Green Village Delft – integration of an autarkic water supply in a local sustainable energy system

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ABSTRACT

For the Green Village at the campus of Delft University of Technology, an autarkic water circuit was developed. The aim was to avoid connections to the public water supply system, the sewerage, the electricity grid and cable systems. It should produce its own drinking water and electricity, and clean its organic waste streams in a sustainable way. Due to the strict Dutch drinking water regulations, only one water quality will be supplied: drinking water. Drinking water will be produced from greywater (53%) supplemented with rainwater (47%). In the treatment scheme, the multiple barrier approach will be used to comply with the Dutch drinking water quality standards. For greywater treatment, a triple barrier is suggested: ozonation – ultrafiltration – UV disinfection. For rainwater treatment a dual barrier is suggested: ultrafiltration – UV disinfection. By separating wastewater streams at the point of origin into greywater and blackwater, and by replacing conventional toilets with low water consumption vacuum systems as part of the water conservation measures, it will be possible to collect a concentrated blackwater stream suitable for recovery energy. For this purpose the upflow anaerobic sludge blanket reactor is suggested. The proposed water circuit results in an autarkic water management, but not in an autarkic energy management.

Key words | blackwater, drinking water, energy recovery, greywater, wastewater, water reuse

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INTRODUCTION

At Delft University of Technology a team of scientists, students and companies is working on the Green Campus project. The aim is to create a sustainable, lively and entrepreneurial campus at Delft University of Technology and learn how to solve society's urgent challenges. These challenges are related to subjects as dependence on fossil fuel, overexploitation and misuse of resources, climate change, and water scarcity (Frijns *et al.* 2013).

As start of this ambitious project, the Green Village concept was born, as a temporary test and try-out laboratory site on the campus prior to the development of the Green Campus. The Green Village will not be connected to electricity and water supply, the sewerage and cable systems. The aim is to develop the Green Village as an autarkic system, producing its own electricity and drinking water, and clean its organic waste streams in a sustainable way. It will make use of innovative, sometimes experimental systems, developed by business, students and researchers. The Green Village will be built as a sea container village: 30 recycled sea containers will be turned into attractive working areas, meeting places, a restaurant and laboratories. An important aspect in the Green Village is the selection of the best suited sustainable water management concept for recovery of valuable resources and reuse of available sources for potable water supply in closed loop systems, in compliance with health-based targets and with the ambition to minimize energy consumption.

As the Green Village will not be connected to the drinking water supply and sewage system, it can be characterized as a decentralized system. Decentralized systems can be defined as systems provided for water, wastewater and

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stormwater services at the property, cluster and development scale that utilize alternative water resources, including rainwater, wastewater and stormwater, based on a 'fit-for-purpose' concept. These systems can be managed as stand-alone systems, or integrated with centralized systems (Sharma *et al.* 2013). 'Decentralized' and 'fit-for-purpose' are two important concepts in this definition.

In the Netherlands, the experience with decentralized drinking water supply and sewage systems is limited. In the city of Sneek, the DeSaH project is running (Zeeman *et al.* 2008; De Graaff *et al.* 2010). In this project 32 houses are provided with collection, transport and treatment systems for blackwater and greywater. The concept of separation at source and decentralized treatment have led to an efficient utilization of valuable components, like nutrients, the production of energy and the reduction of potable water consumption. In contrast to the Green Village project, in the DeSaH project drinking water is still supplied by the central system.

