First implementation of a SEMIZENTRAL resource recovery center

J. Tolksdorf, D. Lu and P. Cornel

ABSTRACT

The SEMIZENTRAL approach has been developed for fast growing cities, to meet their challenges regarding the supply of water and the treatment of biowaste and wastewater. Key elements of the SEMIZENTRAL integrated infrastructure approach are high resource efficiency due to urban water reuse and the usage of the energy potential of wastewater/sludge and waste, as well as its system size between central and decentral. In Qingdao (PR China), the SEMIZENTRAL Resource Recovery Center (RRC) has been implemented for the first time worldwide at full scale. The goal of high resource efficiency, which includes generating service water, has a significant influence on the process design of the RRC. Moreover, the influence of the site adaptation of the general SEMIZENTRAL approach to the actual location in Qingdao on emissions to the water body and on the energy balance has been investigated. Through comparisons with a conventional wastewater treatment plant, advantages and disadvantages are evaluated. Due to water reuse, energy can be saved, compared to alternative water resources. The discharged nutrient load decreases considerably. Nevertheless, the effort required for wastewater treatment increases.

Key words | energy efficiency, integrated infrastructure systems, urban water reuse

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INTRODUCTION

China is increasingly confronted with regional water scarcity, due to its rapid economic development and population growth, as well as its uneven spatial distribution of water resources: in the northern and western regions water is very scarce, whereas in south China water is abundant (Yi *et al.* 2011). Moreover, industrialization and urbanization lead to a decrease in water quality because of insufficient wastewater treatment (Hu & Cheng 2013). In particular, nutrient removal is still an issue for China's wastewater treatment plants (Jin *et al.* 2014).

For fast growing urban areas, the implementation of physical (pipe-based) infrastructures is challenging. For example, according to the United Nation's World Urbanization Prospect (United Nations 2011) Qingdao has, statistically, a growth rate of 15 persons per hour (a moderate growth rate compared to Shanghai with 67 C/h); i.e., each year, an additional 131,000 persons live in Qingdao. Based on an inhabitant-specific water consumption of 109 L/(C·d) (Bi 2004), these people need 14,300 m³ of fresh water daily and produce an equivalent amount of wastewater. To supply the increasing population of Qingdao, a seawater desalination plant with a capacity of 100,000 m³/d was commissioned in 2013. Although improvements in the energy consumption for desalination have been achieved, it is still an energy intensive process consuming 3–4 kWh/m³ (Ghaffour *et al.* 2013). Urban water reuse, by contrast, can protect valuable resources and reduce energy consumption as reuse water can be produced with less than 1 kWh/m³. Relatively decentralized systems (meaning, in the context of China's fast growing cities, 20,000–100,000 capita) are more appropriate for fast growing urban areas; centralized supply and treatment infrastructures cannot meet the challenges in such areas because of their long-term planning horizons and, with respect to water shortages, because of the small potential for intra-urban water reuse.

SEMIZENTRAL, an infrastructure approach for fast growing urban areas, has been developed as a possible solution, with a focus on higher resource efficiency. The approach integrates the sectors of water supply, wastewater treatment, and waste treatment, which are normally separated. In addition to system integration, SEMIZENTRAL is characterized by the system's size (Bieker *et al.* 2010; Bieker 2015). The system size is defined by requirements such as increased resource efficiency, flexibility, and adaptability, as well as the necessity for professional operation. Due to urban water reuse and energy recovery from sludge and biowaste, as well as short distances between first use and reuse, higher resource efficiency is achieved. The degree of reuse can range between 40 and almost 100%, depending on the local, adjusted concept. The increased biogas production through integration of biowaste and sludge treatment makes an energy-autarkic operation of the semi-centralized Resource Recovery Center (RRC) possible.

METHODS

The first full-scale RRC was implemented in Qingdao (China) in 2014. Based on a reference design, for which general data from Qingdao were used, the general SEMIZENTRAL concept has been adapted to the actual location in Qingdao ShiYuan. Compared to the reference design, input and output flows have been changed, resulting in differences in treatment efforts. The aim of this paper is to evaluate the adaptation of the general SEMIZENTRAL approach to the actual site of the first RRC in Qingdao ShiYuan. Furthermore, through comparison with a conventional wastewater treatment plant that treats the same amount of wastewater and loads, the impacts of source separation and the integration of food waste on discharged nutrient loads and energy efficiency are investigated.

