Chapter 15
Smarthoods: Aquaponics Integrated Microgrids

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Abstract With the pressure to transition towards a fully renewable energy system increasing, a new type of power system architecture is emerging: the microgrid. A microgrid integrates a multitude of decentralised renewable energy technologies using smart energy management systems, in order to efficiently balance the local production and consumption of renewable energy, resulting in a high degree of flexibility and resilience. Generally, the performance of a microgrid increases with the number of technologies present, although it remains difficult to create a fully autonomous microgrid within economic reason (de Graaf F, New strategies for smart integrated decentralised energy systems, 2018). In order to improve the self-sufficiency and flexibility of these microgrids, this research proposes integrating a neighbourhood microgrid with an urban agriculture facility that houses a decoupled multi-loop aquaponics facility. This new concept is called *Smarthood*, where all Food–Water–Energy flows are circularly connected. In doing so, the performance of the microgrid greatly improves, due to the high flexibility present within the thermal mass, pumps and lighting systems. As a result, it is possible to achieve 95.38% power and 100% heat self-sufficiency. This result is promising, as it could pave the way towards realising these fully circular, decentralised Food–Water–Energy systems.

Keywords Smart grids · Urban agriculture · Microgrids · Blockchains · Self-sufficiency · Energy system modelling

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15.1   Introduction

Switching towards a fully sustainable energy system will partly require switching from a centralised generation and distribution system, towards a decentralised system, due to the rise of decentralised energy generation technologies using wind and rooftop solar radiation. In addition, integrating the heat and transport sectors into the electricity system will lead to a very significant increase in peak demand. These developments require massive and costly adaptations to the energy infrastructure, while the utilisation of existing production assets is expected to drop from 55% to 35% by 2035 (Strbac et al. 2015). This poses a major challenge, but also an opportunity: if the energy flows can be balanced locally in *microgrids*, the demand for expensive infrastructure upgrade can be minimised, while providing extra stability to the main grid. For these reasons, 'microgrids have been identified as a key component of the Smart Grid for improving power reliability and quality, increasing system energy efficiency' (Strbac et al. 2015).

Microgrids can provide much-needed resilience and flexibility, and are therefore likely to play an important role in the energy system of the future. It is estimated that by 2050, over half of EU households will be generating their own electricity (Pudjianto et al. 2007). Unlocking flexible resources within microgrids is therefore needed in order to balance the intermittent renewable energy generation.

Urban agriculture systems, such as aquaponics (dos Santos 2016), can provide this much-needed energy flexibility (Goddek and Körner 2019; Yogev et al. 2016). Plants can grow within a wide range of external conditions, since they are used to doing so in nature. The same applies to fish in an aquaculture system, which can thrive in a broad temperature range. These flexible operating conditions allow for a buffering effect on energy input requirements, which create a large degree of flexibility within the system. The high thermal mass embodied by the aquaculture system allows for vast amounts of heat to be stored within the system. The lights can be turned on and off depending on the abundance of electricity, allowing for excess electricity generation to essentially be curtailed by turning it into valuable biomass. Pumps can be operated in synchronicity with peak power generation times (e.g. noon) to limit net peak power (peak shaving). Optimal distillation units (Chap. 8) also have a very flexible heat demand and can be turned off as soon as there is an oversupply of heat or electricity (i.e. the heat pump would then convert electric energy into thermal energy). All these aspects make aquaponic systems well-suited to provide flexibility to a microgrid.

Next to providing flexibility in consumption, a multi-loop aquaponics system can be further integrated to also provide flexibility in production. Biogas is produced as a byproduct from the UASB in the aquaponic facility. This biogas can be combusted in order to produce both heat and power, by incorporating a micro-CHP in the microgrid. Integrating aquaponic systems within microgrids can therefore enhance energy flexibility both on the demand and supply sides.

15.2 The Smarthoods Concept

To unlock the full potential of the Food–Water–Energy nexus with respect to decentralised microgrids, a fully integrated approach focuses not only on energy (microgrid) and food (aquaponics) but also on utilising the local water cycle. The integration of various water systems (such as rainwater collection, storage and wastewater treatment) within aquaponic-integrated microgrids yields the biggest potential for efficiency, resilience and circularity. The concept of a fully integrated and decentralised Food–Water–Energy microgrid will from now on be referred to as a *Smarthood* (smart neighbourhood) and is depicted in Fig. 15.2.