Considering the concept 'fit-for-purpose', the options to introduce this concept in the drinking water supply in the Netherlands are very limited. At the end of the last century there were several experiments with a dual water supply to households: a drinking water supply for high quality use such as drinking and showering, and a household water supply for non-drinking purposes such as washing laundry, toilet flushing, car washing and gardening. One experiment concerned the application of a dual system in a new housing estate in Amsterdam, IJburg (van der Hoek *et al.* 1999; Bonné *et al.* 2002). Because in several experiments there were severe problems with the safety of these dual supplies with regards to public health, and because there were doubts about the environmental and financial benefits, an evaluation was made (Oesterholt 2003). The evaluation focused on public health aspects, environmental aspects and customer acceptance. The main conclusions were that household water is not always microbiologically safe, it is not biologically stable and may result in regrowth, there is a severe risk of cross connections which leads to contamination of the drinking water, and the environmental benefits are very limited. Customers appreciate household water but good information about the use is required. Based on this evaluation, the regulations on the application of household water in the Dutch Drinking Water Decree, which came into force in 2011, are quite strict (State Journal 2011). An exemption from the Ministry in charge of drinking water affairs is required to deliver and use household water. Only rainwater harvested from roofs and groundwater may be used as sources for household water. In case the quantity is not enough it has to be amended with drinking water. The only allowed application is toilet flushing.

In contrast to the Netherlands, the experiments with water reuse and decentralized systems in other countries are extended. Systems vary from rainwater harvesting (Way *et al.* 2010; Adler *et al.* 2011; Campisano & Modica 2012; Ghimire *et al.* 2012; Campisano *et al.* 2013; Kus *et al.* 2013; Schuetze 2013), greywater treatment (Meda & Cornel 2010; Cobacho *et al.* 2012; Smith & Bani-Melhem 2012; Alfiya *et al.* 2013; Boyjoo *et al.* 2013; Sinclair *et al.* 2013), water recycling for indirect potable use (Wintgens *et al.* 2008) to direct drinking water reclamation from wastewater, as applied in Windhoek Namibia (du Pisani & Menge 2013). Much attention is given to decentralized systems, especially in Australia (Moglia *et al.* 2011; Sharma *et al.* 2013).

In this study, the best technological approach for water supply and treatment in the autarkic circuit of the Green Village has been established, taking into account the limited experiences in the Netherlands with decentralized and autarkic systems, and the strict regulations in the Netherlands with respect to drinking water quality and dual water supply systems. The aim was to develop a conceptual design which provides safe and clean water for the Green Village, reduces as much as possible the water consumption by means of the use of efficient appliances, uses available water resources that can be upgraded to usable water in the Green Village, and recovers valuable resources that lead to increasing the overall energy efficiency of the system.

METHODS

The research concerned a desktop study to determine the optimal technical approach for water supply and treatment in the not yet existing Green Village. After a thorough literature survey, the conceptual design of the water management system for the Green Village was conducted. The methodology consisted of five steps. First, the number of water qualities required for the different purposes in the Green Village was defined, taking into account the strict regulations in the Netherlands for drinking water supply and household water supply. Secondly, the water consumption in the Green Village was calculated, taking into account conservation measures to reduce water consumption. Thirdly, the wastewater management was considered, in which a distinction was made between greywater and blackwater. Fourthly, a water balance was made, in which the water demand was balanced with the potential sources for water supply. Finally, an integrated concept was developed in which the production, recovery and consumption of water and energy were tightly bound.

RESULTS AND DISCUSSION

Required water qualities

The intention is to realize the Green Village as a sustainable village. In that sense it may be beneficial to supply different qualities of water: a high water quality for drinking water purposes, and a lower quality for non-drinking purposes. The latter requires a lower treatment effort, and by reducing the amount of water with drinking water quality, less chemicals and energy may be required in the water treatment system, reducing the environmental impact and thus improving the sustainability. However, the Dutch drinking water legislation does not offer possibilities to supply a lower water quality for non-drinking purposes. To comply with the Dutch regulations, and to avoid the complicated system in the Green Village of applying a dual water supply system, it was decided that only one water quality will be supplied in the Green Village for all purposes: drinking water quality which complies with the Dutch drinking water standards.

Water consumption

In the first phase of the Green Village, an initial amount of 30 containers was chosen as the basis of design purposes. The Green Village is thought for a total of 80 persons in the initial phase, including visitors and regular staff. Because the Green Village is aimed to serve as a 'company incubator and testing site' most of the containers will be considered for office workplaces. In total there will be twenty office containers with room for three people per container, totalling sixty people. Also envisaged is the inclusion of five dormitory containers which are thought to be for students related to the project. Five additional containers are also considered: one lunchroom, two restrooms, one shop and a laboratory showcase.

