to estimate the level of acceptance a for a certain decentralized WEN system for the different perspectives. For example, a customer with a *down to earth & confident* perspective doesn't want to be bothered with new responsibilities and would have a lower probability of acceptance than someone with an *aware & committed* perspective. Based on the different levels of acceptance (Table 6), it is possible to give a score to the user comfort indicator:

$$x_6(a) = \sum_{i=1}^{n} d_n * c_n(a) \tag{7}$$

Table 6: Qualitative evaluation format for user comfort indicator

Verbal Expressions	Score c_n [-]	Context
Very high acceptance	> 8.0	The scenario is entirely accepted, and there is very little resistance.
High acceptance	6.0 – 8.0	The scenario is generally accepted with a few exceptions. Some specific measures are too extreme, reducing the willingness to choose a scenario.
Neutral acceptance	4.0 – 6.0	There is no specific preference, as certain measures are (not) accepted.
Low acceptance	2.0 – 4.0	There is high resistance to the scenario as the is little willingness to live in a neighborhood with specific measures.
Very low acceptance	< 2.0	There is no acceptance of the scenario as it fundamentally conflicts with their interest.

The user comfort indicator (x_6) for a specific scenario (a) will be expressed as a score without an unit. All customer perspectives have a fixed share (d_n) that have been mentioned earlier. For each scenario, the researcher will determine qualitatively the level of acceptance (c_n) for the different costumer perspectives (n). The researcher interprets to what extent there is much or little user comfort for certain decentralized WEN systems. An user comfort score of 0 [-] will be given to a scenario if there is no acceptance at all among the different customer perspectives. A maximum score of 10 [-] will be given if there is a very high acceptance.

3.4.7. Indicator 7: Reduced external energy demand

For this this indicator, the same principle was used from the indicator that assessed the reduced external DW demand (section 0). This indicator was created to determine the dependency on energy from that originates from the grid. This indicator was inspired on the study of van der Roest et al. (2019) which included assessing the total amount of energy (electricity) that was bought from the grid [67]. With the Power-to-X model (section 3.3.1), it was possible to assess the reduced external energy demand:

$$x_7(a) = \begin{cases} minimum\ score & if\ \mathrm{E}_{benchmark} \leq E_{grid}(a) \\ \mathrm{E}_{benchmark} - E_{grid,import}(a) & otherwise \end{cases} \tag{8}$$

The total reduced external energy demand (x_7) for a specific scenario (a) will be expressed in the units MWh/year. The maximum reduction of the external DW demand will be based on the current energy demand (electricity, heating/cooling and mobility) for a modern house in the Netherlands. The parameters have already been given in the water and energy balance (section 3.3). As the actual energy demand of a neighborhood depends on the characteristics of a house (e.g. surface area), it was not possible at this stage to determine the benchmark ($\mathrm{E}_{benchmark}$). The benchmark, the total sum of the energy demand, was determined after the case study selection (section 3.1). Ultimately, this will be compared with the actual external energy demand of a scenario (E_{grid}). A lower external energy demand will therefore result in a higher score. If the external energy demand is greater or equal than the benchmark, a minimum score of 0 MWh/year will be given.

3.4.8. Indicator 8: Local renewable energy use

This indicator was formed to determine the yearly amount of renewable energy that is produced and used within the neighborhood. This indicator was inspired on the study of van der Roest et al. (2019) which included assessing the total amount of renewable energy that was produced locally [67]. With the Power-to-X model (section 3.3.1), it was possible to assess the local renewable energy use:

$$x_8(a) = \frac{E_{produced,local}(a) - E_{grid,export}(a)}{E_{total}(a)} * 100\% \tag{9}$$

The yearly local renewable energy use (x_8) for a specific scenario (a) will be given in percentages. For this indicator, energy is expressed in MWh/year. To compute the local renewable energy use, the total amount of energy (E_{total}) that is used, the total amount of renewable energy that is locally produced ($E_{produced,local}$) and the exported ($E_{grid,export}$) energy from/to the grid must be determined. The sum ($E_{produced,local} - E_{grid,export}$) equals total 'net' local renewable energy that is used within the neighborhood on a yearly basis. A minimum score of 0% will be given if there is no renewable energy produced and used within the neighborhood. A maximum score of 100% will be given if only locally produced renewable energy is used.

3.4.9. Indicator 9: CO_2 footprint

The CO_2 footprint of different system components will be used to determine the yearly emissions of CO_2 for every scenario. The CO_2 footprint is often used in studies as an indicator to compare and evaluate different scenarios [40], [41], [46]. The CO_2 parameters can be found in Table 7. The CO_2 footprint only focused on water- and energy system elements that were related and present in a neighborhood. For example, the assessment on the CO_2 footprint on the construction of houses fall outside of the scope as it primarily focusses on the water and energy system. In the Netherlands, 12.5% of the electricity originates from renewable energy [100]. It is assumed that this is the fixed use of renewable energy and the remaining 87.5% originates from fossil fuel. The same applies for the hydrogen demand, the current production of green hydrogen is 1.3% and the remaining 98.7% is produced with grey energy (fossil energy) [101]. The overall impact will be assessed by using a methodology of Zubelzu and Hernández (2016) that incorporates the carbon footprint in the urban planning process as a reference [102]:

$$x_9(a) = \sum_{i=1}^{n} Eco_i \cdot X_i \tag{10}$$

Table 7: CO_2 footprint parameters for water- and energy systems

System element	CO_2 footprint (Eco_i)
Electricity (fossil energy)	0.523 kg CO_2/kWh [103]
Electricity (renewable energy)	0 kg CO_2/kWh [103]
Biogas (blackwater)	0.044 kg CO_2/kWh [103]
Hydrogen production (renewable)	1.092 kg CO_2/kg H_2 [103]
Electric vehicle (grey energy)	0.104 kg CO_2/km [103]
Electric vehicle (renewable energy)	0.003 kg CO_2/km [103]
Fuel cell electric vehicle (grey energy)	0.112 kg CO_2/km [103]
Fuel cell electric vehicle (renewable energy)	0.007 kg CO_2/km [103]
Centralized wastewater treatment	1.090 kg CO_2/m^3 [104]
Decentralized greywater treatment	1.300 kg CO_2/m^3 [105]
Centralized drinking water production	0.163 kg CO_2/m^3 [58]
Decentralized drinking water production	0.019 kg CO_2/m^3 [58]

The CO_2 footprint (x_9) for a specific scenario (a) will be expressed as tonnes CO_2/year. The CO_2 footprint per system element (Eco_i) and will be multiplied by the total amount of that particular system element (X_i). A neighborhood without any decentralized WEN systems will be used to define the CO_2 footprint benchmark. This will be based on water and energy demands for a selected case study. A scenario with a similar or higher CO_2 footprint as the benchmark will be given a minimum score in tonnes CO_2/year. A maximum score will be given if CO_2 footprint is 0 tonnes CO_2/year.

3.4.10. Indicator 10: Financial value

The capital expenditures (CAPEX), operation and maintenance (OM) costs, and the lifetime were be used to determine the yearly costs (or financial value) for the water- and energy system. The economic parameters (Table 8) were used to compute the financial value for every component of the water and energy system. The study of van der Roest et al. (2021) was used to assess the financial value based on future tariffs for the year 2030 [67]:

$$SC_j = \alpha \cdot CAPEX_j + OM_j \tag{11}$$

The yearly system costs (SC_j) for each system for every system component (j) will be calculated in EUR/year (or €/year). This will be calculated by taking the sum of the capital expenditures ($CAPEX_j$) and operation and maintenance (OM_j) costs in EUR/year.

$$\alpha = \frac{r}{1-(1+r)^{-L_j}} \tag{12}$$

The CAPEX is multiplied with a capital recovery factor (α) that allows it to determine the yearly capital expenditures including discount rate (r) and lifetime (L_j) of a component [67]. In this equation, the discount rate is fixed at 3% for all system components. The lifetime L_i depends on the system component.

$$x_{10}(a) = \frac{\sum_{i=1}^{j} SC_j}{N_{residents}} \tag{13}$$

The financial value (x_{10}) for a scenario (a) will be expressed in EUR/person/year (or €/person/year) based on the total number of residents ($N_{residents}$). This can be calculated with equation. The scenario with the highest financial in €/person/year will be considered as the benchmark with a minimum score. A maximum score of 0 €/household/year will be given if there is no financial value.

Table 8: Economic parameters for financial value indicator

	CAPEX	Lifetime (years)	OM costs (% of CAPEX or otherwise)
Water system			
Water storage			
Rainwater tank[a]	120 €/m³ [106]	40 [106]	7.90 €/m³/year [106]
Non-potable water tank[a]	120 €/m³ [106]	40 [106]	7.90 €/m³/year [106]
Additional costs households			
Non-potable piping	200 €/apartment [55]	40*	1%*
Sewage piping	200 €/apartment [55]	40*	1%*
Vacuum toilet	200 €/apartment [55]	20*	1.5%*
Recirculating shower	2,000 €/apartment*	15*	2%*
Food grinder	1,000 €/apartment [55]	15*	2%*
Drainage and treatment			
Drainage original centralized scenario [b]	5,246,000 € [55]	40*	30,000 €/year [55]
Drainage improved centralized scenario [b]	5,246,000 € [55]	40*	30,000 €/year [55]
Drainage hybrid scenario [b]	7,042,000 € [55]	40*	45,000 €/year [55]
Drainage almost decentralized scenario [b]	5,660,000 € [55]	40*	43,000 €/year [55]
Centralized WWTP [b]	100 €/apartment [55]	40*	-
Decentralized GWTP [b]	220 €/apartment [55]	40*	-
Decentralized GWTP and BWTP [b]	250 €/apartment [55]	40*	-
Centralized DWTP [c]	1.38 €/m³ [82]	40*	-
Decentralized DWTP + storage [d]	3.28 €/m³ [39]	40*	-
Energy system			
Battery storage [e]	300,000 €/MWh [107]	12 [107]	1% [67]
Electrolyzer [e]	500 €/kWh [70]	20 [70]	2% [70]
Fuel cell [e]	500 €/kW [108]	15 [67]	2% [67]
Hydrogen (import) [e]	3.09 €/kg [109]	-	-
Heat pump [e]	400 €/kWth [110]	20 [110]	2% [110]
Heat storage system [e]	0.10 €/kWhth [111]	40 [11]	1.5% [11]
District heating network [e]	6000 €/apartment [112]	40 [67]	2%*
PV panels [e]	870 €/kWp [67]	25 [67]	1.2% [67]
Water heat pump hh [e]	3,500 €/apartment [113]	15 [67]	2% [67]
Electricity grid costs [f]	270 €/apartment [44]	40*	-
Elecitricity rate (from grid) [f]	0.40 €/kWh [44]	-	-

* In some cases, the CAPEX, lifetime and/or OM costs are assumed if there wasn't any information available. [a] The yearly costs for water storage is based on an existing project that computed the costs for an underground water tank of 14,000 m³ (with a total cost of €1,665,000). [b] All costs are based on a reference case study that looked into different sanitation scenarios. The yearly costs were normalized to €/apartment as the results were based on a neighborhood with 1,200 houses. [c] The price per m³ of drinking from a central production facility is based on the average tariff of 2021.[d] The price per m³ of drinking from a decentral production facility is based on the average costs that uses surface water as a source with a recovery of 60-70% from RO. [e] Most of the financial costs are based on the same paper as these values were also used for the Power-to-X model.
[f] These are the current tariffs for 2022 in the Netherlands.

3.4.11. Indicator 11: Integrality

Integrality was used to measure the level of multi-value creation. A concept with a high level of integrality contributes to improved participation (involvement from different groups/sectors), pluralism (diversity of approaches/concepts) and consciousness (awareness on water and energy resources) [75]. This indicator will be assessed qualitatively, based on a study of Dorado-Rubín et al. (2021) that developed a concept to analyze integrality in the design of urban development plans [25]. This study defined integrality on three different dimensions (Table 9): (1) comprehensiveness, (2) integration and (3) governance:

$$x_{11}(a) = \frac{D_1(a) + D_2(a) + D_3(a)}{3} * 2 \tag{14}$$

The level of integrality (x_{11}) for a specific scenario (a) will be expressed as a score without an unit. The dimensions (D_x) can be scored on a five-point Likert scale from strongly disagree to strongly agree as the minimum (1.0) and maximum (5.0) values respectively [114]. The average score of the three dimensions will be taken to get the final score of integrality. The researcher interprets the level of integrality for a specific scenario and gives the score per dimension. It is also possible to have the score given by an urban developer who has insight in the level of integrality for a certain concept. However, at this stage of the research, expert input hasn't yet been applied for this particular indicator. A minimum integrality score of 0 [-] will be given if there is no integrality, or multi-value creation. A maximum integrality score of 10 [-] will be given if there is a very high level of integrality.

Table 9: Different dimensions to measure integrality (source: Dorado-Rubín et al., 2021)

Dimensions	D_x	Items
Comprehensiveness (shared vision of problems)	D_1	Analyses the interrelationships between the problems/needs of the diagnosis, their dependency relationships, the extent to which they influence each other.
Integration (congruence and consistency between objectives and actions)	D_2	Analyses the interrelationship between the project's objectives, their dependency relationships, that is, the extent to which the achievement of some influences the achievement of others. Analyses the interrelationship between the actions, their dependency relationships, that is, the extent to which the development of some complements the development of others.
Governance (internal, horizontal and vertical coordination mechanisms)	D_3	Specifies how various municipal departments will participate in the project. Establishes how the project's relationship with the social partners who will collaborate in the project's development will be guaranteed. Establishes how the project's relationship with other agencies and administrations will be guaranteed.

3.4.12. Indicator 12: Self-sufficiency

A self-sufficient neighborhood will have enough water and energy resources during the whole year. The demand and supply for both water and energy vary over time (seasonal change, non-linear consumption pattern, e.g.) which may lead to deficits that need to be supplemented with external sources. The study of Bouziotas et al. (2019) a similar indicator to assess the reliability of the water system [30]. This was performed with a simulation-based framework that could compute the total time steps of which a system would operate well. For this research the self-sufficiency (or reliability) will be assessed for both the water and energy system with the UWOT and Power-to-X model:

$$x_{12}(a) = \frac{\sum_{i=1}^{t} DW_{t,0}(a) + \sum_{i=1}^{t} E_{t,0}\,(a)}{2 * t} * 100\% \tag{15}$$

The self-sufficiency (x_{12}) for a specific scenario (a) will be given in percentages and based on a yearly average. In contrast to other indicators (e.g., water recovery and local renewable energy use), this indicator will be based on the sum of hourly time steps (t). The smaller time scale allows to zoom in on the hourly water- and energy balance when there is no external DW ($DW_{t,0}$) or energy demand ($E_{t,0}$). A minimum score (x_{12}) of 0% will be given if the neighborhood entirely depends on external water and energy[4] sources. A maximum score (x_{12}) of 100% will be given if the neighborhood is entirely independent and doesn't require any additional water- and energy sources.

3.4.13. Indicator 13: Resource recovery

The level of resource recovery for a specific scenario will be used to assess how much of the nutrients originating from WW can be recovered. A study of Besson et al. (2019) was used to determine what effect BW and GW separation would have on resource recovery [46]. This study looked into the recovery for four different scenarios (Figure 14) of source separation:

Reference: This represents a 'centralized' scenario with the recovery of phosphorus and nitrogen compounds in a WWTP

Urine: This can be characterized as a scenario with urine source separation whereas the rest of the WW called 'grey-brownwater' is recovered in a centralized WWTP.

BW: For this scenario, BW is treated in a decentralized treatment facility and the effluent together with the GW is discharged to a centralized WWTP for further resource recovery

BW/GW: This scenario represents a complete decentralized system where BW and GW is separated for local treatment and resource recovery.

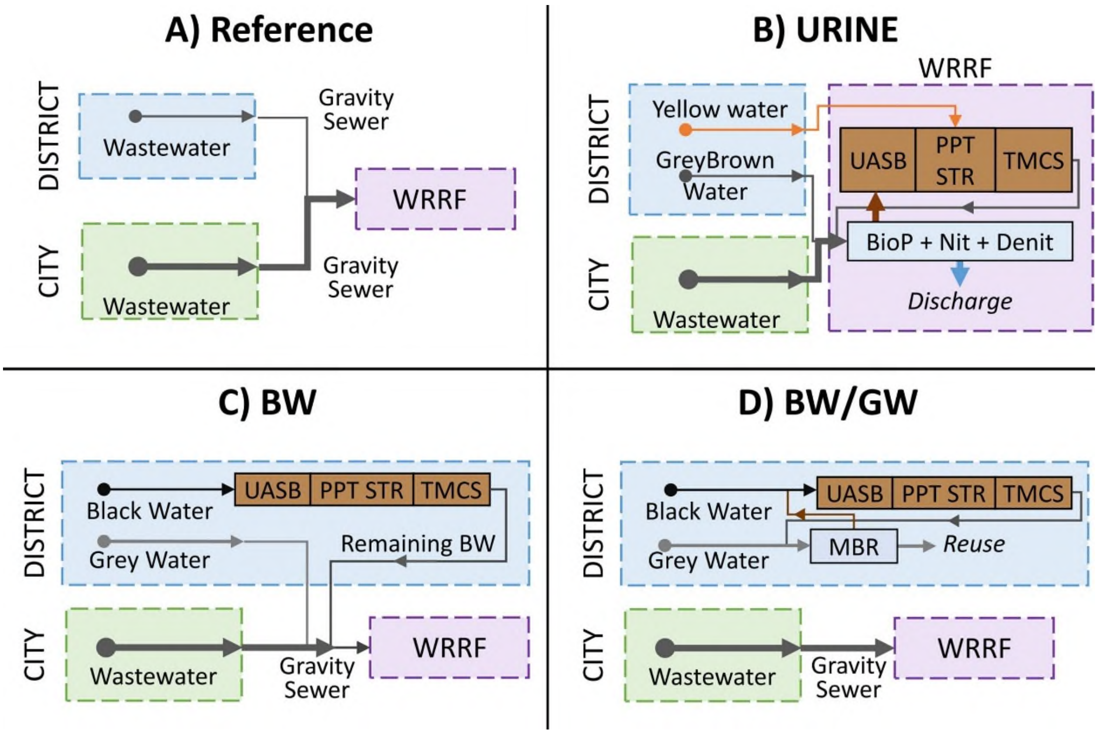


Figure 14: Example of resource recovery scenarios (Besson et al., 2019)

[4] Hydrogen demand will not be considered as imported hydrogen will only be used for hydrogen vehicles and not for the household demand.

The scenarios from this study are already specified and may be different compared to the designed scenarios from the different decentralized WEN systems. Therefore, this indicator will be evaluated qualitatively by making an assumption if the type of source separation from a designed scenario can be related to one or multiple concepts of Besson et al. (2019) [46]. Based on the level of source separation, each concept has a certain resource recovery which will be used:

$$x_{13}(a) = \frac{\sum RR_N + \sum RR_P + \sum RR_{COD}}{\sum RR_{potential}} * 100\% \tag{16}$$

The level of resource recovery (x_{13}) for a specific scenario (a) will be expressed in percentages. This will be based on the total mass of resources that can be recovered from nitrogen ($\sum RR_N$), phosphorus ($\sum RR_P$) and oxidizable pollutants expressed as COD ($\sum RR_{COD}$) in tonnes/year. The resource recovery is relative to the total amount of nitrogen, phosphorus and COD ($\sum RR_{potential}$) in tonnes/year. For this research, struvite, ammonium sulfate and biogas are resources that will indicate the resource efficiency. Gas (atmosphere) and effluent (discharge) are considered as 'losses' which would end up in the environment. For this research, sludge was also considered as a 'waste' product as further treatment of sludge is required to achieve resource recovery [115]. A minimum score will be given if there is 0% resource recovery. A maximum score will be given if there is 100% resource recovery.

3.5. Step 5: Indicator normalization

For the next step, the evaluation indicators that have been formed will be normalized. Normalization is a principle that can be found in the literature that allows to evaluate indicators in the same range [3], [40], [76]. This principle will be followed to get the same normalized scores for all indicators:

$$v_m(a) = 10 \cdot \frac{x_m(a) - x_{m,min}}{x_{m,max} - x_{m,min}} \tag{17}$$

$$v_m(a) = 10 \cdot \left(1 - \frac{x_m(a) - x_{m,min}}{x_{m,max} - x_{m,min}}\right) \tag{18}$$

The normalized indicator score (v_m) for a specific scenario (a) will be expressed as a score without an unit. For the normalization, the minimum and maximum scores have been defined as the lowest and highest possible outcomes (Table 10). For both equations, $x_m(a)$ represents the relative indicator score for a certain scenario. The minimum and maximum scores for a scenario are defined as $x_{m,min}$ and $x_{m,max}$. All values will be computed in the range of 0 to 10 [-] as lowest and highest scores respectively. For this research, equation (17) will be used if the maximum score is higher than the minimum score. Equation (18) will be used if the minimum score is higher than the maximum score.

$$V_{normalized}(a) = \sum_{i=1}^{m} \frac{1}{m} v_m(a) \tag{19}$$

At last the normalized score ($V_{normalized}$) for a scenario (a) can be determined with equation (19). All indicators (m) have an equal contribution ($\frac{1}{m}$) for the normalized score.

Table 10: Overview of minimum and maximum values for the 13 indicators

[#]	Indicator (v_m)	Unit	Minimum score ($x_{m,min}$)	Maximum score ($x_{m,max}$)	Conversion equation
	Water system				
1	Reduced external drinking water demand	[m^3/year]	0	Benchmark	(17)
2	Water recovery	[%]	0	100	(17)
	Value for people				
3	Quality of living environment	[m^2/residence]	0	Benchmark	(17)
4	Public health*	[-]	0	10	(17)
5	Safety	[-]	0	100	(17)
6	User comfort*	[-]	0	10	(17)
	Energy system				
7	Reduced external energy demand	[MWh/year]	0	Benchmark	(17)
8	Local renewable energy use	[%]	0	100	(17)
	General characteristics				
9	CO_2 footprint	[tonnes CO_2/year]	Benchmark	0	(18)
10	Financial value	[€/person/year]	Priciest scenario	Cheapest scenario	(18)
11	Integrality*	[-]	0	10	(17)
12	Self-sufficiency	[%]	0	100	(17)
13	Resource recovery*	[%]	0	100	(17)

* Qualitative indicators

3.6. Step 6: Indicator weighting with stakeholder perspectives

The last step of the generic assessment framework is to include the stakeholder perspectives as a part of the decision making process. In contrast to the normalized scores, the stakeholder perspectives will be used to add a specific weight per indicator. This allows to get a score that is based on indicators that are more/less prioritized. To combine the stakeholder perspectives with the normalized indicator scores, the study of Grafakos et al. (2010) was used as reference [76]. In this study, a method was presented that allows to quantify the stakeholder interviews into a weighting factor which can be used to get a weighted score for scenario. The normalized scores and the relative scores from the stakeholder perspectives will be evaluated in the last part of this section.

3.6.1. Quantifying stakeholder input

The interviews will consist of three parts that will result in a rank and score of the 13 indicators. At first, the scope of the research, together with the indicators, will be described to ensure that all stakeholders use the same definitions. The second step is for each stakeholder to rank all indicators from 1 to 13 as most important and least important. The last step is to divide 130 points among all indicators. This gives a unique ratio of indicators that are more/less prioritized. No minimum or maximum amount of points can be given for a single indicator as long as there are exactly 130 points distribution between all indicators. It is also possible to give multiple indicators the same amount of points. It should be verified that the amount of points given to a certain indicator is not more than a higher-ranked indicator. Otherwise, the ranking of the indicators should be reconsidered. Once the points are distributed among all indicators, it is possible to give a score:

$$w_m(s) = 10 * \frac{\mathrm{X}_m(s)}{130} \tag{20}$$

For this equation, the weighted score (w_m) for a certain indicator (m) will be determined for the different stakeholders (s) and expressed without an unit. This is based on the number of points that are given to an indicator (X_m) relative to the maximum 130 points that are given to the indicators. The weighted score can vary from 0 to 10 as minimum and maximum score respectively. The weighted score can indicate what indicators were given a higher priority compared to others.

3.6.2. Total weighted scores per stakeholder perspective

The weighted scores (w_m) for the different indicators can be combined with the normalized indicator scores (v_m):

$$V_s(a,s) = \frac{1}{10} * \sum_{i=1}^{m} w_m(a,s) * v_m(a,s) \tag{21}$$

The total weighted score (V_s) can be defined per scenario (a) and stakeholder perspective (s) which is expressed without an unit. This allows to compare the weighted score per stakeholder perspective with the normalized score ($V_{normalized}$) for the different scenarios.

3.6.3. Evaluating normalized and weighted scores

The normalized (v_m) and weighted (W_m) scores from the stakeholder perspectives will be evaluated. Both scores are in a range between 0 and 10. The normalized scores provide insight in whether or not it an indicator has reached its maximum possible score (section 3.5). With the weighted scores, it becomes clear to see how much impact an individual indicator has on the overall total weighted score (V_s). In other words, an indicator with a high normalized and weighted score has a positive impact on the total weighted score. It will be the other way around if an indicator has a low normalized score in combination with a high weighted score. In this way, it is possible to quantify the impact of indicator weighting relative to a score on which all indicators would have the same prioritization or 'weighting':

$$\gamma(a,s) = \left(\frac{V_s(a,s)}{V_{normalized}(a,s)} - 1\right) * 100\% \tag{22}$$

The difference (γ) between the total normalized ($V_{normalized}$) and weighted (V_s) indicator scores for a specific scenario (a) and stakeholder perspective (s) will be expressed in percentages. The difference is positive if the weighted score is higher than the (initial) normalized score and negative if it is the other way around.

4. Results

In this chapter, the developed generic assessment framework will be demonstrated with a selected case study in Nieuwegein, the Netherlands. The results of the selected case study can be found in are represented in the same six steps that form the generic assessment framework. At first, the selected case study in Nieuwegein will be described (section 4.1). The next section illustrate the designed scenarios (section 0) that will be evaluated. The water- and energy balance (section 0) gives an overview of all the key parameters and results of the demands and supplies for the different decentralized WEN systems. The next steps form the multi-criteria analysis (MCA) on which the individual indicators are described (section 4.4) before the indicators are normalized to get an average score per scenario (section 4.5). The last step includes the stakeholder perspectives that resulted in weighted scores (section 0).

4.1. Step 1: Case study selection

This research uses a real case planning area called *City Nieuwegein*, located at the city center of Nieuwegein, the Netherlands. Neighborhoods in the Netherlands vary depending on their construction year and housing density. City Nieuwegein can be categorized as a modern Dutch neighborhood with a high building density of multiple-floor apartments. In addition, modern buildings should be constructed according to the latest energy standards, almost climate-neutral buildings (BENG), that results in residences with an reduced energy demand compared to older building [89]. Modern Dutch neighborhoods are often designed as high-rise buildings to create many new housing spaces in relatively small areas. This scope has been chosen as this is also in line with the urbanization trend and the increased housing demand in the Netherlands [116]. Additionally, modern Dutch neighborhoods have a lower complexity in designing the water and energy system compared to an existing neighborhoods with more difficulties to make changes in the current infrastructure.

City Nieuwegein has an area of approximately 4.7 hectares (47,000 m^2) and comprises six different building blocks indicated as blocks *C1* to *C5* and *B1* (Figure 15). The planning area also contains public spaces that are either permeable or impermeable. The key numbers of City Nieuwegein originate from public concept plans written by the municipality Nieuwegein (Table 11) [77]. These numbers will be used to elaborate the water-energy balance further. A total of 2,304 residents are expected to live in this neighborhood, and on average, 1.8 persons will live in one of the 1,280 apartments. It is assumed that an apartment is on average 70 m^2.

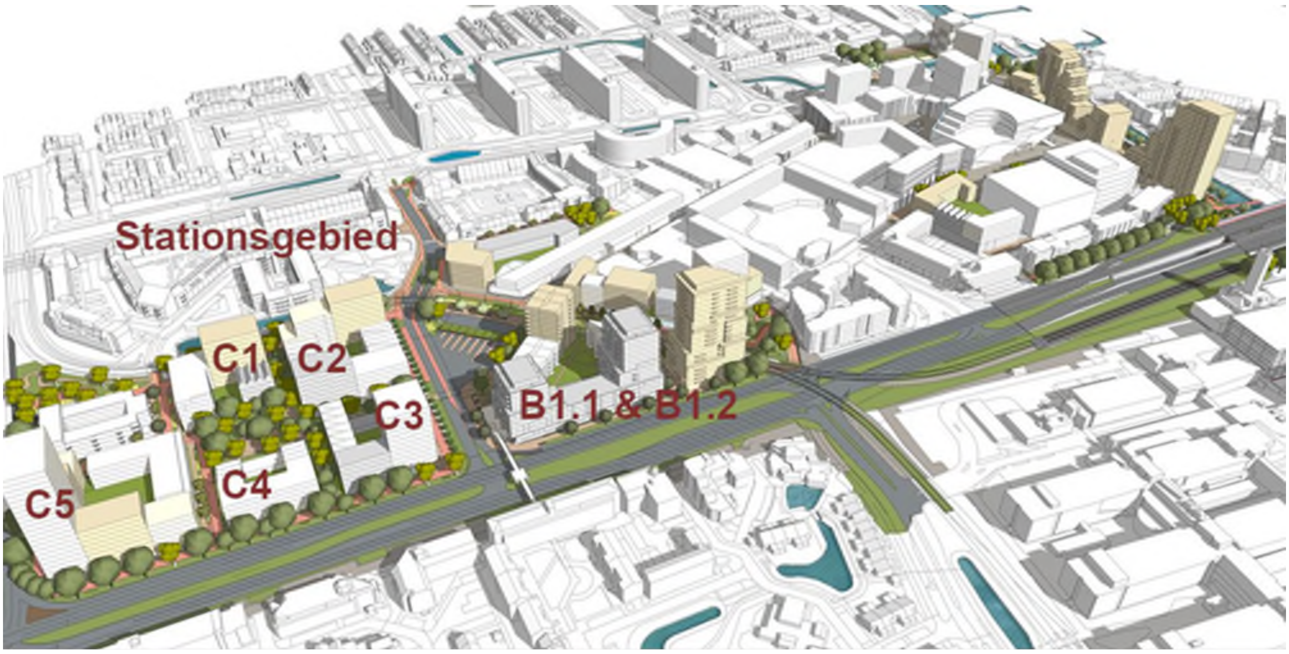


Figure 15: Visual impression of City Nieuwegein (van den Broeke et al., 2022)

Table 11: Key numbers for City Nieuwegein

Planning area	Number of houses [-]	Number of residents [-]	Total area [m^2]
Bus station (impermeable)	-	-	7,000
Block B1 (B1.1 & B1.2)	467	841	6,280
Block C1 to C4	600	1,080	10,400
Block C5	213	383	4,550
Public space (permeable)	-	-	7,200
Public space (impermeable)	-	-	11,570
Total	**1,280**	**2,304**	**47,000**

The properties (Table 12) for this neighborhood are inspired by the real-case design of City Nieuwegein. It is assumed that there is no runoff at the permeable public green spaces and the green spaces within the building blocks (only evaporation and local infiltration) [77]. Based on the properties of building block C5, it is assumed that there is a 1:2 ratio of open spaces and rooftops [117]. For the open spaces of the building blocks, it is assumed that there is an equal distribution of green spaces and impervious areas [117]. With regards to the vegetational water demand, only public green spaces and green facades require additional water for irrigation. Green spaces and optionally courtyard gardens within the building blocks will also have a vegetational water demand if there is no local water storage available. In addition, it is assumed that all street pavements have a runoff of 50% [117]. For the total rooftop area (14,160 m^2), it is assumed that 3,900 m^2 of all building blocks are provided with PV panels (runoff of 80%) [77]. It is assumed that 5,050 m^2 of the vertical panels are east-southeast (ESE) oriented and 10,250 m^2 of the PV panels are south-southwest (SSW) oriented [71]. There are optionally blue-green rooftops that have a runoff of 32% and do not require additional water for their vegetation [77]. Optionally, there is also a possibility to have facades with PV panels.

Table 12: Distribution of (im)pervious areas

Planning area	(public) Green space [m^2]	Pavement [m^2]	Blue-green/regular rooftop [m^2]	PV rooftop [m^2]	Total area [m^2]	Facade with PV [m^2]	Green facade [m^2]
Bus station (impermeable)	-	7,000	-	-	7,000	-	-
Block B1 (B1.1 & B1.2)	1,050	1,050	2,300	1,880	6,280	4,370	1,770
Block C1-C4	1,730	1,720	5,540	1,410	10,400	3,280	2,950
Block C5	760	760	2,420	610	4,550	7,650	1,280
Public space (permeable)	7,200	-	-	-	7,200	-	-
Public space (impermeable)	-	11,570	-	-	11,570	-	-
Total	**10,740**	**22,100**	**10,260**	**3,900**	**47,000**	**15,300**	**6,000**

Regarding mobility, the municipality plans to have 0.5 parking spaces per apartment [118]. This includes both individual car use (0.25 per apartment), shared car use (0.05 per apartment), and visitor parking (0.2 per apartment). This means that there is space for 640 vehicles within the neighborhood. For this study, an assumption is made that there is a similar distribution of (bio-)fuel, electric, and hydrogen vehicles for all three scenarios. There will be 320 (bio-)fuel, 160 electric, and 160 fuel cell electric vehicles. It is assumed that the (bio)fuel cars fall outside the scope of this research as they will be provided with fuel outside the neighborhood. For both the electric and hydrogen vehicles, a 50/50 charging distribution is assumed in loading in or outside the neighborhood area.

4.2. Step 2: Design of scenarios

For this research, four different scenarios have been designed with different degrees of decentralized WEN systems. The main differences between the scenarios can be found on a neighborhood scale (Table 13 and Table 14) that leads to a more decentralized WEN system. In some cases, there are also water-energy-saving appliances present which will be further described. The characteristics of the different system components have been finalized through optimization with the modeling tools (section 3.3.1).

For all scenarios, an aquifer thermal energy storage (ATES) system will be used to fulfill the heating and cooling demand. With a heat exchanger, heat and cold can be stored in the ATES system in a warm aquifer (15-20 °C) and cold aquifer (5-10 °C). For this neighborhood, a collective heat pump is used to regenerate the ATES system, with the Lek canal as the source for the heat pump. This ensures that the temperature of the warm aquifer can be regulated. The heating network uses two separate pipe systems that can either transport heat and cold. The flow direction of the two pipe networks depends on the heat or cold demand. The building blocks use household or building heat pumps to get the required water temperature. A temperature of approximately 35 °C is considered for the heating of apartments and at least 60 °C for warm tap/DW to prevent microbial growth, such as *Legionella* [119].

Table 13: Design choices water- and energy systems

Demand/supply	Reference	Improved centralized	Hybrid	Almost decentralized
Rainfall	RWH system	RWH system	RWH system	RWH system
Vegetational water demand	Public green space and courtyard gardens	Public green space*	Public green space*	Public green space and green facades*
Non-potable water demand	Not available	Not available	GW for toilet and washing machine	GW for toilet and washing machine
Drinking water demand	From DWTP	From DWTP	From DWTP	From DWTP and local DW production facility
Wastewater discharge	To WWTP	To WWTP	Local treatment light-GW, rest WWTP	Only local treatment
Demi water and hydrogen demand	All imported	All imported	All imported	Primarily locally produced, rest imported
Electricity demand	From grid and PV panels	From grid and PV panels	From grid and PV panels	From grid, PV panels, fuel cell and biogas
Heating and cooling demand	Heat exchanger and heat pump	Heat exchanger and heat pump	Heat exchanger and heat pump	Heat exchanger and heat pump
Surplus energy (conversion/storage)	ATES	ATES	ATES and battery	ATES, battery and electrolyzer

* Vegetational water demand for courtyard gardens was excluded as it was assumed that local water storage was present that could be used during dry periods

Table 14: Main characteristics water- and energy systems

Scenario	Rainwater tank [m^3]	Non-potable water tank [m^3]	Drinking water tank [m^3]	Blackwater tank/digestor [yes/no]	Collective battery [kWh]	Hydrogen tank [kg]	Electrolyzer [kW]	Fuel cell [kW]
Reference	1,500	-	-	-	-	-	-	-
Improved centralized	1,000	-	-	-	-	-	-	-
Hybrid	1,000	500	-	-	1,000	-	-	-
Almost decentralized	1,000	500	1,000	yes	2,000	300	1,000	500

4.2.1. Reference scenario

The *reference scenario* (Figure 16) will represent a neighborhood according to the current building standards in the Netherlands without any water-energy-saving appliances. The so-called 'centralized' water and energy production facilities outside of the neighborhood fulfill most of the water and energy demands. However, some decentralized technologies will be taken into account. A RWHS is present that is used the cover the vegetational water demand. DW can be used as a last alternative during periods without collected rainwater. All domestic WW will be transported to a WW treatment plant outside the neighborhood area. Rainwater is not being discharged to a WW treatment plant due to the presence of a rainwater harvesting system. The demi water and hydrogen demand that is required for all FCEVs originates from an external supplier outside of the neighborhood area. The electricity demand covers all household applications and EVs. In addition, the electricity demand that applies for the water system (pumping station, treatment process, e.g.) will also be considered. The primary electricity provision originates from the grid. PV panels on rooftops will also cover a part of the energy demand within the neighborhood. This implies electricity, heating and cooling. Surplus energy from the PV rooftops will be returned to the central electricity network.

4.2.2. Improved centralized scenario

The *improved centralized scenario* (Figure 16) has some additional innovative technologies compared to the *reference scenario*. For this scenario, water-energy-saving appliances have been considered. In addition to rooftops with PV panels, blue-green rooftops have be included. The other characteristics with regards to the water and energy system are the same as the *reference scenario*.