The calculation followed the German design standard ATV-A 131E (ATV-DVWK 2000) and included consideration of the Chinese effluent standards GB/T 18920–2002 and GB/T 18918-2002 (TN ≤ 15 mg/L, TP ≤ 0.5 mg/L). For the nutrient balance, 14, and 0.3 mg/L for the total nitrogen (TN) and total phosphorus (TP) effluent concentrations has been assumed, according to the design calculation of the RRC in Qingdao ShiYuan in 2013.

The calculation of electrical energy consumption (as a plant-specific optimal value) for the RRC in Qingdao ShiYuan is based on the machinery list, using empirical values from the German draft standard DWA-A 216 (DWA 2013). Smaller consumers, such as the instrumentation, control and automation systems or lighting, have been neglected. For the rough calculation of the electricity consumption for the reference design and a conventional system, the same boundary conditions (e.g., discharge head for pumps or specific electricity consumption for machines) are used. Data related to the electricity demand for waste and sludge treatment, as well as exhaust air purification, are not discussed in this paper, although they contribute considerably to the energy requirements of an RRC (Tolksdorf *et al.* 2015). Table 1 gives an overview of the scenarios. For all scenarios, 12,000 population equivalent was assumed.

SEMIZENTRAL reference design

For the general conditions in Qingdao (regarding water demand, wastewater volume, and loads), a reference

Table 1 │ Characteristics of scenarios

	SEMIZENTRAL reference design	SEMIZENTRAL Qingdao ShiYuan	Conventional system A	Conventional system B
Wastewater L/(C·d)	Greywater: 41 Blackwater: 68	Greywater: 60 Blackwater: 68	Total: 128	Total: 282
Water reuse	Treated greywater for toilet flushing	Treated greywater for toilet flushing Treated blackwater for irrigation	None	None
Co-substrate gDS/(C·d)	Biowaste: 270	Food waste: 171	None	None

DS – dry solids.

design for an RRC has been developed. As the acceptance of the reuse of treated greywater in households is believed to be higher, compared to treated total wastewater, greywater (from showers, wash basins, and washing machines) is collected separately from blackwater (wastewater from toilets and kitchen sinks) and, following treatment, is reused for toilet flushing. The specific greywater generation of 41 L/(C·d) corresponds well with the specific water demand for toilet flushing of 33 L/(C·d) (Bieker *et al.* 2010). Treated blackwater is discharged to the water body. Household biowaste (270 gDS/(C·d)) is anaerobically co-treated with sewage sludge; the resulting biogas is used for electricity and heat production by a combined heat and power plant (CHP).

SEMIZENTRAL Qingdao Shiyuan (as built)

The RRC in Qingdao is sized for a catchment area with 12,000 population equivalent (based on 100 gCOD/(C·d) with 12.3 g COD/(C·d) in greywater and 87.7 gCOD/(C·d) in blackwater; chemical oxygen demand (COD)). The catchment area currently consists of two newly built housing areas and the so-called ShiYuan village, where three hotels, office buildings, guest houses, and canteens are located. A further residential area will be developed and connected to the RRC in Qingdao ShiYuan. At the actual location, the catchment area does not consist of a purely residential area, as assumed for the reference design. Due to the hotels, the specific greywater production is expected to be higher (see below). At present, the two existing residential areas are not supplied with service water; for the third residential area, as well as for the ShiYuan village, the reuse of treated greywater for toilet flushing is planned. Treated blackwater is reused for irrigation; thus, multiple reuse is realized. Instead of biowaste, food waste is co-digested with sludge. The amount of food waste is lower than the amount of biowaste in the reference design.

Conventional system A

The same wastewater flow and loads as for the RRC in Qingdao ShiYuan are assumed. For wastewater treatment, the same process technology as for blackwater treatment in the RRC in Qingdao ShiYuan is chosen. Therefore, the influence of source separation and integration of water and waste sectors, rather than of process technology, is investigated.

Conventional system B

The same wastewater loads are calculated but with a higher wastewater flow. With the chosen flow rate, the resulting concentrations are in the typical range for municipal wastewater in China. In China, the influent concentration is usually considerably lower than that estimated for the RRC in Qingdao ShiYuan, either because of higher water consumption and/or due to dilution with sewer infiltration water.