Based on the envisaged activities in the Green Village, water consumption will be a mixture of water use typical for households and water use typical for offices. For the former, the consumption per appliance reference for Netherlands' households was used (Fokkema & van Thiel 2011). Not many studies in office water consumption in the Netherlands have been realized. Therefore, for the latter the benchmark study referring to the best use in a UK office building was used (Waggett & Arotsky 2006). Taking into account these two consumption patterns, and applying water conservation measures (Hofman-Caris 2013), the water consumption for the Green Village was estimated to be 1,337 L/day, as shown in Table 1. For the shower, sink faucet and laundry, it is assumed that a 35% reduction can be achieved. For dishwashing it is assumed that a 60% reduction can be achieved by using low-water consumption dishwashers. Kitchen faucets are only used for cleaning and washing hands and water use is assumed to be 2.7 L/person/day. For toilets, vacuum toilets are used with single flush consumption as low as 1 L. In offices, the rate of flushing is approximately three times per day (Gleick *et al.* 2003).

Wastewater management

In order to design an optimal water management system for the Green Village, a distinction was made between greywater and blackwater. Separating wastewater at the source and treating the different flows separately will offer possibilities to recover nutrients, energy and clean water. Greywater is domestic wastewater excluding toilet wastewater (Jefferson *et al.* 2000).

Greywater is less polluted than blackwater and can be a resource for high quality water (Meda & Cornel 2010). Blackwater is defined as wastewater collected from toilets,

Table 1 | Estimated water consumption in the Green Village

Appliance	Intended use	Consumption in the Netherlands[a] (L/person/day)	Green Village consumption (L/person/day)	No. of persons	Total use (L/day)
Shower	Dormitory	48.6	31.6	5	158
Sink faucets	Office and dormitory	5.0	3.2	80	256
Dishwashing, hand + machine	Canteen and dormitory	6.1	2.0	80	160
Food preparation	Canteen and dormitory	1.4	1.4	80	112
Kitchen faucets	Office and dormitory	5.3	2.7	80	216
Drinking water	Office and dormitory	0.6	0.6	80	48
Coffee and tea	Office and dormitory	1.2	1.2	80	96
Laundry	Dormitory	15.4	9.7	5	48
Toilet flushing	Office and dormitory	33.7	3.0	80	240
Bath	Dormitory	2.8	0	5	0

[a] Based on Fokkema & van Thiel (2011).

namely feces and urine. It represents a relatively concentrated stream with a high potential for resource recovery (Zeeman & Lettinga 1999; De Graaff 2010). Figure 1 shows the principle of separation of wastewater at source, and includes also rainwater harvesting.

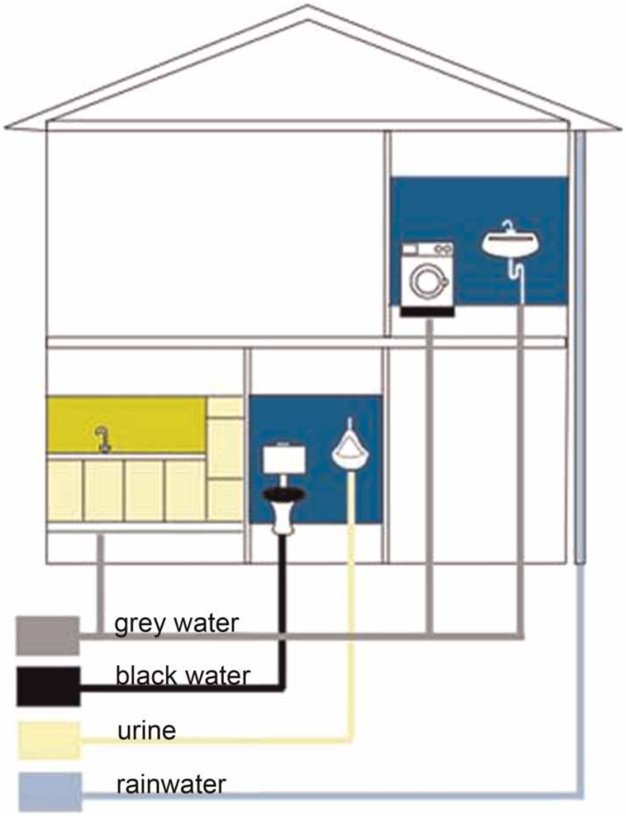

Figure 1 | The separation at source concept.