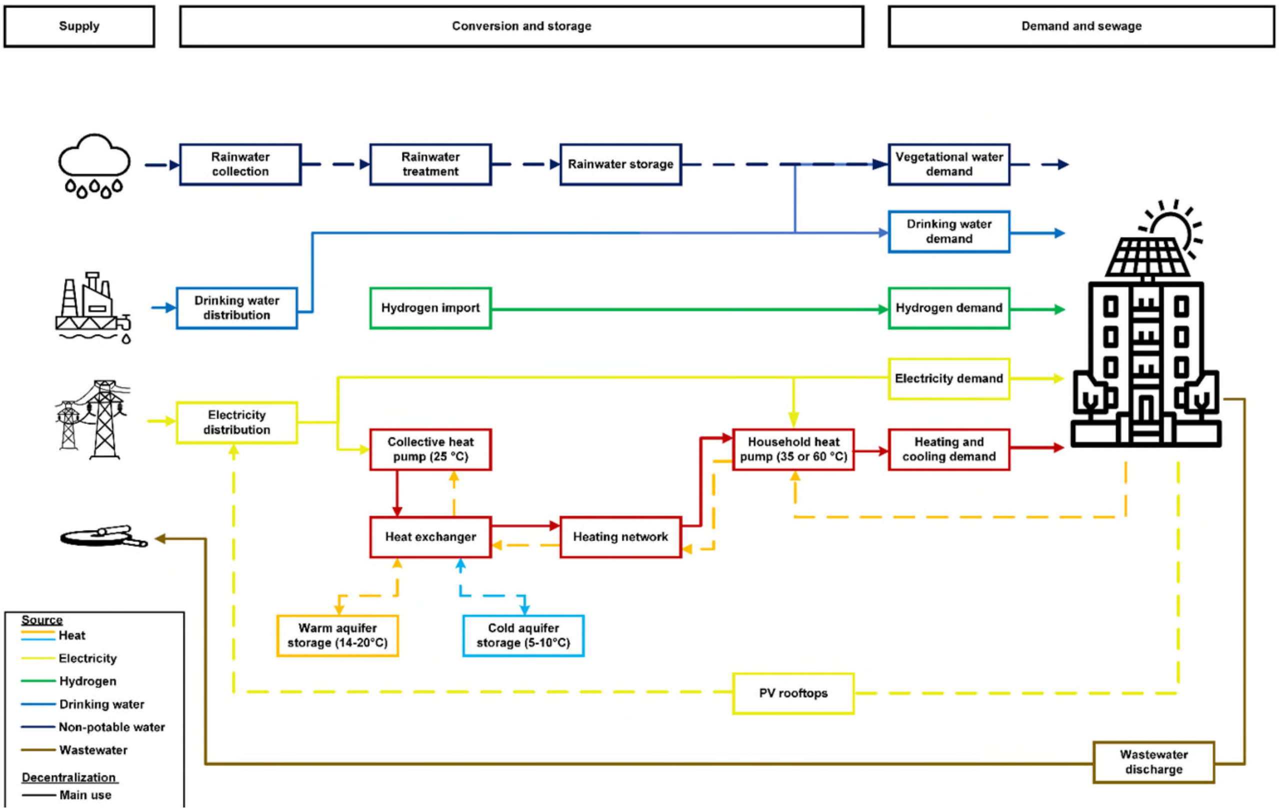


Figure 16: Water- and energy system for reference scenario and improved centralized scenario

4.2.3. Hybrid scenario

The *hybrid scenario* (Figure 17) has even more decentralized WEN systems compared to the previous scenarios. The case study of City Nieuwegein has been used as a reference. This concept also uses a RWHS and blue-green rooftops for rainwater collection and runoff reduction. In addition, rainwater and light-greywater (LGW) is recycled to cover not only the vegetational water demand but also toilet flushing and the washing machine. For the remaining water demand, only DW from a centralized DWTP is used. The total WW discharge is reduced because LGW is recycled. The last main difference between the *reference scenario* and *improved centralized scenario* is the presence of a collective battery to store surplus energy.

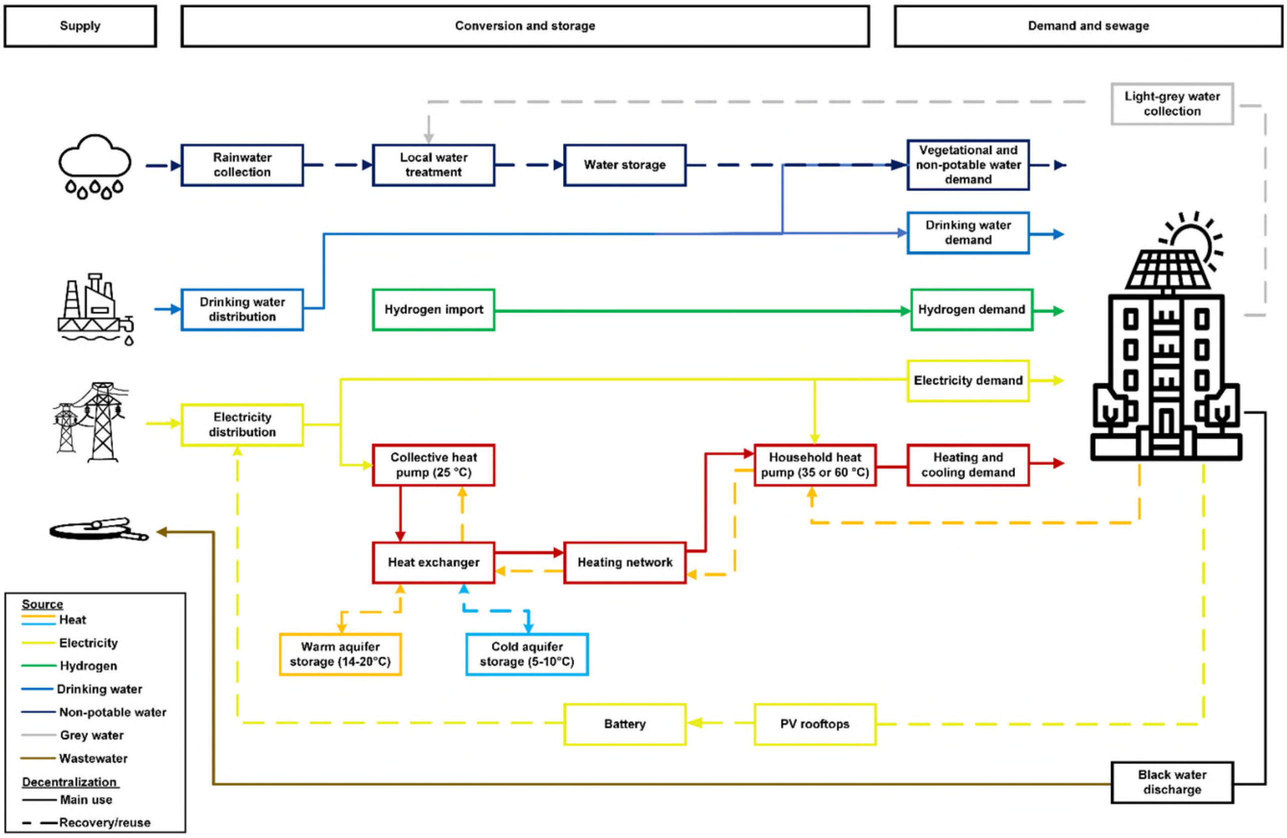


Figure 17: Water- and energy system for hybrid scenario

4.2.4. Almost decentralized scenario

The *almost decentralized scenario* (Figure 18) is a neighborhood with the highest level of decentralized WEN systems that was found applicable. This scenario has the same innovative technologies that were mentioned (e.g. RWHS, LGW recycling and collective battery) for the other three scenarios. In addition to those technologies, green facades were included to increase the amount of vegetation present in the neighborhood. In contrast to the *hybrid scenario*, this scenario recycles GW instead of LGW to maximize the availability of WW that can be reused. In addition, a decentralized DW treatment facility was included to produce DW with collected GW and rainwater. Distributed DW from a centralized DWTP still covers the remaining DW demand. An extra purification step is included to produce demi water. All WW will be treated locally either with helophyte filters (rainwater and GW) or a BW digestor. With regards to the energy system, more renewable energy can be produced locally due to the presence PV panels both the rooftops and facades. Surplus energy can either be stored in a collective battery or converted into hydrogen. At last, the BW digestor produces biogas that can be used for the electricity and heating demand.

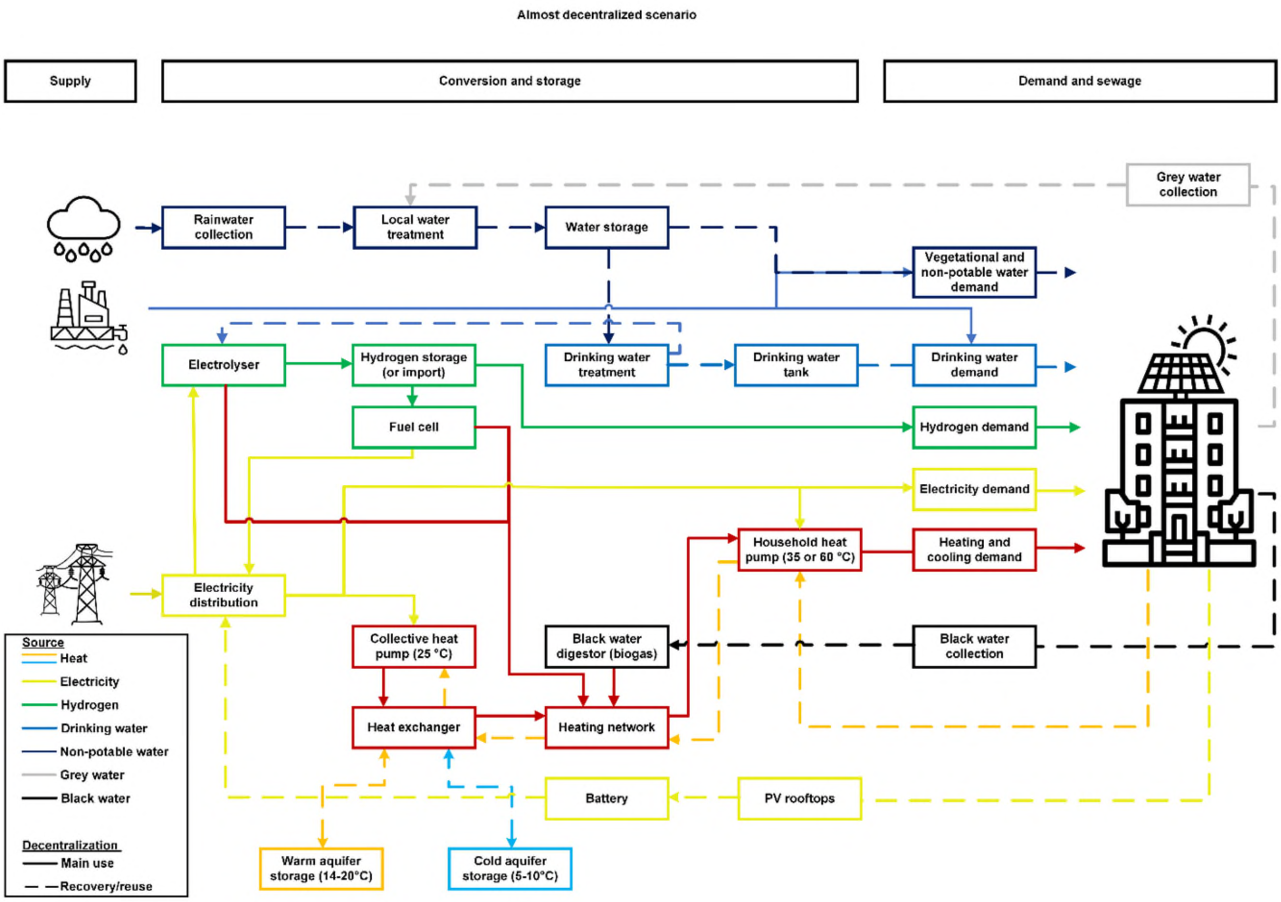


Figure 18: Water- and energy system for almost decentralized scenario

4.3. Step 3: Water and energy balance

This section describes the results of the water and energy balance for the different scenarios. The required modeling tools and meteorological data were used to further elaborate the water and energy parameters. All scenarios were performed by using a 10-year time interval (2011-2020), resulting in a total of 87,672 timesteps.

4.3.1. Modeling tools

The modeling tools that have been described in section 3.3.1 provided hourly data to quantify the water and energy demands/supplies.

SIMDEUM

The hourly DW patterns for a whole week that were generated with SIMDEUM can be found in Appendix A. The characteristics of *City Nieuwegein* (number of people per apartment, water demand per application, e.g.) were used for SIMDEUM. As a result, SIMDEUM generated unique DW patterns for each scenario (Table 15) depending on the type of appliance and if non-potable water was used within the apartments. The average runtime to get the DW patterns took approximately 5 minutes.

Table 15: Overview of water household appliances per scenario

Appliance (initial water source)	Reference	Improved centralized	Hybrid	Almost decentralized
Shower	Regular (DW)	Recirculating (DW)	Recirculating (DW)	Recirculating (DW)
Toilet	Regular (DW)	Vacuum (DW)	Vacuum (NPW)	Vacuum (NPW)
Washing machine	Regular (DW)	Eco-friendly (DW)	Eco-friendly (NPW)	Eco-friendly (NPW)
Dishwasher	Regular (DW)	Eco-friendly (DW)	Eco-friendly (DW)	Eco-friendly (DW)
Sink	Regular (DW)	Water-saving faucet (DW)	Water-saving faucet (DW)	Water-saving faucet (DW)
Other	Regular (DW)	Regular (DW)	Regular (DW)	Regular (DW)
Food preparation and drinking	Regular (DW)	Regular (DW)	Regular (DW)	Regular (DW)

UWOT

The different UWOT models that were developed for the 4 scenarios can be found in Appendix B. The UWOT model produced output data for the water demands and supplies. The average runtime for each scenario took approximately 5 minutes.

Power-to-X

The parameters that were used for each scenario can be found in Appendix C. The scenarios were performed in a phase with and without MODFLOW. For the simulation with MODFLOW, the runtime took approximately 5 hours whereas the simulation without MODFLOW took approximately 2 hours. Ultimately, all results of the Power-to-X models were based on the simulate with MODFLOW as this incorporated the changes of groundwater flow and temperature. The simulation without MODFLOW was mainly used to make quicker changes and validations before simulating the final results.

4.3.2. Rainfall and other meteorological data

The meteorological data of KNMI has been used to simulate the water and energy balance for a time interval of 10 years (2011-2020). This period has been chosen as there was a variety of extreme climatological conditions such as heavy rainfall events (>50 mm/day), dry and hot periods and cold conditions.

Rainfall

For this case study, the hourly rainfall time series from De Bilt, the Netherlands, were used. For each scenario, the total runoff area (Table 16) was determined based on the different surface types. By incorporating more blue-green spaces the total runoff area will be reduced. As a result, the *reference* *scenario* has a total runoff area of 22,380 m^2 whereas the other scenarios have a total runoff area of 17,460 m^2.

Table 16: Overview of (im)pervious areas per scenario

Scenario	Green spaces (0% runoff) [m^2]	Pavement (50% runoff) [m^2]	Green rooftops (32% runoff) [m^2]	Regular rooftop (80% runoff) [m^2]	PV rooftop (80% runoff) [m^2]	Total runoff area [m^2]
Reference	10,735	22,105	-	10,260	3,900	22,380
Improved centralized	10,735	22,105	10,260	-	3,900	17,460
Hybrid	10,735	22,105	10,260	-	3,900	17,460
Almost decentralized	10,735	22,105	10,260	-	3,900	17,460

Surface water temperature

The results of the surface water heat that has been used for the ATES system can be found in the yearly energy balance (section 4.3.9).

Solar irradiation

The results of solar power from PV panels can be found in the energy balance (section 4.3.9). All scenarios (Table 17) have the same amount of PV panels on rooftops. Only the *almost decentralized scenario* has additional PV panels on the facades which is either east-southeast (ESE) or south-southwest (SSW) oriented.

Table 17: Overview of PV panels per scenario

Scenario	PV rooftop [m^2]	PV facade (ESE) [m^2]	PV facade (SSW) [m^2]	Total PV [m^2]
Reference	3,900	-	-	**3,900**
Improved centralized	3,900	-	-	**3,900**
Hybrid	3,900	-	-	**3,900**
Almost decentralized	3,900	5,100	10,200	**19,200**

4.3.3. Vegetational water demand

The results of the vegetational water demand for the different scenarios can be found in the water balance (section 4.3.8). All scenarios have a vegetational water demand (Table 18) for the public green spaces. The *refence scenario* has an additional vegetational water demand for the courtyard gardens. For the *almost decentralized scenario*, there is an additional vegetational water demand for the green facades.

Table 18: Overview of vegetational water demand per scenario

Scenario	Public green (600 mm/year) [m^3/year]	Courtyard garden (600mm/year) [m^3/year]	Green facades (700mm/year) [m^3/year]	Yearly vegetational water demand [m^3/year]
Reference	4,320	2,120	-	6,440
Improved centralized	4,320	-	-	4,320
Hybrid	4,320	-	-	4,320
Almost decentralized	4,320	-	4,200	8,520

4.3.4. Drinking water and non-potable water demand (domestic water)

The results of the domestic water demand for the different scenarios can be found in the water balance (section 4.3.8). Each scenario has a specific DW demand (Table 19). For the *reference scenario*, the domestic water demand is based on the daily average in the Netherlands which is 119.3 L/person/day [82]. The other three scenarios have a lower DW demand by considering water-energy-saving appliances. The *improved centralized scenario* only uses DW for the different purposes resulting in a DW demand of 56.2 L/person/day. For the *hybrid scenario* and *almost decentralized scenario*, the DW demand is further reduced to 39.3 L/person/day by using non-potable water for toilet flushing and the washing machine.

Table 19: Overview of domestic drinking water demand per scenario

Scenario	Shower [L/p/d]	Toilet [L/p/d]	Washing machine [L/p/d]	Dishwasher [L/p/d]	Sink [L/p/d]	Kitchen [L/p/d]	Other [L/p/d]	Total DW demand [L/p/d]
Reference	51.1	34.6	15.4	6.0	5.2	4.5	2.5	**119.3**
Improved centralized	24.7	5.8	11.1	4.0	3.6	4.5	2.5	**56.2**
Hybrid	24.7	-	-	4.0	3.6	4.5	2.5	**39.3**
Almost decentralized	24.7	-	-	4.0	3.6	4.5	2.5	**39.3**

4.3.5. Wastewater discharge (water treatment parameters)

The effects of the different water treatment facilities that are used for the scenarios can be found in the water balance (section 4.3.8) and energy balance (section 4.3.9). The average daily treatment capacity (Table 20) differs between the *hybrid scenario* and *almost decentralized scenario* depending on the total amount of GW that was recycled. In addition, the *almost decentralized scenario* also produces DW and has a BW digestor. The *refence scenario* and *improved centralized scenario* do not have any decentralized treatment facilities as only rainwater is being harvested and used for the vegetational demand.

Table 20: Water treatment parameters per scenario

Scenario	DW purification [m^3/day]	Helophyte filter [m^3/day]	BW digestor [m^3/day]
Reference	-	-	-
Improved centralized	-	-	-
Hybrid	-	100	-
Almost decentralized	50	100	30

4.3.6. Demi water and hydrogen demand

The total amount of demi water and hydrogen that was used for the different can be found in the water balance (section 4.3.8) and energy balance (section 4.3.9). Only the *almost decentralized scenario* produced demi water and hydrogen locally that could be used for FCEVs or as an additional energy carrier to fulfill the domestic energy demand. The other three scenarios only imported hydrogen, and indirectly demi water, that was only used for the FCEVs.

4.3.7. Electricity, heating and cooling demand

The results of the domestic energy demand for the different scenarios can be found in the yearly energy balance (section 4.3.9). Each scenario has a specific energy demand (Table 21).

<u>Domestic energy demand</u>

For the *reference scenario*, the domestic energy demand for a household is 3,600 kWh/year. The other three scenarios have a lower domestic energy demand of 2,975 kWh/year per household by considering water-energy-saving appliances.

<u>Mobility</u>

As previously mentioned in the case study selection (section 4.1), the energy demand for (bio-)fueled vehicles is outside this research's scope as there won't be a petrol station within the neighborhood. The outcomes of the energy demand that is required for 160 electric vehicles (EVs) and 160 fuel cell electric vehicles (EVs) for each scenario can be found in the yearly energy balance (section 4.3.9). Only 50% of the energy demand for the EVs and FCEVs will be fulfilled within the neighborhood. Based on the yearly energy demand for a single EV is 1,950 kWh, the yearly energy demand for all EVs within the neighborhood is 156,000 kWh (or 156 MWh). Based on the yearly energy demand for a single FCEV of 5,100 kWh, the yearly energy demand for all FCEVs within the neighborhood is 408,000 kWh (or 408 MWh).

Table 21: Overview of energy demand per scenario

Scenario	Heating and cooling [MWh/year]	Warm tap water [MWh/year]	Domestic appliances [MWh/year]	Electric vehicles [MWh/year]	Fuel cell electric vehicles [MWh/year]	Total domestic energy demand [MWh/year]
Reference*	5,820	2,050	2,560	**160**	**410**	**11,000**
Improved centralized	5,820	1,410	2,400	**160**	**410**	**10,200**
Hybrid	5,820	1,410	2,400	**160**	**410**	**10,200**
Almost decentralized	5,820	1,410	2,400	**160**	**410**	**10,200**

* Used as the benchmark for the reduced external energy demand

4.3.8. Yearly water balance

The yearly water balance (Table 22) is based on the average year characteristics over a period of 10 years (2011-2020). The water demands and supplies for the different scenarios are visualized with a Sankey diagram.

Table 22: Key values yearly water balance

Water source (percentages)	Reference	Improved centralized	Hybrid	Almost decentralized
Vegetational water demand				
From rainwater	90%	92%	74%	68%
From local (light-)greywater	0%	0%	26%	29%
From external drinking water	10%	8%	0%	3%
Domestic water demand				
From local drinking water	0%	0%	0%	36%
From rainwater	0%	0%	8%	9%
From local (light-)greywater	0%	0%	22%	21%
From external drinking water	100%	100%	70%	34%
Demi water demand				
From local demi water	0%	0%	0%	97%
From external demi water	100%	100%	100%	3%

Water source (m^3/year)	Reference	Improved centralized	Hybrid	Almost decentralized
Vegetational water demand				
From rainwater	6,180	4,230	3,340	6,050
From local (light-)greywater	0	0	1,170	2,580
From external drinking water	690	390	0	280
Domestic water demand				
From local drinking water	0	0	0	17,230
From rainwater	0	0	3,780	4,300
From local (light-)greywater	0	0	10,400	10,050
From external drinking water	100,400	47,300	33,080	15,850
Demi water demand				
From local demi water	0	0	0	160
From external demi water	100	100	100	5

<u>Yearly water balance reference scenario</u>

The *reference scenario* (Figure 19) shows a very linear water use pattern, as there is only rainwater harvesting for the vegetational water demand. Rainwater collection covers 90% of the vegetational water demand and the remaining part is fulfilled with DW (10%). However, it does show a disbalance because there is on average 13,310 m^3 of runoff to nearby surface water whereas the total vegetational water demand is 6,870 m^3. Extended dry periods during the growing season lead to a constant reduction in the rainwater tank without any other water supply besides importing external DW when the rainwater tank is empty. As only water is extracted from the rainwater tanks during the growing season, a lot of excess rainwater in the 'off-season' isn't used and is therefore drained to the nearby surface water. No water-energy-saving appliances are present in this scenario resulting in a yearly external DW demand of 101,090 m^3. The yearly WW discharge that goes to a centralized WWTP is 100,400 m^3. The total amount of demi water that is required to produce hydrogen for the FCEVs is 100 m^3.

Yearly water balance improved centralized scenario

The *improved centralized scenario* (Figure 20) shows a very linear water use pattern, just like the *reference scenario*. The overall vegetational water demand is 4,620 m^3. This is 33% lower compared to the *reference scenario* because there are no courtyard due to the presence of local water storage. Similarly to the *reference scenario*, there is a disbalance during dry periods because there is no recycling of GW (and not enough rainwater is available). In total, 8% (390 m^3/year) over the vegetational water demand is fulfilled with DW. This scenario used blue-green rooftops instead of regular rooftops which resulted in a reduced runoff of 15% (11,310 m^3/year) compared to the *reference scenario*. In contrast to the *reference scenario*, this scenario does have water-energy-saving appliances resulting in a yearly external DW demand of 47,690 m^3/year. The yearly WW discharge that goes to a centralized WWTP is 47,300 m^3. The total amount of demi water that is required to produce hydrogen for the FCEVs is 100 m^3.

Yearly water balance hybrid scenario

The *hybrid scenario* (Figure 21) shows a more circular water use pattern, as rainwater and LGW is reused for vegetation and other non-potable purposes. The overall vegetational water demand of 4,510 m^3 is in the same order of the *improved centralized scenario* because of the same amount of greenery present in this scenario. The total amount of excess rainwater that comes to runoff is 24,600 m^3 which is 76% lower compared to the *reference scenario* and 80% lower than the *improved centralized scenario*. The runoff is lower because rainwater is harvested and treated for non-potable water purposes. In addition, LGW which is on a yearly average 30,130 m^3, is being treated and used for vegetation and non-potable water purposes. As a result, DW is not required for the vegetational water demand. However, because the total amount of treated rainwater and LGW is higher than the non-potable water demand, a total of 24,520 m^3 is discharged. In this scenario water-energy-saving appliances are applied. By using non-potable water for domestic purposes, the yearly external DW demand is 33,080 m^3/year. The yearly WW discharge that goes to a centralized WWTP is 17,170 m^3 because LGW is reused within the neighborhood. The total amount of demi water that is required to produce hydrogen for the FCEVs is 100 m^3.

Yearly water balance almost decentralized scenario

The *almost decentralized scenario* (Figure 22) shows a very circular water use pattern because rainwater and GW is treated into non-potable and DW for different water demands. The yearly vegetational water demand is 8,890 m^3 which is higher than in the other three scenarios. The reason for that is because green facades are used. The total amount of excess rainwater that comes to runoff is 270 m^3 which is 96-98% lower compared to the other scenarios. Based on the total availability of GW and rainwater that can be collected, this is not enough to fulfill the total domestic water demand of 47,300 m^3 because of the temporal disbalance in demand/supply and the water losses during treatment. With rainwater harvesting, GWR and local DW treatment, the yearly external DW demand is 16,300 m^3/year or 34% of the total domestic water demand. The yearly amount of BW that is collected for local digestion is 10,770 m^3. The yearly amount of demi water that is required to produce hydrogen for the FCEVs or for the domestic energy demand is 175 m^3 of which 170 m^3 is locally produced and 5 m^3 from an external production location.

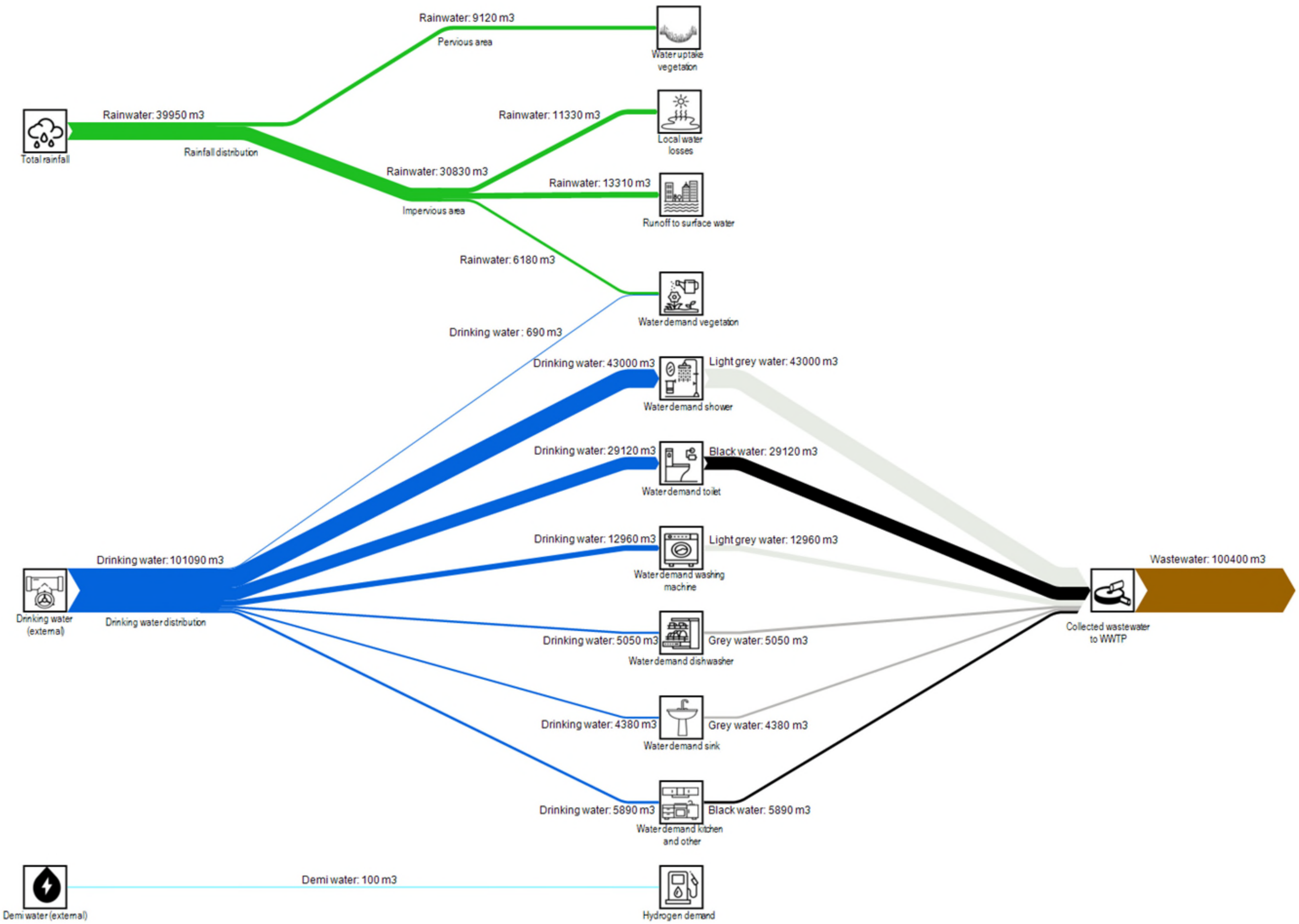


Figure 19: Sankey diagram yearly water balance reference scenario

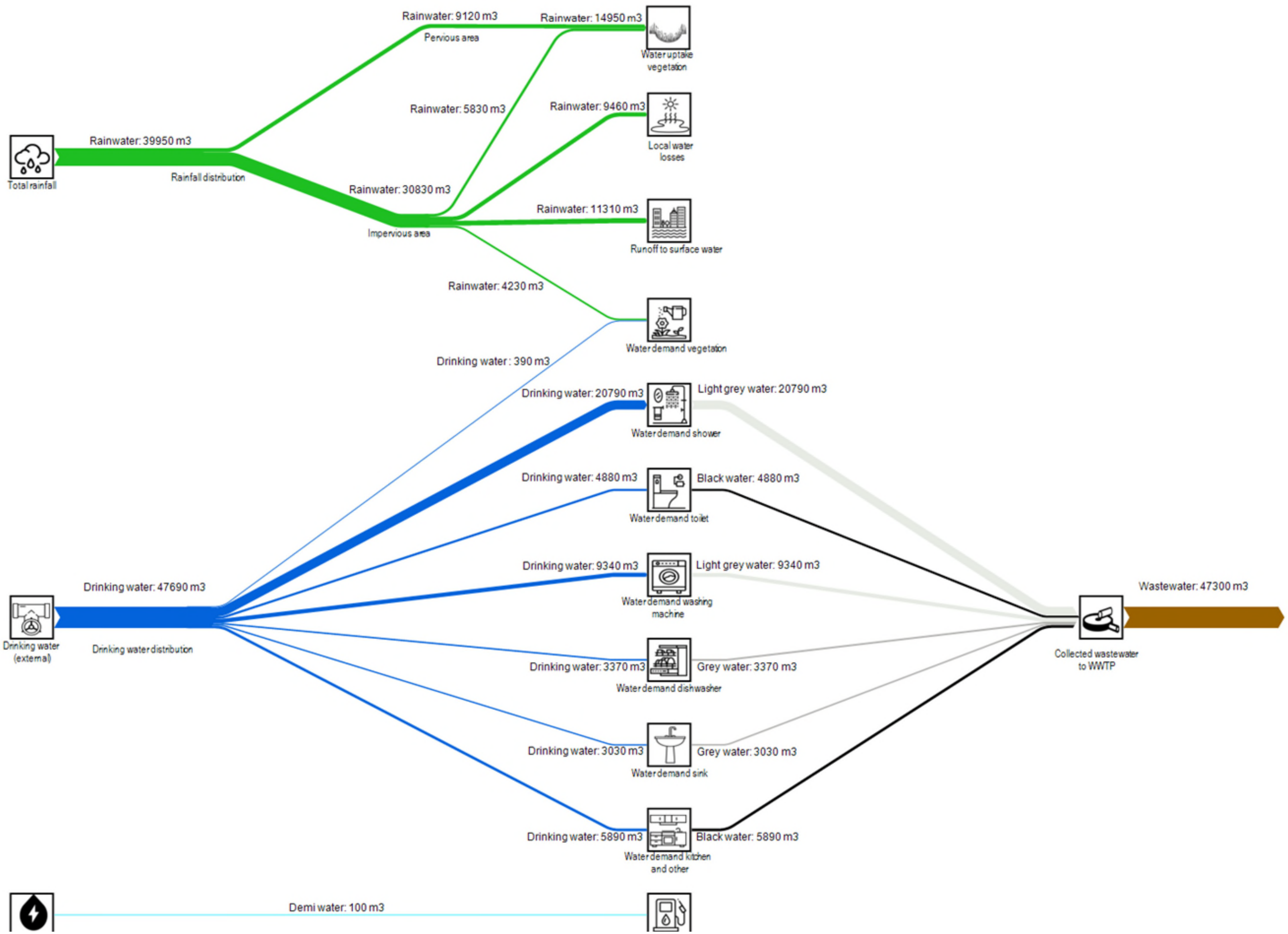
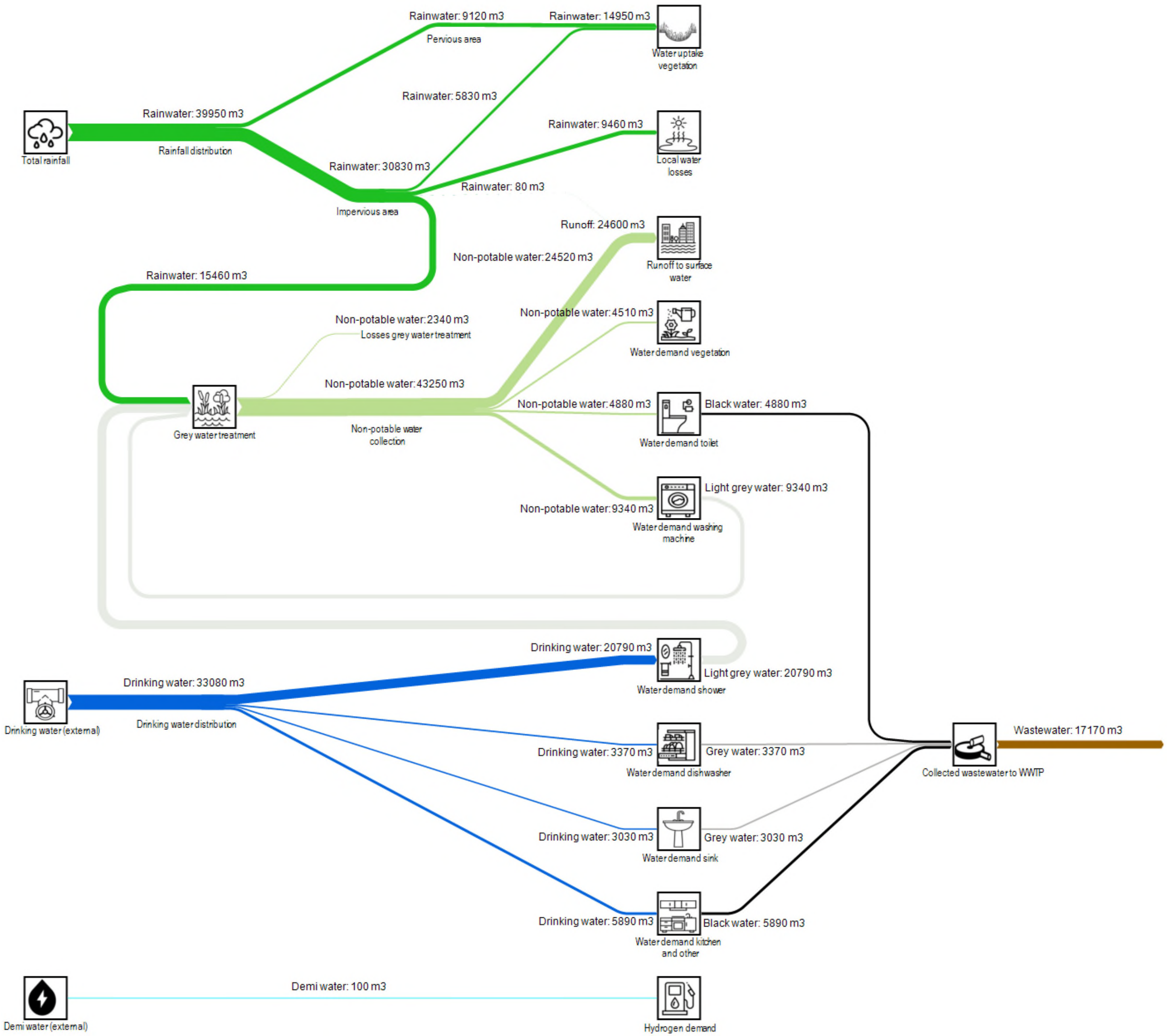


Figure 20: Sankey diagram yearly water balance improved centralized scenario



Total rainfall
Rainwater: 39950 m3
Rainfall distribution
Rainwater: 9120 m3
Pervious area
Rainwater: 14950 m3
Water uptake vegetation
Rainwater: 5830 m3
Rainwater: 9460 m3
Local water losses
Rainwater: 30830 m3
Impervious area
Rainwater: 80 m3
Runoff: 24600 m3
Runoff to surface water
Non-potable water: 24520 m3
Rainwater: 15460 m3
Non-potable water: 2340 m3
Losses grey water treatment
Non-potable water: 4510 m3
Water demand vegetation
Non-potable water: 43250 m3
Grey water treatment
Non-potable water collection
Non-potable water: 4880 m3
Water demand toilet
Black water: 4880 m3
Light grey water: 9340 m3
Non-potable water: 9340 m3
Water demand washing machine
Drinking water: 20790 m3
Water demand shower
Light grey water: 20790 m3
Drinking water: 33080 m3
Drinking water (external)
Drinking water distribution
Wastewater: 17170 m3
Drinking water: 3370 m3
Grey water: 3370 m3
Water demand dishwasher
Collected wastewater to WWTP
Drinking water: 3030 m3
Grey water: 3030 m3
Water demand sink
Drinking water: 5890 m3
Black water: 5890 m3
Water demand kitchen and other
Demi water: 100 m3
Demi water (external)
Hydrogen demand

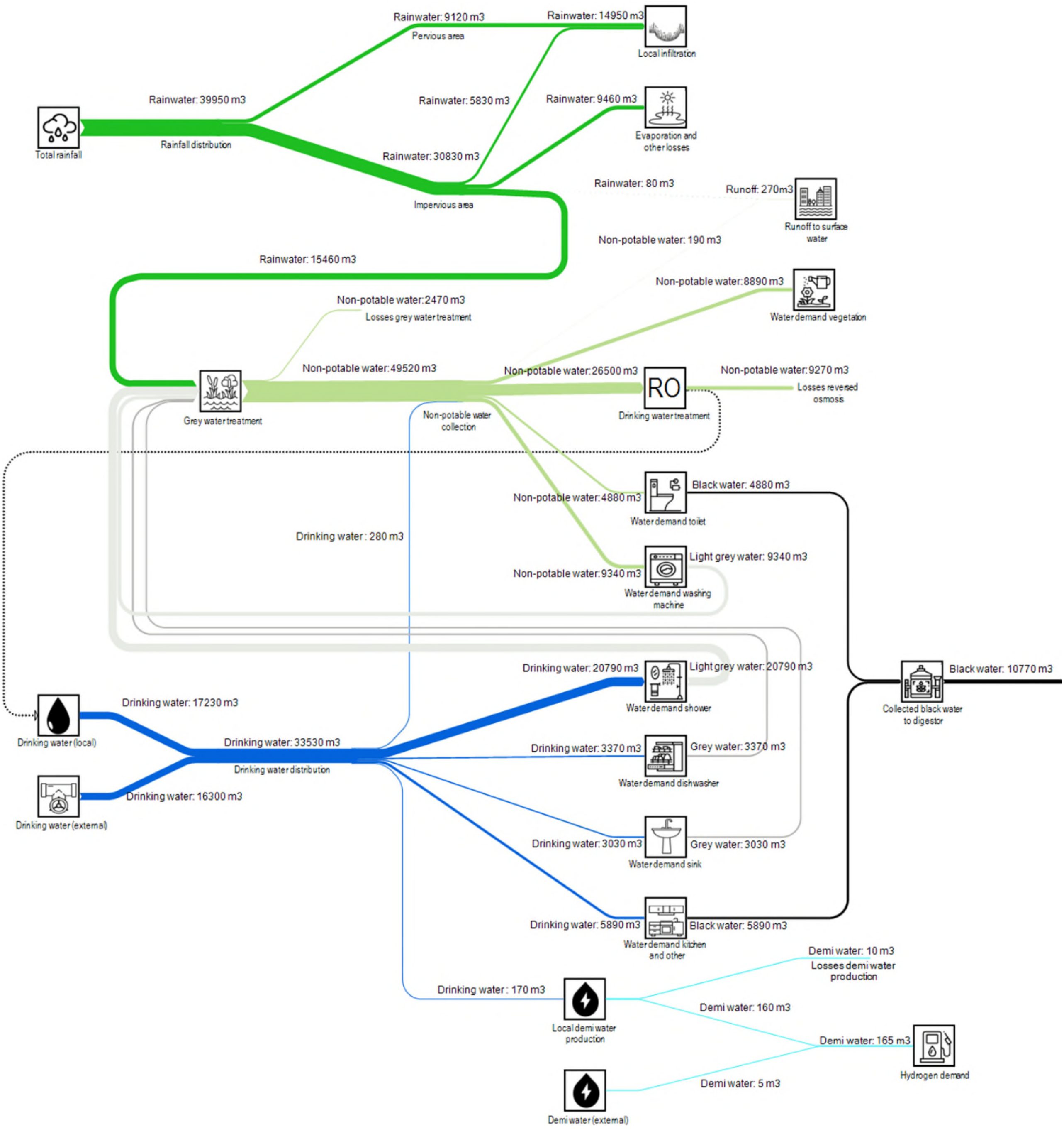


Figure 22: Sankey diagram yearly water balance almost decentralized scenario

4.3.9. Yearly energy balance

Similarly to the yearly water balance (Table 23), the yearly energy balance is based on the average year characteristics over a period of 10 years (2011-2020). The energy demands and supplies for the different scenarios are visualized with a Sankey diagram.