RESULTS

First realization of an RRC in Qingdao ShiYuan – process technology

Wastewater characteristics

Total wastewater loads are estimated according to the GB 50101-2005 standard (the basis for the design of wastewater treatment plants in China) and the load proportion in grey- and blackwater according to Bi (2004). The specific COD and biological oxygen demand (BOD) load in blackwater is higher than reported in literature (e.g., 50 gCOD/(C·d) and 32 gBOD/(C·d) by Meinzinger & Oldenburg (2009) for excreta, or 74 gCOD/(C·d) by Todt *et al.* (2015)). Usually, blackwater is wastewater from toilets; in contrast, the blackwater flow to the RRC in Qingdao additionally includes kitchen wastewater. Thus, a higher specific organic load is calculated (see Table 2). An inhabitant-specific wastewater amount of 109 L/(C·d) is assumed according to Bi (2004) for the dimensioning of the RRC. This corresponds well with the water consumption of 111 L/(C·d) in 2012 in Qingdao (China Statistics Press 2013). For the hotels in the catchment area, the specific greywater production is expected to be higher (150 L/(guest·d) or 300 L/(guest·d) for 3-star and 5-star hotels), leading to a hydraulic population equivalent of 17,500 instead of 12,000, or an increase in the average inhabitant-specific amount of greywater from 41 to 60 L/(C·d). The C/N ratio

Table 2 | Influent characteristics – comparison of data for RRC Qingdao and literature values for China

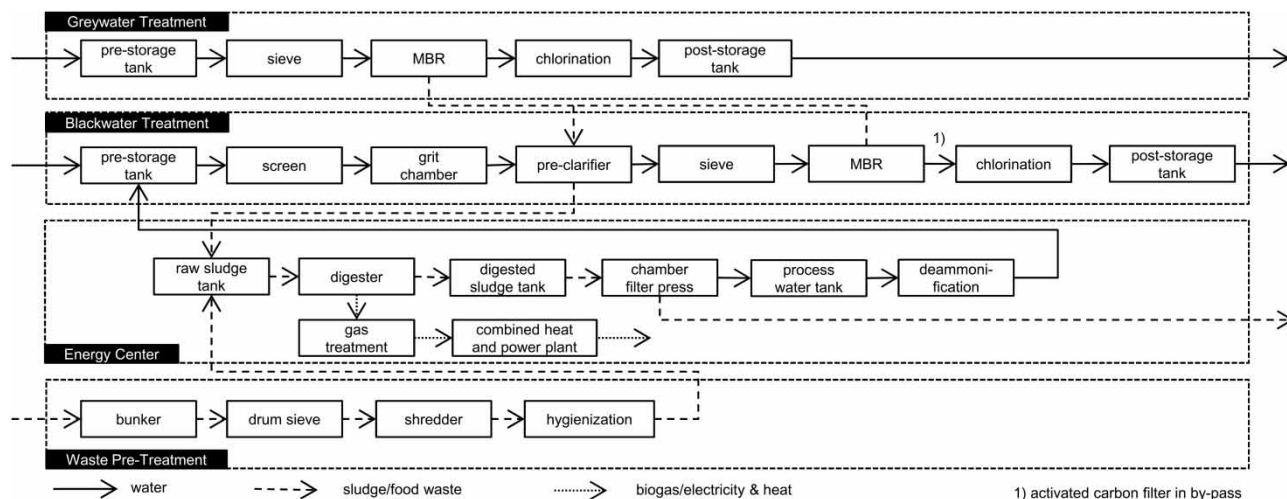|	GB 50101–2005	RRC Qingdao (and reference design[1])			Mean values in China[2]	RRC Qingdao (and reference design)		
	WW	Total	GW	BW	WW	Total	GW	BW
	Load g/(C·d)				Concentration mg/L			
COD	–	100	12.3	87.7	300–440	781 (917)	206 (300)	1,290
BOD	25–50	50	4.9	45.1	–	391 (459)	82 (120)	663
SS	40–65	65	10.3	54.8	–	508 (596)	171 (251)	805
TN	5–11	11.3	0.3	11	34–40	88 (104)	5 (7)	162
TP	0.7–1.4	1.56	0.16	1.4	4–5.4	12 (14)	3 (4)	21
Q in L/(C·d)	–	128 (109)	60 (41)	68	–	–	–	–

[1]Bi (2004); [2]Qiu et al. (2010); GW – greywater; BW – blackwater; WW – wastewater; SS – suspended solids; Q – flow.

in total wastewater is low, but not unusual. In China, COD often has to be dosed, because denitrification is impeded by the low C/N ratio (Xiao et al. 2014).