Taking into account the predicted water consumption as shown in Table 1, and assuming that water for ingestion (e.g. drinking water, coffee and tea, and food preparation) is not discharged in the Green Village, it can be calculated that greywater amounts to 834 L/day and blackwater amounts to 240 L/day. Table 2 summarizes these flows.

Water supply balance

For the Green Village only water with drinking water quality will be supplied. The greywater will be used as the source for the drinking water supply. From the daily 834 L of greywater, it is assumed that 15% of the greywater will be lost in the treatment process to purify the greywater to drinking water and that 85% can be recovered as potable water, i.e. 709 L/day. Therefore, there is an imbalance of 628 L to match the overall water consumption (1,337 L). This amount is projected to be covered with treated rainwater.

Table 2 | Separation at source, daily water distribution (in L)

	Ingestion	To greywater	To blackwater	Total
Office	135	225	225	585
Dormitory	16	233	15	264
Canteen	112	376	0	488
Totals	263	834	240	1,337

Hence, 53% of the drinking water will originate from greywater and 47% from rainwater.

Treatment concept of greywater and rainwater

Greywater and rainwater will be used as sources for drinking water. Although greywater is less contaminated than blackwater due to the absence of feces and urine, the composition of greywater requires an extensive treatment. Greywater contains microbial contaminants including pathogens, organic material, nutrients, suspended solids, surfactants, detergents and heavy metals (Ottoson & Stenström 2003; Smith & Bani-Melhem 2012; Boyjoo *et al.* 2013). Greywater may also contain emerging contaminants (Wintgens *et al.* 2008). Although in contrast to blackwater the presence of hormones and medicines in greywater is unlikely, a major concern is the presence of personal care products. Potential harmful effects of several personal care products including carcinogenicity, mutagenicity and estrogenicity have been demonstrated for several personal care products and therefore could restrict the reuse options for greywater (Temmink *et al.* 2011). Thus, when using greywater as an alternative water source for drinking water production a major concern is the safety of this exploitation. In 2005–2006 a study was carried out into the reuse of wastewater for drinking water purposes at one of the wastewater treatment plants in Amsterdam, The Netherlands. It was concluded that under normal conditions, drinking water that meets the Dutch drinking water quality standards could be produced from treated wastewater effluent, but that additional redundancy should be built in to meet the standards under extreme operation conditions (Rietveld *et al.* 2009).

In the Netherlands, no persistent disinfectant is used in drinking water treatment and distribution and therefore multiple barriers are used against micro-organisms (van der Kooij *et al.* 1995). In Windhoek direct drinking water reclamation from wastewater has already applied successfully for more than 40 years based on the multiple barrier concept to reduce the risk and improve the water quality (du Pisani & Menge 2013).

Based on these considerations, the multiple barrier approach will be applied for upgrading greywater to drinking water in the Green Village. The suggested treatment scheme is shown in Figure 2.

The first block consists of an equalization tank with a skimmer to collect grease and fat which may be present in the wastewater. Then the system continues with a membrane bioreactor coupled with a submerged hollow fiber ultrafiltration membrane. This step is used to degrade biological and organic content and serves as a first removal stage for surfactants and a physical barrier for suspended solids. The third block includes ozonation and activated carbon filtration.