Table 23: Key values yearly energy balance

Energy origin (percentage)	Reference	Improved centralized	Hybrid	Almost decentralized
Electricity				
From direct PV	16%	18%	18%	31%
From grid	84%	82%	82%	58%
From battery	0%	0%	<1%	3%
From fuel cell	0%	0%	0%	7%
From biogas (CHP)	0%	0%	0%	1%
Hydrogen (mobility)				
From direct PV	0%	0%	0%	98%
From H_2 import	100%	100%	100%	2%
Heat				
From ATES	75%	78%	77%	77%
From electricity/rest heat	25%	22%	23%	23%

Energy origin (MWh/year)	Reference	Improved centralized	Hybrid	Almost decentralized
Electricity				
From direct PV	720	690	690	1,260
From grid	3,650	3,250	3,230	2,370
From battery	0	0	20	100
From fuel cell	0	0	0	180
From biogas (CHP)	0	0	0	40
Hydrogen (mobility)				
From direct PV	0	0	0	400
From H_2 import	410	410	410	10
Heat				
From ATES	4,950	4,890	4,600	4,690
From electricity/rest heat	1,660	1,390	1,390	1,400

<u>Yearly energy balance reference scenario</u>

The *reference scenario* (Figure 23) shows a very linear energy use pattern, as there are no energy storage components besides an ATES system that stores heat and cold for seasonal use. The PV panels from the rooftops produce on a yearly average 739 MWh. In total, 715 MWh (97%) of the energy production is directly used for the domestic energy demand. The remaining of the PV production is used for the ATES system (14 MWh), or goes to the grid (10 MWh) because there is not enough energy demand. The total grid import (4,491 MWh) is mainly used for domestic energy demand (81%) and the rest for the ATES system (16%) or district heating network (3%). All hydrogen (411 MWh) is imported from an external production facility. The Sankey diagram also considered the energy that required for the local pumping system (1 MWh) and for the external DW production/transport (51 MWh) and WW treatment/transport (68 MWh).

<u>Yearly energy balance hybrid scenario</u>

The *hybrid scenario* (Figure 24) shows a more circular energy use because of the added collective battery. Similarly to the *reference scenario* and *improved centralized scenario*, the PV panels from the rooftops produce on a yearly average 739 MWh. The collective battery was designed to store surplus energy from the PV panels and preventing it from being exported to the grid. As a result, 21 MWh of surplus energy from the PV panels is stored which was in the *improved centralized scenario* exported to the grid. The total grid import (3,976 MWh) is mainly used for domestic energy demand (81%) and the rest for the ATES system (16%) or district heating network (3%). All hydrogen (411 MWh) is imported from an external production facility. The Sankey diagram also considered the energy that required for the local pumping system (5 MWh), for the external DW production/transport (17 MWh) and WW treatment/transport (27 MWh).

Yearly energy balance hybrid scenario

The *hybrid scenario* (Figure 25) shows a more circular energy use because of the added collective battery. Similarly to the *reference scenario* and *improved centralized scenario*, the PV panels from the rooftops produce on a yearly average 739 MWh. The collective battery was designed to store surplus energy from the PV panels and preventing it from being exported to the grid. As a result, 21 MWh of surplus energy from the PV panels is stored which was in the *improved centralized scenario* exported to the grid. The total grid import (3,976 MWh) is mainly used for domestic energy demand (81%) and the rest for the ATES system (16%) or district heating network (3%). All hydrogen (411 MWh) is imported from an external production facility. The Sankey diagram also considered the energy that required for the local pumping system (5 MWh), for the external DW production/transport (17 MWh) and WW treatment/transport (27 MWh).

Yearly energy balance almost decentralized scenario

The *almost decentralized scenario* (Figure 26) shows a more circular energy use compared to the other scenarios because of the different energy carriers (battery, hydrogen and biogas) that are being used. This scenario used PV panels on both rooftops and facades resulting in a total energy production of 2,527 MWh which is 242% higher compared to the other scenarios. The collective battery and electrolyzer for the hydrogen tank were designed to store surplus energy from the PV panels. As a result, 110 MWh was stored in a collective battery and 935 MWh went to the electrolyzer for hydrogen production. At only a few moments (1% of all timesteps), there was not enough energy storage/conversion capacity resulting in a grid export of 15 MWh. The total grid export from PV panels counts for less than 1% relative to the total PV energy production. Besides the increased energy production from PV panels, there is also biogas production with the use of a local BW digestor. On a yearly average, 57 MWh of heat and 52 MWh of electricity originates from biogas. The total grid import (2,908 MWh) is mainly used for domestic energy demand (81%) and the rest for the ATES system (15%) or district heating network (4%). Most of the hydrogen is locally produced (696 MWh) and a part is imported from an external production facility (10 MWh) if there is not enough hydrogen stored for the FCEVs. The Sankey diagram also considered the energy that required for the local pumping system (9 MWh), local DW treatment (17 MWh) and for the external DW production/transport (8 MWh).

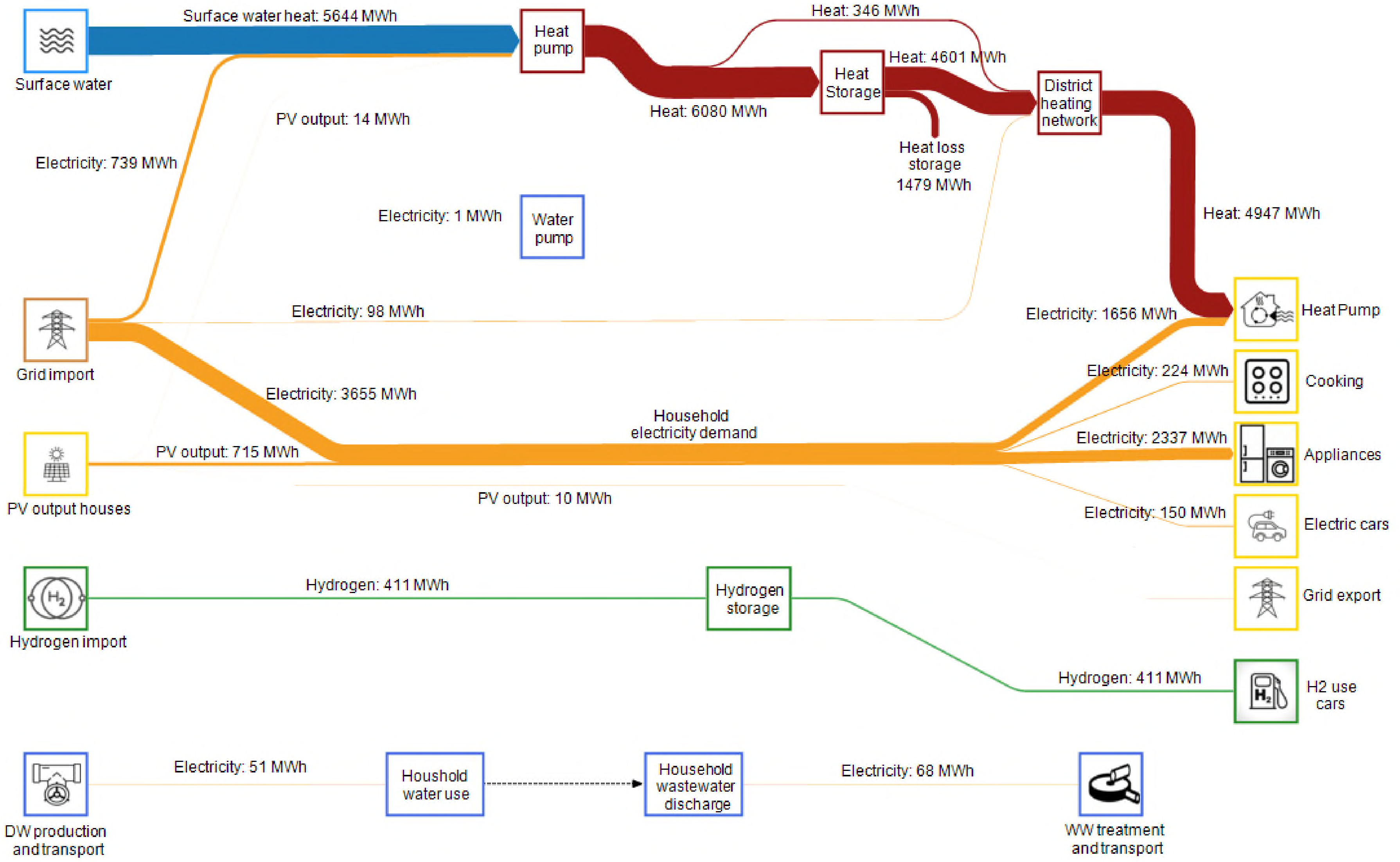


Figure 23: Sankey diagram yearly energy balance reference scenario

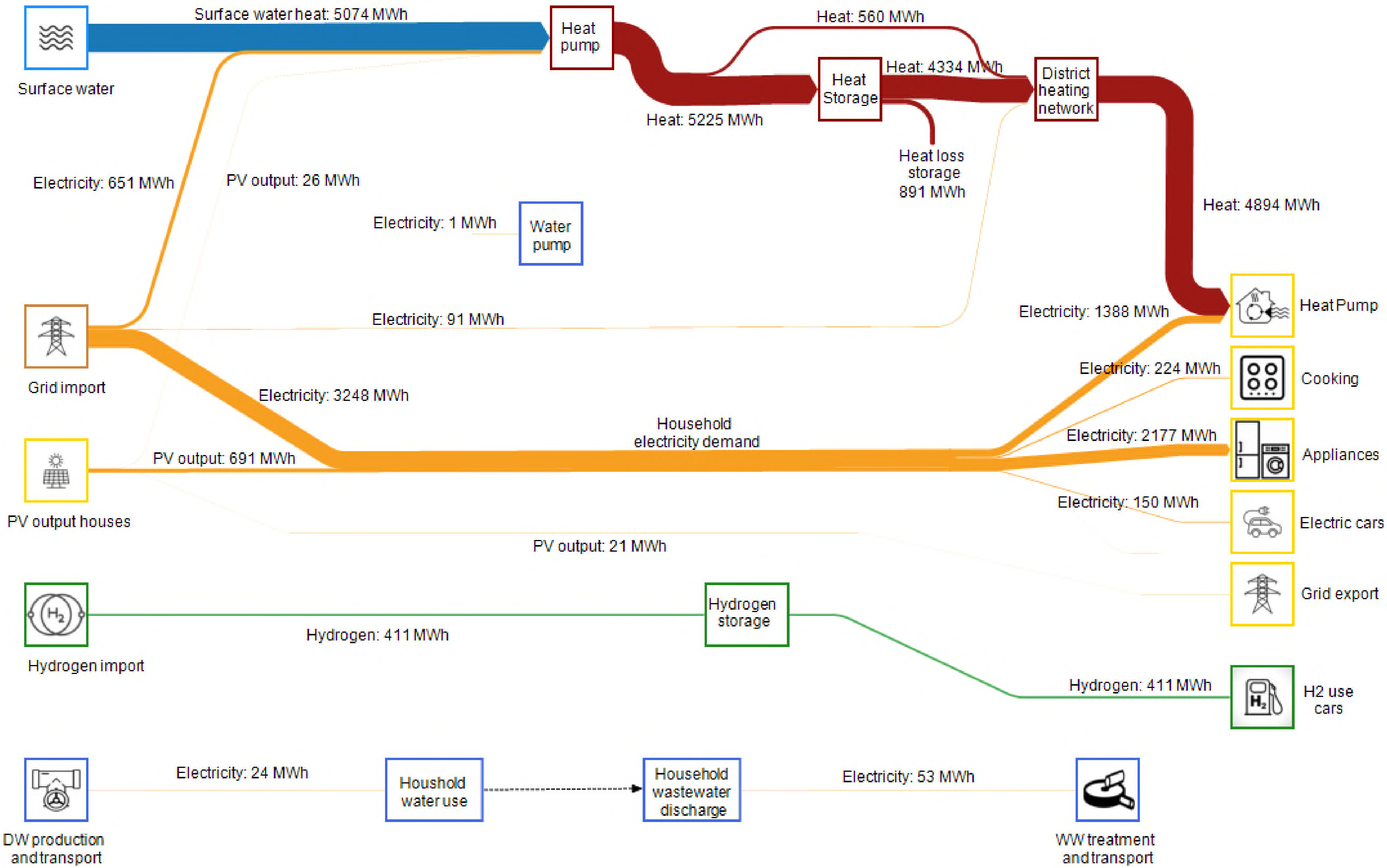


Figure 24: Sankey diagram yearly energy balance improved centralized scenario

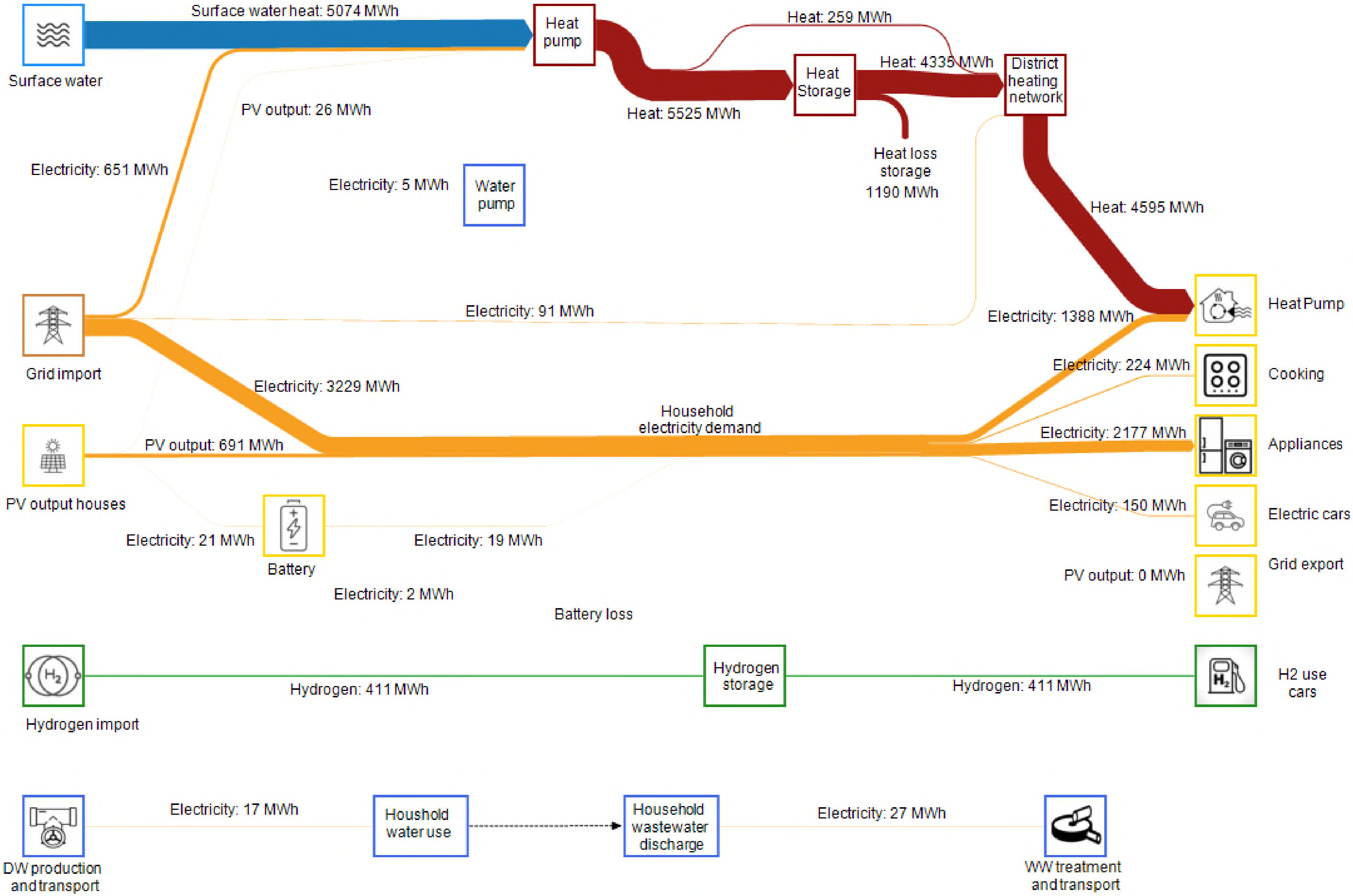


Figure 25: Sankey diagram yearly energy balance hybrid scenario

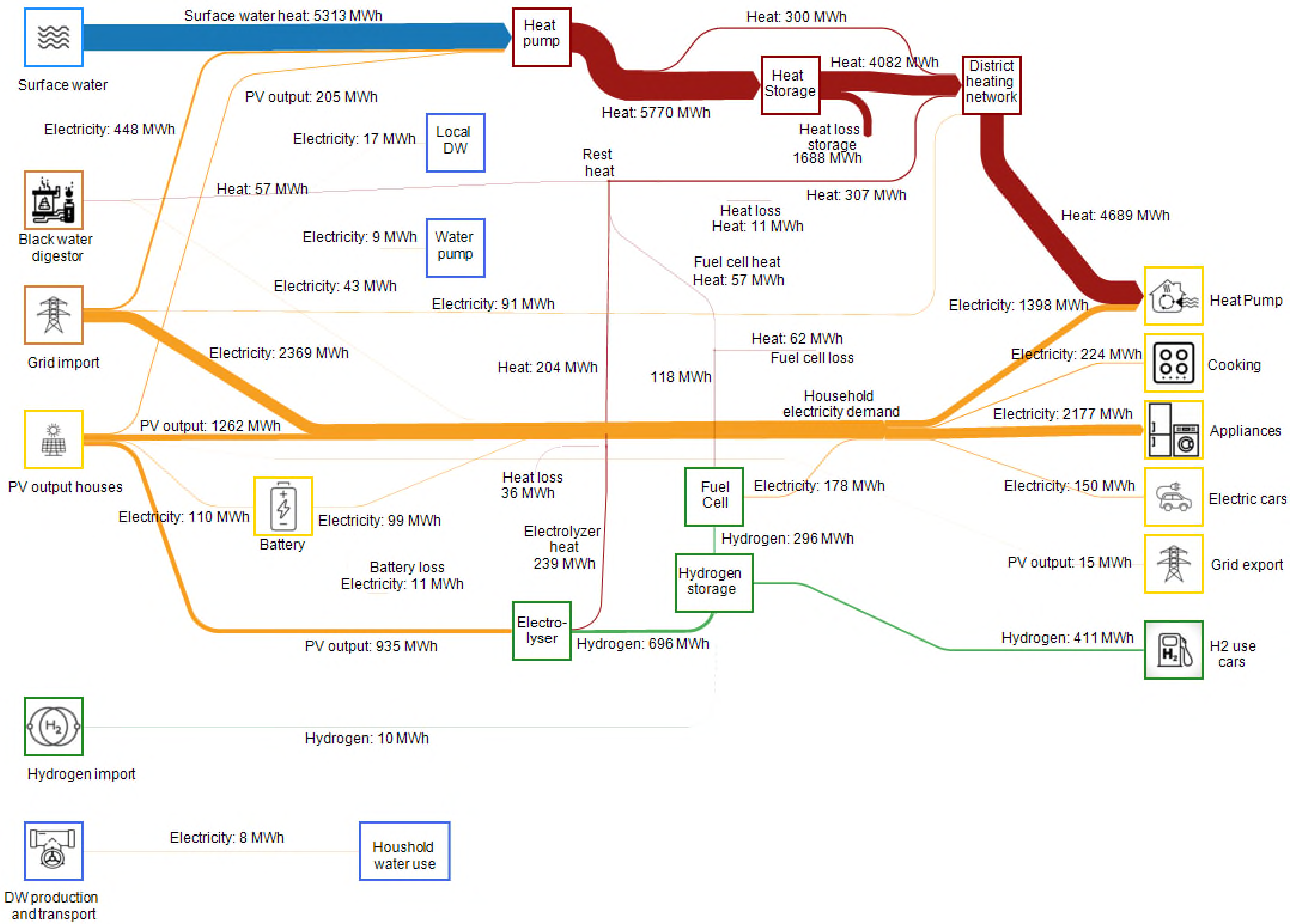


Figure 26: Sankey diagram yearly energy balance almost decentralized scenario

4.4. Step 4: Evaluation indicators

The individual indicator results per scenario will be described in this section. The outcomes are based on the specific characteristics of a scenario together with the results of the yearly water- and balance. All indicator results are therefore based on a yearly average for a period of 10 years (2011-2020).

4.4.1. Indicator 1: Reduced external drinking water demand

The yearly reduced external DW demand (Table 24) from a centralized DWTP was assessed with the UWOT model results. The benchmark of the external DW demand was set at 43.6 m^3/person/year (119.3 L/person/day). With the total population of City Nieuwegein (2,304 residents), the benchmark for the neighborhood was 100,400 m^3/year.

The *reference scenario* has a total external DW demand of 101,090 m^3/year (120 L/person/day). This is <1% higher than the initial benchmark because of the additional DW demand that was required for irrigation. The *improved centralized scenario* has an external DW demand of 47,690 m^3/year (57 L/person/day). This is 53% lower compared to the benchmark, primarily because of the water-energy-saving appliances that were used. The *hybrid scenario* has an external DW demand of 33,080 m^3/year (39 L/person/day). This led to a 67% reduction relative to the benchmark because of the water-energy-saving appliances combined with the reuse of rainwater and LGW for non-potable purposes. The *almost decentralized scenario* has a total DW demand of 16,660 m^3/year (20 L/person/day). This scenario also used water-energy-saving appliances. In addition, rainwater and GW was collected and treated for non-potable purposes, but also for local DW production. As a result, the external DW demand was 83% lower than the benchmark.

Table 24: Result reduced external drinking water demand indicator

Scenario	Benchmark [m^3/year]	External drinking water demand [m^3/year]	Reduced external drinking water demand (x_1) [m^3/year]
Reference	100,400	101,090	**0***
Centralized improved	100,400	47,690	**52,710**
Hybrid	100,400	33,080	**67,320**
Almost decentralized	100,400	16,300	**84,100**

* The score is zero because a negative value will not be given

4.4.2. Indicator 2: Water recovery

With the UWOT model, the data could be gathered to determine the total water recovery (Table 25) for each scenario. A more detailed overview of the water recovery for a certain scenario can be found in Appendix D. The total amount of (incoming) rainwater stayed the same for all scenarios because the same neighborhood was used with a fixed surface area of 47,000 m^2.

The total water recovery for the *reference scenario* was 19.4%. This recovery was primarily achieved with the rainwater harvesting system and green spaces for local infiltration. This reduced the runoff of 67% relative to the total amount of rainwater. For the *improved centralized scenario*, the total water recovery was 71% higher than the reference scenario. This was achieved by more greenery that reduced the total runoff and water-energy-saving appliances that resulted in 53% less external DW demand and WW discharge. The total water recovery for the *hybrid scenario* was 39.7%. The local treatment and reuse of LGW resulted in a 20% higher water recovery than the *centralized scenario*. The highest water recovery of 59.5% was achieved for the *almost decentralized scenario* by collecting and reusing more rainwater and GW. Compared to the *reference scenario*, the water recovery has tripled even though that 21% of all incoming water was lost from treatment losses.

Table 25: Results water recovery indicator

Scenario	Incoming water		Outgoing water					Recovery (x_2) [%]
	Rainwater [m³/year]	DW (external) [m³/year]	Total runoff [m³/year]	WW discharge [m³/year]	GW treatment losses [m³/year]	DW treatment losses [m³/year]	Demi water production losses [m³/year]	
Reference	39,950	101,090	13,310	100,400	-	-	-	**19.4**
Improved centralized	39,950	47,690	11,310	47,300	-	-	-	**33.1**
Hybrid	39,950	33,080	24,600	17,170	2,160	-	-	**39.7**
Almost decentralized	39,950	16,300	270	10,770	2,470	9,270	10	**59.5**

4.4.3. Indicator 3: Quality of living environment

The outcomes for the quality of living environment are were based on the characteristics of City Nieuwegein and the design of the scenarios. The results of this indicator (Table 26) were based on the fixed 1,280 apartments for this neighborhood.

All scenarios have 10,740 m² of (public) green spaces. For the *reference scenario*, this is considered as the only area of blue and green spaces resulting in a blue-green area of 8.4 m²/apartment. For the *improved centralized scenario* and *hybrid scenario*, there were also green rooftops present resulting in a blue-green area of 16.4 m²/apartment. This is almost twice the amount of blue-green area relative to the *reference scenario*. The *almost decentralized scenario* has the highest a blue-green area of 21.1 m²/apartment. This increase is due to the green facades that are also present besides (public) green spaces and green rooftops.

Table 26: Results quality of living environment indicator

Scenario	(public) Green space [m²]	Green rooftop [m²]	Green facade [m²]	Total blue-green area [m²]	Blue-green area (x_3) [m²/apartment]
Reference	10,740	-	-	10,740	**8.4**
Improved centralized	10,740	10,260	-	21,000	**16.4**
Hybrid	10,740	10,260	-	21,000	**16.4**
Almost decentralized	10,740	10,260	6,000	27,000	**21.1**

4.4.4. Indicator 4: Public health

As mentioned in the materials and methods chapter, public health was evaluated qualitatively. It was assumed that the maximum chance of infection caused by pathogenic microorganisms is one infection per 10,000 persons per year (pppy) [53], [58]. The possible exposure routes for this research were: inhalation through aerosolized non-potable water from toilet flushing and showering with non-potable water due to cross-connection between the rainwater/GW system and the DW system [53]. For all scenarios, it was assumed that the distributed drinking from a centralized or decentralized facility was always of safe quality [120].

For the *reference scenario*, there non-potable water was not used within the apartments. Only harvested WW was used for irrigation of the (public) green spaces but this falls outside of the scope of the QMRA which only looked into possible exposure routes within residences. This scenario was therefore given a maximum score (x_4) of 10 [-] because only DW from a centralized DWTP was distributed to the apartments that meets the benchmark [120]. The *improved centralized scenario* only uses DW from a centralized DTWP within the apartments. Unlike the *reference scenario*, this scenario uses water-energy-saving appliances. All appliances must be safe and in possession of a certification mark [121] before it can be used. However, a recirculating shower does have more guidelines than a conventional shower in terms of usage and maintenance. It is advised to use a limited amount of biodegradable soap and the recirculating shower must be cleaned at least once a week [43]. Due to these extra user actions, which cannot always be followed properly in practice, it has been decided to give a score (x_4) of 9.0 [-] which is still in the range of a very safe water system. The *hybrid scenario* uses rainwater and LGW for toilet flushing/washing machine and has water-energy-saving appliances. Without sufficient treatment of rainwater and LGW, there is a high infection risk[5] though inhalation of aerosols from toilet flushing [53]. An effective mitigation strategy is to close the lid before flushing [53] which is also recommended to reduce the noise of the vacuum toilet [122]. The risks from cross connected water can be preventing with a solid procedure of installing and inspecting a non-potable water system [53]. It has been decided to give a score (x_4) of 8.0 [-] to the *hybrid scenario* as it should be a safe water system with the correct measures. The *almost decentralized scenario* reuses rainwater and GW for toilet flushing/washing machine and it has the possibility to produce DW locally. In addition, this scenario also uses water-energy-saving appliances. The same possible exposure routes as the *hybrid scenario* were considered for evaluating this scenario. In addition, a study that did a QMRA of decentralized DW supply was considered [58]. The results of this study showed the DW can be produced safely in a decentralized system (infection risk of 7×10^{-5} pppy). However, it is generally not recommend to produce DW with a decentralized system because it requires sufficient treatment steps and a thorough monitoring/maintenance program that doesn't yet exist [58]. Because of these advices, it was decided to give the *almost decentralized scenario* a score (x_4) of 6.0 [-].

4.4.5. Indicator 5: Safety

For this indicator, a peak flood event of 50 mm within 24 hours (23 June 2016) was used to evaluate the different scenarios on safety (Table 27). The relative storage capacity from all scenarios are based on the pre-defined buffer capacity and total runoff are. All scenarios have been modeled in UWOT with the minimal buffer capacity of 40-60 L/m^2 (40-60 mm of rainfall) that is required in the Netherlands [99]. With the UWOT model, it was possible to visualize the runoff (Appendix E) for the different scenarios.

The *reference scenario* has a 1,500 m^3 rainwater tank that gives a relative storage capacity of 67.0 mm. For the peak flood event, the reduced runoff is 4.1% whereas the theoretical storage capacity is higher than the peak flood event. The reason for that is because the rainwater tank was already filled for 95% with rainwater from previous events. The *improved centralized* has a reduced runoff of 6.1% even though that the total buffer capacity (1,000 m^3) is 50% lower and the relative storage capacity is 14% lower than the *reference scenario*. The rainwater tank was filled for 95% which is in the same order of the *reference scenario*. However, the total runoff area (17,460 m^2) is 22% lower than the *reference scenario* because of the blue-green rooftops that used as an alternative. The *hybrid scenario* has a reduced runoff of 3.1%. This scenario has similar to the *improved centralized scenario*, a relative storage capacity of 57.3 mm. However, the non-potable water tanks is already completely filled before the peak flood event. As a result, both rainwater and treated LGW that cannot be stored will come to runoff. The total amount of recycled LGW (66.1 m^3/day) is higher than the non-potable water demand (38.9 m^3/day) resulting in 27,2 m^3/day of surplus light-GW. For the *almost decentralized scenario*, the reduced runoff was with 56.4% the highest score of all scenarios. All tank tanks combined were filled for 26% before the peak flood event. The higher initial storage capacity is because more rainwater and GW was reused for GWR or decentralized DW production. The total amount of GW (113.4 m^3/day) that can be recycled, is lower than the domestic water demand (129.5 m^3/day). This results in a water deficit of 16,1 m^3/day that is extracted from the non-potable and DW tank.

[5] The annual infection risk from Legionella pneumophila in untreaded rainwater is 0.71 (pppy) which is significantly higher than the benchmark of 10^{-4} pppy [53]. To get the infection risks below the benchmark, treatment with at least 5-log removal is required.

Table 27: Results flood safety

Scenario	Rainwater tank [m³]	Non-potable water tank [m³]	Drinking water tank [m³]	Total runoff area [m²]	Relative storage capacity* [mm]	Reduced runoff (x_5) [%]
Reference	1,500	-	-	22,380	67.0	**4.1**
Improved centralized	1,000	-	-	17,460	57.3	**6.1**
Hybrid	1,000	500	-	17,460	57.3	**5.8**
Almost decentralized	1,000	500	1,000	17,460	57.3	**91.0**

* Other storage not considered (treatment capacity has an impact)

4.4.6. Indicator 6: User comfort

The user comfort indicator was assessed qualitatively (Table 28) after consultation with an expert (Stijn Brouwer) to what extent a specific perspective would (not) accept a certain scenario. The substantiation for the different customer perspectives will be described for each scenario

For the residents with a *quality & health concerned* perspective, it was assumed that a score of 7.0 [-] was given to the *reference scenario* and *improved centralized scenario* as there was no rainwater or (light-)greywater reused within the apartments. The *improved centralized scenario* does have water-energy-saving appliances but it is assumed that this doesn't have a negative impact as the appliances should be safe to use. The *hybrid scenario* was given a lower score of 6.0 [-] because rainwater and LGW was used as a non-potable water source within the apartments for toilet flushing and the washing machine. The *almost decentralized scenario* was given a score of 5.0 [-] because it is assumed that there would be an even lower acceptance due to decentralized DW production.

Residents with an *aware & committed* perspective are expected to have a higher acceptance on neighborhoods that have a low water and energy footprint. As a result the *reference scenario* was given a score of 4.0 [-] as there is only a rainwater harvesting system. A score of 6.0 [-] was given to the *improved centralized scenario* that used water-energy-saving appliances. The *hybrid scenario* and *almost decentralized scenario* were given a score of 7.0 [-] and 8.0 [-] respectively, because they had a more decentralized WEN system.

For the *egalitarian & solidary* perspective, scenarios with an advanced decentralized WEN system were given a lower score because it is expected that the invest costs are higher for such systems [39]. The *reference scenario* was given a score of 6.0 [-] because it is a neighborhood without any complexities. Though, the *improved centralized scenario* was given a score of 8.0 [-] because of the water-energy-saving appliances that are available for everybody and cost-effective for the longer term [42]. The *hybrid scenario* was given a score of 7.0 [-], because LGW recycling was assumed to be an advanced system. The *almost decentralized scenario* was given a score of 4.0 [-] for the same reason as the *hybrid scenario*. GWR and decentralized DW production combined were assumed to be very advanced systems with high investment costs and a low availability.