Legal limits for the effluent and process technology

SEMIZENTRAL is, fundamentally, an open-process approach: the choice of process technology depends on local conditions. Hereby, 'fit for purpose' is the basic principle. In Qingdao ShiYuan, the treated greywater is reused for toilet flushing; treated blackwater is reused for irrigation. The surplus water is discharged. Therefore, for both treatment modules, the Chinese Standard GB/T 18920-2002 for

urban water reuse as well as the discharge standard GB 18918-2002 Class 1A have to be fulfilled. For irrigation, a limiting value for total nitrogen is not given; for NH₄-N, the legal limit is 20 mg/L. In urban areas, the blackwater flow is assumed to be higher than the demand for irrigation water; therefore, nutrient elimination is necessary to meet the discharge standard. To realize a multi-barrier concept, because of high quality requirements for water reuse (colony forming unit (CFU) < 3/L, see GB/T 18920-2002), a membrane bioreactor (MBR) followed by chlorine disinfection is chosen for greywater as well as for blackwater treatment (see Figure 1). Disinfection by chlorination is required by the standard for urban water reuse.

Figure 1 | Process technology of RRC Qingdao ShiYuan.

Greywater treatment

Due to the presence of an influent storage tank, an equalization of flow and loads to the MBR is possible. The pre-treatment consists of a 1 mm sieve for the removal of fibrous substances. The nitrogen influent concentration for greywater is very low (see Table 2), hence the removal of organic carbon is sufficient. Nevertheless, a sludge age of 25 days for reducing membrane fouling processes is recommended (Meda *et al.* 2012). To equalize service water demand and production, a storage tank after chlorination has been built.

Blackwater treatment

The pre-treatment of blackwater consists of a screen, grit chamber, primary clarifier, and a sieve (see Figure 1). Because of high estimated phosphorus (P) influent concentrations (27 mg/L for blackwater including pre-treated process water from digestion of food waste and sludge) and the low legal limiting value for the effluent (0.5 mg/L), P is removed by pre-precipitation in the primary clarifier, as well as by simultaneous P-precipitation. Due to pre-precipitation, the C/N ratio is markedly decreased, compared to pre-clarification without precipitation. Therefore, with regard to denitrification, the necessity for pre-precipitation should be evaluated during operation: the P-load in process water might be lower. To improve the C/N ratio, the (partial) bypass of the pre-clarifier should be considered. Special attention had to be paid to the planning of the denitrification of blackwater, because of the high influent concentration and the required high N-elimination rate. Denitrification occurs through a combination of pre-denitrification and post-denitrification with external organic carbon dosage (Tolksdorf *et al.* 2015). The effluent has to meet the limit of 30 degrees for color (GB 18918-2002; GB/T 18920-2002), which cannot be guaranteed with biological treatment alone (Knerr *et al.* 2011; Cornel *et al.* 2013). The yellowish color originates from refractory organic substances, although their origin, either from urine/feces or from metabolic by-products, is undetermined (Abegglen *et al.* 2009). Therefore, an activated carbon filter after the membrane filtration has been built, in case decolorization is required.

Food waste pre-treatment and energy center

Prior to co-digestion, mechanical pre-treatment of the food waste with a drum sieve and a shredder for homogenization and removal of impurities is necessary. In China, hygienization of waste is not required. Therefore, the planning was oriented to European Regulation No. 1774/2002. Compared to the reference design, an additional hygienization step (heating to 70 °C for 1 hour) is necessary. For biowaste, a thermophilic anaerobic treatment with a hydraulic retention time of 20 d would have been sufficient. Following the thermophilic co-digestion, the digested sludge is dewatered by a chamber filter press. To reduce the N return load, the sludge water (process water) is pre-treated with a deammonification process prior to its discharge to the blackwater module.

Influence of site adaptation

The site adaptation of the general approach (reference design) to the actual site (RRC Qingdao ShiYuan) influences the nutrient balance and the treatment efforts.