The benefit of implementing aquaponics into the Smarthoods concept is its potential to contribute to optimise integrated nutrient, energy and water flows (Fig. 15.1). This integration potential goes well beyond the already-mentioned

The Food–Water–Energy Nexus

30% of global energy demand is used for agriculture
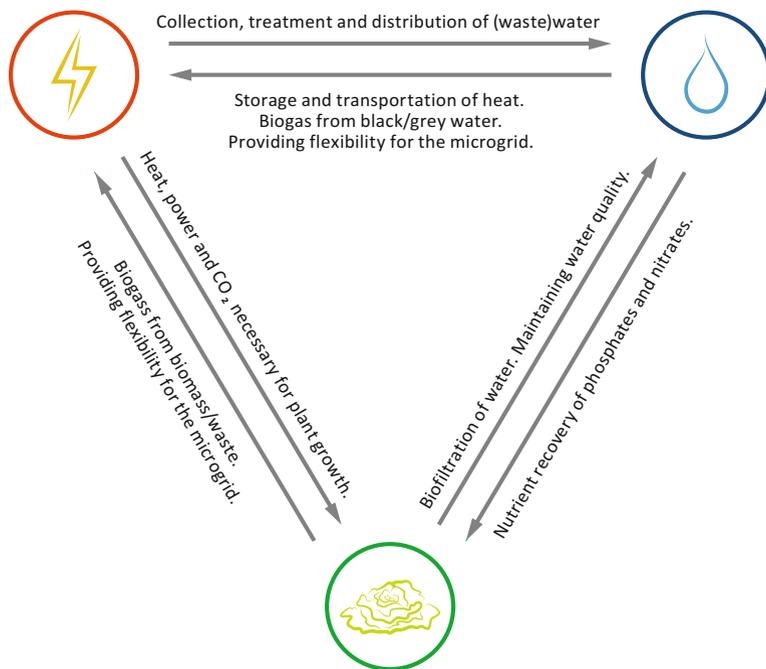70% of global freshwater demand is used for agriculture

Fig. 15.1 The Food–Water–Energy nexus shows the interplay between energy, water and food production (based on IRENA 2015)
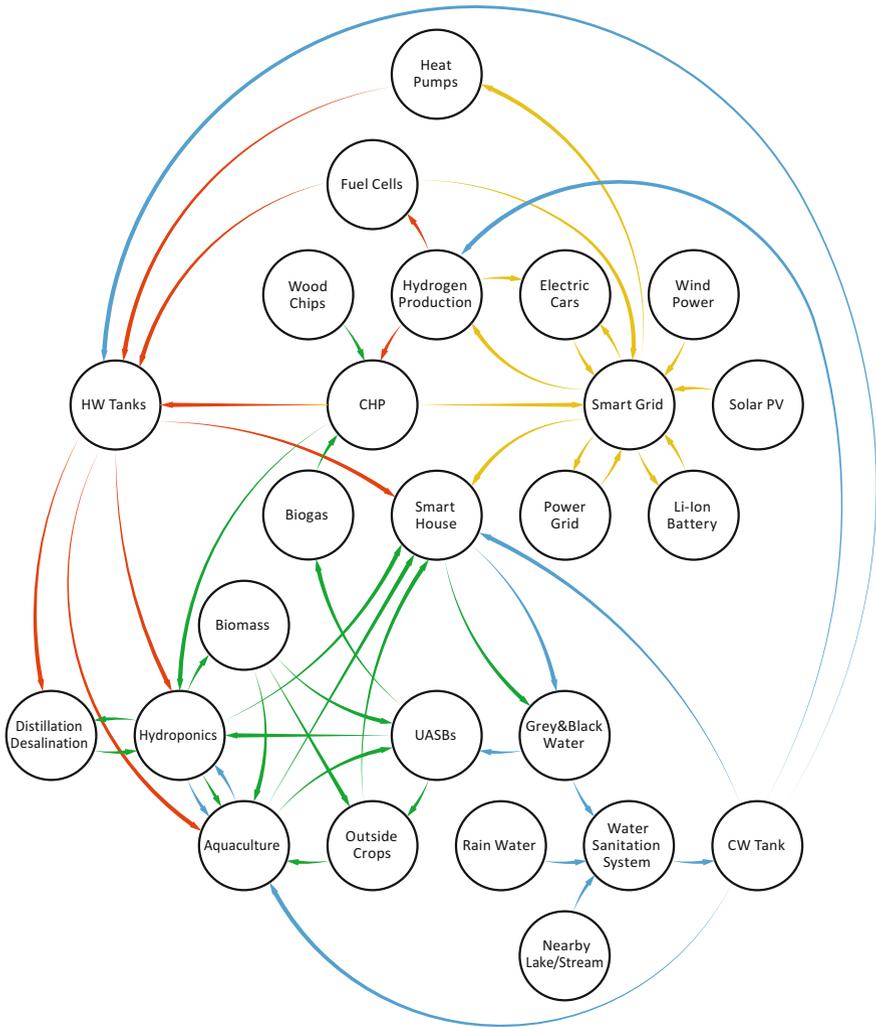
Decoupled Aquaponics Systems in a Smarthood

