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Circular Economy in Wastewater Treatment Plant–Challenges and Barriers †

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Abstract: The urban wastewater treatment plants can be an important part of circular sustainability due to integration of energy production and resource recovery during clean water production. Currently the main drivers for developing wastewater industry are global nutrient needs and water and energy recovery from wastewater. The article presents current trends in wastewater treatment plants development based on Circular Economy assumptions, challenges and barriers which prevent the implementation of the CE and Smart Cities concept with WWTPs as an important player. WWTPs in the near future are to become "ecologically sustainable" technological systems and a very important nexus in SMART cities.

Keywords: circular economy; wastewater treatment plant; resource recovery

1. Introduction

The circular economy (CE) is the concept in which products, materials (and raw materials) should remain in the economy for as long as possible, and waste should be treated as secondary raw materials that can be recycled to process and re-use [1]. This distinguishes it from a linear economy based on the, 'take-make-use-dispose' system, in which waste is usually the last stage of the product life cycle. CE is a concept promotes sustainable management of materials and energy by minimalizing the amount of waste generation and their reuse as a secondary material. The main reasons for implementing a circular economy in Europe include: limited availability of raw materials, dependence of the European economy on the import of raw materials (high prices, market volatility, uncertain political situation in selected countries), and decreasing competitiveness of the European economy in global economies.

The urban wastewater treatment plants (WWTPs) can be an important part of circular sustainability due to integration of energy production and resource recovery during clean water production [2,3]. WWTPs in the near future are to become "ecologically sustainable" technological systems. Over the past 25 years though, a number of major drivers emphasize the need of the recovery of the resources available in the wastewater. The main drivers for developing wastewater industry are global nutrient needs and recovery of water and energy from wastewater.

In May 2014, phosphate rock was listed as a critical raw material by European Commission so its recovery from renewable resources has gained importance [4]. Cordell et al., estimated that 20% of the mineral phosphorus consumed is excreted by humans [5]. It is also estimated that it is technically possible to supply the mineral phosphorus market by recourses at excreta streams (including domestic animals). Potassium has not affected economic impact like phosphorus on farming however it could be fully serviced from waste stream while nitrogen market on the level of

50%. Moreover, effluent from WWTP can be recycled for agricultural, industrial processes and other beneficial purpose reducing demand for potable water.

Most of the WWTPs are designed to meet the requirements for the effluent quality without consideration of energy requirements. According to the European Benchmarking Cooperation [6], the average electricity consumption for wastewater treatment was 33.4 kWh/PE. The WssTP report [7] shows the values of energy consumption in Europe at sewage treatment plants by means of activated sludge at the level of 0.15–0.7 kWh/m^3. The average energy consumption in Germany, the United Kingdom, the Netherlands and the United States is 0.67, 0.64, 0.47 and 0.45 kWh/m^3, respectively, and for Italy values between 0.40 and 0.70 kWh/m^3 have been measured. Depending on the type of plant [8]. Because sustainable supplies of water and energy is strongly connected with carbon emission the energy-water nexus has become the main topics of current policy research.

The article presents current trends in WWTPs development based on Circular Economy assumptions as well as challenges and barriers which prevent the implementation of the CE and Smart Cities concept with WWTPs as an important player.

2. Resources Recovery at Wastewater Treatment Plant

2.1. Nutrient Recovery

Nutrient recycling from WWTPs has positive impact on environment by reducing the demand of conventional fossil-based fertilizers and consequently, reduce the consumption of water and energy. It is possible to recover nutrient from raw wastewater, semi-treated wastewater streams and sewage sludge (biosolids) [9]. Land application of biosolids are the oldest method which use wastewater treatment by-product as a fertilizer and covered their spreading on soil surface or injection into the soil. Those biosolids before application can be treated at WWTP by the following process: anaerobic or aerobic digestion, composting, drying and chemical treatment (mostly alkaline treatment). Land application of sewage sludge is widely practiced in Europe and other countries. In 2015 about 968 thousand of Mg of sewage sludge were used in agriculture [10]. In Europe application of sewage sludge in agriculture is mostly practiced in Germany and France. The main problems associated with this direction of biosolids disposal are the health and safety issues, odour, nuisance and public acceptance.

Phosphorus recycling from wastewater, beyond directly land application, can be achieved through technical recycling from sewage sludge or wastewater, and from ashes of incinerated sludge. Currently, phosphorus is recycled at WWTPs mainly by struvite crystallization process e.g., Pearl, NuReSys, and AirPrex technologies which have been implemented at full scale [11]. Currently, in Europe more than 2000 Mg P/year is technically recovered [12]. The main problems associated with struvite crystallization are the high chemical costs and unintentional struvite formation which leads to blocking of valves, pipes, pumps etc.

Another option for nutrient recovery is urine separation from the main wastewater stream. It is estimated that about 70–80% of nitrogen and 50% of phosphorus is contained in urine, which can be theoretically recovered on the level of 70% using the urine-collecting system in toilets [13]. The urine-collecting system is widely used in developed country when urine is applied for land application. Due to serious technical problems and public acceptance this technology has not been widely used in developed countries.