Increased greywater volume, decreased service water demand

Compared to the reference design, the effluent flow to the water body in Qingdao ShiYuan is higher (see Figure 2). Greywater has a very low influent nitrogen concentration of 5–7 mg/L (see Table 2); the expected very low effluent concentration of 1.5–2.1 mg/L results from biomass intake alone. For this reason, the discharged nitrogen load is only slightly increased. By contrast, the TP influent concentration of greywater (3–4 mg/L) is assumed to be above the legal limit. Therefore, TP has to be removed by precipitation to reach the required effluent concentration (0.5 mg/L). Consequently, the treated greywater contributes significantly to the discharged TP load (160 g/d from treated greywater in 440 g/d total discharged TP load). In the reference design, considerably less treated greywater, and therefore TP, is discharged (20 g/d with treated greywater, 300 g/d in total). Due to the increased greywater volume, the energy demand for greywater treatment increases (see Figure 3, right). A larger membrane area, and therefore higher cross-flow aeration, is necessary. The cross-flow aeration is the
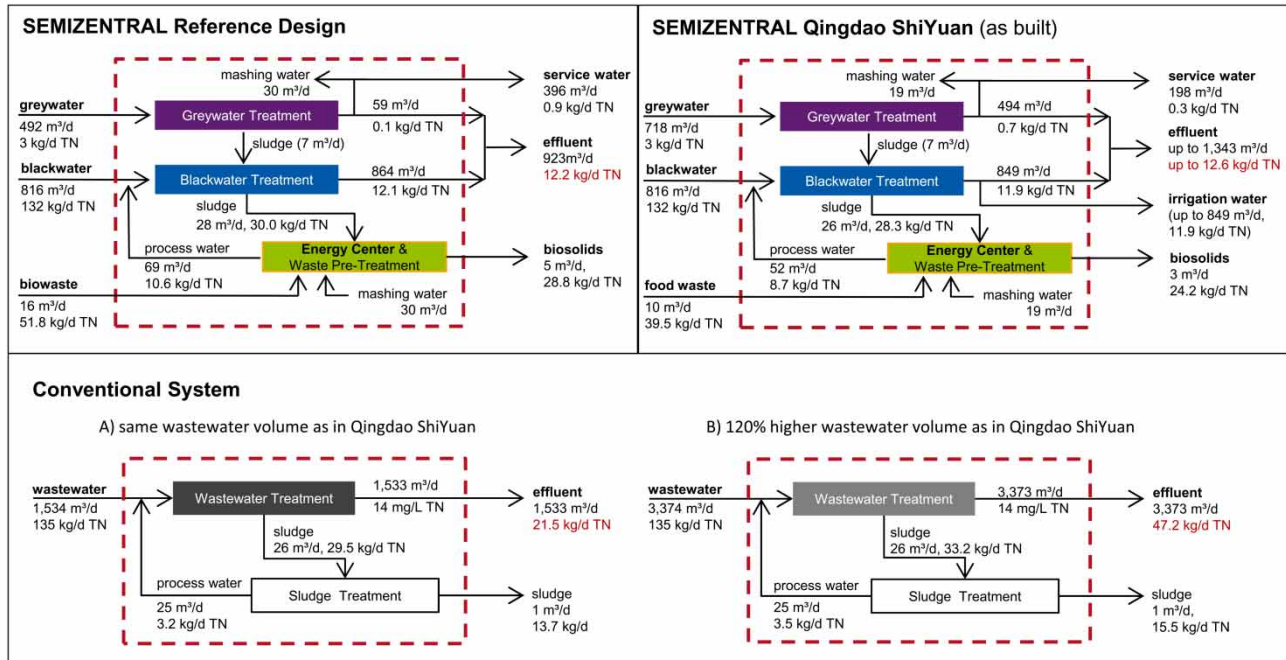
Figure 2 │ Nitrogen balance – comparison of SEMIZENTRAL and conventional systems.
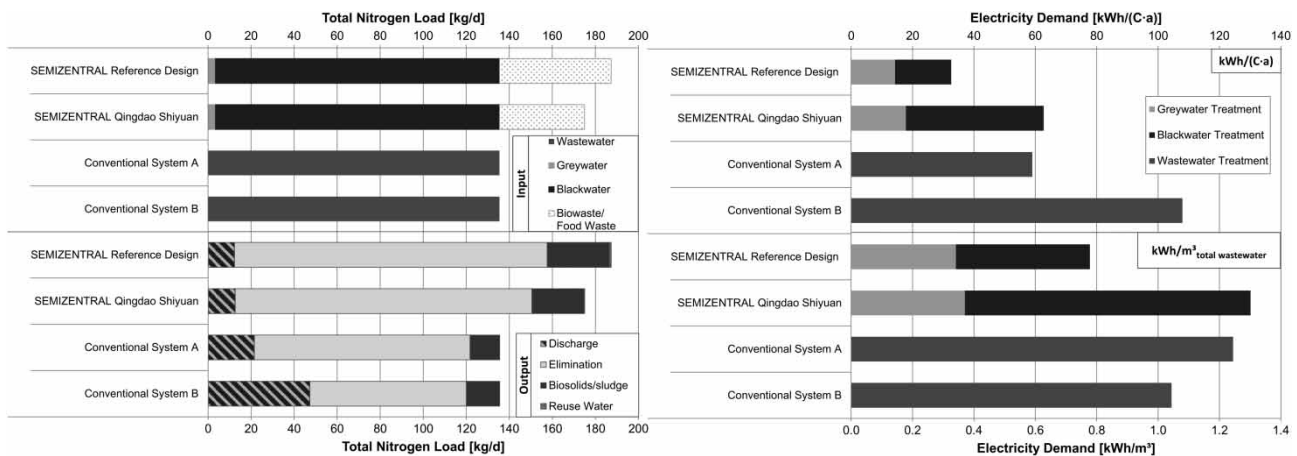