The last perspectives, *down to earth & confident*, was assessed by looking at the responsibilities that are expected from the residents because these customers are expected to have a higher preference for scenarios with little responsibilities. The *reference scenario* was given a score of 8.0 [-] as there were no additional guidelines that had to be followed for the use a appliances. This would be different for neighborhoods with water-energy-saving appliances, such as the *improved centralized scenario*. A recirculating shower for example, requires more maintenance compared to a conventional shower [84]. As a result, this scenario was given a score of 7.0 [-]. The *hybrid scenario* was given a score of 5.0 [-], because it was assumed that LGW recycling would result in more monitoring and maintenance. The *almost decentralized scenario* was given a score of 3.0 [-]. GWR and decentralized DW production combined were assumed to be very advanced systems that would require a lot of monitoring and maintenance the assure a sufficient system. The study of Roest et al. (2016) stated that "a decentralized DW supply may be challenging for consumers with limited knowledge of health risks" [58].

Table 28: Results user comfort indicator

Scenario	Quality & health concerned (12.6%) [-]	Aware & committed (32.7%) [-]	Egalitarian & solidary (28.3%) [-]	Down to earth & confident (26.4%) [-]	Score (x_6) [-]
Reference	7.0	4.0	6.0	8.0	**6.0**
Improved centralized	7.0	6.0	8.0	7.0	**7.0**
Hybrid	6.0	7.0	7.0	5.0	**6.3**
Almost decentralized	5.0	8.0	4.0	3.0	**5.2**

4.4.7. Indicator 7: Reduced external energy demand

The yearly reduced external energy demand (Table 29) from the grid was assessed with the Power-to-X model results. Based on a population of 2,304 inhabitants and 1,280 apartments, the benchmark for the external energy demand was set at 11,000 MWh/year.

The *reference scenario* has a total external energy demand of 4,900 MWh/year. This is 55% lower than the initial benchmark, mainly because of the ATES system which led to a lower energy demand for heating and cooling. The *improved centralized scenario* has an external DW demand of 4,400 MWh/year. This is 60% lower compared to the benchmark, primarily because of ATES systems and the water-energy-saving appliances that were used. And thus, the *hybrid scenario* has an external DW demand of 4,390 MWh/year. This is 10 MWh/year lower than *improved centralized scenario*, mainly because of the collective battery that could store surplus energy from the PV panels. The *almost decentralized scenario* has a total energy demand of 2,930 MWh/year. This scenario also used water-energy-saving appliances. In addition, more energy carriers (local hydrogen and biogas production) were present besides a collective battery. As a result, the external energy demand was reduced by 73% compared to the benchmark.

Table 29: Results reduced external energy demand indicator

Scenario	Benchmark [MWh/year]	Grid import [MWh]	Hydrogen import [MWh]	Additional energy import [MWh]	Total energy demand [MWh/year]	Reduced external energy demand (x_7) [MWh]
Reference	11,000	4,390	410	100	4,900	6,100
Centralized improved	11,000	3,900	410	90	4,400	6,600
Hybrid	11,000	3,880	410	100	4,390	6,610
Almost decentralized	11,000	2,820	10	100	2,930	8,070

4.4.8. Indicator 8: Local renewable energy use

The yearly local renewable energy use was assessed with the Power-to-X model results (Table 30). A more detailed overview of the monthly energy balance that highlights the seasonal energy trends can be found in Appendix F.

The *reference scenario* has a total local renewable energy use of 54.8% that originates from PV panels and surface water that was used for the ATES system. The *improved centralized scenario* has a total local renewable energy use of 57.6%. This is 5% higher than the *reference scenario* because of the water-energy-saving appliances that resulted in a lower energy demand. The *hybrid scenario* has a total local renewable energy use of 56.5% which is approximately 2% lower than the *improved centralized scenario* that also used water-energy-saving appliances. At last, the almost decentralized scenario has a total local renewable energy use of 68.6%. This scenario used PV panels on both the rooftops and facades which resulted in more local renewable energy use and a lower energy demand from the grid. In addition, a BW digestor also produces renewable energy. The presence of a collective battery and hydrogen tank with electrolyzer and fuel cell reduces the grid export.

Table 30: Results local renewable energy use indicator

Scenario	Total energy demand [MWh]	Local renewable energy produced* [MWh]	Grid export [MWh]	Local renewable energy use (x_8) [%]
Reference	9,726	739	10	7.5
Improved centralized	9,245	739	21	7.8
Hybrid	8,950	739	0	8.3
Almost decentralized	9,075	2,612	15	28.6

* Heat from the Lek canal was not included as local renewable energy as this falls outside the neighborhood area. Biogas produced from the BW digestor was included.

4.4.9. Indicator 9: CO_2 footprint

The results of the CO_2 footprint indicator (Table 31) were based on the pre-determined CO_2 parameters together with the specific water- and energy demands per scenario. The benchmark for this indicators was set at 5,110 tonnes CO_2/year. This was the CO_2 footprint for a neighborhood without any decentralized WEN systems.

The *reference scenario* has a CO_2 footprint of approximately 2,320 tonnes CO_2/year which is 55% lower than the benchmark. These reductions mainly originate from a lower energy demand due to the ATES system that was used. The CO_2 footprint for the *improved centralized scenario* was 12% lower than the *reference scenario* and 60% lower than the benchmark. Similar to the *reference scenario* the CO_2 mainly originate from the ATES system, but also the water-energy-saving appliances that resulted in a lower energy demand. The CO_2 footprint for the *hybrid scenario* is in the same order of the *improved centralized scenario*. However, the CO_2 footprint is approximately 15 tonnes CO_2/year higher even though that the CO_2 footprint for the electricity import, centralized DW production and WW treatment is more than 40 tonnes CO_2/year lower. Ultimately, decentralized GW treatment (56.1 tonnes CO_2/year) resulted in a higher CO_2 footprint. The *almost decentralized scenario* had the lowest CO_2 footprint which was around 1,530 tonnes CO_2/year. This is 25-70% compared to the other scenarios or the benchmark. An important contributor to the reduced CO_2 footprint was due to the additional PV panels that were used to produce renewable energy. This was used to produce green hydrogen for the FCEVs and the reduce the energy demand from the grid.

Table 31: Results CO_2 footprint indicator

System element	Reference scenario [tonnes CO_2/year]	Improved centralized scenario [tonnes CO_2/year]	Hybrid scenario [tonnes CO_2/year]	Almost decentralized scenario [tonnes CO_2/year]
Electricity (fossil energy)	2,056	1,826	1,820	1,335
Electricity (renewable energy)	0	0	0	0
Biogas (blackwater)	0	0	0	5
Hydrogen local production (renewable)	0	0	0	8
Electric vehicle (grey energy)	18	21	21	97
Electric vehicle (renewable energy)	3	3	3	<1
Hydrogen vehicle (fossil energy)	115	115	115	3
Hydrogen vehicle (renewable energy)	0.1	1	1	7
Centralized wastewater treatment	109	52	19	0
Decentralized greywater treatment	0	0	56	68
Centralized drinking water production	17	8	5	3
Decentralized drinking water production	0	0	0	3
Total CO_2 footprint (x_9)	**2,320**	**2,020**	**2,040**	**1,530**

4.4.10. Indicator 10: Financial value

The yearly financial value was calculated using CAPEX and OM (Table 32). The details of the financial value can be found in Appendix G. More decentralization results in a higher financial value even though the costs of external DW and energy resources are decreased. Most of the increase in financial value originates from decentralized WEN systems. As a result, the *reference scenario* has the lowest financial value. The financial value increases from 11-51% depending on the amount of decentralization. As a result, the *almost decentralized scenario* has the highest financial value.

Table 32: Results financial value indicator

	Total financial value [x10^3 €/year]	**Financial value per person (x_{10}) [€/person/year]**
Reference	1,740	760
Improved centralized	1,940	840
Hybrid	2,230	970
Almost decentralized	2,640	1,140

4.4.11. Indicator 11: Integrality

The user comfort indicator (Table 33) results were assessed qualitatively based on a study of Dorado-Rubín et al. (2021) that considered three dimensions: (1) comprehensiveness, (2) integration and (3) governance [25]. The *reference scenario* was given a score of 5.7 [-]. This scenario scores 'neutral' on the three dimensions. There are no major decentralized WEN systems besides a rainwater harvesting systems. It was therefore assumed that there were not many additional interrelationships between the parties that would participate in such an urban development project. The *improved centralized scenario* was given a score of 7.0 [-] as there are more decentralized WEN systems that would lead to better multi-value creation. The implementation of blue-green rooftops and water-energy-saving appliances requires more involvement from parties that have experience with these systems. The same would apply for maintaining these systems thoroughly. For a *hybrid scenario*, in addition to the mentioned decentralized WEN systems of the *improved centralized scenario*, it was decided to recycle LGW for more water reuse and to use a collective battery to store surplus energy. As a result, this scenario scored higher on the three dimensions which led to a score of 7.7 [-]. At last, the *almost decentralized scenario* was given a score of 9.3 [-] as this is a large variety of decentralized WEN systems that would lead to a high multi-value creation. For example, using green facades improve the quality of living environment and improving the participant involvement [27].

Table 33: Results integrality indicator

Scenario	**Comprehensiveness [-]**	**Integration [-]**	**Governance [-]**	**Average [-]**	**Score (x_{11}) [-]**
Reference	3.0	3.0	2.5	**2.8**	**5.7**
Improved centralized	3.5	3.0	4.0	**3.5**	**7.0**
Hybrid	4.0	4.0	3.5	**3.8**	**7.7**
Almost decentralized	4.5	5.0	4.5	**4.7**	**9.3**

4.4.12. Indicator 12: Self-sufficiency

The yearly self-sufficiency was assessed with the UWOT and Power-to-X model results. The results (Table 34) represent the yearly average self-sufficiency of the water and energy system. A more detailed overview on the hourly water and energy balance, that shows the self-sufficiency, can be found in Appendix H.

The *reference scenario*, *improved centralized scenario*, and *hybrid scenario* all have a total self-sufficiency of 2.2-3.8%. The self-sufficiency is low for these three scenarios as there are no storage and reuse technologies for surplus water and energy. A collective battery from the *hybrid scenario* only leads to a 1% increase for the energy system compared to an *improved centralized scenario*. The *almost decentralized scenario* has a total self-sufficiency of 36.8%. This is almost 10 times higher than the *hybrid scenario* because of a decentralized DW production facility and higher local renewable energy from PV panels (rooftops and facades).

Table 34: Results self-sufficiency indicator

Scenario	Water system		Energy system		Total self-sufficiency (x_{12}) [%]
	Total hours self-sufficient [-]	Self-sufficiency [%]	Total hours self-sufficient [-]	Self-sufficiency [%]	
Reference	1,566	1.8	1,953	2.2	2.0
Centralized improved	1,566	1.8	3,258	3.7	2.8
Hybrid	2,610	3.0	4,140	4.7	3.8
Almost decentralized	33,532	38.2	31,039	35.4	36.8

4.4.13. Indicator 13: Resource recovery

The results of the resource recovery indicator were based on qualitative assessment. More details of the outcomes can be found in Appendix I. An assumption was made on how the designed scenarios are related to the four resource recovery scenarios (section 3.4.13) based on the of study Besson et al. (2019) [46]. For this research, the results of the designed *reference scenario* and *improved centralized scenario* are based on the outcomes of the 'reference' resource recovery. Both of these scenarios have no decentralized water treatment facilities. The *improved centralized scenario* would have a higher concentration of compounds due to lower discharge. As it is discharged to a centralized WWTP, it is assumed that the effects can be neglected as it is mixed with WW from other neighborhoods. The *hybrid scenario* had GWRwhich should result in more resource recovery compared to the *reference scenario* and *improved centralized scenario*. As the study didn't have results for such a system, it was assumed that the outcomes were based on an equal distribution between the 'reference', 'urine' and 'BW' resource recovery. At last, the outcomes of the *almost decentralized scenario* are based on the 'BW/GW' resource recovery. The *almost decentralized scenario* has a decentralized treatment facility for separated GW and BW which is same principle as the 'BW/GW' scenario.

The outcomes of the resource recovery are provided in the yearly mass flow compounds (Table 35) and relative recovery (Table 36) for a specific compound. The *reference scenario* and *improved centralized scenario* both have a resource recovery of 24.7%. The *hybrid scenario* has a total resource recovery of 36.9%. Compared to the *reference scenario* and *improved centralized scenario*, it is estimated that this scenario has a 28% higher resource recovery on biogas. The resource recovery of ammonium sulfate more than 5 times higher. The *almost decentralized* has the highest resource recovery of 44.4%. The tables show that the recovery is particularly high on ammonium sulfate (57.3%) and struvite (67.9%) from phosphorus compounds. With a decentralized treatment facility, the effluent and gas (atmosphere) is reduced with by 26% compared to a situation with only a centralized WWTP.

Table 35: Overview mass flow compound for resoruce recovery indicator

Mass flow compounds	Reference	Improved centralized	Hybrid*	Almost decentralized
Total mass [tonnes/year]	**104.9**	**104.9**	**104.9**	**104.9**
COD [tonnes/year]	**86.7**	**86.7**	**86.7**	**86.7**
Struvite[a]	0.6	0.6	0.8	1.0
Biogas[a]	23.9	23.9	30.4	34.2
Sludge[b]	25.2	25.2	24.1	20.1
Gas (atmosphere)[c]	30.4	30.4	25.8	29.5
Effluent[c]	6.7	6.7	5.6	2.0
Nitrogen compounds [tonnes/year]	**15.6**	**15.6**	**15.6**	**15.6**
Ammonium sulfate[a]	1.0	1.0	5.6	8.9
Struvite[a]	0.2	0.2	0.6	0.8
Sludge[b]	2.2	2.2	2.0	1.0
Gas (atmosphere)[c]	10.5	10.5	5.6	3.3
Effluent[c]	1.8	1.8	1.7	1.6
Phosphorus compounds [tonnes/year]	**2.6**	**2.6**	**2.6**	**2.6**
Struvite[a]	0.3	0.3	1.3	1.8
Sludge[b]	2.1	2.1	1.2	0.7
Effluent[c]	0.2	0.2	0.2	0.2
Total losses [%]	**47.2**	**47.2**	**37.1**	**34.8**
Total sludge (unprocessed) [%]	**28.1**	**28.1**	**26.0**	**20.8**
Total resource recovery (x_{13}) [%]	**24.7**	**24.7**	**36.9**	**44.4**

* Based on assumptions and a combination of different results. [a] Struvite, biogas and ammonium sulfate was considered as resources that can be recovered directly. [b] Sludge has not been considered as a recovered resource in this research, but it can be when including additional treatment steps. [c] Gas to atmosphere and effluent were considered as losses as it ends up in the environment.

Table 36: Results resource recovery indicator

Relative recovery	Reference	Centralized improved	Hybrid*	Almost decentralized
COD [%]	**100.0**	**100.0**	**100.0**	**100.0**
Struvite	0.7	0.7	0.9	1.1
Biogas	27.5	27.5	35.1	39.4
Sludge	29.1	29.1	27.8	23.2
Gas (atmosphere)	35.0	35.0	29.8	34.0
Effluent	7.7	7.7	6.4	2.3
Nitrogen compounds [%]	**100.0**	**100.0**	**100.0**	**100.0**
Ammonium sulfate	6.3	6.3	36.2	57.3
Struvite	1.1	1.1	3.8	4.9
Sludge	13.9	13.9	13.1	6.4
Gas (atmosphere)	67.4	67.4	36.0	21.1
Effluent	11.3	11.3	11.0	10.3
Phosphorus compounds [%]	**100.0**	**100.0**	**100.0**	**100.0**
Struvite	13.1	13.1	48.1	67.9
Sludge	79.9	79.9	45.1	25.7
Effluent	7.0	7.0	6.8	6.4

4.5. Step 5: Indicator normalization

Based on the outcomes of the different indicators, the next step was to normalize the score (Table 37) for the 4 scenarios. These outcomes have been visualized (Figure 27) to get overview of all indicators combined.

The *reference scenario* had a normalized score of 4.0 [-]. This scenario scored particularly high on *public health* and *financial value*. The outcomes for the remaining indicators were rather low because of the limited decentralized water-energy systems that resulted in a higher water and energy footprint compared to the other scenarios. The *improved centralized scenario* and *hybrid scenario* both have a normalized score of 4.8 [-]. In total, 10 out of the 13 normalized indicator scores are within a range of 1.0 [-]. The *improved centralized scenario* had the highest normalized score for the *user comfort* indicator. At last, the *almost decentralized scenario* had the highest normalized score of 5.9 [-]. A total of 10 out of the 13 normalized indicator scores were the highest for this scenario. This scenario had the lowest scores for the *public health*, *user comfort* and *financial value* indicators because of the more advanced decentralized WEN systems.

Table 37: Overview normalized scores

[#]	Indicator (v_m)	Reference scenario [-]	Improved centralized scenario [-]	Hybrid scenario [-]	Almost decentralized scenario [-]
	Water system				
1	Reduced external drinking water demand	0.0	5.3	6.7	**8.4****
2	Water recovery	1.9	3.3	4.0	**6.0****
	Value for people				
3	Quality of the living environment	1.1	2.2	2.2	**2.8****
4	Public health*	**10.0****	9.0	8.0	6.0
5	Safety	0.4	0.6	0.6	**9.1****
6	User comfort*	6.0	**7.0****	6.3	5.2
	Energy system				
7	Reduced external energy demand	5.5	6.0	6.0	**7.3****
8	Local renewable energy use	0.8	0.8	0.8	**2.8****
	General characteristics				
9	CO_2 footprint	5.5	6.0	6.0	**7.0****
10	Financial value	**10.0****	7.8	4.5	0.0
11	Integrality*	5.7	7.0	7.7	**9.3****
12	Self-sufficiency	0.2	0.3	0.4	**3.7****
13	Resource recovery*	2.5	2.5	3.7	**4.4****
	Average score	**3.8**	**4.4**	**4.4**	**5.5**

* Qualitative indicators
** Highest indicator score

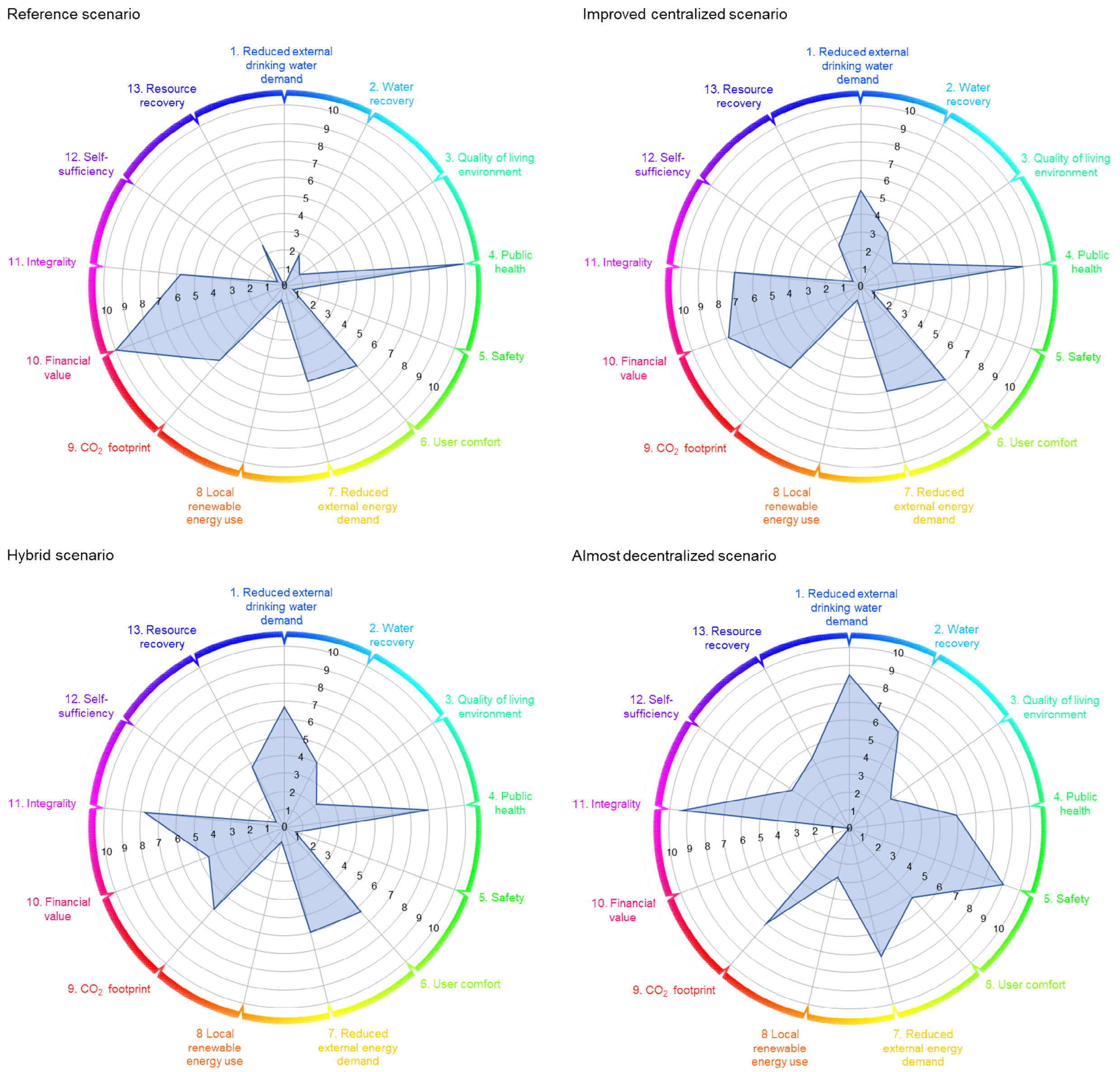


Figure 27: Visual results normalized scores

4.6. Step 6: Indicator weighting with stakeholder perspectives

For this research, a total of six stakeholders were considered: (1) the municipality of Nieuwegein, (2) the province of Utrecht, (3) the local drinking water company (Vitens), (4) the local water board (Hoogheemraadschap De Stichtse Rijnlanden), (5) a water research institute (KWR), and (6) a real estate developer. These stakeholders have been selected as they are also involved in the project of City Nieuwegein. One expert per stakeholder was interviewed anonymously. All detailed outcomes of the interviews and calculations can be found in Appendix J. The input from the real estate developer was based on a study of ten Brinke et al. (2022)[8] as it wasn't possible to conduct an interview. A requirement was that the interviewee must be engaged in urban planning projects. Interviews with these stakeholders will give a better understanding of aspects that should be considered when designing a new neighborhood. All six stakeholders have unique accountabilities that could result in different prioritizations specifically for a new neighborhood such as *City Nieuwegein*.

Stakeholder 1: Municipality

The municipality has a vital role in housing policy and urban planning. This implies that the municipality can determine the requirements for new neighborhoods. In addition, they make the construction of new-built homes spatial possible. In addition, the municipality is also responsible for the drainage of WW and rainwater.

Stakeholder 2: Province

The province is responsible for integrating and considering spatial tasks of (supra)regional interest. One of the tasks is to preserve freshwater sources, mainly groundwater, found in the province of Utrecht.

Stakeholder 3: Drinking water company

A drinking water company has the primary task of producing and distributing safe DW that is of good quality, available all the time, and has a reasonable water price. The regulations concerning DW are stated in the Drinking Water Act [123].

Stakeholder 4: Water board

The Water Board is responsible for the treatment of WW. Other responsibilities are to regulate the water level of groundwater and surface water and nature management in and around water bodies.

Stakeholder 5: Water research institute

A water research institute generates knowledge to enable the water sector to operate water-wisely in the urbanized society [124]. It has a professional and social responsibility for water quality. Their scientific findings and practical innovations contribute to creating a sustainable water provision within the urban water cycle. In this specific case, they were also involved in the design process of City Nieuwegein, and therefore relevant

Stakeholder 6: Real estate developer

Real estate developers are often constructing many new residential areas. As a land owner, it is responsible for arranging construction permits and contracts with a general contractor.

4.6.1. Quantifying stakeholder input

The stakeholder input was used to compute the relative score (RS_m) and the weighting factors (w_m) for the different indicators. The score were given by the experts that have been interviewed, except for the *real estate developer* which was based on interpretation of a study [8]. The input from the stakeholder were provided with additional context to explain how it was decided to come up with the scores.

Stakeholder 1: Municipality

The results (Table 38 and Figure 28) show that *safety* is the leading indicator for a municipality. Based on the experts' input, it was stated that these indicators form an important base of having a neighborhood that has a high 'value for people' (*living environment*, *public health* and *safety*). A municipality is responsible for the drainage system which can be related to the *safety* indicator. A sufficient 'water system' can contribute in better flood management by reducing the discharge of WW and runoff from rainfall events. The interviewee prioritized the *reduced external drinking water demand* above the *water recovery* indicator with a score of 6.0 [-] and 2.8 [-] respectively. The remaining indicators were given a lower score as this is not the main responsibility for a municipality. It was acknowledged that these lower-scoring indicators are also important for urban development projects. A lot of indicators, such as *local renewable energy use*, *CO_2 footprint* and integrality are often implemented in guidelines and requirements when constructing new neighborhoods [26].

Table 38: Results municipality perspectives

Indicator [#]	Rank [#]	Weighted score (w_m) [-]	Weighting factor [-]
Water system			
1	4	6.0	0.115
2	9	2.8	0.054
Value for people			
3	3	6.0	0.115
4	2	6.0	0.115
5	1	10.0	0.192
6	13	0.8	0.015
Energy system			
7	10	0.8	0.015
8	11	0.8	0.015
General characteristics			
9	7	4.4	0.085
10	8	4.4	0.085
11	6	4.8	0.092
12	12	2.0	0.038
13	5	3.2	0.062

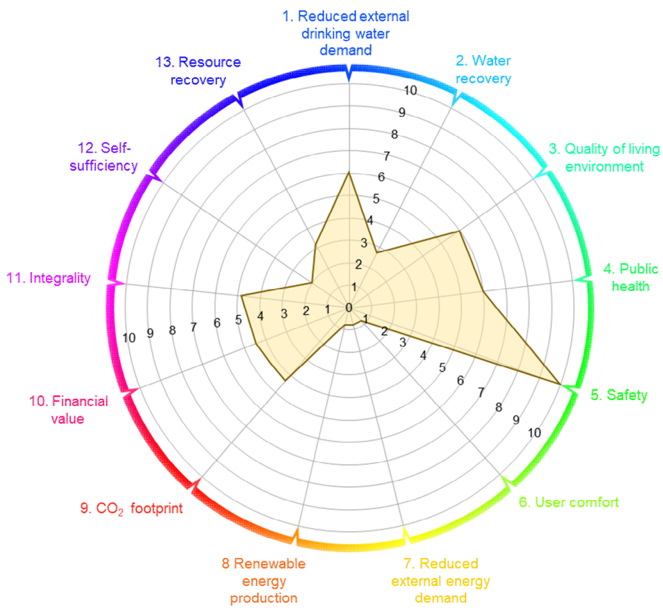


Figure 28: Visual overview municipality results

Stakeholder 2: Province

For this stakeholder, results (Table 39 and Figure 29) show that the primary indicators are *reduced external drinking water demand* and *water recovery*. One of the responsibilities of the province is to preserve freshwater sources. Therefore, the 'water system' indicators were given the highest scores by the expert. The interviewee recommended the use of decentralized WEN system that could reduce the footprint of water and energy resources. It was acknowledged that an improved water system would indirectly have a positive impact on other indicators (*reduced external energy demand*, *CO_2 footprint*, e.g.). Indicator such as *user comfort* and *financial value* were given a score of 2.0 [-] and 1.2 [-] respectively as it was found that these indicators should not be the main drivers to select a scenario. It was stated that *user comfort*, or the level of acceptance by a consumer, is a subjective indicator. This could eventually lead to a higher score over time, for example due to habituation.

Table 39: Results province perspectives

Indicator [#]	Rank [#]	Weighted score (w_m) [-]	Weighting factor [-]
Water system			
1	1	10.0	0.192
2	2	10.0	0.192
Value for people			
3	4	4.0	0.077
4	10	2.0	0.038
5	11	2.0	0.038
6	12	2.0	0.038
Energy system			
7	8	3.2	0.062
8	5	3.2	0.062
General characteristics			
9	3	4.0	0.077
10	13	1.2	0.023
11	9	3.2	0.062
12	6	4.0	0.077
13	7	3.2	0.062

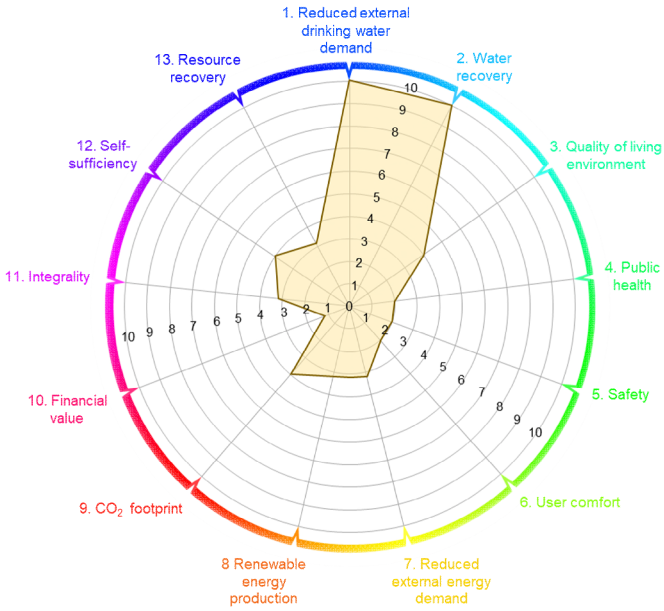


Figure 29: Visual overview province results

Stakeholder 3: Drinking water company

The *reduced external drinking water demand* and *public health* are the leading indicators for a drinking water company when looking at the results (Table 40 and Figure 30) from the interviewee. These are also related to the main responsibilities of a drinking water company, providing DW that is of a good quality and always available for the consumer. For that reason, *water recovery* was also given a high score of 8.0 [-] as this contributes to an improved 'water system'. The *integrality* indicator was given a score of 6.0 [-] by the interviewed expert as is was found an important indicator to guarantee a well-functioning neighborhood between the stakeholders that are involved. Other indicators were less prioritized by the interviewee for the decision making process. For example, *self-sufficiency* with a decentralized water-energy system was not considered to be most important as a centralized facility is reliable in provide DW and energy.

Table 40: Results drinking water company perspectives

Indicator [#]	Rank [#]	Weighted score (w_m) [-]	Weighting factor [-]
Water system			
1	1	10.0	0.192
2	3	8.0	0.154
Value for people			
3	11	1.2	0.023
4	2	10.0	0.192
5	13	0.4	0.008
6	5	4.0	0.077
Energy system			
7	9	2.0	0.038
8	10	2.0	0.038
General characteristics			
9	6	4.0	0.077
10	7	2.0	0.038
11	4	6.0	0.115
12	8	2.0	0.038
13	12	0.4	0.008

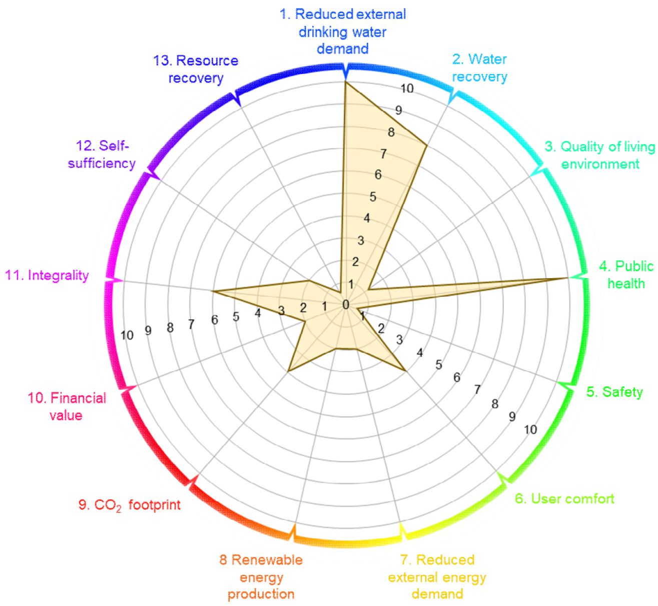


Figure 30: Visual overview drinking water company results

Stakeholder 4: Water board

The results (Table 41 and Figure 31) show that *public health* is the primary indicator for a water board. Other indicators from 'value for people' were also given high score varying between 6.5 [-] and 7.0 [-]. Based om the main tasks for a water board, such as WW treatment and groundwater/surface water management, *water recovery* was given a higher priority than *reduced external drinking water demand.* Based on the experts' perspectives, indicator from the 'energy system' were not highly prioritized as this is not the main focus. It was stated that reducing the *CO_2 footprint* is important indicator when selecting a concept. Indicators such as *financial value* and *integrality* were not given a high prioritization compared to other indicators.

Table 41: Results water board perspectives

Indicator [#]	Rank [#]	Weighted score (w_m) [-]	Weighting factor [-]
Water system			
1	11	3.0	0.046
2	7	5.0	0.077
Value for people			
3	2	7.5	0.115
4	1	10.0	0.154
5	4	6.5	0.100
6	3	7.0	0.108
Energy system			
7	8	4.5	0.069
8	9	4.0	0.062
General characteristics			
9	5	6.0	0.092
10	12	1.0	0.015
11	13	1.0	0.015
12	10	4.0	0.062
13	6	5.5	0.085

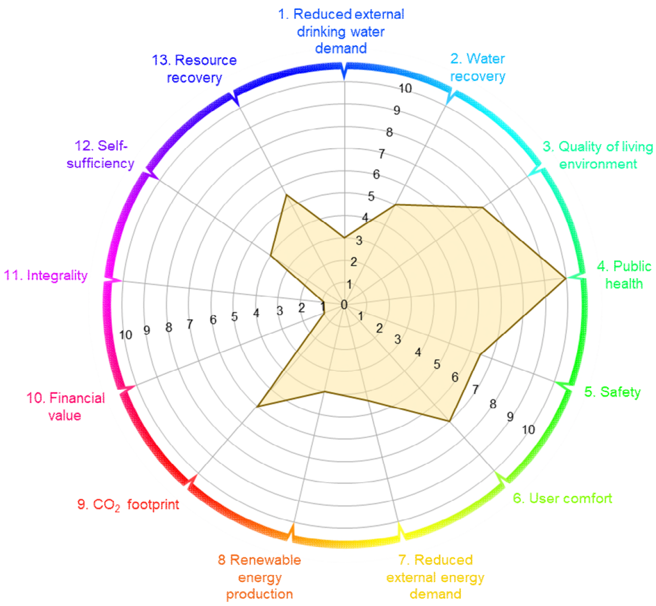


Figure 31: Visual overview water board results

Stakeholder 5: Water research institute

The interviewee prioritized the indicator *public health* above the other indicators (Table 42 and Figure 32). As mentioned in the stakeholder description, a water research institute has a responsibility with regards to ensuring a good water quality. This was stated by the expert who was interviewed. Another indicator that was highly prioritized was *quality of living environment* with a score of 9.0 [-]. These two indicators were found the most important indicators when selecting different concepts of an urban development project. Indicators from the 'water system', 'energy system' and *CO_2 footprint* were all prioritized within a range of 4.8 [-] and 5.2 [-]. With regards to the 'water system' and 'energy system', the indicators *reduced external drinking water demand* and *reduced external energy demand* were given a higher prioritization compared to the indicators *water recovery* and *local renewable energy use*.

Table 42: Results water research institute perspectives

Indicator [#]	Rank [#]	Weighted score (w_m) [-]	Weighting factor [-]
Water system			
1	5	5.2	0.085
2	6	4.8	0.077
Value for people			
3	2	9.5	0.154
4	1	10.0	0.162
5	12	1.9	0.031
6	3	5.2	0.085
Energy system			
7	7	4.8	0.077
8	8	4.8	0.077
General characteristics			
9	4	5.2	0.085
10	10	2.9	0.046
11	9	3.3	0.054
12	13	1.4	0.023
13	11	2.9	0.046

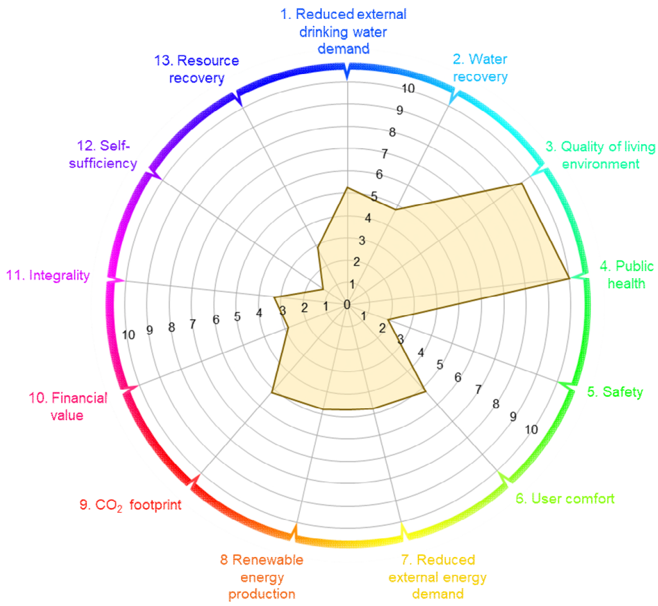


Figure 32: Visual overview water research institute results

Stakeholder 6: Real estate developer

The outcomes for the project developer (Table 43 and Figure 33) were based on a paper of ten Brinke et al. (2022) that looked into the main drivers of the private sector for urban development projects in the Netherlands [8]. This study found that the three leading private sector drivers were:

Achieve high-quality living environment: This aspect was found to an essential driver for private developers, such as having a property with enough green spaces [8].