Fig. 15.2 The integration of decoupled aquaponics systems (as described in Chap. 8) in a decentralised local environment as designed for the Smarthoods concept. The green arrows show to what extent an aquaponics system can interact with the overall system. The red arrows represent heat flows, the blue arrows water flows and the yellow arrows power flows

crossovers between the energy and food systems. For instance, occurring biodegradable waste streams can be treated in anaerobic reactors (e.g. UASBs) and generate both biogas and bio-fertiliser (Goddek et al. 2018). Even the demineralized waste sludge can be utilised as liquid manure on conventional cropland.

Fig. 15.3 Illustrated photo of *De Ceuvel* (source: Metabolic – www.metabolic.nl)

Example 15.1

An early example of an urban integrated aquaponic microgrid development is *De Ceuvel*, a previously abandoned shipyard in Amsterdam-North that has been converted into a self-sufficient office space and recreational hub. *De Ceuvel* serves as a testbed for new technologies and policies aimed at creating a circular economy. It features an all-electric microgrid including solar PV, heat pumps and peer-to-peer energy trading over the blockchain using their own energy token: the *Jouliette*.[1] A small aquaponic facility produces herbs and vegetables for the on-site restaurant. The same restaurant utilises biogas extracted from locally produced organic waste for their cooking activities as well as space heating. In addition, there is a lab present that is used for testing the water quality and extracting phosphates and nitrates.

Although *De Ceuvel* is currently not actively using the aquaponics facility to increase the flexibility of its microgrid, sensors are being installed to monitor the energy and nutrient flows in order to assess its performance. This data will be used to aid in the development of newer and smarter urban integrated aquaponics microgrids, such as the Smarthoods concept proposed in this chapter. Early use cases found in urban living labs like De Ceuvel are essential to the successful development of the Smarthoods concept (Fig. 15.3).

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[1]https://www.jouliette.net

Although a holistic approach to urban FWE systems such as the *Smarthoods* concepts yields many benefits, the integration of aquaponics systems within microgrids remains very case-dependent. Aquaponic food production systems are characterised by a higher yield and a lower water, nutrient and energy footprint than conventional agricultural systems; however, they are also more costly to build. They are therefore best suited in locations that require high yields due to, for instance, space limitations. In dense urban areas, there may not always be sufficient space to build an aquaponics facility, whereas for rural areas the cost of land may be too low to warrant building a state-of-the-art aquaponics facility; a standard agricultural facility with lower financing costs and yield will be more suited in such cases. The most optimal use case for an integrated aquaponic facility is one where sufficient space is available, and a high yield per area is required to offset the cost of land use. Suburban neighbourhoods and other urban areas (e.g. an abandoned warehouse) are therefore most likely to see the first implementation of microgrids integrated with an aquaponic facility (see Example 15.1).

15.3 Goal

The goal of this research is to quantify the degree of self-sufficiency and flexibility for a microgrid integrated with a decoupled multi-loop aquaponics system.

15.4 Method

A neighbourhood of 50 households was assumed a 'Smarthood', with a decoupled multi-loop aquaponics facility present that is capable of providing fish and vegetables for all the 100 inhabitants of the Smarthood.