Figure 3 │ Nitrogen loads (left) and electricity demand (right) for SEMIZENTRAL and conventional systems.

largest electricity consumer in the greywater module; therefore, the energy demand for greywater treatment depends strongly on the flow rate.

Reuse of treated blackwater for irrigation

As described above, blackwater treatment in the RRC in Qingdao ShiYuan occurs in an MBR. For the reference design, the sequencing batch reactor (SBR) was chosen, because the SBR process is sufficient to meet the legal limit for discharge (Class 1A GB 18918-2002). Therefore, in contrast to the reference design, the mechanical pre-treatment is supplemented by a sieve (see Figure 1) in the RRC in Qingdao ShiYuan, to avoid problems at the membrane modules. However, this results in a further decrease of the already low C/N ratio to the

biological step, because the sieve does not remove nitrogen but only COD. A by-pass of the sieve is not recommended. For this reason, the required COD dosage for denitrification is higher for the RRC in Qingdao ShiYuan, despite the fact that almost the same nitrate load has to be denitrified (see Table 3). Due to water reuse for irrigation, the discharged nutrient load can be considerably decreased (see Figure 2); depending on the recycle rate: TN down to 0.7 kg/d and TP down to 0.16 kg/d (compared to 12.2 and 0.3 kgP/d for the reference design). However, the MBR process needs considerably more energy than the SBR process (see Figure 3), mainly for cross-flow aeration, permeate and sludge recirculation pumps.

Co-substrate – food waste instead of biowaste

Food waste has higher estimated nitrogen content (2.0% of dry solids (DS)), compared to biowaste (1.6% of DS). However, because of the local boundary conditions, the amount of co-treated food waste is lower than the co-treated biowaste in the reference design. Therefore, the nitrogen load to the RRC in Qingdao ShiYuan, as well as the corresponding N return load from the sludge and biowaste treatment to the blackwater treatment, are lower than in the reference design (see Figure 2). In the reference design, the excess sludge production is higher (see Table 3) because of lower sludge age (16.5 d instead of 25 d) and higher COD influent concentration to the biological treatment step (because less COD is removed by pre-treatment). Therefore, more nitrogen is bound in the sludge, and nearly the same ammonia load has to be nitrified and the same nitrate load denitrified as in the realized RRC in Qingdao ShiYuan (see Table 3). Food waste has a higher organic content and methane yield than biowaste. Consequently, the biogas production in the RRC in Qingdao ShiYuan is only 14% less than in the reference design, although 37% less waste (based on DS load) is co-digested. However, there are uncertainties regarding the composition of food waste. Therefore, the biogas actually produced in the RRC in Qingdao ShiYuan might differ from the currently calculated production. Nevertheless, a self-sufficient operation of the RRC in Qingdao ShiYuan may be possible.