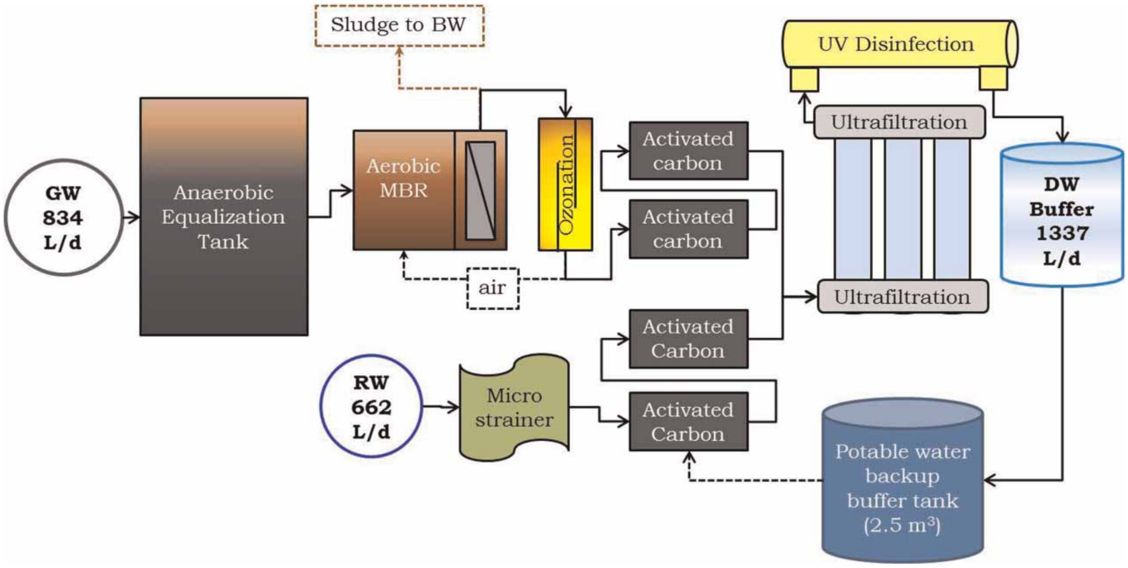

Figure 2 | Integrated greywater and rainwater scheme for the production of drinking water (GW = greywater; BW = blackwater, RW = rainwater).

This combination is used for improving taste and odor and removing micropollutants. Ozonation is also used for disinfection. The fourth stage is an ultrafiltration membrane unit as another physical barrier, mainly for small suspended solids and heavy metals. This unit also serves as a second disinfection barrier for bacteria, viruses and protozoa. The last stage is an ultraviolet treatment for inactivation of the remaining microorganisms (safety disinfection).

To fulfil the drinking water demand of 1,337 L/day, rainwater will be used as an additional water source. Based on the average annual precipitation over the period 1988–2012 (871.2 mm at nearest weather station Rotterdam) (KNMI 2013) and assuming an efficiency of collection of 95% because a small volume of water will be either lost in the first foul flush and/or will be absorbed by the catchment material (Schets *et al.* 2010), the catchment surface should have a dimension of at least 277 m^2 for a usable net collection of 241 m^3 per year, i.e. 661 L of usable rainwater per day. Although the quality of rainwater is much better than greywater, rainwater suffers microbiological and chemical contamination from both atmospheric deposition and rooftop runoff (Adler *et al.* 2011; Kus *et al.* 2013). Therefore, the harvested rainwater will be filtered by a micro strainer for removal of suspended solids, and filtered over a separate line of activated carbon filters for removal of organic compounds and spores of heavy metals before it is introduced in the fourth stage (ultrafiltration). Ultrafiltration and UV offer a dual disinfection barrier for the rainwater.

For security of supply, to cover periods without rainfall, a backup buffer tank will be used with a volume of 2.5 m^3. As the water quality may deteriorate in this storage tank it is possible to upgrade it to drinking water quality again by introducing it to the carbon filters.