For the detailed modelling of the Smarthood, a hypothetical reference case of a suburban neighbourhood in Amsterdam was used, consisting of 50 households (houses) with an average household occupancy of 2 persons per household (100 persons total). In addition, one urban aquaponic facility consists of a greenhouse, aquaculture system, a UASB and a distillation unit. The dimensioning of the different components is motivated using data for a typical Dutch household and greenhouse (see Table 15.1).

15.4.1 The Energy System Model

An Energy System Model (ESM) was made that can simulate the energy flows of a wide range of components, whose main specifications are shown in Table 15.2. The ESM is capable of calculating energy flows for each component for each hour of the year.

Table 15.1 Food and energy requirements per persona/household in the Netherlands

	Average (per capita/year)	Total (100 persons)	Source
Food			
Vegetable consumption (the Netherlands)	33 kg[a] (whereas 73 kg are recommended)	7300 kg	EFSA (2018)
Required greenhouse area	Approx. 4 m^2	400 m^2	Estimated based on min. consumption recommendation
Fish consumption	20 kg	2000 kg	FAO (2015)
Required aquaculture volume[b]	0.2 m^3	20 m^3	Estimated
Energy			
Household electricity consumption (Netherlands)	3000 kWh$_e$/house/year	150 MWh$_e$/year	CBS (2018)
Household heat consumption (Netherlands)	6500 kWh$_{th}$/house/year	325 MWh$_{th}$/year	CBS (2018)
RAS electricity consumption	0.05–0.15 kW$_e$/m^3	1–3 kW$_e$ 8,76–28,26 MWh$_e$/year	(Espinal, pers. communication)

[a]The average Dutch person eats 50 kg of vegetables per year. However, only 33 kg of vegetables that can be grown in hydroponics systems, which are fruiting vegetables 31.87 g/day, brassica vegetables 22.11 g/day, leaf vegetables 12.57 g/day, legume vegetables 19.74 g/day, stem vegetables 4.29 g/day
[b]Considering a max. fish density of 80 kg/m^3

Table 15.2 Production components

Component	Size	Specifications
Solar PV	40 kW$_{p,e}$	Eta: 0.15
Urban wind turbine	20 kW$_{p,e}$	Eta: 0.33
Heat pump	10 kW$_{p,e}$	COP: 4.0
CHP	20 kW$_{p,e}$	Eta$_{el}$: 0.24, Eta$_{th}$ = 0.61
Fuel cell	10 kW$_{p,e}$	Eta: 0.55
Electrolyser	20 kW$_{p,e}$	Eta: 0.45
Battery	200 kWh	Eta: 0.90
Hot water tank	930 kWh	40–60°C
Hydrogen tank	1000 kWh	30 kg of H$_2$ storage

The energy system was modelled in MATLAB using energy profile data for Amsterdam obtained through DesignBuilder. The numerical time-series model incorporates a wide selection of energy technologies, listed in Table 15.2 with their relevant specifications (Fig. 15.4).

The Energy System Model (ESM) uses simple conditional statements for the decision-making process, i.e. it is a rule-based control system. In the current version of this model, the control is centralised, with the objective of self-consumption
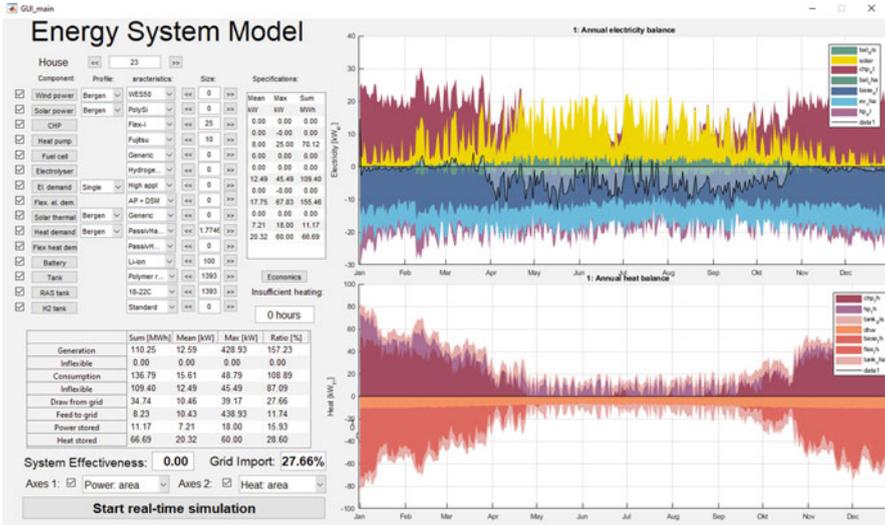
Fig. 15.4 The aquaponics microgrid model (F. de Graaf 2018), showing the energy balances for power (upper diagram) and heat (lower diagram) for the reference case (Amsterdam)

maximisation for the system as a whole (in a future version, the control architecture will be decentralised, see Sect. 15.5). The conditional statements to achieve this can be stated as follows:

1. Keep the heat storage to a minimum.
2. Forecast the predicted inflexible electricity production and consumption.
3. (a) If the battery will be full, turn on flexible consumption.
   (b) If the battery will be empty, turn on flexible generation.

By keeping the heat storage to a minimum, the buffer for flexible energy balancing is maximised. If there is an overproduction of inflexible electricity (i.e. electricity production that cannot be flexibly scheduled or controlled, such as solar or wind), the heat pump can be turned on to create a buffer provided by hot water storage and the thermal mass of the aquaponic RAS system. Conversely, if there is an underproduction of electricity, flexible generation such as the CHP and the fuel cell can be turned on, thereby utilising the thermal storage capacity.

For both heat and power, the energy balance is equivalent to

$$P_{gen,flex} + P_{gen,inflex} + P_{grid} = P_{cons,inflex} + P_{cons,flex} + P_{storage} \qquad (15.1)$$

Flexible generations include the heat pump, Combined Heat and Power (CHP) unit, fuel cell, battery and smart/flexible devices (e.g. aquaponic pumps). Wind, solar photovoltaics (PV) and solar collectors are classified as inflexible generation. Non-flexible devices make up the bulk of electricity consumption, especially in winter (due to the need for instant lighting) (Fig. 15.5).
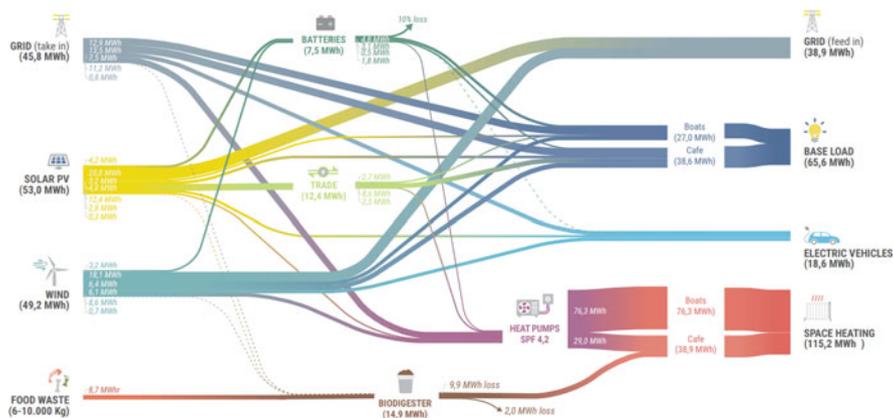
Fig. 15.5 Example of the energy flows (Sankey diagram) of a possible integrated microgrid configuration at De Ceuvel (de Graaf 2018), including a biodigester for the production of biogas. This particular configuration does not include the Combined Heat and Power unit that is present within the Smarthood concept, nor does it take into account a large aquaponics facility

15.5 Results

The total electrical and thermal consumption of both the houses and the aquaponic greenhouse facility (modelled from the data in Tables 15.1 and 15.2) is shown in Table 15.3. The aquaponic greenhouse facility is responsible for 38.3% of power consumption and 51.4% of heat consumption. The power demand for an aquaponics facility integrated in a residential microgrid is therefore slightly over one-third of the total local energy demand, given that all of the residential energy and vegetable/fish production is done locally. The heat demand comprises roughly 50% of the total heat demand, which can be attributed for a large part to the distillation unit running on high-temperature water.

As can be seen in Figs. 15.4 and 15.6, the Smarthoods energy system is capable of balancing production and demand most of the time. The total share of imported electricity from the grid is 4.62% for the reference case. At times, a slight imbalance of power can be observed, which can be attributed to suboptimal control for the current version of the model for the most part. The CHP, for instance, switches from an on- to off-state multiple times over the course of several hours, resulting in an overproduction of electricity. Such behaviour will not occur for a more optimised control system, since the CHP can be ramped down in coordination with the heat pump in order to deliver the precise amount of electricity and heat needed.