Influence of integrated systems on water quality and energy balance

Discharged nutrient load

Due to separated collection of greywater and blackwater, the concentration levels to the treatment plant and the C/N ratio change. Because of the low nutrient influent concentration in the greywater, the organic carbon removal is sufficient and low nitrogen effluent concentrations can be reached. Blackwater, in contrast, is highly concentrated, compared to total wastewater (see Table 2); the N return load is increased by co-treatment with food waste. For blackwater treatment, the same legal limit (15 mg/L inorganic nitrogen) as for a conventional wastewater treatment plant is required. Therefore, an elimination rate of 91% for nitrogen in blackwater is necessary. In comparison with conventional system A (with the same wastewater volume and loads), 14% more NO_3-N has to be denitrified in the RRC in Qingdao ShiYuan (see Table 3). The C/N ratio in blackwater (7.9) is lower than in total wastewater (8.8). In the influent to the biological step, the C/N ratio of blackwater is 5.5, compared to 6.1 in conventional systems. In sum, a 42% higher external organic carbon dosage is calculated for the RRC in Qingdao ShiYuan. Because of this, together with the reduced discharged water flow due to water reuse, the effluent nitrogen load is considerably lower (at least 41%, see Figure 3). Because the discharged water amount is decreased by 12%, the discharged TP load declines by the same proportion.

For conventional system B, the water flow is 120% higher than in the RRC in Qingdao ShiYuan, resulting in influent concentrations that are common in China. Although the same influent load as in conventional system A is assumed, no COD dosage is needed for denitrification. Because the TP influent concentration in conventional system B is relatively low, no pre-precipitation is calculated. As a consequence, the C/N ratio is not decreased as much by pre-clarification as in conventional system A (see Table 3). Moreover, considerably less NO_3-N has to be denitrified. However, under this boundary condition, discharged TN and TP loads are 3.7 and 2.5 times higher, respectively, compared to the RRC in Qingdao ShiYuan (see Figure 3).

Table 3 | Data from design calculation

	RRC reference design		RRC Qingdao ShiYuan		Conventional system A	Conventional system B
	BW	GW	BW	GW	WW	WW
Influent (incl. process water)						
Q [m³/d]	885	492	868	718	1,559	3,399
COD [mg/L]	1,271	300	1,281	206	782	359
TN [mg/L]	161	7	162	5	89	41
TP [mg/L]	26	4	27	3	15	7
C/N ratio influent (incl. process water)	7.9	42.9	7.9	42.9	8.8	8.8
C/N ratio influent aeration basin	6	38.6	5.5	38.6	6.1	6.5
Effluent concentration (mean values according to design calculation)						
COD [mg/L]	<50	<50	<50	<50	<50	<50
TN [mg/L]	14	2.1	14	1.5	14	14
TN removal	91%	70%	91%	69%	84%	66%
TP [mg/L]	0.33	0.33	0.33	0.33	0.33	0.33
TP removal	99%	92%	99%	88%	98%	95%
Dimensioning and operation parameters (according to design calculation)						
$V_{required}$ [m³]	1,731	201	755	199	800	1,014
SRT [d]	16.5	25	25	25	25	25
HRT [h]	47	10	21	7	12	7
MLSS [g/L]	3.5	10	10	10	10	10
Net flux [L/m²/h]	- (SBR)	17.5	11.3	18.7	12.5	13.1
Elimination process (according to design calculation)						
NO_3-N denitrified [kg N/d]	104	–	103	–	90	61
COD dosage [kg COD/d]	260	–	287	–	202	–
NH_4-N nitrified [kg N/d]	110	–	109	–	101	84
O_{air} [Nm³/d]	647	52	638	52	627	629
Primary sludge production [kg DS/d]	456	–	452	–	525	390
Excess sludge production [kg DS/d]	355	80	302	80	320	405
Electric energy demand for GW, BW, WW treatment [kWh/(C·a)]						
Influent pumps	2.0	1.0	1.9	1.4	3.5	7.7
Aeration (biol.)	13.4	1.0	13.4	1.0	13.0	13.0
Filtration + cross-flow aeration	–	9.1	23.3	10.6	38.2	79.5
Effluent pumps	–	1.7	1.6	0.9	–	–
Others	2.9	1.5	4.7	4.0	4.3	7.7
Sum	33		63		59	108
Electric energy production [kWh/(C·a)]	110		95		12	11

GW – greywater; BW – blackwater; WW – wastewater; SRT – sludge retention time; MLSS – mixed liquor suspended solids.