Treatment concept of blackwater

The blackwater to be treated concerns the water collected from toilets (feces and urine) and the separated sludge from the membrane bioreactor in the greywater treatment system. The blackwater thus will contain a large fraction of the main components of domestic wastewater: organics, nutrients (nitrogen, phosphorus, potassium), pathogens, pharmaceutical residues and hormones, as all these constituents are originally present in a very small volume of feces and urine (Kujawa-Roeleveld & Zeeman 2006). Due to the use of vacuum toilets, the concentrations will be relatively high. Compared to aerobic systems, anaerobic systems have the advantage of low costs, energy recovery in the form of biogas, operational simplicity, low energy consumption and low production of digested sludge (de Graaff *et al.* 2010; Khan *et al.* 2011). Addition of grinded kitchen waste to the blackwater, with a high organic load to increase biogas production, is not yet considered. Also the separate collection of urine for N and P recovery will not be part of the Green Village. Both would require a more complex and more expensive piping system.

For anaerobic treatment of the blackwater, the upflow anaerobic sludge blanket (UASB) reactor seems very feasible in the Green Village project. In comparable projects high removal efficiencies for chemical oxygen demand and suspended solids were measured, 78 and 93% respectively. Nitrogen was conserved for more than 91% in the liquid effluent, mainly as ammonium. Phosphorus was conserved for 61% in the effluent, mainly as phosphate (de Graaff *et al.* 2010).

As the anaerobic digestion alone does not provide 'full treatment', post-treatment will be required to upgrade the anaerobic effluent to standards for discharge. This applies mainly to the remaining biodegradable organic matter, nitrogen and phosphorus, pathogens, and organic micropollutants, although the removal of the latter is not required by current regulations in the Netherlands. For post-treatment, the vertical flow constructed wetlands system has been selected, which is less susceptible to clogging than horizontal flow constructed wetlands system (Tilley *et al.* 2008). This is a semi-natural, extensive system that can be aesthetically incorporated in the landscape of the Green Village. Figure 3 is a schematic representation of this post-treatment system. An additional final polishing pond may be used to create a natural connection between the treatment system and nature. This multi-step system will result in an efficient removal of pathogens and may also remove micro-pollutants (Van den Boomen *et al.* 2012).

Figure 4 shows the suggested blackwater treatment scheme.

The integrated concept

The lay-out of the integrated water management system, suggested for the Green Village, is shown in Figure 5. By

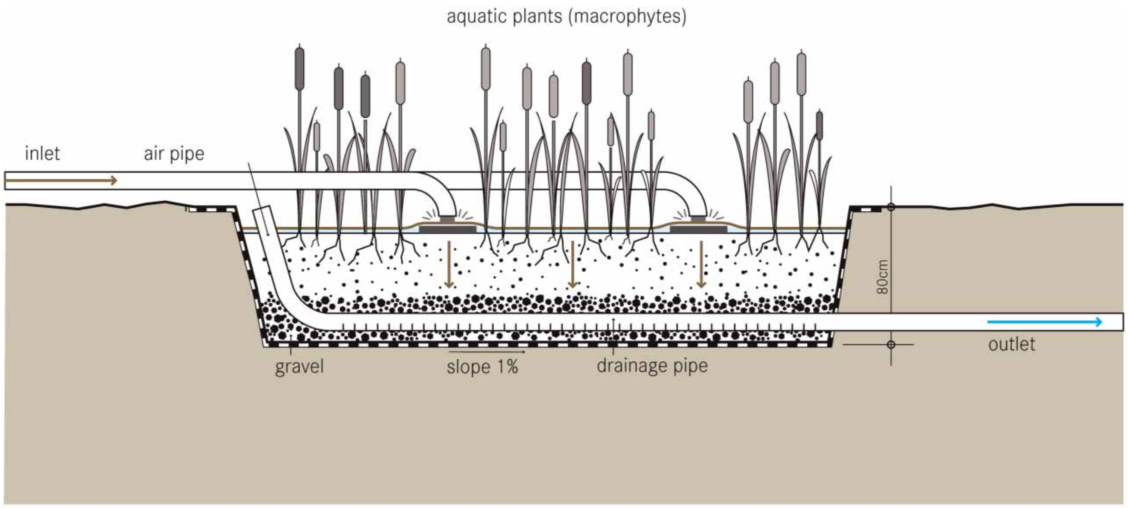

Figure 3 | The vertical flow constructed wetland system for post-treatment of blackwater (Tilley *et al.* 2008).