15.5.1 Flexibility

The system is highly flexible as a result of the CHP and the aquaponics facility with its flexible lighting and pumps, and high thermal buffering capacity, as well as the

Table 15.3 Electrical and thermal load for different aspects of the microgrid

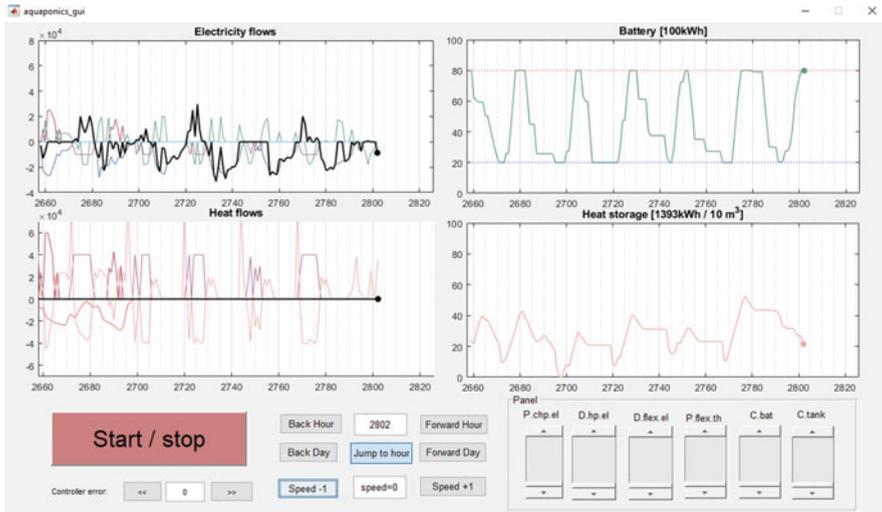|	Residential	Aquaponic facility
Electrical average demand	17.2 kW	10.2 kW
Electrical peak demand	47.6 kW$_p$	15.2 kW$_p$
Electrical total demand	**143.2 MWh/year**	**89.2 MWh/year**
Thermal average demand	37.1 kW	39.3 kW
Thermal peak demand	148.4 kW	121.2 kW
Thermal total demand	**325.0 MWh$_{th}$/year**	**344.2 MWh$_{th}$/year**

Fig. 15.6 Time-series graphical diagrams for the power (top-left) and heat (bottom-left) energy balances (in W) of the Smarthood system. Storage capacity (in kWh) is indicated on the right side for power (top-right) and heat (bottom-right). The x-axis represents number of hours since the start of the year. The black line represents the imbalance of energy

battery, and the hydrogen system. The aquaponic system, especially, greatly increases the overall flexibility of the system, as it can function for a wide range of energy input, as can be derived from Table 15.4. As a result of this flexibility, the system manages to achieve near total (95.38%) power self-sufficiency and 100% heat self-sufficiency.

15.6 Discussion

Self-Sufficiency The energy system proposed for the Smarthood concept is capable of achieving near full grid-independence through the use of the flexibility provided by the various system components. The aquaponic system, especially, has a positive

Table 15.4 Flexible demand of the aquaponic system

Component	Order of magnitude	Flexibility
Pumps	$0.05–0.15 \text{ kW}_e \text{ M}^{-3}$ $1–3 \text{ kW}_e$ $8{,}76–28{,}26 \text{ MWh}_e/\text{year}$	Not all pumps have to run continuously. Main processes (oxygen control, ammonia control, CO_2 control, tank exchanges, suspended solids control) must run continuously. Smaller processes such as pH buffer dosing, backwash routines, water exchanges or back-up oxygenation do not have to run continuously
Lighting	$80–150 \text{ W/m}^2$ With a capacity factor of 10–20% this leads to $28–105 \text{ MWh}_e/\text{year kW}_e$	Plants need ~4–6 h of darkness, the rest of the day they can be lit artificially. This leaves approx. 0 (summer) to 12 (winter) hours of flexible additional lighting
Space heating (underfloor) and aquaculture tank heating	$444 \text{ kW}_{th}/\text{m}^2/\text{year}$ $177{,}8 \text{ MWh}_{th}/\text{year}$	Due to the high thermal mass of the concrete floor and the large water volume in the RAS tank, the heat load is extremely flexible
Distillation unit	$50 \text{ kW}_{th} \text{ MWh}_e/\text{year}$ $166{,}4 \text{ MWh}_{th}/\text{year}$	The distillation unit operates on hot water (70–90 °C) and can be operated with a significant degree of flexibility (MemSys 2017)

effect on the overall flexibility of the system. With 95.38% power self-sufficiency, this system performs better than any other economically feasible system assessed in previous research (de Graaf 2018).