Thus, with regard to the protection of local water resources, the SEMIZENTRAL approach is advantageous.

Energy demand

The energy demand for grey- and blackwater treatment in the RRC in Qingdao ShiYuan is slightly higher than for wastewater treatment in conventional system A, because of the higher nitrification, and therefore higher energy demand for aeration. Due to the co-digestion with food waste in the RRC in Qingdao ShiYuan, the biogas production increases markedly (see Table 3). For this reason, even with the higher energy demand, energy self-sufficient operation of the RRC in Qingdao ShiYuan is possible, depending on the amount of co-treated food waste. If the wastewater flow is considerably higher (conventional system B), the electrical energy consumption increases, although the requirement for nutrient elimination decreases (see Figure 3). A larger membrane area and, therefore, more cross-flow aeration is needed. If the electrical energy consumption is related to the treated wastewater flow, conventional system B has the lowest specific energy demand (1 kWh/m³) compared to 1.2 kWh/m³ for conventional system A and 1.3 kWh/m³ for the RRC in Qingdao ShiYuan (0.8 and 1.7 kWh/m³ for greywater and blackwater treatment, respectively). Here, the nitrogen elimination rate, rather than the wastewater volume, is crucial.

The average electrical energy consumption for a municipal wastewater MBR built after 2010 in China is 0.5 kWh/m³ (range: 0.4–0.6 kWh/m³) (Xiao *et al.* 2014), and thus smaller than the calculated consumption for the RRC in Qingdao ShiYuan and even for conventional system B. The MBR plants in China usually have a higher capacity (10,000–50,000 m³/d) (Xiao *et al.* 2014). The energy calculation in this study has been performed with the boundary conditions for the RRC in Qingdao ShiYuan. Thus, e.g., lower motor efficiency due to low nominal power is assumed. Moreover, because of the topography of the catchment area, a high discharge head for the influent pump is needed. Nevertheless, the comparability of nitrogen elimination might not be given; no detailed data are provided by Xiao *et al.* (2014). In China, 58.5% of the wastewater treatment plants have the discharge standard class 1B (Jin *et al.* 2014), which corresponds to an inorganic nitrogen effluent concentration of 20 mg/L.

Furthermore, according to experts (sufficient data on nutrient removal efficiency in China are lacking), 90% of treatment plants in China have problems with nutrient removal; about 50% cannot meet the discharge standard (Jin *et al.* 2014).

CONCLUSIONS

The adaptation to the actual location in Qingdao ShiYuan influences in- and output flows, discharged nutrient load, and the energy balance. The chosen co-substrate, as well as its amount, has the main influence on the potential for an energy self-sufficient operation of the RRC. The additional nitrogen load delivered by the co-substrate to the RRC treatment processes and, consequently, the increased treatment efforts, should be considered. The degree of water reuse mainly influences the discharged nutrient load. Therefore, a high water reuse rate can protect water bodies, in addition to reducing the usage of local water resources. Compared to conventional systems, the nutrient load discharged by the RRC is lower, but the usage of chemicals (such as external carbon and precipitant) and energy is higher. A site-specific evaluation of pros and cons is necessary. The influent concentration to the treatment plant is an important factor: higher influent concentrations at constant effluent concentrations lead to greater treatment effort. More decentralized systems (with shorter sewers and, possibly, pressure mains) as well as increasing awareness of the necessity to save water might lead to increased influent concentrations.

In Qingdao, water for the future development of housing and industry needs to be produced partly by seawater desalination. This needs 3–4 kWh/m³ (Ghaffour *et al.* 2013). For service water production from grey- and blackwater in the RRC in Qingdao ShiYuan, 0.8 and 1.7 kWh/m³ are calculated, respectively. Therefore, using the produced service water saves energy. With respect to China's current energy mixture, with its high proportion of fossil fuel, this represents a contribution to the reduction of greenhouse gases.

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