Reduced time to sell (popularity): Properties that can be sold rapidly is an important driver that is considered when forming urban development projects [8].

Corporate image enhancement: It was found that this is an relevant driver as this can have a positive impact on future corporate opportunities [8].

The three main drivers of this paper were related to the *quality of living environment* and *financial value* indicators and assumed to be the indicators that would be prioritized. Other indicators from related to 'value for people' were also given a score between 6.0 [-] and 7.5 [-] as these are indicators that can contribute in a reduced selling time. For example, a neighborhood with a high user comfort can have a positive impact on selling a house right away. The remaining indicators were given a lower prioritization. When giving the scores, it was based on assuming to what extent an indicator would contribute to the main private sector drivers. Having a neighborhood with a high level of *integrality* was given a score 6.5 [-]. The paper of ten Brinke et al. (2022) found that a collaboration between municipalities and the private sector is important when forming new adaption requirements, such as climate change mitigation (reduced CO_2 *footprint*).

Table 43: Results real estate developer perspectives

Indicator [#]	Rank [#]	Weighted score (w_m) [-]	Weighting factor [-]
Water system			
1	9	2.5	0.038
2	11	1.5	0.023
Value for people			
3	1	10.0	0.154
4	3	7.5	0.115
5	4	7.5	0.115
6	5	6.5	0.100
Energy system			
7	10	2.5	0.038
8	8	4.0	0.062
General characteristics			
9	7	5.0	0.077
10	2	10.0	0.154
11	6	6.5	0.100
12	13	0.5	0.008
13	12	1.0	0.015

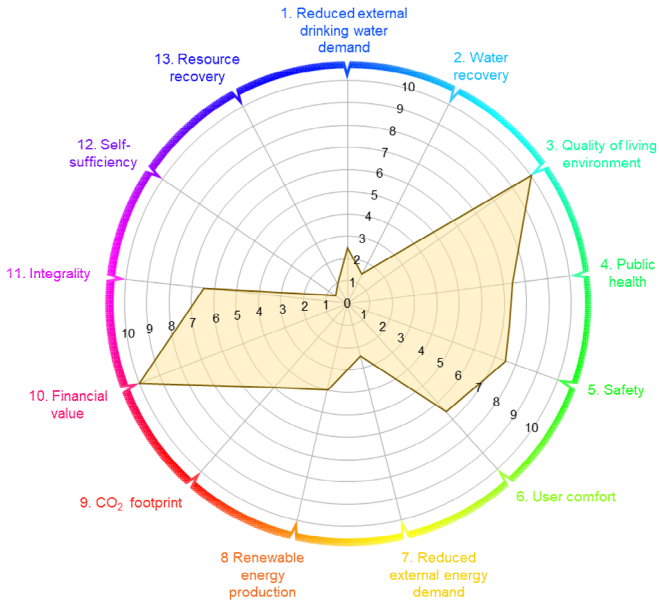


Figure 33: Visual overview real estate developer results

4.6.2. Total weighted scores per stakeholder perspective

The weighted factors were used to get a score (Table 44) for a scenario which was based on the stakeholder perspectives. The calculations that were made to come up with these the weighted scores can be found Appendix K.

The weighted scores of the *reference scenario* were in the range of 2.9 [-] and 5.1 [-]. The lowest score originated from the province perspective, mainly because the ‘water system’ indicators were highly prioritized whilst this scenario had the lowest score on *reduced external drinking water demand* and *water recovery* compared to the other scenarios. The highest score was related to the real estate developer. For this stakeholder, *financial value* was an highly prioritized indicator which scored best on for the *reference scenario*. The *improved centralized scenario* and *hybrid scenario* showed similar weighted scores for the different stakeholder perspectives as the individual indicator scores are mostly in the same order. The *improved centralized scenario* did score 10% higher that *hybrid scenario* for the real estate developer perspective as there was a 15% difference for the *financial value* score which was highly prioritized. It was found that the *almost decentralized scenario* had the highest weighted scores for the different stakeholder perspectives. The lowest score of 5.4 [-] was related to the real estate developer, mainly because the low *financial value* score. The *improved centralized scenario* also had a weighted score of 5.4 [-] resulting in two scenarios that had the highest score for the real estate developer perspective. The highest score originated from the drinking water company. The ‘water system’ indicator were given a high prioritization. The *public health* indicator was also highly prioritized by this stakeholder. The *almost decentralized scenario* scored a 6.0 [-], which was the lowest score for all scenarios. As the other indicators of the *almost decentralized scenario* were in general higher than the other scenarios, the average score with the drinking water company perspective the highest with a weighted score of 6.6 [-].

Table 44: Overviewed weighted score per stakeholder and scenario

Scenario	Normalized score (v_m) [-]	Municipality [-]	Province [-]	Drinking water company [-]	Water board [-]	Water research institute [-]	Real estate developer [-]
Reference	4.2	3.7	2.9	4.6	4.2	4.7	5.1
Improved centralized	4.8	4.5	4.4	5.9	4.7	5.4	**5.4***
Hybrid	4.8	4.4	4.8	6.0	4.7	5.3	4.9
Almost decentralized	**5.9***	**6.2***	**6.3***	**6.6***	**5.9***	**5.8***	**5.4***

* Highest scenario score

4.6.3. Evaluating normalized scores and weighted scores

The normalized indicator scores (v_m) and the weighted scores (v_m) have been evaluated and visualized. After that, the difference (γ) between the total normalized score ($V_{normalized}$) and total weighted score (V_s) for a specific scenario (a) and stakeholder perspective (s) was determined. The results of a municipality (Figure 34) illustrate the impact of indicator prioritization. The results of the remaining stakeholders can be found in Appendix K.

Similar to the previous step (section 3.5), the normalized scores (blue) represent the indicator scores. The weighted scores (yellow) show what indicators were given a higher prioritization than others. To give an example, the indicator *safety* was given the highest prioritization with a score of 10 [-]. Therefore, the outcome of the total weighted score highly depends on the normalized indicator score of *safety*. The results show that the *almost decentralized scenario* scored best for this indicator compared to the other scenarios. The *almost decentralized scenario* scored +11.2% higher compared to the average of all normalized indicator scores. The other scenarios were given a lower weighted score in a range of -4.4% to –1.2% compared to the average of the normalized scores.

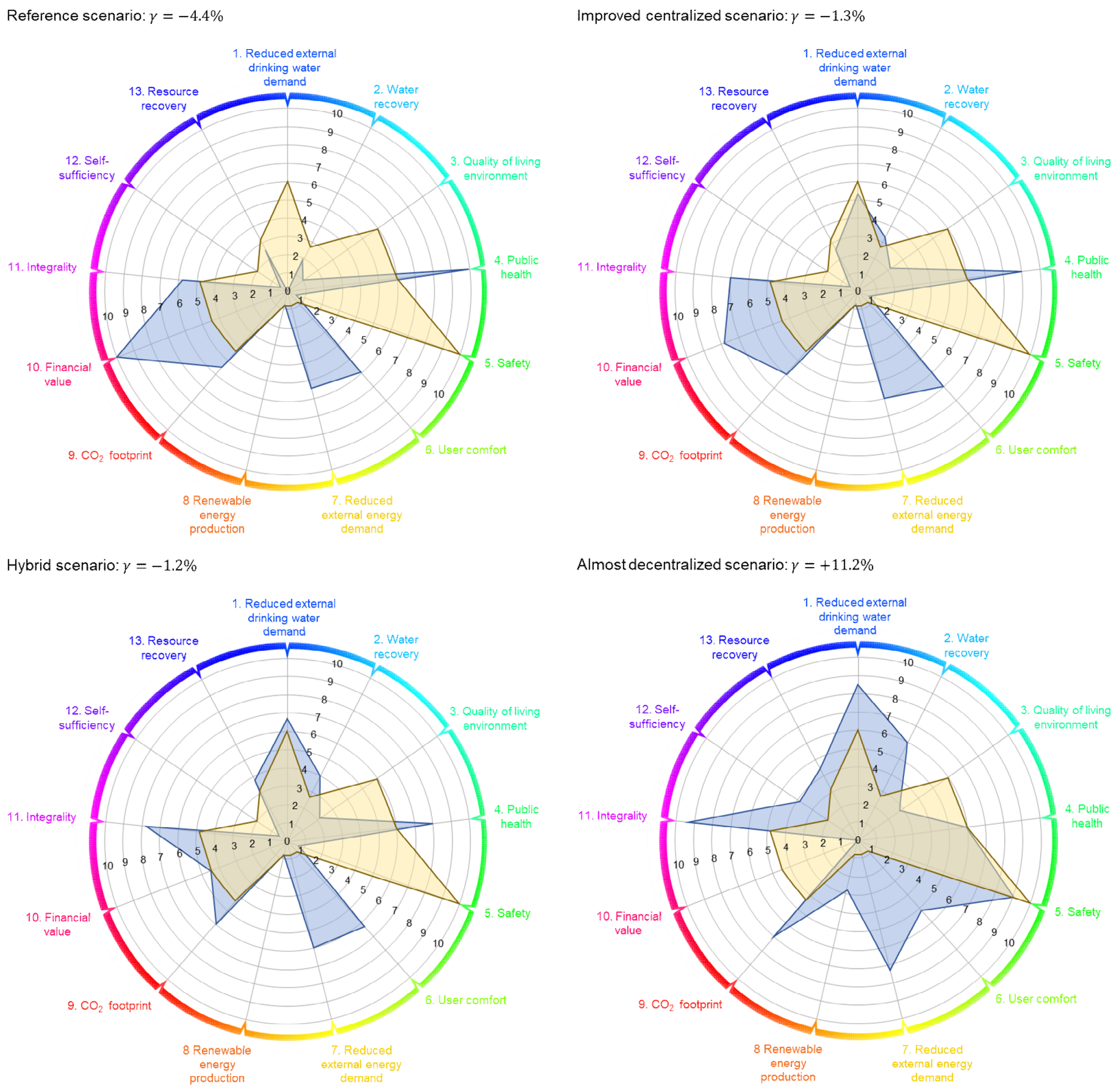


Figure 34: Visual overviewed weighted scores municipality

5. Discussion

5.1. Generic assessment framework

The case study results showed that the generic assessment framework could be used to evaluate different decentralized WEN systems. However, there are some discussion points and limitations to the generic assessment framework. This can be divided into three topics: (1) applicability and comparability, (2) modeling tools and datasets, and (3) implementation of evaluation indicators. The last sub-section will provide recommendations for further improvements to the generic assessment framework.

5.1.1. Applicability of generic assessment framework

This research aimed to develop a generic assessment framework with a high applicability that can be used for neighborhood with different characteristics (e.g. building density, building year and population). With the correct modeling tools and dataset, it was proven possible to assess different strategies of decentralized WEN systems in neighborhoods. The generic assessment framework can be used for various purposes depending on the user's objectives. The six steps should be followed accordingly, but within the steps, there is flexibility in making adjustments. Selecting a modern neighborhood and elaborating its characteristics can be done in a matter of hours. For this research, data on City Nieuwegein was already publicly available [26], [77], [118]. If this information is not accessible, an estimation should be made. There is a possibility to use the same four scenarios that have been designed for this research or new concepts can be developed. It is estimated that all steps of the generic assessment, assuming that all necessary data is available, could be completed within a week. The exact time that is required is difficult to estimate as this depends on the research objectives (e.g., different case studies, number of scenarios and parameters changes)

Similar to the study of Bouziotas et al. (2019) [30], the generic assessment was applied on a modern Dutch neighborhood. It is also possible to assess an existing neighborhood in the Netherlands, but this would require a modification in the pre-defined characteristics. At first, the neighborhood characteristics and the designed scenarios should be applied to the following steps of the generic assessment framework. In addition, the *reduced external energy demand* and *financial value* indicators are based on a modern neighborhood. Further research would be necessary to determine the domestic energy demand [89] and the system costs for an existing neighborhood. Additional research would also be required when evaluating a neighborhood that isn't located in the Netherlands. More than half of the indicators (#1, 3, 4, 6, 7, 9 and 10) are based on Dutch-oriented data and characteristics, such as the average DW demand [82] and the customer perspectives [20], [24].

The generic assessment framework was developed to either evaluate one neighborhood with different decentralized WEN systems or different neighborhoods that would use the same technologies. The generic assessment framework is not applicable for assessing different neighborhoods and various decentralized WEN systems at the same time. In that case, it could be difficult to interpret the results as it can be impacted by either the characteristics of the neighborhood or the chosen infrastructure. This framework was primarily developed to highlight the strengths and weaknesses of a neighborhood with decentralized WEN systems. This framework includes social-political indicators making it more complex to give a score. With the normalized and relative scores, it was possible to determine which scenario scores 'best' overall. Frameworks that primarily focus on evaluating technical aspects, such as the study of Besson et al. (2021), are more practical in quantification. However, this framework intentionally used various indicators to get a better overview of the aspects that were found relevant for a decentralized WEN system. Ultimately, the decision-makers could select the highest-scoring scenario based on their preferences as well as weighting factors. However, it could be argued if the designed scenarios are the best options or whether a combination of different concepts would be preferable.

5.1.2. Modeling tools and datasets

Dutch neighborhoods can use meteorological data from KNMI and Rijkswaterstaat that is publicly available. Neighborhoods in other countries should use meteorological data from their national institutes that have data on historical weather events. However, it should be taken into consideration that a dataset of 10 years does not provide a complete overview on how a neighborhood would perform on (more) extreme weather events. The research of Bouziotas et al. (2019) used a rainfall dataset of 31 years to evaluate the performance of different water systems, such as annual runoff reduction and flood event reduction [30]. This study indicated that a relative small dataset can still provide probabilistic results with a high confidence if synthetic (or artificially generated) rainfall events would be added to the simulation. In addition, the scenarios can be evaluated for specific years with infrequent meteorological characteristics (e.g. dry year). To illustrate, the study of Contreras Navarro (2022) evaluated different concepts of water- and energy systems by based on two datasets with minimum and maximum amount of yearly rainfall [125].

It should be considered that the modeling tools (SIMDEUM, UWOT and Power-to-X) are currently not publicly available and can only be used if permission has been granted by the developer. The SIMDEUM and UWOT models could produce the required output data within 5 minutes. As a result, it was possible to make quick adjustments to the parameters for further optimization. The Power-to-X model on the other hand had a longer simulation time (around 2 hours without MODFLOW and 5 hours with MODFLOW) because it uses both technical, energetic and economic parameters [79]. In general, it would be more time efficient to automate parameter changes. For example, the study of Contreras Navarro (2022) used 'multi-objective optimization' to simulate different storage and treatment capacities for water system concepts [125]. At last, some data on the water-energy system connections (energy demand RO and pumping systems, biogas CHP, e.g.) had to be added manually as this wasn't considered for the UWOT and Power-to-X model. This is an important step to have insight in the WEN.

5.1.3. Legal limits

It should be considered that this research used decentralized WEN systems that are in some cases, legally prohibited in the Netherlands. For instance, it is not allowed to dispose kitchen waste in a food grinder that is connected to a WW (sewer) system [126]. The disposal of kitchen waste in the sewer system can potentially lead to clogging, but also result in an increase of organic waste in WW which is disadvantageous [127]. In practice, this can be mitigated with the use of a vacuum sewer which is already used in neighborhood in European neighborhoods, such as Superlocal (Kerkrade, the Netherlands), Nieuwe Dokken (Ghent, Belgium), Jenfelder AU (Hamburg, Germany) and H+ (Helsingborg, Sweden) [122]. According to the Dutch regulations, only rainwater and groundwater can be used as non-potable water for toilet flushing [128]. At last, a drinking water company is obliged to produce and distribute DW [128]. For the use of decentralized DW production facilities, a drinking water company should be involved for monitoring and maintenance for such as system.

5.1.4. Implementation and interpretation of evaluation indicators

The indicators related to the 'water system' and 'energy system' can be quantified directly once the output data from the modeling tools is available. The same would apply for the *quality of living environment*, *safety*, *CO_2 footprint*, *financial value* and *self-sufficiency* indicators that can also be quantified. For this research, the scoring process on qualitative indicators was based on existing literature. The *public health* indicator could be further elaborated by assessing the impact of strategies to have a secure decentralized WEN system. The study of Kusumawardhana et al. (2021) already provided some mitigation strategies, such as lid closing before toilet flushing, when rainwater and GW are used in houses [53]. Based on the research of Roest et al. (2016), it would be essential to use treatment technologies that are practicle in monitoring and maintenance [58]. For the *user comfort* indicator, the research of Brouwer et al. (2021) was used that looked into the different costumer perspectives and level of tap (or drinking) water awareness [20], [24]. However, the results on tap water awareness did not look into the acceptance on decentralized WEN system but on the willingness to save DW and the behavior on water consumption (e.g. water-saving appliances). Thus, the *user comfort* indictor was based on interpretation of the researcher, making the research less objective at this stage. For the *integrality* indicator, further research would be needed to better measure the level of multi-value creation. The study of Dorado-Rubín et al. (2021) provided a concept to analyze integrality in the design of urban development plans [25]. However, this indicator could be further specified for example with a list of aspects that would define multi-value creation (involved stakeholders, integrative solutions, e.g.). More research is required for the *resource recovery* indicator to measure the impact of source separation for GW and BW. The paper of Besson et al. (2021) assessed the resource recovery potential for decentralized treatment of urine, BW or GW/BW [46]. The separation of urine hasn't yet been used as an innovative water technology for the generic assessment framework, but can ultimately be included as well.

The stakeholder perspectives were used to prioritize the 13 indicators for the generic assessment framework. This would provide insight in evaluating the normalized scores with the weighted scores. With the multiple stakeholder interviews that were held, the impact on indicator prioritization could be assessed. However, this would primarily provide insight on the impact of the overall score of a scenario. To identify the uncertainty of indicator parameters, a sensitivity analysis could be used as an additional step. For instance, the study of Farahani et al. (2020) showed that a sensitivity analysis can be used to assess the changes on capital expenditures and lifetime parameters. As a result, sensitivity on the outcomes of the *financial value* indicator could be further elaborated.

When using the generic assessment framework, it could be argued whether or not it is biased for decentralized scenarios. This framework was developed using the circular economy approach as a base for the formation of the evaluation indicators. Therefore, indicators, such as water recovery, local renewable energy production and self-sufficiency score in general higher for more decentralized scenarios. On the other hand, this framework also included indicators that could potentially score lower for more decentralized scenarios, such as financial value and user comfort. The variety of indicators covers all elements that were found relevant when assessing the performance of the water- and energy system. Ultimately, the stakeholders decide during the indicator prioritization what the weighting should be per indicator.

5.2. Case study results

5.2.1. Water and energy balance with(out) decentralization

The results of the water balance for the different scenarios showed the effects of using decentralized WEN systems. All scenarios with water-energy-saving appliances used RWHS and optionally recycled (light-)greywater. This led to a reduced DW demand between 53% and 84%. The total reduction in DW demand was in the same range as with studies that looked into the effect of RHWS [7] [33] [17]. Those studies showed an reduced DW demand between 26% and 79%. However, the results cannot be compared one-to-one as those studies didn't include water-energy-saving appliances, GWR and the vegetational water demand. When looking at the water balance of the *almost decentralized scenario*, there is still an external DW demand. For neighborhoods with a high building density, such as City Nieuwegein, it is not possible to become completely independent from external DW supply.

The results of the energy balance for all scenarios showed a minimum reduced external energy demand of 55% and up to 73% with more local energy production and storage. This reduction in energy demand is mainly caused by using an ATES system to cover most of the heating demand (75-78%) for 1,280 apartments. The study of van der Roest et al. (2021) showed that heat storage could cover the heating demand by 90% with 2,000 houses [67]. However, it should be mentioned that this study used a high-temperature aquifer system (HT-ATES) that stores water at a temperature of 40-60 °C instead of 15-20 °C for an ATES system [63]. Furthermore, the use of PV panels on both rooftops and facades covered 31% of the electricity demand which is similar to the study of van der Roest et al. (2021) on which the PV panels covered 30% of the electricity demand [67]. It was found that the electricity supply of a collective battery is minimal (<1%) if it only uses surplus energy from PV panels on rooftops. It becomes more valuable in a scenario that has more surplus energy like the *almost decentralized scenario*. However, this would still cover only 3% of the electricity demand as most of the surplus energy went to the electrolizer for hydrogen production. It should be considered that batteries need a relatively large amount of space, because it has to be located above the subsurface [67]. In addition, the use of a collective battery is most likely not cost-efficient. The Power-to-X model results showed that there were approximately 1,500 charging cycles over a period of 10 years. This is less than half of what is normally estimated (3,000 charging cycles during an operative lifetime of 12 years) [107]. Hydrogen conversion on the other hand covered 7% of the electricity demand, 98% of the hydrogen demand for FCEVs and rest heat could be used for the heating demand. Thereby, hydrogen as an energy carrier is more suitable for longer (seasonal) energy storage [67].

5.2.2. Self-sufficiency and peak demand/supply reduction

Spatial limitations can also play a role in the feasibility of decentralized WEN system. For example, the study of Hofman-Caris et al. (2019) found that a minimum storage capacity of 20 m^3 per house/apartment would be required to maximize the total amount of rainwater that can be harvested [33]. When considering this as a benchmark, a total storage capacity of 25,600 m^3 would be required for *City Nieuwegein*. This is far more than the maximum storage capacity (2,500 m^3) of the *almost decentralized scenario* which had the highest storage capacity. In addition, the required space for energy storage/conversion systems (collective battery, biogas- and hydrogen tank, e.g.) should also be included in the design process.

The UWOT simulations showed that on a yearly average, approximately 38% of the total hours can be covered with local water sources with an *almost decentralized scenario*. Similarly to other literature, external DW supply would still be necessary to have a well-functioning system [33]. For the *almost decentralized scenario*, the external DW demand peak would be reduced by 45% by also using GWR. For a *hybrid scenario*, the external DW demand peak would be reduced even further with 53%, but the vegetational water demand was also lower (no green facades). As a result, the investment costs could be reduced because a lower distribution capacity would be possible. A drawback for a scenario with a higher self-sufficiency is that a longer residence time of DW in the distribution system could reduce the water quality [129]. For the *almost decentralized scenario*, it was found that the decentralized could cover all water demands up to 50 days. In that case, the centralized distribution network would require careful monitoring with regards to the DW quality. The other three (more centralized) scenarios do not have this problem as DW from the centralized distribution network is always needed throughout the day.

Similar to the water system, a complete self-sufficient energy system was not possible for all scenarios that used decentralized WEN systems. Depending on the given scenario, the total amount of surplus electricity that would go to the grid was between 0 and 21 MWh/year (<1% of total energy demand). This was primarily the case for the *reference scenario* (10 MWh/year) and *improved centralized scenario* (21 MWh/year) that didn't have energy storage and conversion options. For the *hybrid scenario,* all surplus energy could be stored with the use of a collective battery. This was not the case for the *almost decentralized scenario* (15 MWh/year) as more renewable energy was produced that could be stored or converted. In addition, a lower grid import or export can reduce the pressure on the grid network during peak demand or production from PV systems [67]. Including the effects on overvoltage mitigation strategies would be useful for stakeholders and decision makers in (re-)designing a neighborhood [130].

5.2.3. Pre-defined benchmark

For some indicators, available benchmarks were used to set to boundaries for the minimum and maximum values. For instance, the boundaries for the *reduced external drinking water demand* and *reduced external energy demand* indicators were based on the average water- and energy demand for Dutch household. The same principle was followed for the *qualitive of living environment* indicator. The benchmark of 75 m^2/residence from Bezemer and Visschedijk (2003) was used as the benchmark for this research [97]. The scores for this indicators were in the range of 1.1 to 2.8 [-]. Based on the high building density of *City Nieuwegein*, the total amount of blue-green spaces should be at least 96,000 m^2. This is more than twice the size of the neighborhood (47,000 m^2) itself. This would only theoretically be possible if more green facades would be realized. Though, this would also result in a higher vegetational water demand and less PV panels on facades could be placed. Furthermore, the potential maintenance (costs) on green facades hasn't yet been considered in the generic assessment framework. An adjusted benchmark for a neighborhood with a high building density of multiple-floor apartments would therefore be necessary. The current benchmark was based on a city scale on which city greenery (parks, sports fields, forests, e.g.) would count in the assessing the *quality of living environment*.

5.2.4. Stakeholder involvement

The results of the stakeholder interviews showed that incorporating the indicator prioritization was beneficial in evaluating the weighted scores. For future users of the generic assessment, it would be valuable to include more stakeholders besides public utilities such as the energy sector (network operators), urban ecologists and future/local inhabitants. The study of Dorado-Rubín et al. (2021) highlighted the importance of high stakeholder involvement in the design phase which could increase the support in the realization phase. Furthermore, interviewing more people per stakeholder gives a more representative result on the stakeholder perspectives. At this stage of the research, one person per stakeholder was interviewed to give a first impression what input and results can be expected during the last step of the generic assessment framework.

6. Conclusions and recommendations

A generic assessment framework was developed to evaluate the impact of different decentralized WEN systems and to support the decision-making process of stakeholders. After the framework was created, a Dutch neighborhood (*City* Nieuwegein) with a high building density was selected as a case study to assess the impact of decentralization.

6.1. Conclusions

Four sub-research questions were formed to better understand how a generic assessment framework can be developed and applied.

(1A) What innovative water and energy technologies can be used in a neighborhood that are relevant for decentralized water-energy nexus systems?

A literature review explored different innovative water and energy technologies that could be used in a neighborhood. On a household scale, several water-energy-saving appliances (vacuum toilet, recirculating shower, e.g.) were considered valuable in reducing the overall water- and energy footprint. Additionally, various innovative technologies can be applied on a neighborhood scale. Rainwater harvesting (RHW) and greywater recycling (GWR) can be used to collect and reuse local water sources. Blue-green infrastructure (helophyte filters, blue-green rooftops, e.g.) can be used for stormwater control and local water treatment. Furthermore, it positively impacts the biodiversity and reduces the heat island effect (UHI). At last, innovative energy technologies were explored to increase local energy storage/production, such as aquifer thermal energy storage (ATES), battery, hydrogen production, and anaerobic BW digestion to produce biogas.

(1B) How does a generic assessment framework look like that allows to evaluate different decentralized water-energy nexus systems and includes the stakeholder perspectives?

Different assessment frameworks were reviewed and used as a reference to develop a generic assessment framework. The generic assessment framework (Figure 35) allows decision-makers and researchers to evaluate decentralized WEN systems for one or multiple neighborhoods. By following the six steps accordingly, it is possible to have a comprehensive overview of the strengths and weaknesses of the 13 evaluation indicators (divided over four different themes). Moreover, the stakeholder perspectives can be included and used as weighting factors for the indicators.

(1C) How do different degrees of decentralized water-energy nexus systems impact the performance of a neighborhood?

Four different scenarios (*reference*, *improved centralized*, *hybrid,* and *almost decentralized*) were designed and evaluated from minor towards many decentralized WEN systems. The results showed that more innovative technologies positively impact most evaluation indicators (e.g., *water recovery*, *safety* and *CO_2 footprint*). However, the *public health*, *user comfort,* and *financial impact* indicators generally had lower scores, as more decentralization would lead to higher complexity and system costs (CAPEX and OM). When looking at the results of the water- and energy balance, the total external DW demand could be reduced by 84% and up to 73% with regards to the external energy demand. And not to mention, the capacity of external DW distribution network could be reduced by more than 50% due to lower peak demands. The electricity network could also benefit from more decentralization as grid overvoltage can be limited due to local conversion and storage and electricity peak demands can be reduced. At last, with an *almost decentralized scenario* it is possible to reach an self-sufficiency of 38% and 35% for the water- and energy system respectively.

(1D) How does the perception of stakeholders impact the assessment of different decentralized water-energy nexus systems?

Incorporating the stakeholder perspectives in the last step of the generic assessment framework allowed the researcher to include indicator prioritization as a part of the decision-making process. Experts from five different public organizations (municipality, province, drinking water company, water board, and water research institute) were interviewed. Based on existing literature, the theoretical perspective from a real estate developer was added, which represented a stakeholder from the private sector. The results showed that *public health*, *reduced external drinking water demand* and *quality of living environment* were overall the most important indicators. Different prioritized indicators were identified for a municipality (*safety*) and real estate developer (*financial value*). Indicators such as *self-sufficiency*, *resource recovery* and *reduced external energy demand* had the lowest prioritization. The results of weighted scores, showed that scenarios with more decentralized WEN systems were preferred for all six stakeholder perspectives.

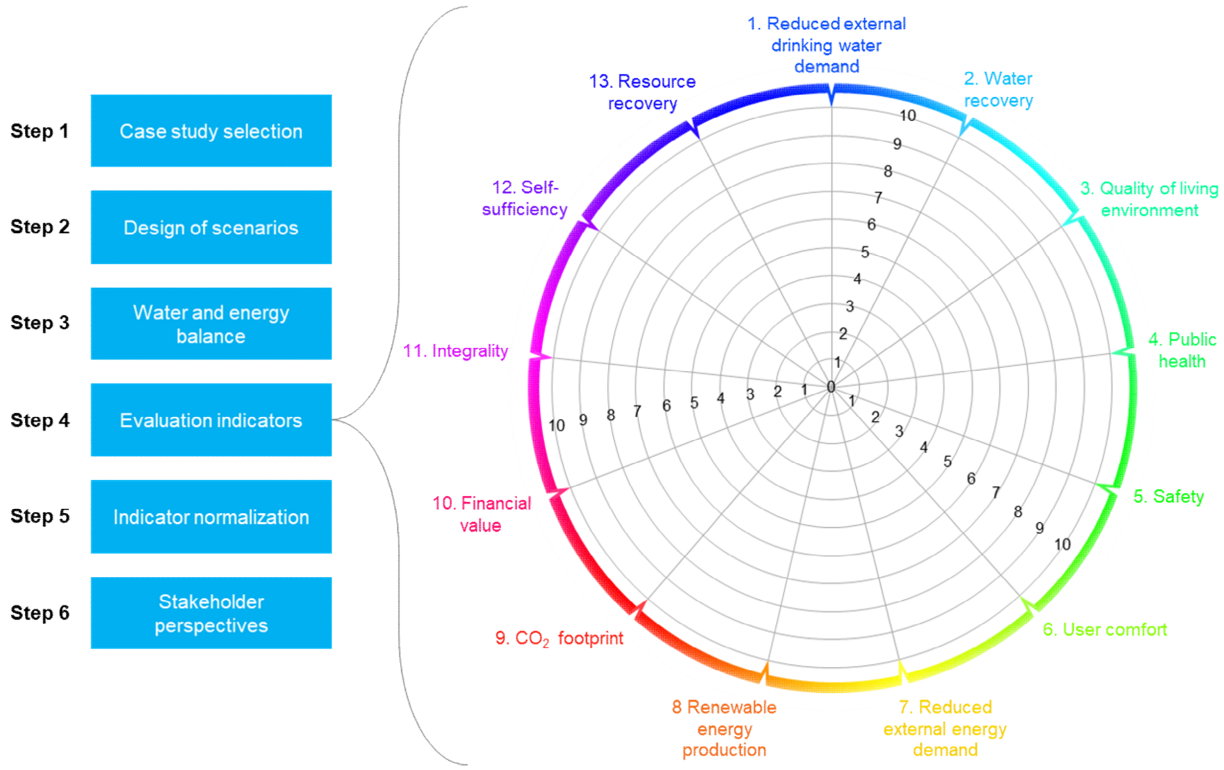


Figure 35: Overview generic assessment framework

6.1.1. Answering the main research question

Based on the outcomes of the generic assessment framework that was developed and implemented for a selected case study, it was possible to answer the main research question.

How can the impact of different decentralized strategies for a water-energy nexus system in a neighborhood be assessed, thereby incorporating the decision-making process of stakeholders?

A generic assessment framework was developed that would allow to evaluate different decentralized WEN system. A total of 13 diverse evaluation indicators were formed that are highly applicable for assessing neighborhoods. Besides, the generic assessment framework includes stakeholder perspectives so that it can facilitate the decision-making process of stakeholders. After developing a generic assessment framework, *City Nieuwegein*, a modern neighborhood with a high building density of multiple-floor apartments, was used as a case study. This made it possible to evaluate how the generic assessment framework would work in practice. Depending on the user's objectives, the generic assessment framework can be used to evaluate Dutch neighborhoods, and optionally also in other countries. Furthermore, there is a possibility to assess both modern and existing neighborhoods.

6.2. Recommendations

During this research, different limitations and results were found. This section will describe how the generic assessment framework can be further developed and improved. Moreover, recommendations will be provided for the users of the generic assessment framework on how the results can be interpreted.

6.2.1. Recommendations on further developing generic assessment framework

For further improving the generic assessment framework, it is recommended to include a sensitivity analysis. This can be used to identify uncertainties of indicator parameters and to assess potential changes in outcomes for the scenarios.

In addition, it is recommended to use a larger meteorological dataset (50-100 years) with optionally synthetic data. This will provide probabilistic results with a higher confidence. This will contribute in evaluating the performance of a neighborhood, such as (flood) safety and external DW/energy demand, during extreme climatological conditions.

When designing multiple scenarios, it becomes possible to assess the performance for different decentralized WEN systems. However, with the current modeling set-up, the system characteristics (storage, treatment/production capacity, e.g.) have to be adjusted and processed manually to evaluate the changes in results. This makes it more complex to determine how a scenario can be further improved. To make this process more (time-)efficient, it is recommended to include multi-objective optimization in the modeling tools.

For the qualitative indicators (*public health*, *user comfort*, *integrality* and *resource recovery*), the results were based on literature that would provide insight on the effects of using decentralized WEN systems. Further research on assessing the impact of decentralization is recommended to improve the representativeness for these indicators.

6.2.2. Recommendations for users of the generic assessment framework

The results of the selected case study were used as an example to demonstrate how the generic assessment framework can be used. The provided scenarios showed how different decentralized WEN systems have an impact on the performance of a neighborhood. For users (decision-makers, researchers, e.g.) of this framework, it is recommended to also incorporate additional innovative water- and energy technologies that haven’t been used at this stage.

The outcomes of this research are primarily based on the yearly average scores for a period of 10 years (2011-2020). However, to evaluate scenarios specific years under unique characteristics (e.g., dry year and high heating demand), it is recommended to have indicator scores that are based on single year data.

A high stakeholder involvement was found essential to guarantee a high succession rate for (re-)designing and realizing neighborhoods. Therefore, it is recommended to conduct interviews with a variety of (public, private, e.g.) stakeholders that are involved in the design of a neighborhood.

6.2.3. Recommendations for modern neighborhoods with a high building density

Using RWH and GWR optimizes the usage of local water resources. The vegetational water demand is only during the growing season whereas the non-potable water demand (toilet flushing and washing machine) is throughout the year.

It is recommended to have local water tanks that can collect treated rainwater and GW for (non-) potable purposes. This can reduce the capacity of the external DW distribution system up to 53%.

Separate collection of GW and BW is recommended to improve the use of local water- and energy resources. The use of GWR results in a higher *water recovery*. A higher *resource recovery* can be achieved with separate treatment of GW and BW. Anaerobic digestion of BW contributes in increasing the *local renewable energy use*.

Hydrogen conversion and storage is recommended over a collective battery as it is more suitable to convert high peaks of surplus energy. A collective battery requires more spaces for the same storage capacity compared to hydrogen conversion and storage. Though, as a collective battery has a high conversion and storage efficiency (90%), it would be recommended to use this for short term energy storage (<24 hours) if there is enough surplus energy available.

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Appendix A: SIMDEUM drinking water patterns

The different SIMDEUM patterns that were used for the four scenarios in the UWOT model can be found in this appendix. At first, an overview (Figure 36) of the average daily drinking water demand patterns is provided that illustrates the situation without (119.3 L/person/day) and with (56.2 L/person/day) water-saving appliances. The drinking water patterns can be divided among weekday and weekend patterns. The SIMDEUM modeling tool considers a different drinking water patterns between these days.

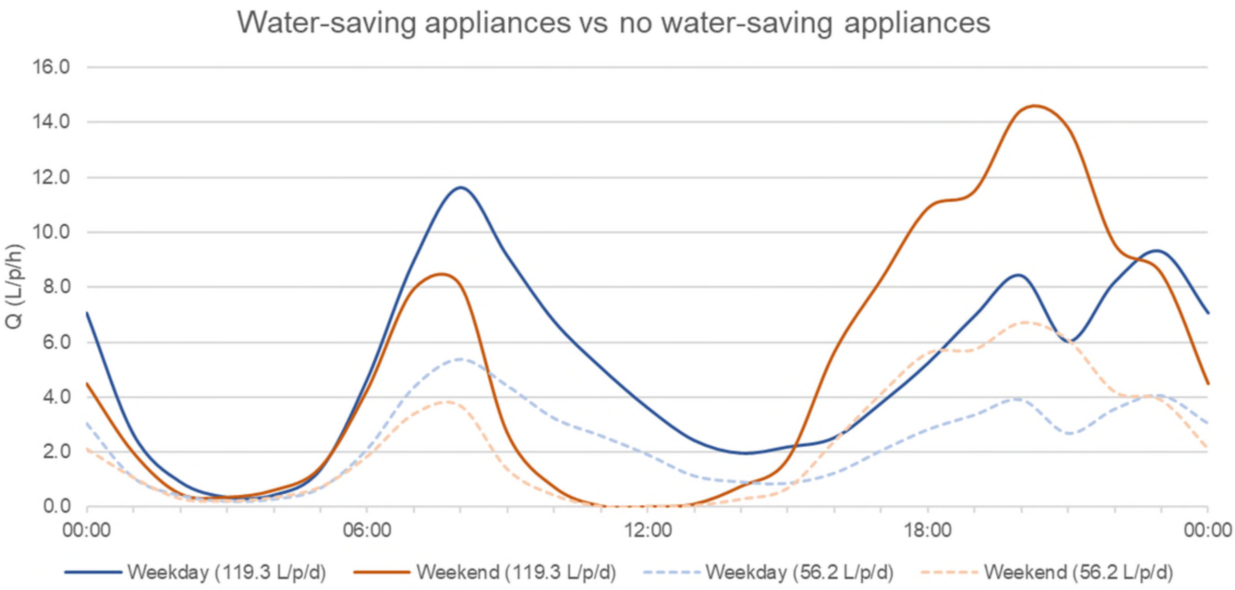


Figure 36: Avereage hourly drinking water pattern from SIMDEUM

These drinking water patterns can be divided among the different domestic drinking water demands (showering, toilet flushing, washing machine, e.g.). For the *reference scenario*, both the weekdays (Figure 37) and (Figure 38) weekend days have an average daily drinking water demand of 119.3 L/person/day. There are no water-saving appliances and only drinking water is used as a water source.