Control Architecture Facilitating a decentralised local energy economy, such as the one proposed in the *Smarthoods* concept, requires a platform that keeps track of all the peer-to-peer transactions occurring within the neighbourhood. The corresponding peer-to-peer network can be classified as a multi-agent system (MAS) approach, in which multiple nodes (e.g. households or utility buildings) function as independent agents with their own objective (e.g. minimise cost or maximise energy saving) and corresponding decision-making process. Such a decentralised, multi-agent decision-making approach is necessary due to the complexity of the system. There is simply too much information and too many variables for the computation of a hierarchical, top-down and centralised control architecture.

Blockchain A blockchain-based multi-agent system control architecture could potentially provide the necessary framework to accommodate a decentralised peer-to-peer network. A vast number of distributed nodes ensure stability and security for the network, and an alternative to mining can be used: minting. With minting, tokens/coins are generated based on the data provided by a real-world device such as a smart energy metre. Provided that these sources of information can be trusted, i.e. that these devices can be tamper-proofed, a secure and independent ledger can be created in which various stakeholders can exchange goods (e.g. electricity) and

services (e.g. demand-side management). Using smart contracts, complex services such as flexibility trading can be programmed into the control architecture of the system.

Internet of Things The constituent components within the Smarthood system, such as heat pumps, greenhouse lighting or the UASB, can all be controlled using Internet-connected sensors and actuators, known as Internet of Things. An IoT sensor network allows for the extensive acquisition of data, ranging from fish tank nutrient concentration to, for instance, battery load cycles, all on a per-time-step basis. This data can be used to verify the numerical model and optimise the dynamical control of the system.

Artificial Intelligence Optimising the control of the Smarthood system can be done by analysing the data using artificial intelligence algorithms, such as genetic programming (evolutionary algorithms) or machine reinforcement learning. With machine reinforcement learning, for instance, a set of actions and their influence on the environment are passed to the algorithm as input arguments, along with the current state of the system and a cumulative objective/cost function. An incrementally improving, heuristic decision-making process can be implemented at each household that will dynamically adapt to situations in order to find a near-optimal decision-making programme that will manage the energy flows within the house and the *Smarthood*. Each house can run such an algorithm, and as a result, a multi-nodal control system architecture, known as a multi-agent system (MAS), can be created that is relatively computationally inexpensive (compared to centralised control)—and close to optimal.

Legal Barriers The highly innovative nature of various aspects of the Smarthood concept, such as the polygeneration microgrid, the multi-loop aquaponic system and the unconventional urban planning requirements, brings along a unique set of challenges to overcome. For many of these challenges, the current regulatory framework is insufficient to accommodate the developments proposed in the Smarthoods concept.

Microgrids, for instance, work best when there is a local marketplace in which various *prosumers* (consumers that simultaneously produce power) can engage in frictionless peer-to-peer energy trading in a free market. Market forces will then work to create a local energy market in which a fluctuating energy price will result from local supply and demand. This price fluctuation will consequently incentivise smart energy solutions such as energy storage, demand-side management or flexible energy generation. In most EU countries, a free local market is currently impossible due to regulations; taxes have to be paid for every kWh that passes through the electricity metre, the electricity price for consumers is fixed and prosumers are not allowed to participate in the energy market without the intervention of a third party called the *aggregator*. With the expected increase in the development of microgrid projects, regulators will have to find ways to facilitate local energy markets in order to unlock the full potential of highly integrated microgrids (see Example 15.2).