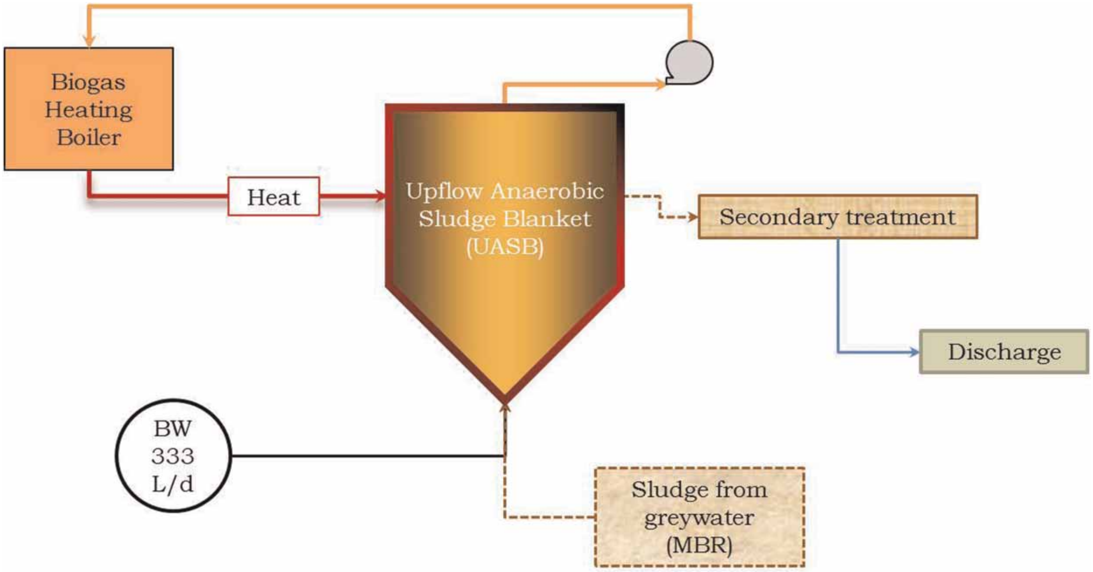

Figure 4 | The blackwater treatment scheme.

using greywater and rainwater as a source for drinking water production, the Green Village will be self-supportive in water supply.

The energy balance of the system includes the electricity for the drinking water production, the electricity needed for collection of blackwater through vacuum toilets, the energy required to heat up the UASB reactor (25 °C) and the biogas production from the UASB reactor.

The energy requirement for the production of drinking water is estimated to be 1.256 kWh per day based on information of equipment suppliers. With a total drinking water production of 1,337 L/day, this means an energy consumption of 0.94 kWh/m^3 which is higher than the average energy use for drinking water production in the Netherlands, 0.50 kWh/m^3 (Geudens & van Beek 2010). The energy requirement for the vacuum toilets is assumed to be 0.44 kWh per day, based on the use pattern in the Green Village and information of equipment suppliers.

In a predictive model (Izar Tenorio 2012), the energy was estimated for heating up the UASB reactor (25 °C) with a