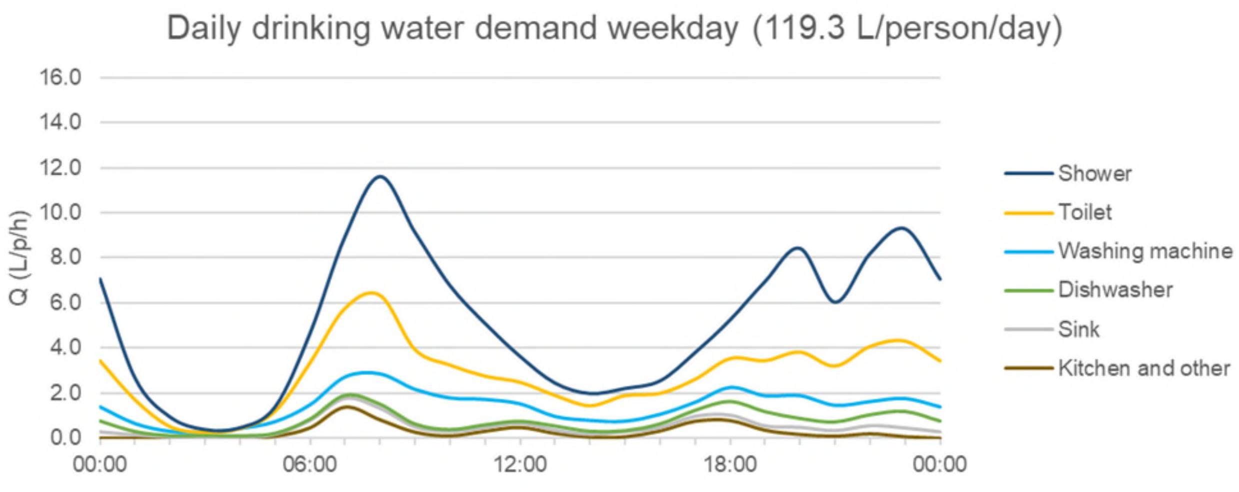


Figure 37: Hourly drinking water distribution without water-saving appliances (weekday)

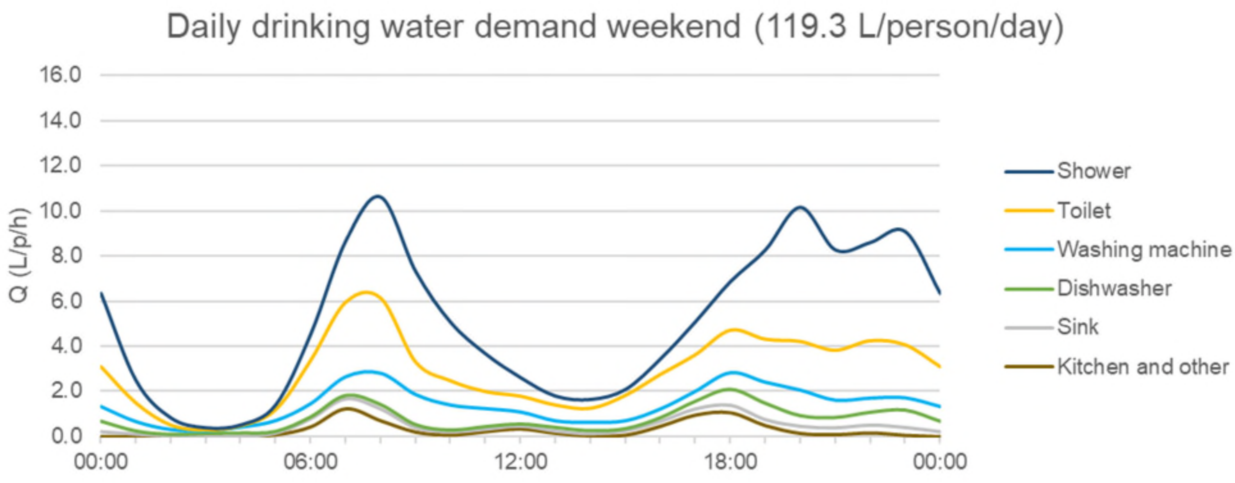


Figure 38: Hourly drinking water distribution without water-saving appliances (weekend)

The *improved centralized scenario* also used only drinking water for all domestic water demands during the weekdays (Figure 40) and (Figure 39) weekend days. With the used of water-saving appliances, the average daily drinking water demand was 56.2 L/person/day.

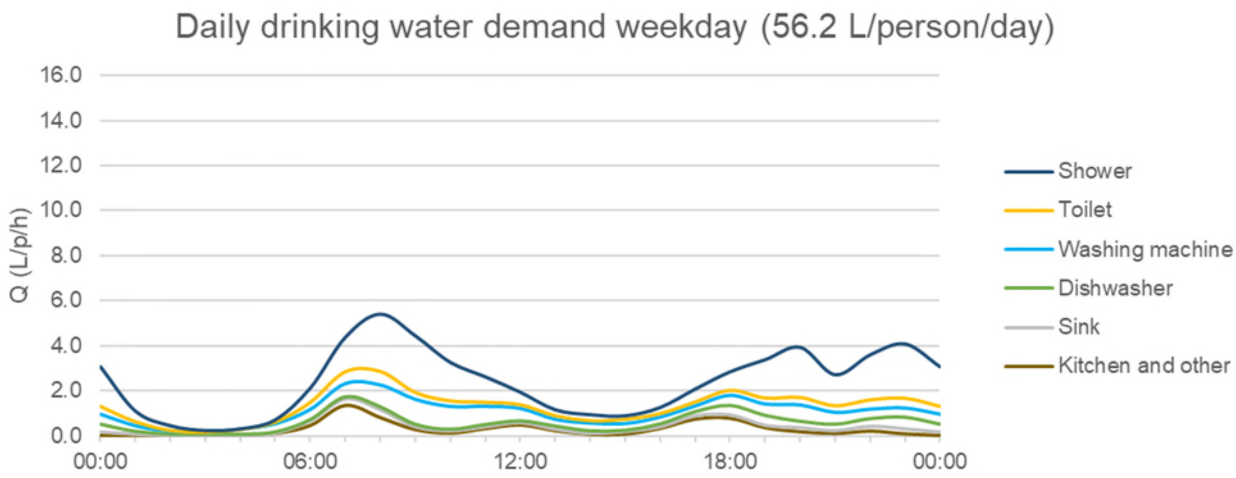


Figure 40: Hourly drinking water distribution with water-saving appliances (weekday)

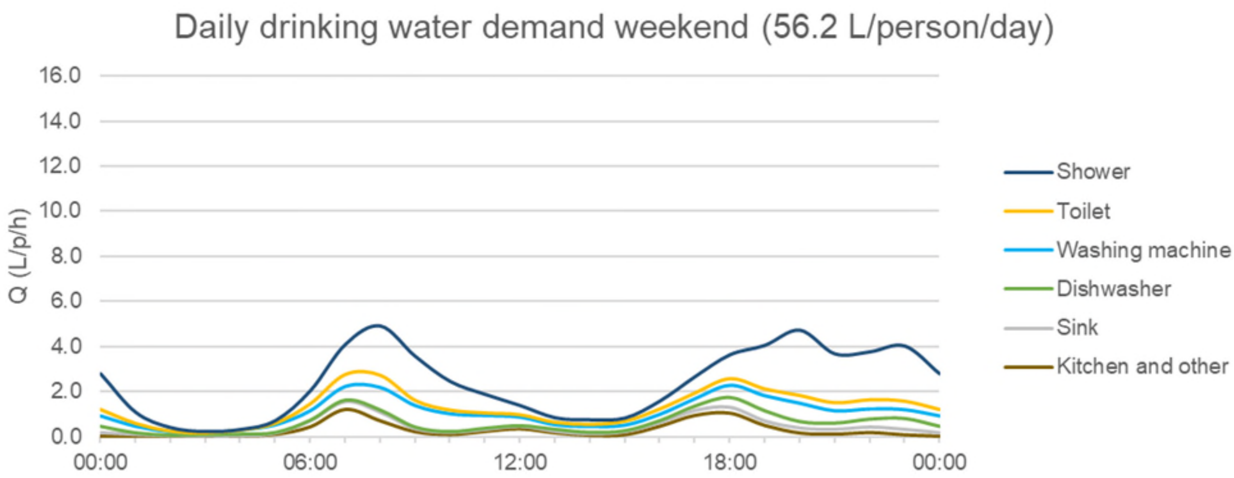


Figure 39: Hourly drinking water distribution with water-saving appliances (weekend)

At last, both the *hybrid scenario* and *almost decentralized scenario* have an average drinking water demand of 39.3 L/person/day. The overall domestic water demand during the weekdays (Figure 42) and (Figure 41) weekend days is also 56.2 like the *improved centralized scenario*. However, because these scenarios used rainwater and (light-)greywater for toilet flushing and the washing machine, the overall drinking water demand was 30% lower.

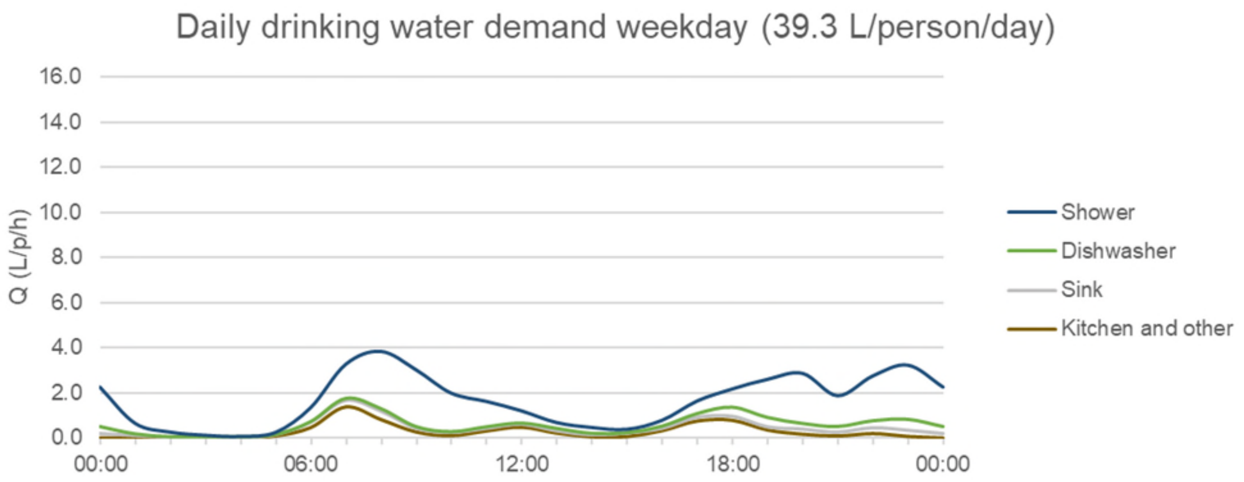


Figure 42: Hourly drinking water with NPW use and water-savings (weekday)

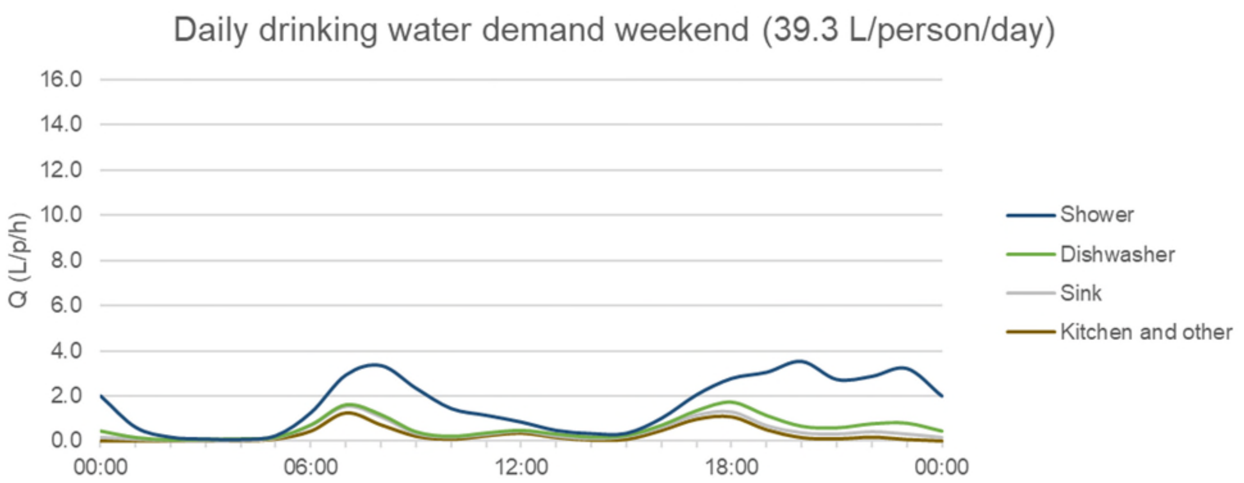


Figure 41: Hourly drinking water with NPW use and water-savings (weekend)

Appendix B: UWOT model

The different UWOT models (or schemes) that have been used are provided in this appendix. The r*eference scenario* and *improved centralized scenario* both used the same UWOT scheme (first figure). Only the datasets within the ‘blocks’ were different. For all schemes, the individual domestic water demand patterns from SIMDEUM were converted into a dataset of 10 years (87,672 hourly timesteps). The same process was done with the meteorological data of KNMI by importing the rainfall and evaporation datasets. All pervious and impervious areas have been implemented to get an runoff that would meet the specific characteristics of the scenarios. The water tanks had a fixed storage capacity according the pre-determined key values. If there were local water losses during treatment steps, a ‘splitter’ was used to take this into account. At last, an optional demi water demand dataset was added which was based on the data from the Power-to-X model.

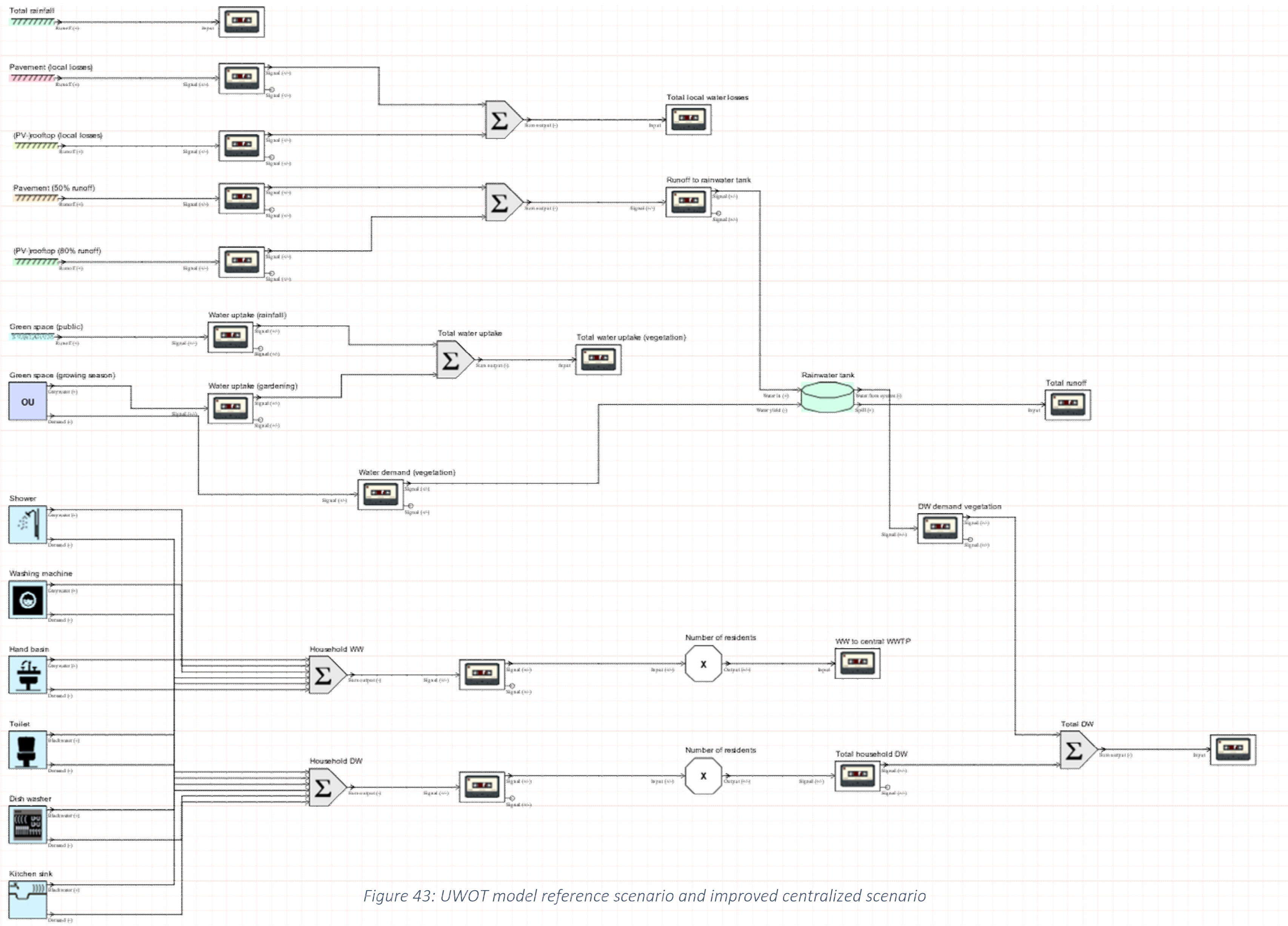


Figure 43: UWOT model reference scenario and improved centralized scenario

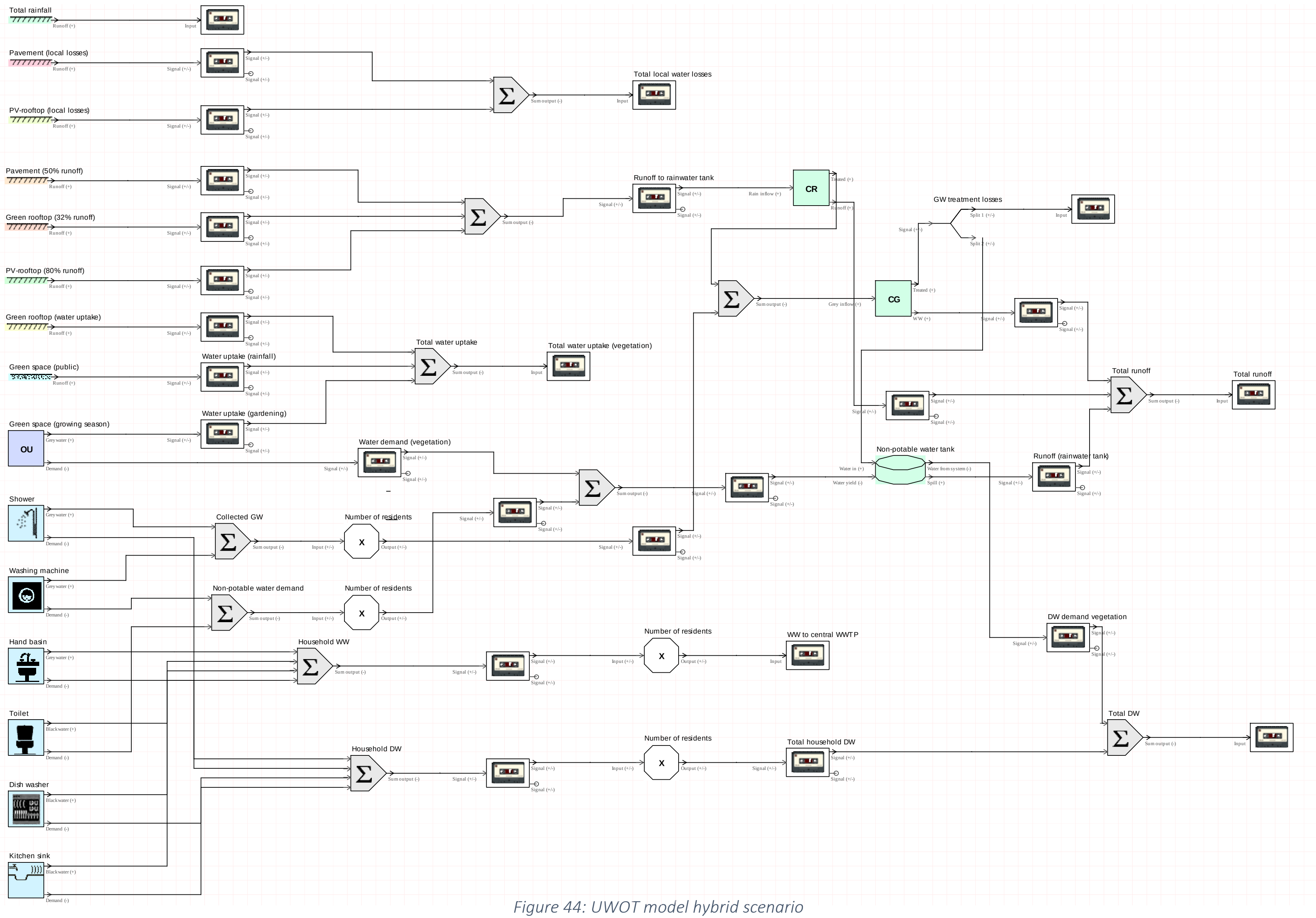


Figure 44: UWOT model hybrid scenario

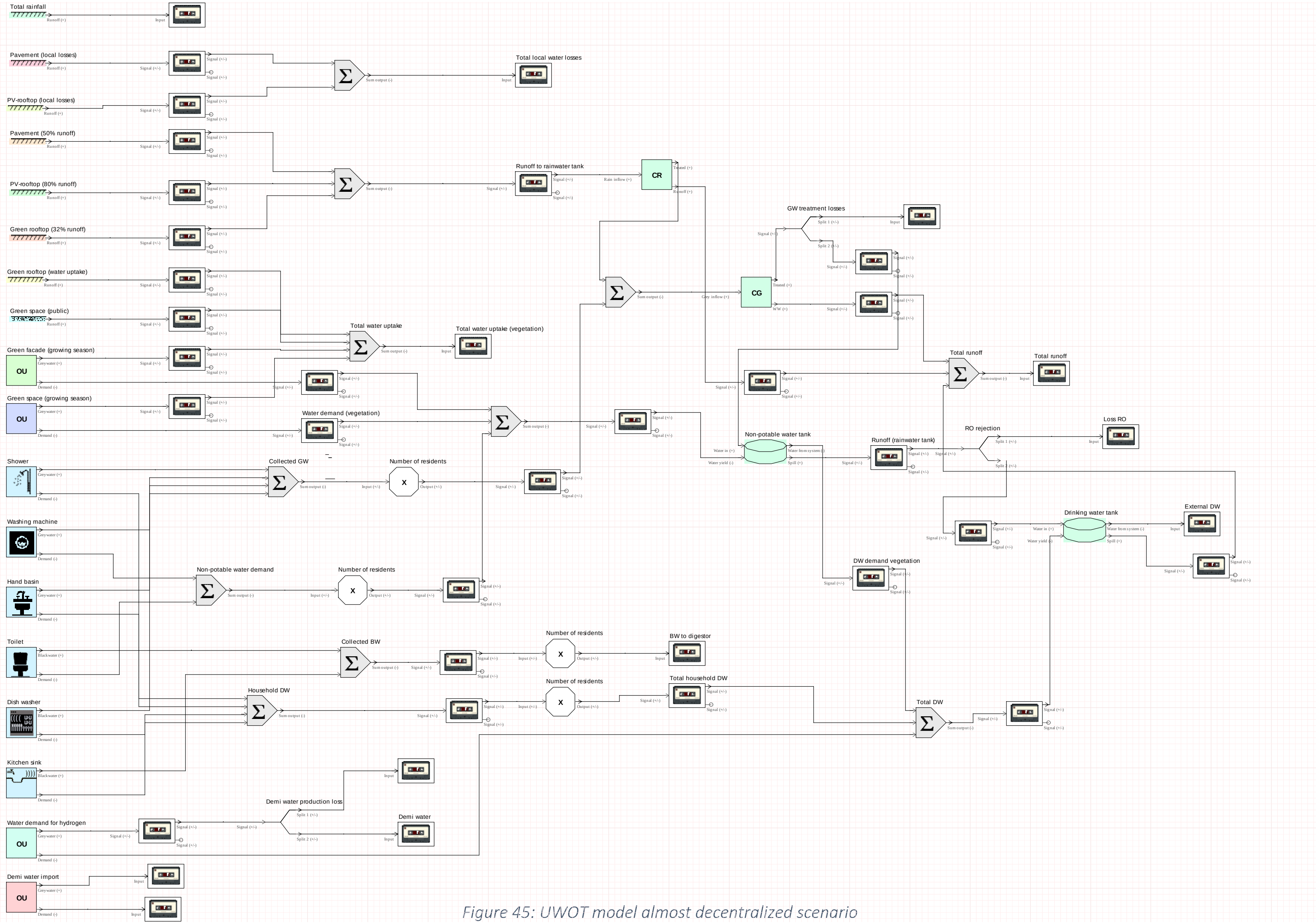


Figure 45: UWOT model almost decentralized scenario

Appendix C: Power-to-X model

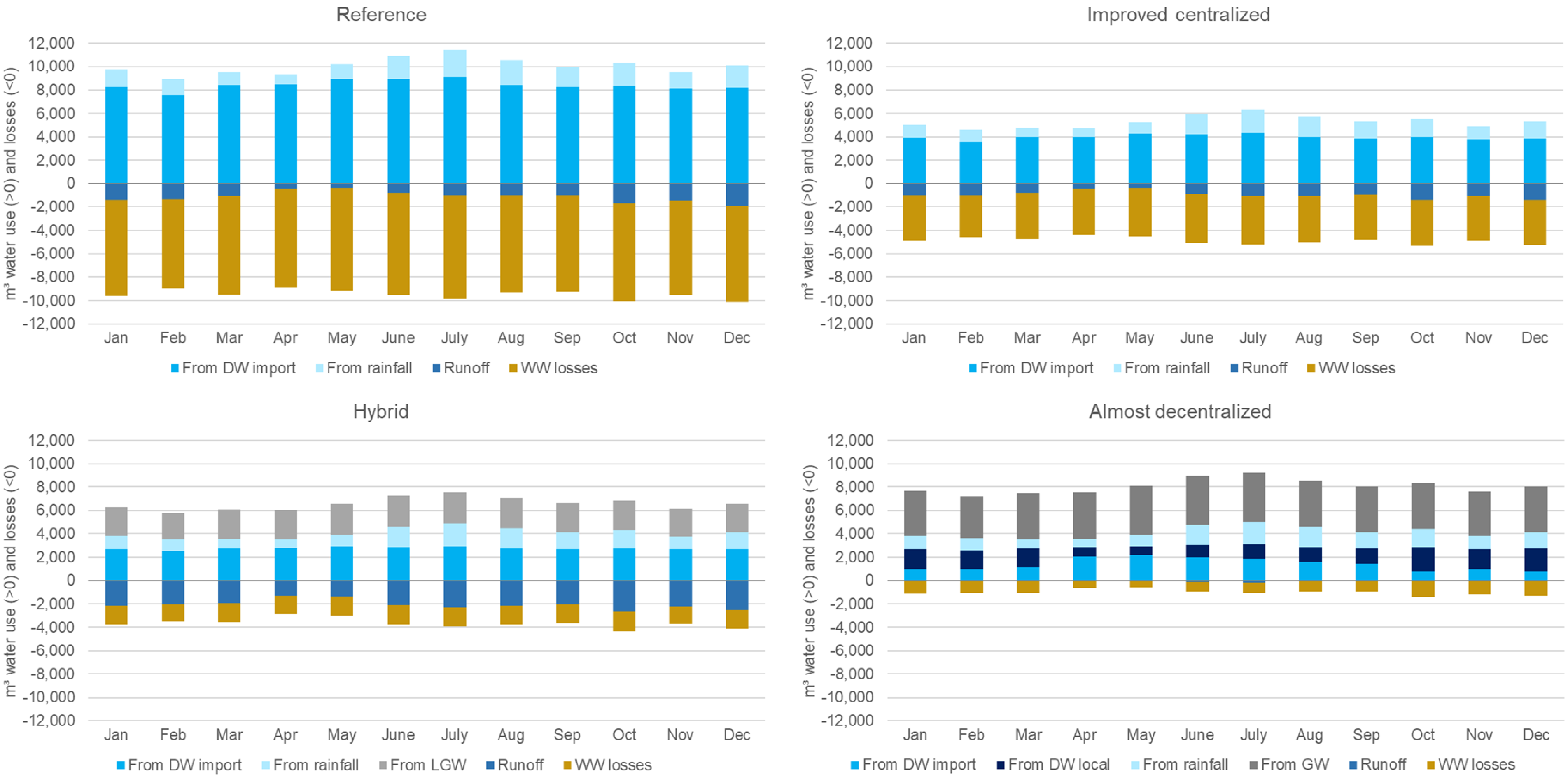
All the parameters (Table 45) that would have to be adjusted, based on the given scenario, can be found in the appendix. The complete parameter file is not added into this appendix, but can potentially be shared.

Table 45: Power-to-X parameters

Power-to-X adjustable parameters							
#	Parameter	Reference	Improved centralized	Hybrid	Almost decentralized	Notes
11	Name	Nieuwegein_XX_YY_ZZ	Nieuwegein_XX_YY_ZZ	Nieuwegein_XX_YY_ZZ	Nieuwegein_XX_YY_ZZ	XX: Scenario (e.g. hybrid) YY: Number of years (e.g. 10Y) ZZ: MODFLOW/NO_MODFLOW
12	startDate	20110101	20110101	20110101	20110101	Start timeseries
13	endDate	20210101	20210101	20210101	20210101	End timeseries
16	con_Modflow	1	1	1	1	0: No MODFLOW 1: MODFLOW
19	saltcavern_stor	1	1	1	-	0: Local hydrogen storage 1: Only hydrogen import
103	max_cap_fuelcell	-	-	-	500	Fuel call capacity (kW)
123	max_E_Electrolyser	-	-	-	1,000	Electrolyser capacity (kW)
133	salt cavern	1,000,000	1,000,000	1,000,000	-	With or without hydrogen import
276	e_cap_battery_coll	-	-	1,000	2,000	not using (kWh)
292	E_tapwater	5.76	3.96	3.96	3.96	Energy demand tap water (GJ/apartment/year)
295	E_spaceheating	12.85	12.85	12.85	12.85	Heating demand (GJ/apartment/year)
299	E_cool	3.53	3.53	3.53	3.53	Cooling demand (GJ/apartment/year)
306	n_house	1,280	1,280	1,280	1,280	Number of apartments
310	p_household	2	2	2	2	Persons per apartment
315	a_h_appartment	70	70	70	70	Apartment area
321	n_pv_roof_new_ap	3	3	3	3	Number of PVs on rooftops
322	n_pv_roof_new_ap_vert_ozo	-	-	-	4	Number of PVs on facades (ESE)
323	n_pv_roof_new_ap_vert_zzw	-	-	-	8	Number of PVs on facades (SSW)
335	e_elec_ap_new	1,825	1,700	1,700	1,700	electricity demand (kWh/apartment/year)
345	e_cooking_ap_new	175	175	175	175	cooking demand (kWh/apartment/year)
351	e_elec_car	1,950	1,950	1,950	1,950	Energy demand Evs (kWh/EV/year)

Appendix D: Monthly water balance (water recovery)

In this appendix, the monthly water balance (Figure 46: Monthly water balance) can be found that was used to describe the *water recovery* indicator. The monthly water balance highlights the seasonal water trends. The vegetational water demand, combined with a higher domestic drinking water demand during the summer months, results in higher water demand during in spring and summer. The key values have already been described in the results of the yearly water balance. However, the monthly water balance visually highlights the water losses from wastewater and rainwater by implementing more decentralized water-energy nexus systems, such as water-saving appliances, RHW and GWR.



Appendix E: Performance water storage tanks during peak rainfall events

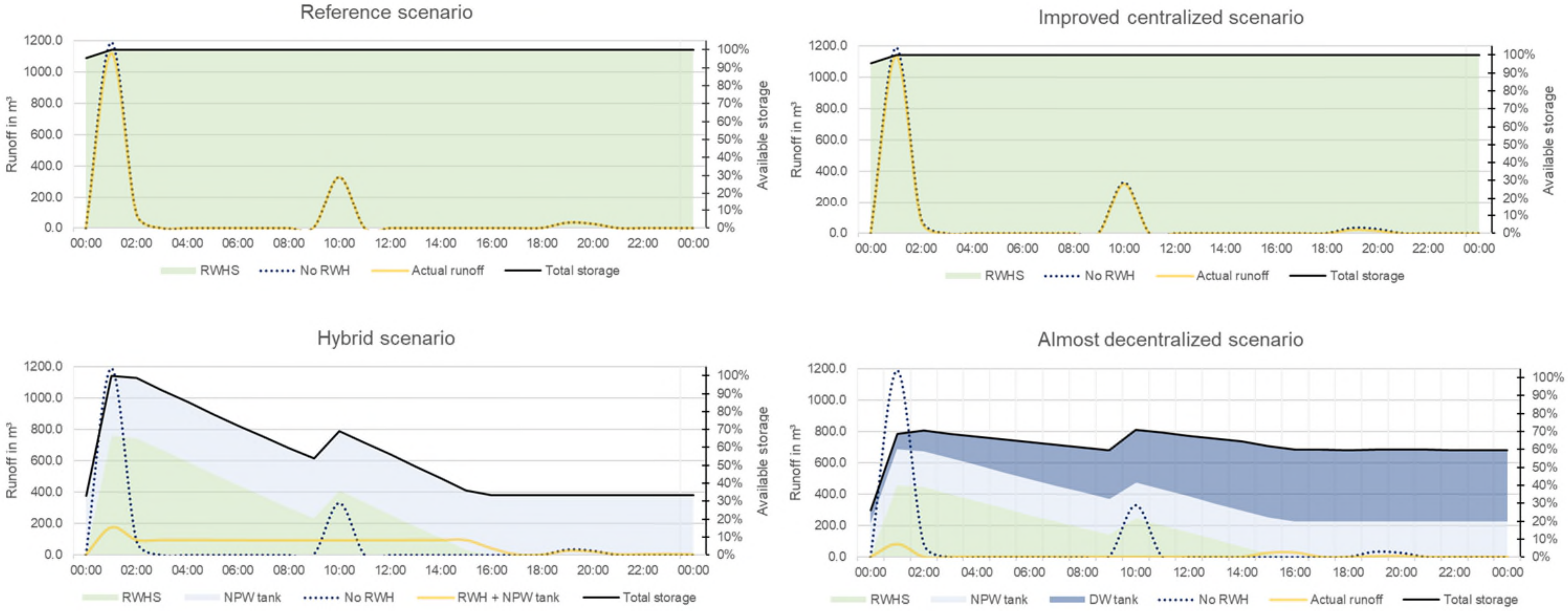
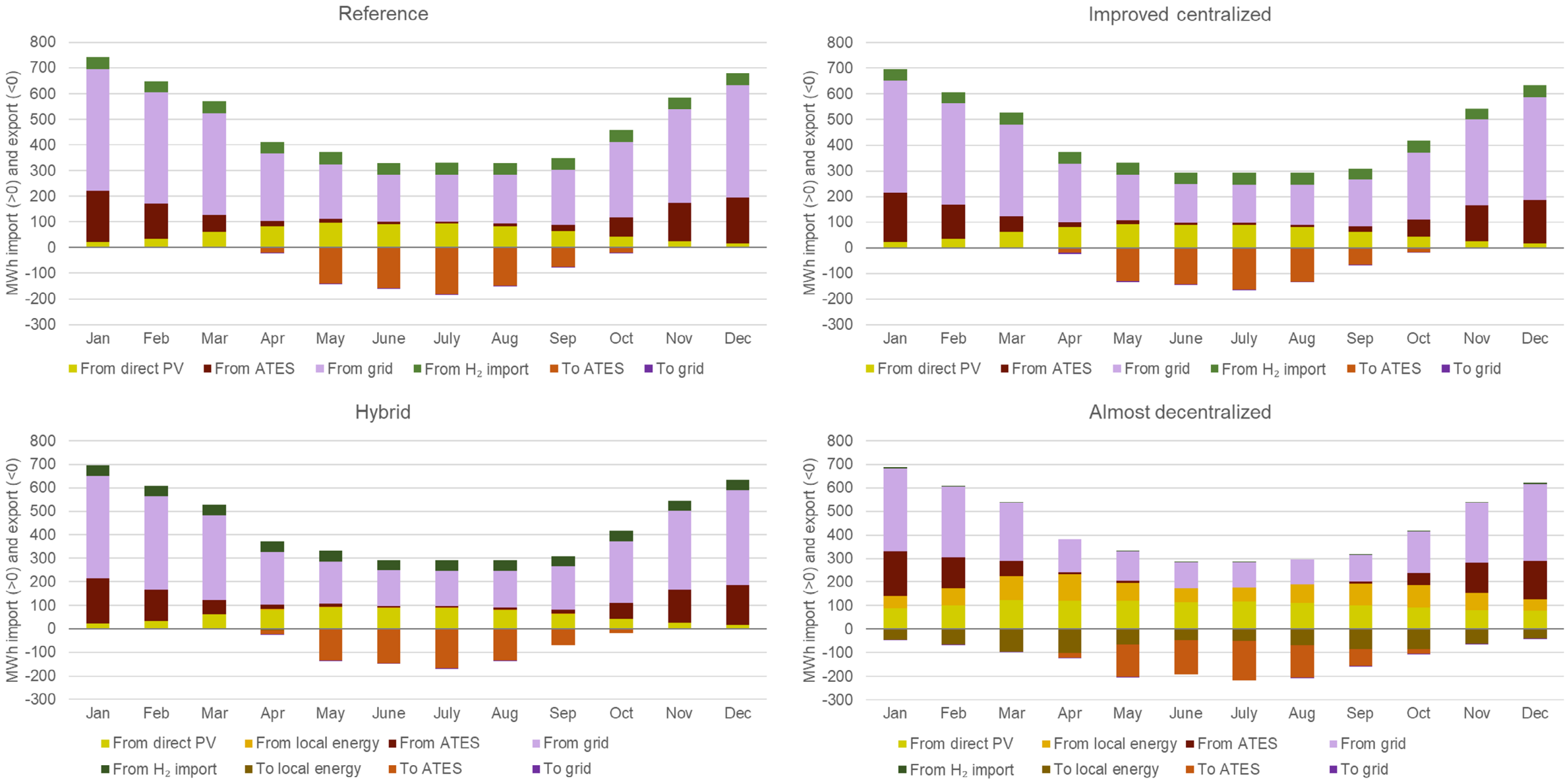


Figure 47: Storage capacity during peak rainfall event

Appendix F: Monthly energy balance (local renewable energy use)

This appendix illustrates the monthly energy balance (Figure 48: Monthly energy balance) that was used to describe the *local renewable energy use* indicator. The monthly water balance highlights the seasonal energy trends, such as the higher heating demand during winter and more surplus energy during summer. Similar to the results of the monthly water balance, the key values of the energy system have already been described in the results of the yearly energy balance. The monthly water balance visually shows how the energy demand is fulfilled and how surplus energy is stored. In this overview, 'local energy' is referred to as biogas, collective battery and hydrogen that has been used for some of the scenarios.