Example 15.2

A recent advancement within the regulatory framework in the Netherlands is the introduction of the *experimenteerregeling,* an experimental law that allows a small number of carefully selected projects (such as de Ceuvel, example Z.1) to allow energy cooperatives to become their own distribution system operator, as if they were behind a single metre connection. This law is indicative of the awareness amongst Dutch regulatory bodies of previously mentioned legal barriers, and will therefore most likely lead to the current electricity law to be revised in the near future in order to better accommodate microgrid developments.

There are also some legal barriers in most EU countries with respect to reusing treated black water for fish and plant production, as it has to be ensured that human pathogens are fully eliminated. More information on the legal framework of aquaponics can be found in Chap. 20.

15.7 Conclusions

The goal of this research was to quantify the degree of flexibility and self-sufficiency that an aquaponics integrated microgrid can provide. In order to attain this answer, a neighbourhood of 50 households was assumed a 'Smarthood', with a decoupled multi-loop aquaponics facility present that is capable of providing fish and vegetables for all the 100 inhabitants of the Smarthood.

The results are promising: thanks to the high degree of flexibility inherent in the aquaponic system as a result of high thermal mass, flexible pumps and adaptive lighting, the overall degree of self-sufficiency is 95.38%, making it nearly completely self-sufficient and grid independent. With the aquaponics system being responsible for 38.3% of power consumption and 51.4% of heat consumption, the impact of the aquaponics facility on the total system's energy balance is very high.

Earlier research (de Graaf 2018) has indicated that it is very difficult to achieve self-consumption levels over 60% without relying on an external biomass source to drive a CHP. Even with this source included, the maximum techno-economically feasible self-consumption did not exceed 89%. In the Smarthood, biomass inputs for the CHP are partially derived from the aquaponic system itself, and the recycling of grey and black water. A higher self-consumption combined with a lower dependence on external biomass inputs, and a resulting self-consumption of 95%, makes the proposed aquaponic-integrated microgrid perform better from a self-sufficiency point of view than any other renewable microgrid known to the authors.

The authors of this chapter therefore strongly believe that with enough experimentation, integrating aquaponic greenhouse systems within microgrids yields great potential for creating highly self-sufficient Food–Water–Energy systems at a local level.

References

CBS (2018) Energieverbruik particuliere woningen; woningtype en regio's [WWW Document]. URL http://statline.cbs.nl/Statweb/publication/?VW=T&DM=SLNL&PA=81528NED&D1=a&D2=a&D3=0&D4=a&HD=161202-1617&HDR=T,G3&STB=G2,G1. Accessed 19 Oct 2018

de Graaf F (2018) New strategies for smart integrated decentralised energy systems

dos Santos MJPL (2016) Smart cities and urban areas—aquaponics as innovative urban agriculture. Urban For Urban Green 20:402–406. https://doi.org/10.1016/j.ufug.2016.10.004

EFSA (2018) The EFSA comprehensive European food consumption database | European [WWW Document]. URL https://www.efsa.europa.eu/en/food-consumption/comprehensive-database. Accessed 19 Oct 2018

FAO (2015) Statistical pocketbook - world food and agriculture

Goddek S, Körner O (2019) A fully integrated simulation model of multi-loop aquaponics: a case study for system sizing in different environments. Agric Syst 171:143–154

Goddek S, Delaide BPL, Joyce A, Wuertz S, Jijakli MH, Gross A, Eding EH, Bläser I, Reuter M, Keizer LCP, Morgenstern R, Körner O, Verreth J, Keesman KJ (2018) Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. Aquac Eng 83:10–19. https://doi.org/10.1016/J.AQUAENG.2018.07.003

IRENA (2015) Renewable energy capacity statistics 2015, Masdar: IRENA

MemSys (2017) Membrane distillation system - MDS 500

Pudjianto D, Ramsay C, Strbac G (2007) Virtual power plant and system integration of distributed energy resources. IET Renew Power Gener 1:10. https://doi.org/10.1049/iet-rpg:20060023

Strbac G, Hatziargyriou N, Lopes JP, Moreira C, Dimeas A, Papadaskalopoulos D (2015) Microgrids: enhancing the resilience of the European megagrid. IEEE Power Energ Mag 13:35–43. https://doi.org/10.1109/MPE.2015.2397336

Yogev U, Barnes A, Gross A (2016) Nutrients and energy balance analysis for a conceptual model of a three loops off grid. Aquaponics Water 8:589. https://doi.org/10.3390/W8120589