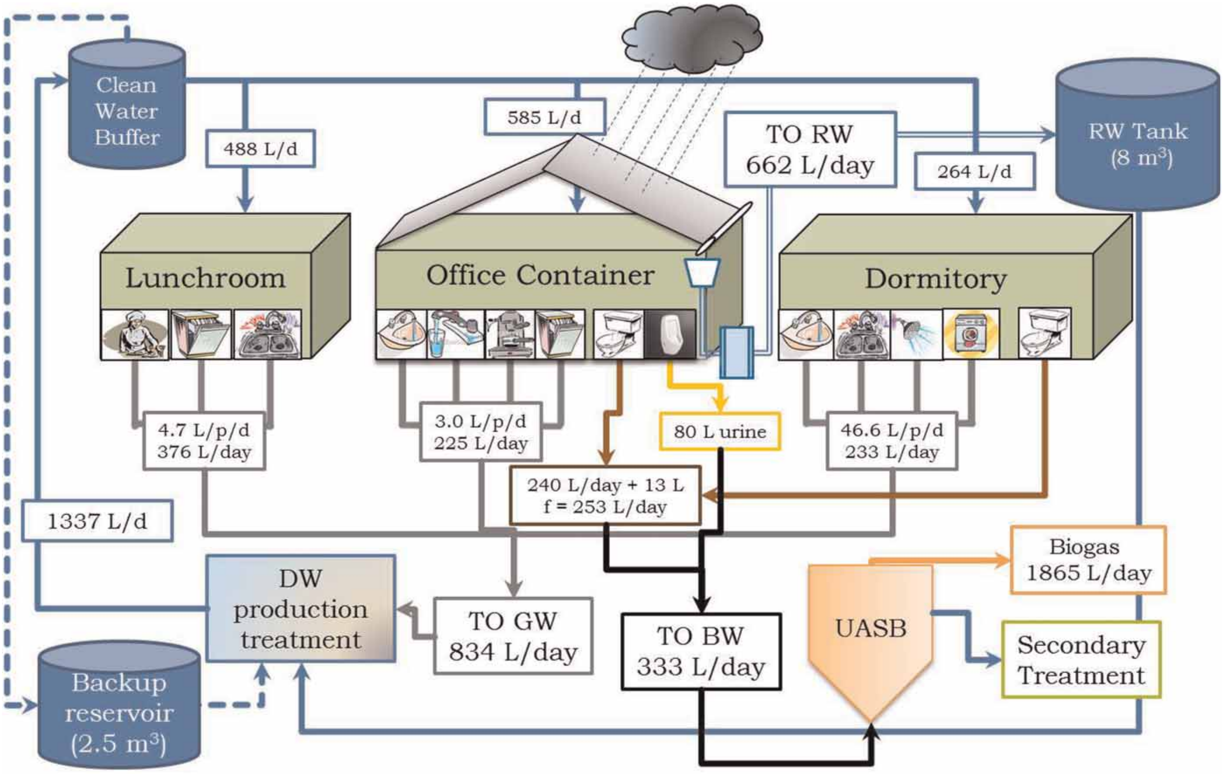

Figure 5 | Lay-out of the integrated water management system in the Green Village.

blackwater temperature of 20 °C at the time of collection. Depending on the ambient temperature, this will range from 10 to 30 MJ/day. In the predictive model, the heat recovery from the biogas, produced in the UASB reactor, was estimated to be 54 MJ/day.

Energy consumption and energy production in the water management system show that additional measures, e.g. use of solar energy and wind energy, will be required to realize autarkic energy conditions in the Green Village.

CONCLUSIONS

To develop the Green Village as an autarkic system, the design and technical approaches for the integration of the water supply and treatment functions for an autarkic water circuit should be based on three concepts: (1) reducing the overall consumption of water by making efficient use of water and applying water conservation measures; (2) using greywater (53%) and rainwater (47%) as raw water sources, and reclaiming them in a multiple barrier treatment concept for drinking water production; (3) treating blackwater anaerobically for energy recovery from the wastewater.

With these three concepts, it will be possible to introduce an autarkic water supply in the Green Village. However, to realize autarkic energy conditions, additional measures will be required, e.g use of wind energy or solar energy.

The water supply management system has been designed specifically for the Green Village, a temporary test and try-out laboratory site which will consist of sea containers. It may also be applied in other cases where there is no connection to the public water supply and sewerage. However, it must be taken into account that in the case of the Green Village some site specific conditions affected the final design. First, due to the strict regulations only one water quality will be supplied: drinking water. In other cases, a dual water supply may be considered: a high quality drinking water combined with a low quality household water. Secondly, the water consumption is strongly determined by the type of activities in the Green Village, and also by the use of vacuum toilets. In other cases, the water consumption may be quite different. Thirdly, in the water balance, rainwater harvesting will play an important role in the Green Village. In other cases, especially in arid or semi-arid regions, other water sources may be needed to supplement greywater as a resource for drinking water. Hence, the water management system of the Green Village cannot be seen as a generic design.

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