Appendix G: Financial value calculations

	Original centralized scenario		Improved centralized scenario		Hybrid scenario		Almost dentralized scenario	
	CAPEX	OM costs	CAPEX	OM costs	CAPEX	OM costs	CAPEX	OM costs
Water system								
Water storage								
Rainwater tank	€ 7,717.70	€ 11,843.30	€ 5,145.13	€ 7,895.54	€ 5,145.13	€ 7,895.54	€ 2,572.57	€ 3,947.77
Non-potable water tank	€ -	€ -	€ -	€ -	€ 2,572.57	€ 3,947.77	€ 5,145.13	€ 7,895.54
Additional costs households								
Non-potable piping	€ -	€ -	€ -	€ -	€ 11,075.17	€ 2,560.00	€ 11,075.17	€ 2,560.00
Sewage piping	€ -	€ -	€ -	€ -	€ 11,075.17	€ 2,560.00	€ 11,075.17	€ 2,560.00
Vacuum toilet	€ -	€ -	€ 17,207.22	€ 3,840.00	€ 17,207.22	€ 3,840.00	€ 17,207.22	€ 3,840.00
Recirculating shower	€ -	€ -	€ 214,442.45	€ 51,200.00	€ 214,442.45	€ 51,200.00	€ 214,442.45	€ 51,200.00
Food grinder	€ -	€ -	€ -	€ -	€ -	€ -	€ 107,221.22	€ 25,600.00
Drainage and treatment								
Drainage original centralized scenario	€ 203,880.34	€ 30,229.15	€ -	€ -	€ -	€ -	€ -	€ -
Drainage improved centralized scenario	€ -	€ -	€ 203,880.34	€ 30,229.15	€ -	€ -	€ -	€ -
Drainage hybrid scenario	€ -	€ -	€ -	€ -	€ 273,695.19	€ 45,311.17	€ -	€ -
Drainage almost decentralized scenario	€ -	€ -	€ -	€ -	€ -	€ -	€ 219,984.82	€ 43,034.71
Centralized WWTP	€ 125,291.69	€ -	€ 125,291.69	€ -	€ -	€ -	€ -	€ -
Decentralized GWTP	€ -	€ -	€ -	€ -	€ 276,730.43	€ -	€ -	€ -
Decentralized GWTP and BWTP	€ -	€ -	€ -	€ -	€ -	€ -	€ 320,892.94	€ -
Centralized DWTP	€ 139,504.20	€ -	€ 65,812.20	€ -	€ 45,650.40	€ -	€ 22,990.80	€ -
Decentralized DWTP + storage	€ -	€ -	€ -	€ -	€ -	€ -	€ 55,333.60	€ -
Energy system								
Battery storage	€ -	€ -	€ -	€ -	€ 30,138.63	€ 3,000.00	€ 60,277.25	€ 6,000.00
Electrolyzer	€ -	€ -	€ -	€ -	€ -	€ -	€ 33,607.85	€ 10,000.00
Fuel cell	€ -	€ -	€ -	€ -	€ -	€ -	€ 20,941.65	€ 5,000.00
Hydrogen (import)	€ 32,136.00		€ 32,136.00		€ 32,136.00		€ 911.86	
Heat pump	€ 111,578.07	€ 33,200.00	€ 111,578.07	€ 33,200.00	€ 111,578.07	€ 33,200.00	€ 111,578.07	€ 33,200.00
Heat storage system	€ 26,303.53	€ 9,120.00	€ 18,749.91	€ 6,501.00	€ 23,902.46	€ 8,287.50	€ 25,165.73	€ 8,725.50
District heating network	€ 332,255.06	€ 153,600.00	€ 332,255.06	€ 153,600.00	€ 332,255.06	€ 153,600.00	€ 332,255.06	€ 153,600.00
PV panels	€ 37,752.72	€ 7,888.73	€ 37,752.72	€ 7,888.73	€ 37,752.72	€ 7,888.73	€ 185,859.56	€ 38,836.80
Water heat pump hh	€ 375,274.28	€ 89,600.00	€ 375,274.28	€ 89,600.00	€ 375,274.28	€ 89,600.00	€ 375,274.28	€ 89,600.00
Electricity grid costs	€ 14,729.97	€ -	€ 14,729.97	€ -	€ 14,729.97	€ -	€ 14,729.97	€ -
Elecitricity rate (from grid)	€ 1,757.60	€ -	€ 1,559.60	€ -	€ 1,552.00	€ -	€ 1,126.80	€ -
Tota financial value	**€ 1,743,662.35**		**€ 1,939,769.07**		**€ 2,229,803.62**		**€ 2,635,269.49**	
Financial value per person	**€ 756.80**		**€ 841.91**		**€ 967.80**		**€ 1,143.78**	
Score [-]	**10.0**		**7.8**		**4.5**		**0.0**	

Table 46: Financial value calculations (CAPEX and OM)

Appendix H: Hourly water- and energy balance

Heavy rainfall event: 50 mm of rainfall primarily within 24 hours (22-24 June 2016)

The rainfall event from 22 to 24 June 2016 (Figure 49) had a high intensity with a peak rainfall intensity of >30 mm/hour (at 01:00 on 23 June 2016). This event occurred during the growing season. In this period, the vegetational water demand (at a fixed time from 08:00 to 09:00) was for all scenarios provided with harvested rainwater. For the *hybrid scenario* and *almost decentralized scenario*, (light-)greywater was also recycled and stored in a non-potable water tank together with rainwater. For the *almost decentralized scenario*, all local water sources could cover the overall water demand in this period. For the other scenarios, external (imported) drinking water was still required.

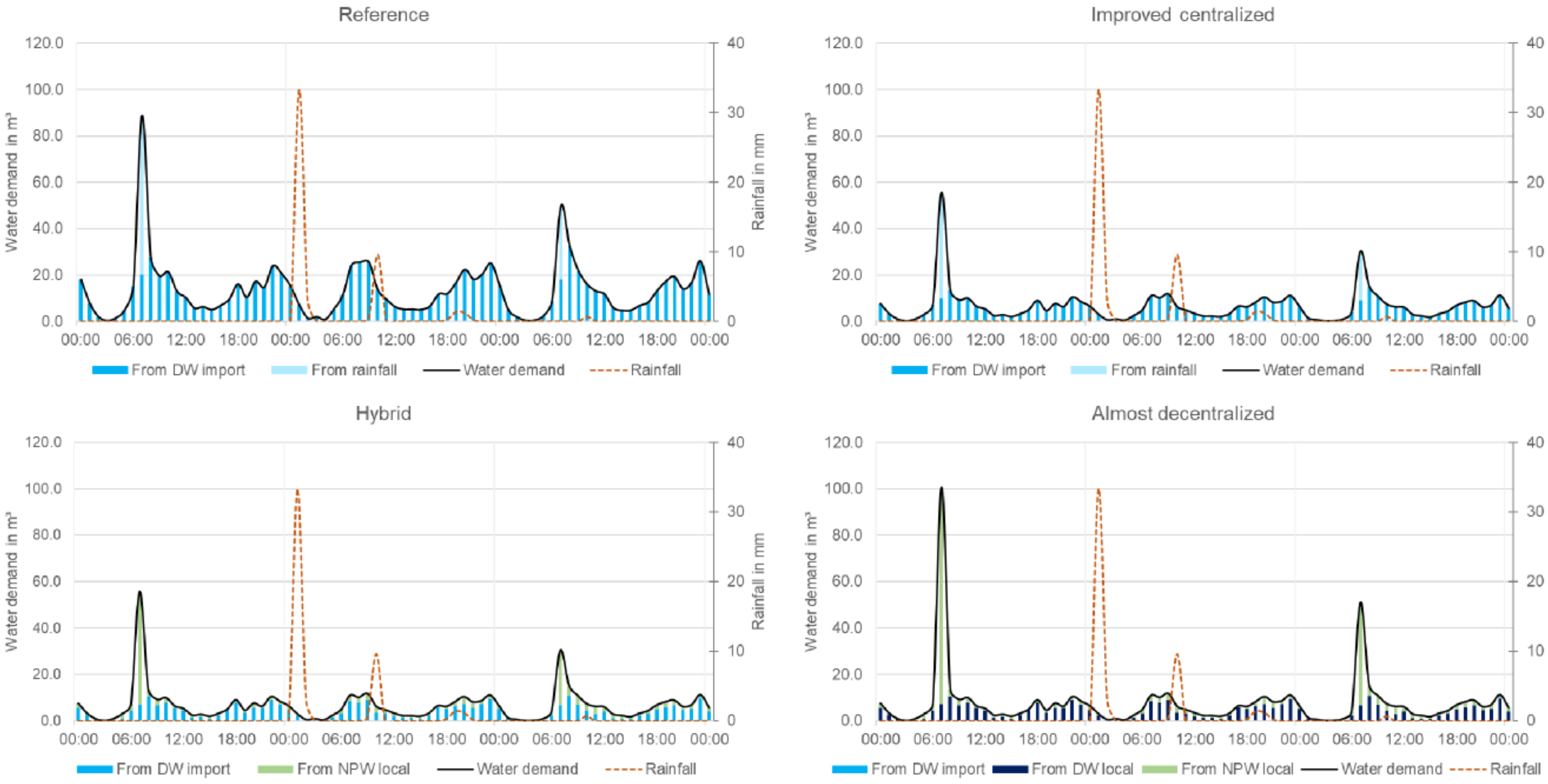


Figure 49: Hourly water balance heavy rainfall event

Heavy rainfall event after dry period: almost 100 mm of rainfall within 48 hours (11-13 July 2011)

The situation from 11 to 13 July 2011 illustrates (Figure 50) the use of harvested rainwater during a dry period (<10 mm of rainfall within two weeks). The results show that all scenarios could cover the vegetational water demand (from 08:00 to 09:00) before a new (peak) rainfall event would occur. However, the *almost decentralized scenario* displays that RHW and GWR couldn't cover the total vegetational- and drinking water demand during a dry period. From the afternoon of 12 July 2011 onward, almost 100 mm of precipitation would fall within 48 hours. Subsequently, it is clearly visible that there is enough water available to for local drinking water production.

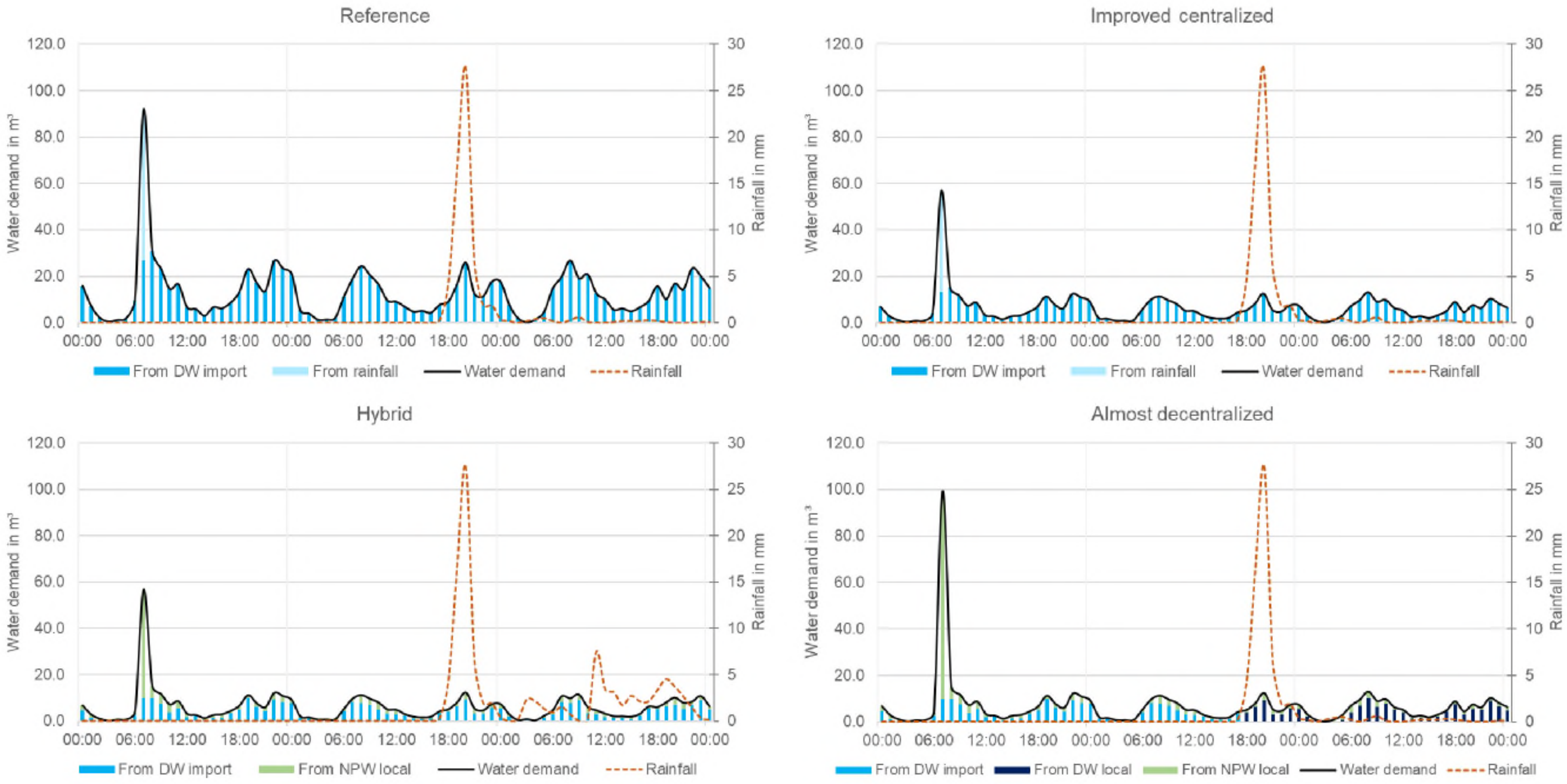


Figure 50: Hourly water balance heavy rainfall after dry period

Dry summer: no rainfall for an extended period (1-3 July 2018)

The summer of 2018 was arid, with only 17 mm of rainfall in the months of June and July and no precipitation from 1 to 3 July 2018 (Figure 51). As a result, most of the water demand is required from imported DW and the vegetational water demand was high (much evapotranspiration). The use of water-saving technologies show a clear reduction in the domestic drinking water demand. For the vegetational water demand (from 08:00 to 09:00), the differences in peaks are related to the total area of green spaces that require water during the growing season. At last, the results show that even during a long period with no rainfall, (light-)greywater recycling could still cover the vegetational- and non-potable water demand.

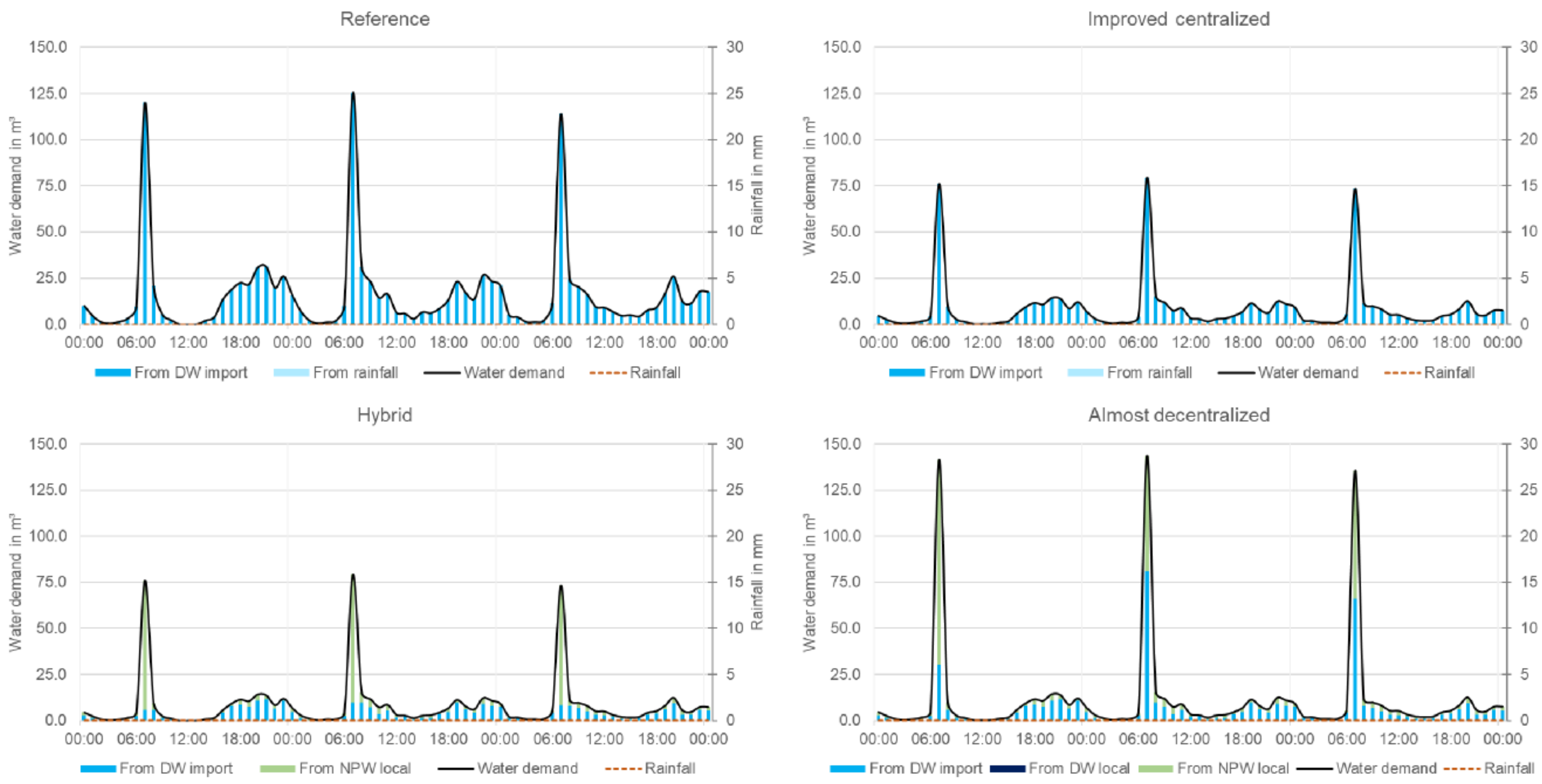


Figure 51: Hourly water balance dry summer

Autumn with little rainfall: no rainfall for an extended period (19-21 November 2011)
The last hourly water balance shows (Figure 52) how the different scenarios perform in during fall with little rainfall (<10 mm within 30 days). Based on the growing, it was assumed that there was no vegetational water demand in this period. As a results, the *reference scenario* and *improved scenario* could not use harvested rainwater outside of the growing season. The *hybrid scenario* could use non-potable water for toilet flushing and the washing machine. The *almost decentralized scenario* produced drinking water locally. The results showed that RWH and GWR couldn’t cover the entire domestic drinking water demand.

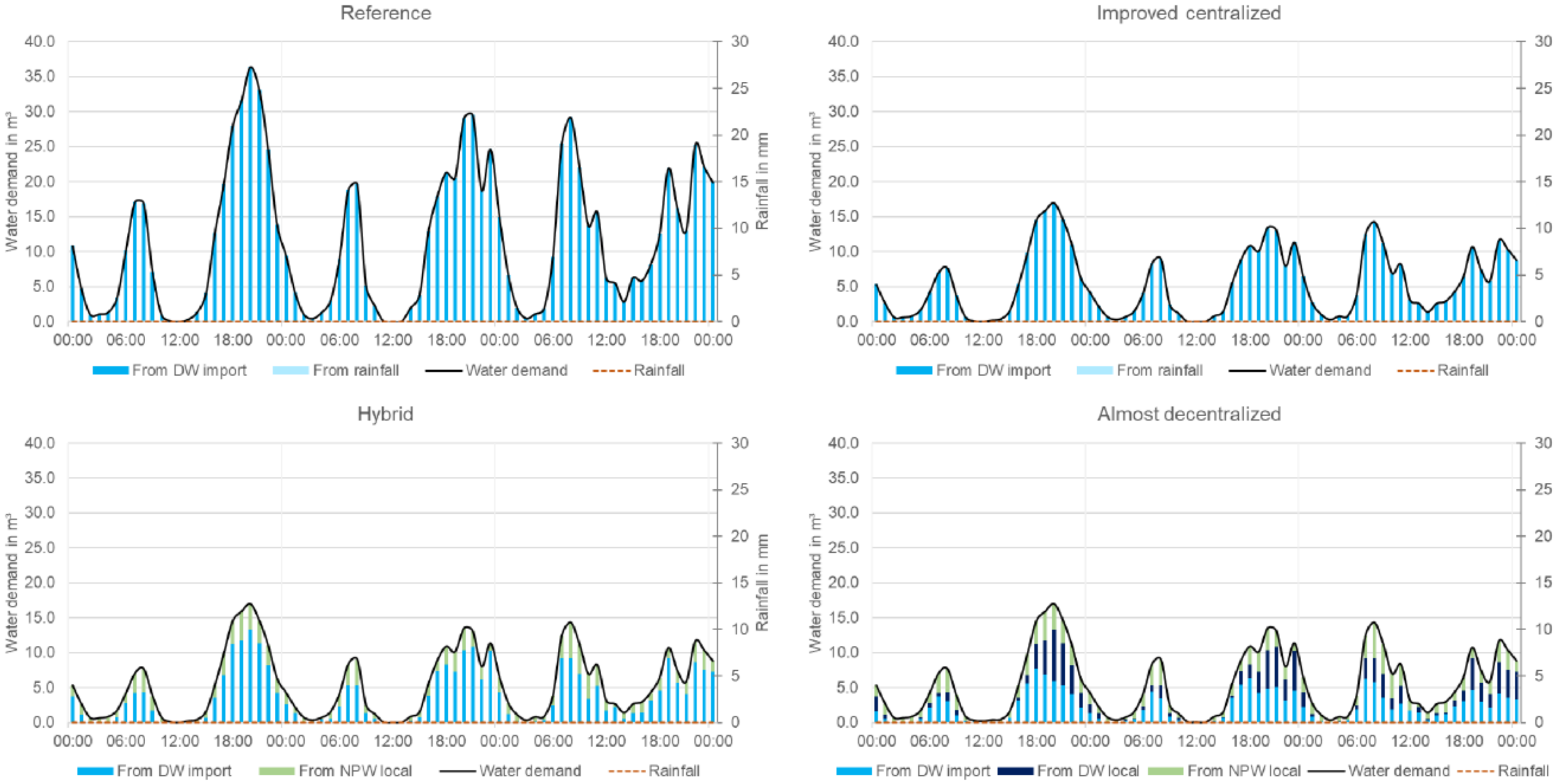


Figure 52: Hourly water balance dry autumn

Cold winter: low temperatures and little solar power (27-29 Decentralized 2014)

The period from 27 to 29 Decentralized 2014 (Figure 53) represents a cold winter with little solar power (cloudy conditions). Because of this conditions, the energy (heating) demand is higher than a 'normal' average day. The *reference*, *improved centralized*, and *hybrid scenarios* show similar patterns in grid import. The *hybrid scenario* doesn't use the collective battery because there is no surplus energy. The *almost decentralized scenario* requires less energy from the grid as the collective batteries could be filled and used with surplus solar power. The results highlight that a collective battery can only be used for a limited period as its capacity is used within a couple of hours. There wasn't any hydrogen available for this scenario, as it was required to meet the hydrogen demand for the FCEVs. Biogas isn't being used as well for this particular case. The use of biogas was for this research specifically modeled to increase self-sufficiency. However, it can also be modeled with a strategy where biogas compensates high demands of imported electricity.

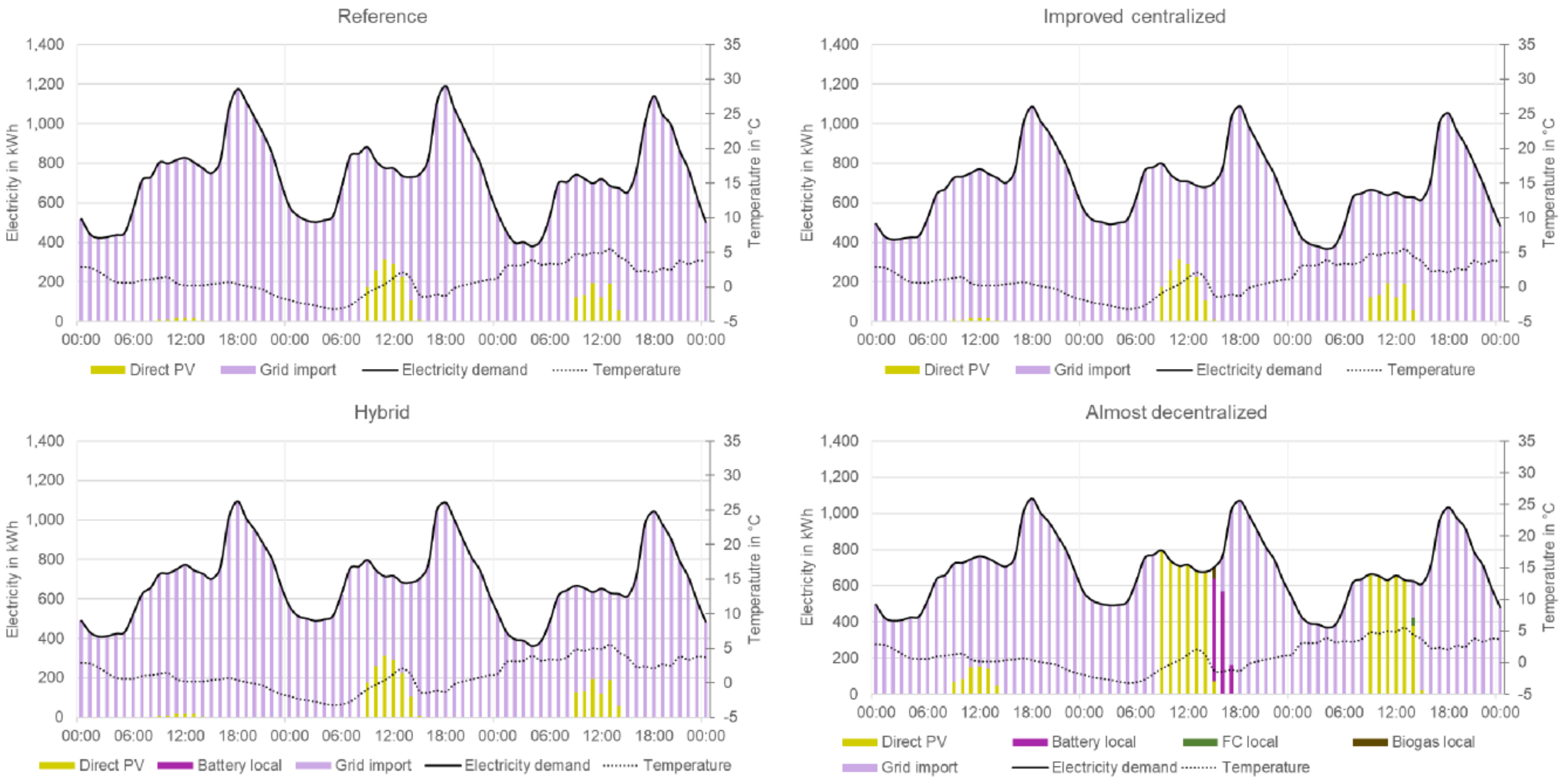


Figure 53: Hourly energy balance cold winter

Warm summer: high temperature and much solar power (7-9 August 2020)

The period from 22 to 24 June 2016 (Figure 54) represents a hot summer, reaching temperatures up to 35 °C. The heating demand is low, resulting in mainly a domestic electricity demand and warm tap water demand. The *reference*, *improved centralized* and *hybrid scenarios* show similar patterns in grid import. The *hybrid scenario* uses surplus which was collected in the collective battery. The contribution of the collective battery for this scenario was low because of the limited availability of surplus energy. The *almost decentralized scenario* requires less energy from the grid because of a higher energy production from PV panels (rooftops and facades) and an additional energy supply from biogas. A part of the energy demand is also covered by hydrogen which was a limited amount for this period because hydrogen should be preserved for the FCEVs. The collective battery isn't used, as most of the surplus energy is goes to the electrolyzer for the production of hydrogen.

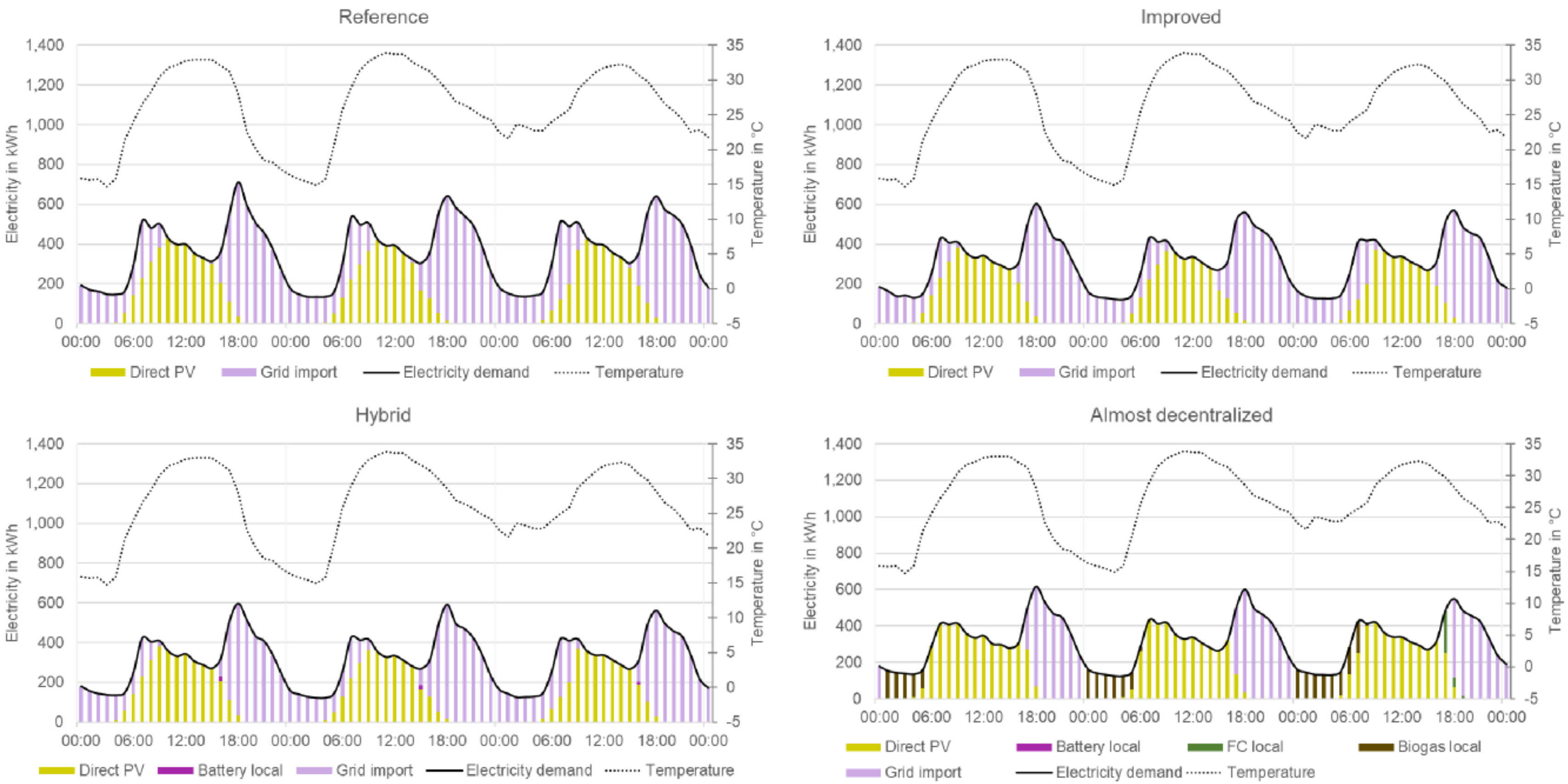


Figure 54: Hourly energy balance warm summer

__High self-sufficiency: much solar power to fulfill much of the total energy demand (17-19 August 2012)__

The days from 17 to 19 August 2012 (Figure 55) represent a situation with high self-sufficiency as there is much solar power and a low energy (heating) demand as this was during summer. The *reference*, *improved centralized*, and *hybrid scenarios* show similar patterns in grid import. The *hybrid scenario* uses the collective battery more often as there is more surplus energy. The *almost decentralized scenario* is almost entirely self-sufficient, as there are only a couple of hours when energy from the grid is required. For this scenario, most of the energy demand is fulfilled by PV production and hydrogen. Additionally, biogas is mainly used in hours with lower energy demand as an alternative for electricity from the grid.

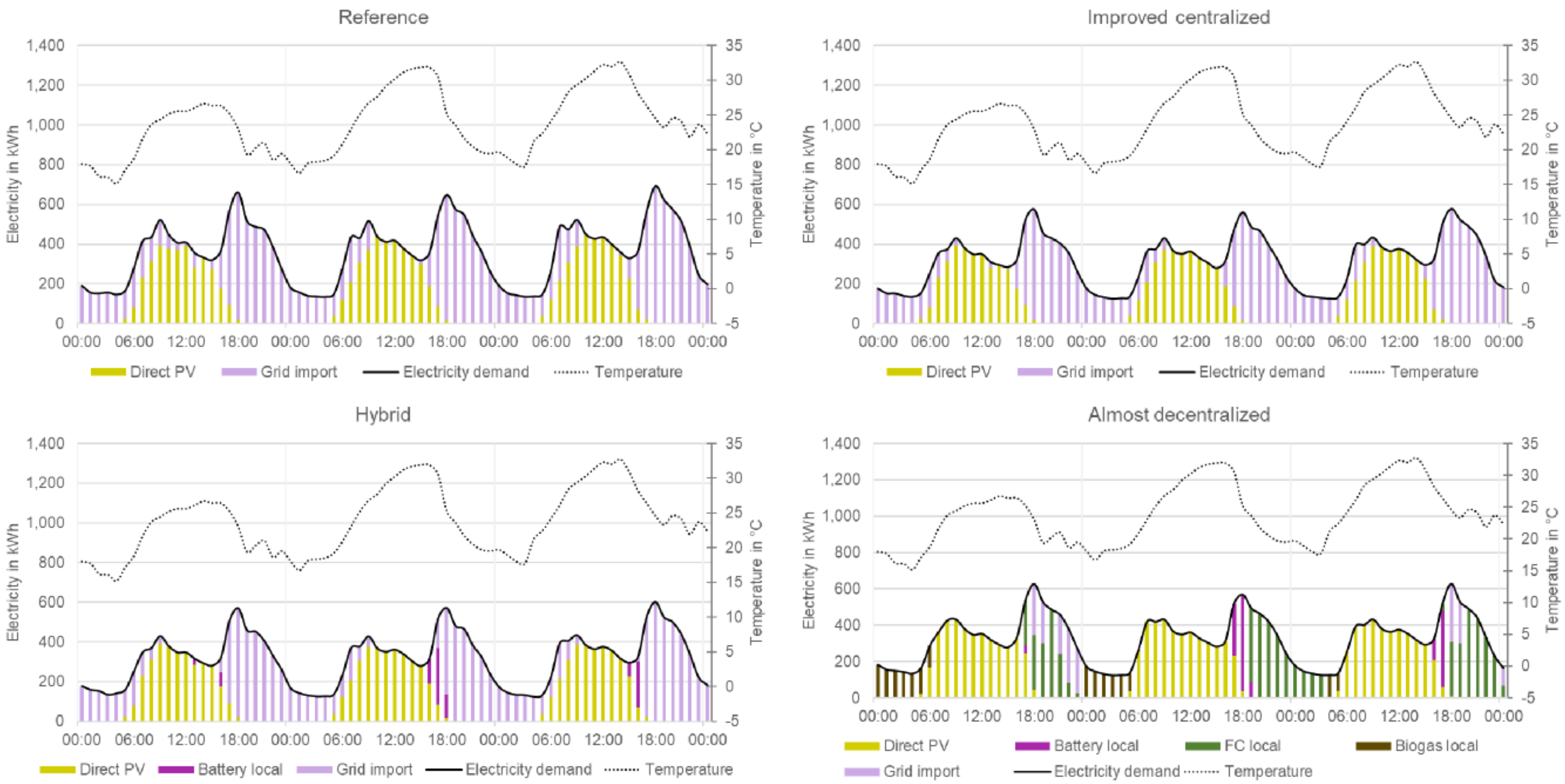


Figure 55: Hourly energy balance high self-sufficiency

Appendix I: Resource recovery calculations

The amount of resources that can be recovered was based on the relative resource recovery in the table below for the four scenarios that were used by Besson et al. (2019) [46]. The results of the mass balance were used to define the distribution of COD, nitrogen- and phosphorus compounds.

Table 47: Relative recovery literature

Relative recovery	Reference	Urine	BW	BW/GW
COD [%]	**100.0**	**100.0**	**100.0**	**100.0**
Struvite	0.7	1.1	1.0	1.1
Biogas	27.5	31.7	46.1	39.4
Sludge	29.1	27.0	27.2	23.2
Gas (atmosphere)	35.0	32.3	22.1	34.0
Effluent	7.7	7.9	3.6	2.3
Nitrogen compounds [%]	**100.0**	**100.0**	**100.0**	**100.0**
Ammonium sulfate	6.3	47.8	54.4	57.3
Struvite	1.1	4.9	5.4	4.9
Sludge	13.9	11.9	13.4	6.4
Gas (atmosphere)	67.4	24.1	16.5	21.1
Effluent	11.3	11.3	10.3	10.3
Phosphorus compounds [%]	**100.0**	**100.0**	**100.0**	**100.0**
Struvite	13.1	58.3	72.8	67.9
Sludge	79.9	34.7	20.8	25.7
Effluent	7.0	7.0	6.4	6.4

The concentration of COD (864 g COD/m^3), nitrogen (155 g N/m^3) and phosphorus (26 g P/m^3) in wastewater was used was used to compute the total amount of resources that could be recovered.

Based on the average wastewater supply (119.3 L/person/day) for without water-energy-saving appliances and the population (2,304 residents) for *City Nieuwegein*, the wastewater flow was set at 100,395 m^3/year (or 275 m^3/day).

The yearly discharge of wastewater was multiplied with the concentrations of the main resources that were investigated. This would give the yearly mass for COD (86.7 tonnes/year), nitrogen 15.6 (tonnes/year) and phosphorus (2.6 tonnes/year). The yearly mass distribution was determined be multiplying the yearly mass of COD, nitrogen and phosphorus with the relative resource recovery for a given compounds. The results of the mass flow compounds are represented in the table below.

The distribution of mass flow compounds were used for the scenarios of *City Nieuwegein*. The *reference scenario* and *improved centralized scenario* used the results of the '*reference scenario*' from the literature. The *hybrid scenario* was based on the average results from the '*reference scenario*', '*Urine scenario*' and '*BW scenario*'. At last, the *almost decentralized scenario* used the results of the '*BW/GW scenario*'

Table 48: Mass flow compounds (literature)

Mass flow compounds	Reference	Urine	BW	BW/GW
Total mass [tonnes/year]	**104.9**	**104.9**	**104.9**	**104.9**
COD [tonnes/year]	**86.7**	**86.7**	**86.7**	**86.7**
Struvite	0.6	1.0	0.9	1.0
Biogas	23.9	27.5	40.0	34.2
Sludge	25.2	23.4	23.6	20.1
Gas (atmosphere)	30.4	28.0	19.2	29.5
Effluent	6.7	6.9	3.1	2.0
Nitrogen compounds [tonnes/year]	**15.6**	**15.6**	**15.6**	**15.6**
Ammonium sulfate	1.0	7.4	8.5	8.9
Struvite	0.2	0.8	0.8	0.8
Sludge	2.2	1.9	2.1	1.0
Gas (atmosphere)	10.5	3.8	2.6	3.3
Effluent	1.8	1.8	1.6	1.6
Phosphorus compounds [tonnes/year]	**2.6**	**2.6**	**2.6**	**2.6**
Struvite	0.3	1.5	1.9	1.8
Sludge	2.1	0.9	0.5	0.7
Effluent	0.2	0.2	0.2	0.2

Appendix J: Scores stakeholder perspectives

The description on how the indicators were prioritized by the stakeholders can be found in the results. In this appendix, an overview is provided of all the points that were given by the stakeholders.

Municipality

Indicator [#]	**Rank [#]**	**Points [-]**	**Relative score (RS_m) [-]**	**Weighting factor [-]**
Drinking water demand	4	15	6.0	0.115
Water recovery	9	7	2.8	0.054
Quality of living environment	3	15	6.0	0.115
Public health	2	15	6.0	0.115
Safety	1	25	10.0	0.192
User comfort	13	2	0.8	0.015
Energy demand	10	2	0.8	0.015
Local renewable energy use	11	2	0.8	0.015
Ecological impact	7	11	4.4	0.085
Financial value	8	11	4.4	0.085
Integrality	6	12	4.8	0.092
Self-sufficiency	12	5	2.0	0.038
Resource recovery	5	8	3.2	0.062
Total	**-**	**130**	**-**	**1.000**

Province

Indicator [#]	**Rank [#]**	**Points [-]**	**Relative score (RS_m) [-]**	**Weighting factor [-]**
Drinking water demand	1	25	10.0	0.192
Water recovery	2	25	10.0	0.192
Quality of living environment	4	10	4.0	0.077
Public health	10	5	2.0	0.038
Safety	11	5	2.0	0.038
User comfort	12	5	2.0	0.038
Energy demand	8	8	3.2	0.062
Local renewable energy use	5	8	3.2	0.062
Ecological impact	3	10	4.0	0.077
Financial value	13	3	1.2	0.023
Integrality	9	8	3.2	0.062
Self-sufficiency	6	10	4.0	0.077
Resource recovery	7	8	3.2	0.062
Total	**-**	**130**	**-**	**1.000**

Drinking water company

Indicator [#]	**Rank [#]**	**Points [-]**	**Relative score (RS_m) [-]**	**Weighting factor [-]**
Drinking water demand	1	25	10.0	0.192
Water recovery	3	20	8.0	0.154
Quality of living environment	11	3	1.2	0.023
Public health	2	25	10.0	0.192
Safety	13	1	0.4	0.0077
User comfort	5	10	4.0	0.077
Energy demand	9	5	2.0	0.038
Local renewable energy use	10	5	2.0	0.038
Ecological impact	6	10	4.0	0.077
Financial value	7	5	2.0	0.038
Integrality	4	15	6.0	0.115
Self-sufficiency	8	5	2.0	0.038
Resource recovery	12	1	0.4	0.008
Total	**-**	**130**	**-**	**1.000**

Water board

Indicator [#]	**Rank [#]**	**Points [-]**	**Relative score (RS_m) [-]**	**Weighting factor [-]**
Drinking water demand	11	6	3	0.046
Water recovery	7	10	5	0.077
Quality of living environment	2	15	7.5	0.115
Public health	1	20	10	0.154
Safety	4	13	6.5	0.100
User comfort	3	14	7	0.108
Energy demand	8	9	4.5	0.069
Local renewable energy use	9	8	4	0.062
Ecological impact	5	12	6	0.092
Financial value	12	2	1	0.015
Integrality	13	2	1	0.015
Self-sufficiency	10	8	4	0.062
Resource recovery	6	11	5.5	0.085
Total	**-**	**130**	**-**	**1.000**

Water research institute

Indicator [#]	Rank [#]	Points [-]	Relative score (RS_m) [-]	Weighting factor [-]
Drinking water demand	5	11	5.2	0.085
Water recovery	6	10	4.8	0.077
Quality of living environment	2	20	9.5	0.154
Public health	1	21	10.0	0.162
Safety	12	4	1.9	0.031
User comfort	3	11	5.2	0.085
Energy demand	7	10	4.8	0.077
Local renewable energy use	8	10	4.8	0.077
Ecological impact	4	11	5.2	0.085
Financial value	10	6	2.9	0.046
Integrality	9	7	3.3	0.054
Self-sufficiency	13	3	1.4	0.023
Resource recovery	11	6	2.9	0.046
Total	**-**	**130**	**-**	**1.000**

Real estate developer

Indicator [#]	Rank [#]	Points [-]	Relative score (RS_m) [-]	Weighting factor [-]
Drinking water demand	9	5	2.5	0.038
Water recovery	11	3	1.5	0.023
Quality of living environment	1	20	10	0.154
Public health	3	15	7.5	0.115
Safety	4	15	7.5	0.115
User comfort	5	13	6.5	0.100
Energy demand	10	5	2.5	0.038
Local renewable energy use	8	8	4	0.062
Ecological impact	7	10	5	0.077
Financial value	2	20	10	0.154
Integrality	6	13	6.5	0.100
Self-sufficiency	13	1	0.5	0.008
Resource recovery	12	2	1	0.015
Total	**-**	**130**	**-**	**1.000**

Appendix K: Overview weighted scores

This appendix will provide an overview of all the weighted indicator scores (z_m) and overall weighted scores (V_s). These outcomes were based on the different stakeholder perspectives.

Municipality

Indicator [#]	Weighting factor [-]	Reference	Improved centralized	Hybrid	Almost decentralized
Drinking water demand	0.115	0.000	0.612	0.773	0.969
Water recovery	0.054	0.104	0.178	0.215	0.323
Quality of living environment	0.115	0.129	0.254	0.254	0.323
Public health	0.115	1.154	1.038	0.923	0.692
Safety	0.192	0.079	0.115	0.115	1.750
User comfort	0.015	0.092	0.108	0.097	0.080
Energy demand	0.015	0.085	0.092	0.092	0.112
Local renewable energy use	0.015	0.012	0.012	0.012	0.043
Ecological impact	0.085	0.462	0.508	0.508	0.592
Financial value	0.085	0.846	0.660	0.381	0.000
Integrality	0.092	0.526	0.646	0.711	0.858
Self-sufficiency	0.038	0.008	0.012	0.015	0.142
Resource recovery	0.062	0.152	0.154	0.228	0.271
Weighted score (V_s)		**3.7**	**4.4**	**4.3**	**6.2**
Relative increase/decrease (γ)		**-4.4%**	**-1.3%**	**-1.2%**	**+11.2%**

Province

Indicator [#]	Weighting factor [-]	Reference	Improved centralized	Hybrid	Almost decentralized
Drinking water demand	0.192	0.000	1.019	1.288	1.615
Water recovery	0.192	0.373	0.635	0.769	1.154
Quality of living environment	0.077	0.086	0.169	0.169	0.215
Public health	0.038	0.385	0.346	0.308	0.231
Safety	0.038	0.016	0.023	0.023	0.350
User comfort	0.038	0.231	0.269	0.242	0.200
Energy demand	0.062	0.341	0.369	0.369	0.449
Local renewable energy use	0.062	0.049	0.049	0.049	0.172
Ecological impact	0.077	0.420	0.462	0.462	0.538
Financial value	0.023	0.231	0.180	0.104	0.000
Integrality	0.062	0.351	0.431	0.474	0.572
Self-sufficiency	0.077	0.015	0.023	0.031	0.285
Resource recovery	0.062	0.152	0.154	0.228	0.271
Weighted score (V_s)		**2.7**	**4.1**	**4.5**	**6.1**
Relative increase/decrease (γ)		**-30.6%**	**-7.1%**	**+3.2%**	**+9.3%**

Drinking water company

Indicator [#]	Weighting factor [-]	Reference	Improved centralized	Hybrid	Almost decentralized
Drinking water demand	0.192	0.000	1.019	1.288	1.615
Water recovery	0.154	0.298	0.508	0.615	0.923
Quality of living environment	0.023	0.026	0.051	0.051	0.065
Public health	0.192	1.923	1.731	1.538	1.154
Safety	0.008	0.003	0.005	0.005	0.070
User comfort	0.077	0.462	0.538	0.485	0.400
Energy demand	0.038	0.213	0.231	0.231	0.281
Local renewable energy use	0.038	0.031	0.031	0.031	0.108
Ecological impact	0.077	0.420	0.462	0.462	0.538
Financial value	0.038	0.385	0.300	0.173	0.000
Integrality	0.115	0.658	0.808	0.888	1.073
Self-sufficiency	0.038	0.008	0.012	0.015	0.142
Resource recovery	0.008	0.019	0.019	0.028	0.034
Weighted score (V_s)		**4.4**	**5.7**	**5.8**	**6.4**
Relative increase/decrease (γ)		**+16.4%**	**+28.5%**	**+32.8%**	**+15.6%**

Water board

Indicator [#]	Weighting factor [-]	Reference	Improved centralized	Hybrid	Almost decentralized
Drinking water demand	0.046	0.000	0.245	0.309	0.388
Water recovery	0.077	0.149	0.254	0.308	0.462
Quality of living environment	0.115	0.129	0.254	0.254	0.323
Public health	0.154	1.538	1.385	1.231	0.923
Safety	0.100	0.041	0.060	0.060	0.910
User comfort	0.108	0.646	0.754	0.678	0.560
Energy demand	0.069	0.384	0.415	0.415	0.505
Local renewable energy use	0.062	0.049	0.049	0.049	0.172
Ecological impact	0.092	0.504	0.554	0.554	0.646
Financial value	0.015	0.154	0.120	0.069	0.000
Integrality	0.015	0.088	0.108	0.118	0.143
Self-sufficiency	0.062	0.012	0.018	0.025	0.228
Resource recovery	0.085	0.209	0.212	0.313	0.372
Weighted score (V_s)		**3.9**	**4.4**	**4.4**	**5.6**
Relative increase/decrease (γ)		**+2.2%**	**-0.4%**	**+0.2%**	**+1.7%**

Water research institute

Indicator [#]	**Weighting factor [-]**	**Reference**	**Improved centralized**	**Hybrid**	**Almost decentralized**
Drinking water demand	0.085	0.000	0.448	0.567	0.711
Water recovery	0.077	0.149	0.254	0.308	0.462
Quality of living environment	0.154	0.172	0.338	0.338	0.431
Public health	0.162	1.615	1.454	1.292	0.969
Safety	0.031	0.013	0.018	0.018	0.280
User comfort	0.085	0.508	0.592	0.533	0.440
Energy demand	0.077	0.427	0.462	0.462	0.562
Local renewable energy use	0,077	0,062	0,062	0,062	0,215
Ecological impact	0.085	0.462	0.508	0.508	0.592
Financial value	0.046	0.462	0.360	0.208	0.000
Integrality	0.054	0.307	0.377	0.415	0.501
Self-sufficiency	0.023	0.005	0.007	0.009	0.085
Resource recovery	0.046	0.114	0.115	0.171	0.203
Weighted score (V_s)		**4.3**	**5.0**	**4.9**	**5.5**
Relative increase/decrease (γ)		**+12.5%**	**+12.4%**	**+11.7%**	**-1.6%**

Real estate developer

Indicator [#]	**Weighting factor [-]**	**Reference**	**Improved centralized**	**Hybrid**	**Almost decentralized**
Drinking water demand	0.038	0.000	0.204	0.258	0.323
Water recovery	0.023	0.045	0.076	0.092	0.138
Quality of living environment	0.154	0.172	0.338	0.338	0.431
Public health	0.115	1.154	1.038	0.923	0.692
Safety	0.115	0.047	0.069	0.069	1.050
User comfort	0.100	0.600	0.700	0.630	0.520
Energy demand	0.038	0.213	0.231	0.231	0.281
Local renewable energy use	0.062	0.049	0.049	0.049	0.172
Ecological impact	0.077	0.420	0.462	0.462	0.538
Financial value	0.154	1.538	1.200	0.692	0.000
Integrality	0.100	0.570	0.700	0.770	0.930
Self-sufficiency	0.008	0.002	0.002	0.003	0.028
Resource recovery	0.015	0.038	0.038	0.057	0.068
Weighted score (V_s)		**4.8**	**5.1**	**4.6**	**5.2**
Relative increase/decrease (γ)		**+27.0%**	**+14.9%**	**+4.5%**	**-6.6%**

Appendix K: Normalized scores and weighted scores visualized

<u>Stakeholder 2: Province</u>

Indicators with the highest prioritization for the province were *reduced external drinking water demand* and *water recovery*. This resulted in a lower weighted scores (Figure 56) for the *reference scenario* (-30.6%) and *improved centralized scenario* (-7.1%) that didn't have high outcomes for these indicators. The weighted score for the *almost decentralized scenario* (+9.3%) was therefore the highest followed by the *hybrid scenario* (+3.2%).

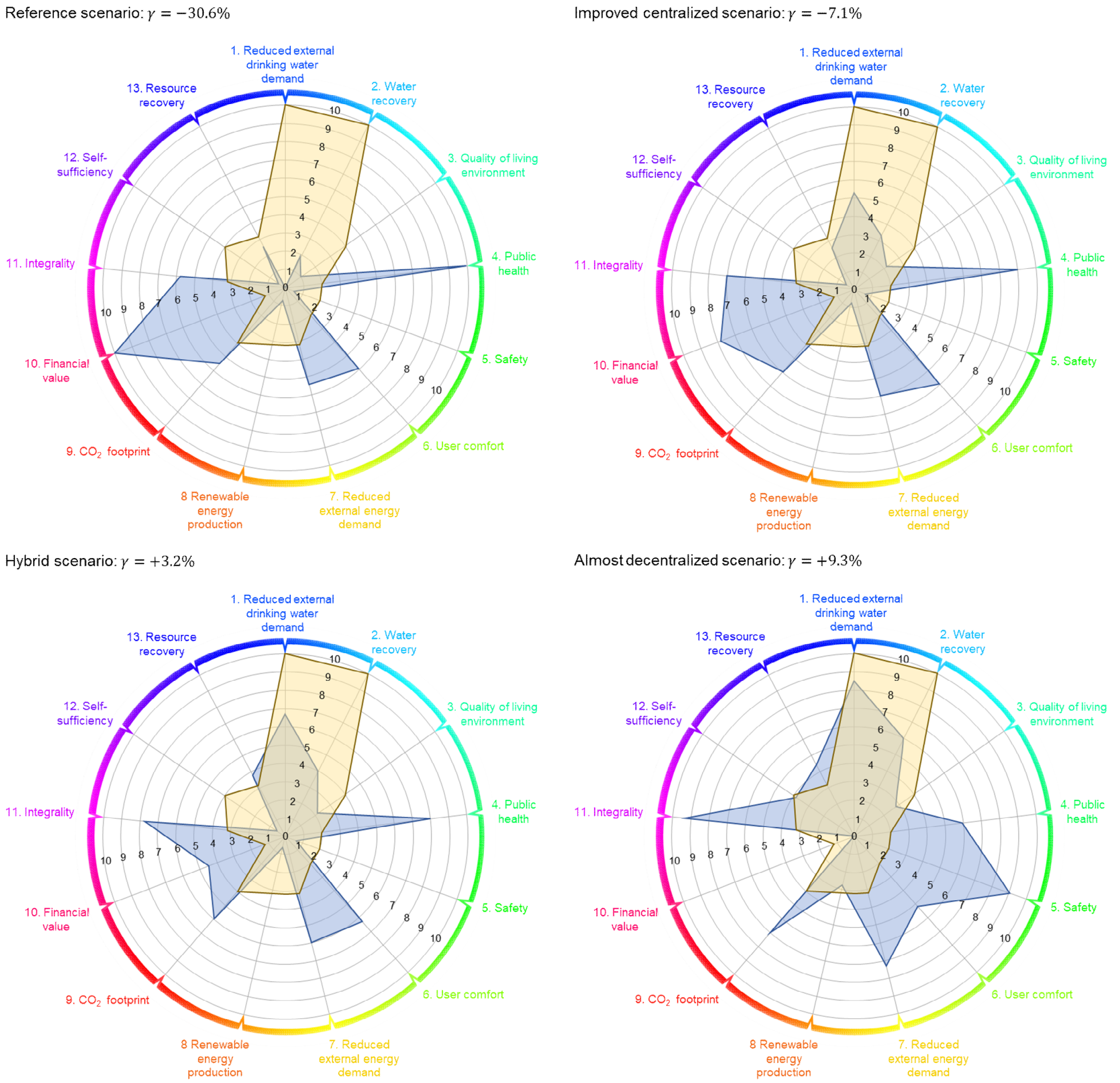


Figure 56: Visual overview weighted scores province

Stakeholder 3: Drinking water company

The most important indicators (*reduced external drinking water demand* and *public health*) resulted in higher weighted indicator scores (Figure 57) for all scenarios. Scenarios with relative high scores for both of these indicators had a positive impact on the outcomes of the weighted score. The highest increase of the weighted score was found for the *improved centralized scenario* (+22.2%). and *hybrid scenario* (+26.2%). The weighted scores for the *reference scenario* (+10.7%) and *almost decentralized scenario* (12.1%) were also higher compared to the normalized score.

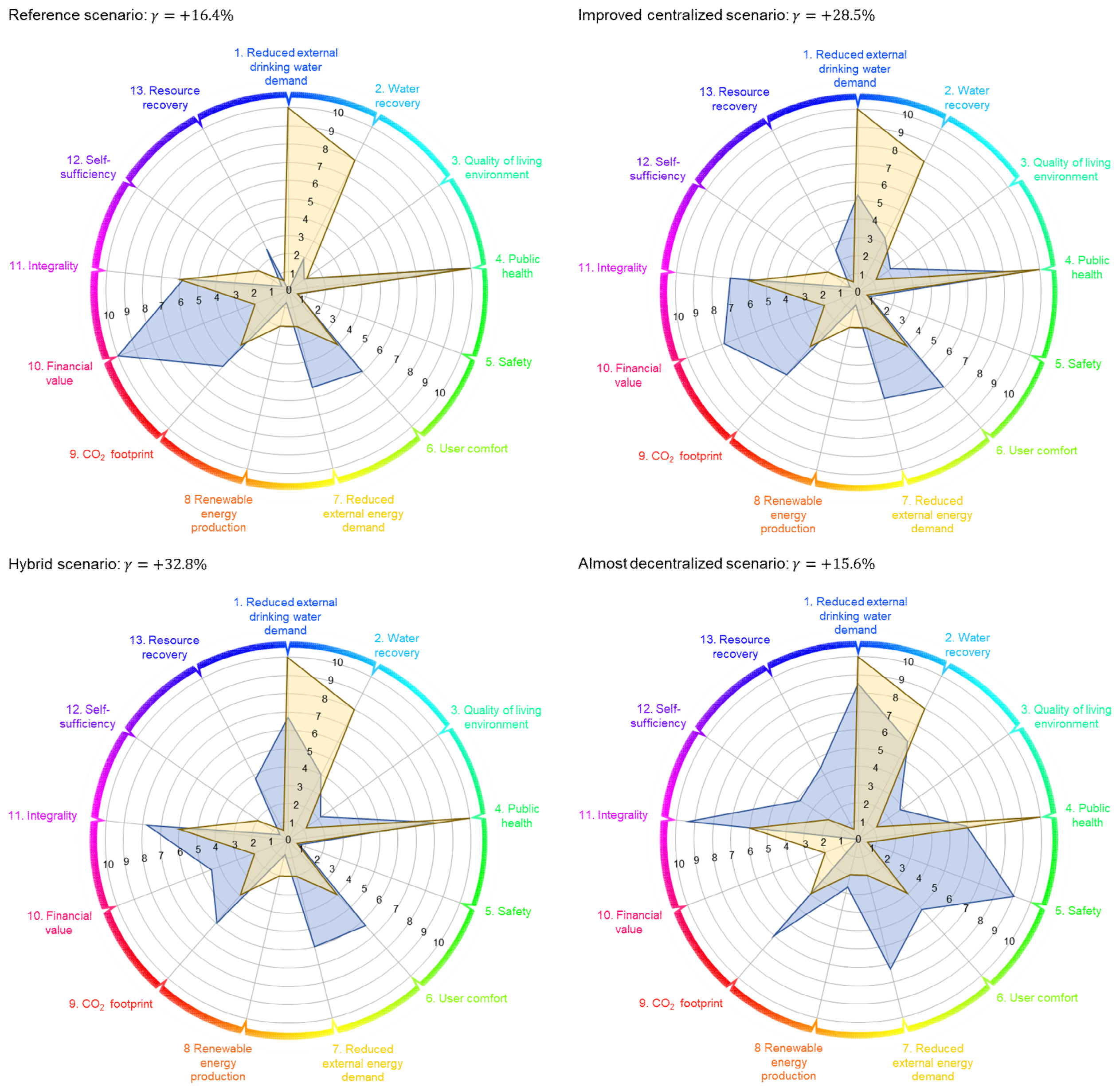


Figure 57: Visual overview weighted scores drinking water company

Stakeholder 4: Water board

When looking at the perspectives of the water board, the difference between weighted and normalized scores (Figure 58) were relatively low varying between -0.4% and +2.2%. For this stakeholder, *public health* was the primary indicator. Indicators with moderate prioritization (*water recovery*, *quality of living environment*, *user comfort*, *CO_2 footprint* and *resource recovery*) had fluctuating outcomes for the different scenarios. For instance, the *almost decentralized scenario* had high indicator scores for *water recovery* and *CO_2 footprint*, but low outcomes for *public health* and *user comfort*.

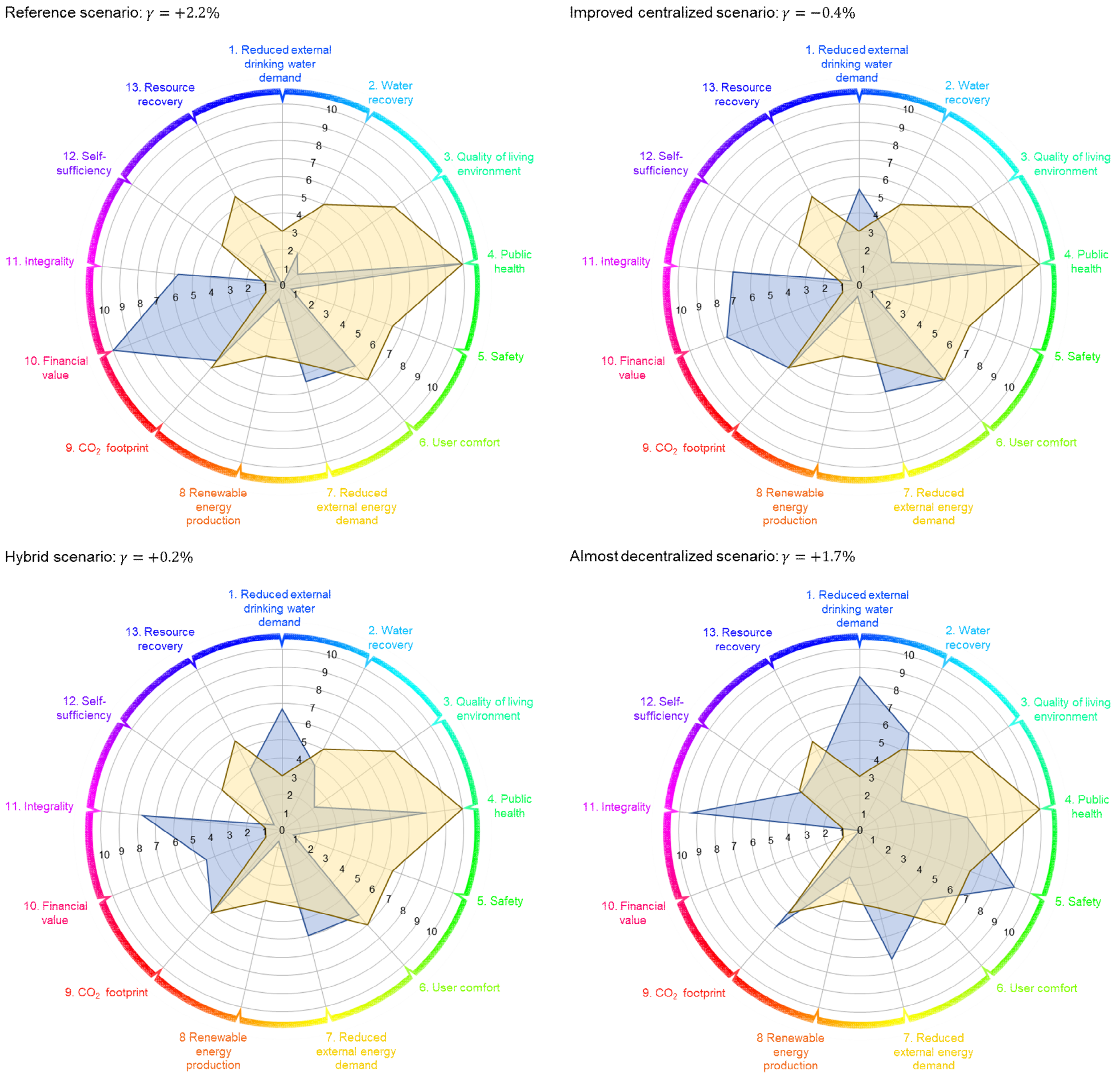


Figure 58: Visual overview weighted scores water board

Stakeholder 5: Water research institute

Based on the perspective of a water research institute, scenarios with a high indicator score on *public health* had higher weighted scores (Figure 59). This was the case for the *reference scenario*, *improved centralized scenario* and *hybrid scenarios* with higher weighted scores between +11.7% and +12.7%. The weighted score for the *almost decentralized scenario* was lower (-1.6%) than the normalized score. This was because of relative low indicator scores for *quality of living environment*, *public health* and *financial value*.

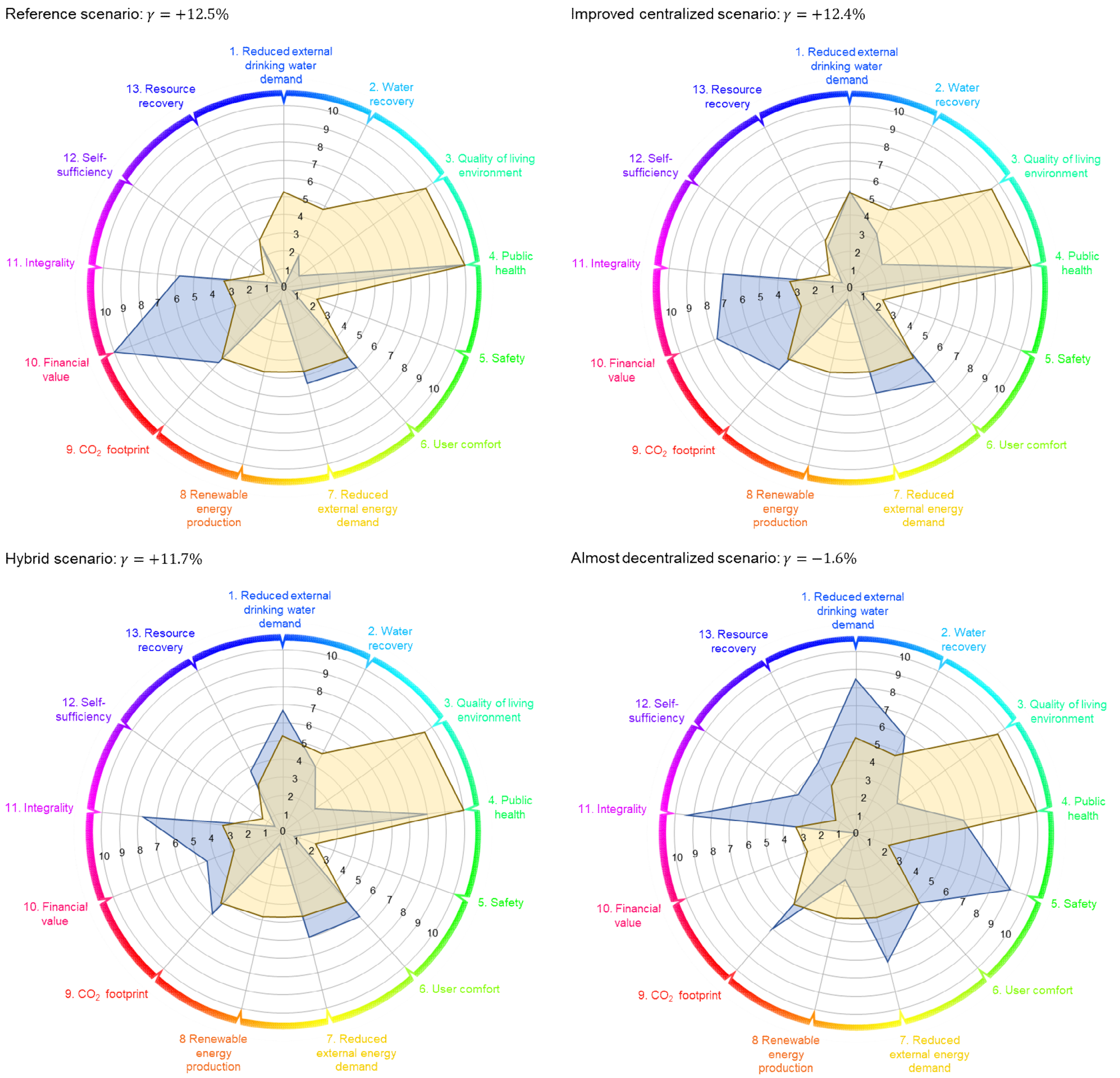


Figure 59: Visual overview weighted scores water research institute

Stakeholder 6: Real estate developer

High variations in weighted scores (Figure 60) can be seen for the perspective of a real estate developer. Because *quality of living environment* and *financial value* were given the highest prioritization, scenarios that scored high for either one or both of these indicators had a high weighted score. This was the case for the *reference scenario* (+27.0%) and *improved centralized scenario* (+14.9%). The for *hybrid scenario* (+4.5%) and *almost decentralized scenario* (-6.6%), the weighted scores were somewhat higher or notably lower as the indicators didn't match the prioritized indicators.

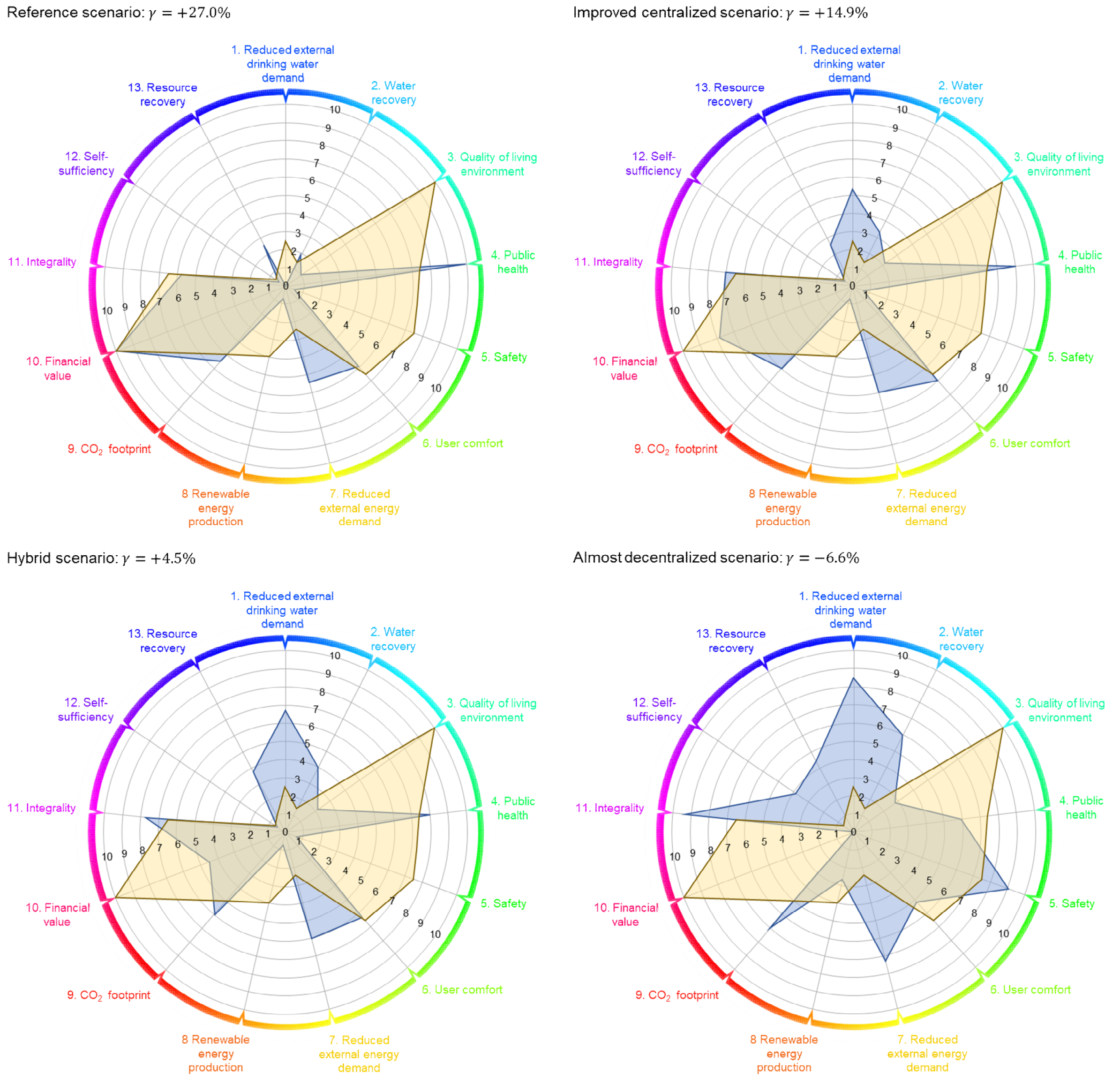


Figure 60: Visual overview weighted scores real estate developer