Nutrients can be also recovered through aqua-species which utilize these compounds in wastewater and then can be used as a fertilizers or animal feeds [14]. For this purpose the following aqua-species could be used: microalgae, crops, wetland plants, duckweed, and so on. Recovering nutrients through aqua-species is recognizing as an environmental friendly technology mainly due to low energy demand and synergy effects between wastewater treatment and nutrient recycling. Despite this technology is not widely used. The only technology which is used in technical scale is constructed wetlands however its application is not covered with nutrients recycle for secondary use.

2.2. Water Reuse

The reuse of treated wastewater from WWTPs for agriculture and land irrigation, industrial purposes, toilet flushing, and groundwater replenishing is key element of currently implemented strategy focused on releasing freshwater for domestic use, improvement the WWTPs effluent quality and as a consequence higher quality of river waters used for abstraction of drinking water [15]. The use of treated wastewater for irrigation in agriculture has been known for many years and can provide to replace of the agriculture demand and reduction of local water stress. In addition, nutrients contained in the wastewater reduce the need for application of commercial fertilizers. It is recommended to use effluent from secondary treatment to irrigation of non-food crops while effluent from tertiary treatment for irrigation of food crops.

Urban wastewater reuse may be planned (direct or indirect) or unplanned which is mostly connected with non-potable uses, however there are cases of unplanned potable reuse. Urban water reuse concerns mainly residential irrigation and commercial use for fire protection, car wash, toilet flushing, etc. The main problems associated with urban reuse are: risks to human health and high cost of dual systems for the reclaimed water delivery. Florida (USA) is the leading state in urban reuse where more than 45% treated wastewater is used for landscape irrigation [16].

In indirect potable reuse high quality WWTP effluent is discharged directly into groundwater or surface water sources with the intent of augmenting drinking water supplies. Another solution can be direct potable reuse (pipe to pipe) by directly introduction of treated wastewater into a water distribution system [17]. However, direct potable reuse strongly increases operational cost due to very high effluent quality requirements. The lack of social acceptance is also important.

2.3. Energy Recovery

Energy recovery at wastewater treatment plants represents an important policy lever for sustainability. It can be done through biogas production, heat pumps in treatment plant effluents, and energy recovery from various high temperature streams by heat exchanger [18].

The biogas produced in a digester via anaerobic digestion (AD) has the energy potential of 6.5 kWh/m^3 (65% methane content) and is the main energy source in WWTP. It was estimated that WWTPs with sludge digestion consume about 40% less net energy than wastewater treatment plant without AD digestion. Gas generation can fluctuate from 0.75 to 1.12 m^3/kg of volatile solid destroyed, while the low heating value of biogas is approximately 22.4 kJ/m^3. The biogas can be used for heating and/or electricity generation. The most adopted technology in the existing self-sufficient WWTPs is Combined Heat and Power (CHP) technologies which generate both electricity and heat from biogas at the same time.

Enhancement of AD efficiency is a common practice to increase the energy self-sufficiency of WWTPs. The optimizations of AD include different pretreatment methods of sewage sludge aiming to higher biodegradability of sludge. Those methods can be divided in mechanical, thermal, chemical and biological as well as different combination of them [19]. Currently the most common technologies available on the market are mechanical and thermal pretreatments. Thermal hydrolysis (THP) technologies like Cambi, Biothelys, Exelys are the most spread technologies used to improve anaerobic digestion in WWTPs. It was observed a 50% higher biogas production in a shorter hydraulic retention time (HRT) (12–15 days) in the first WWTP in North America which applied CAMBI technology (Washington, DC, USA).

Co-digestion of sewage sludge with other biodegradable waste is another option which provides a range of economic and environmental benefits [20]. Co-digestion of organic waste in combination with sewage sludge does not only allow WWTPs to be energy-neutral but also reduce the cost of municipal and industrial organic waste management. For example, co-digestion of sewage sludge with six different co-substrates has been implemented in Mossberg (Germany) for 10 years. The heat and energy production at Mossberg WWTP is significant higher than the internal demand of WWTP. Excess energy produced is fed into the grid, while excess heat is used to dry dewatered sludge from other WWTPs.

Reliable and economical sources of heat for use in heat pumps (HP) are the effluents from municipal WWTPs plants [21]. The heat from HPs can be used for heating and cooling of residential, social and administrative buildings of the plant and/or neighboring infrastructure. The first installations were built more than 20 years ago. Currently heat pumps using wastewater are widely applied in Europe, USA, Japan, South Korea, and China. Thermal ratings of HPs range from 10 kW to 20 MW.

HIAS WWTP in Hamar and Oslo Water and Sewage Works are the national leading utilities in Norway for HP energy recovery in WWTP with over 30 years of experience. It was estimated that HP systems can deliver an effect of 3 MW. The annual energy delivery from the heat pump system is approx. 4000 MWh, while heat pump consumption is 6000 MWh per year [22].

It should be noted that WWTPs employing high temperature sludge treatment processes (i.e., AD digestion, THP, thermal drying) should take into account the possibility of implementing heat exchangers to recover energy from all streams with high temperature (sludge, reject water, condensate, etc.). The recovered energy can be used different purposes i.e., water heating, sludge heating, etc.

2.4. Other Resources

The use of sewage sludge in the construction industry fits perfectly into the CE assumptions. The sewage sludge ash can be used for building materials manufacturing, such as produce bricks or tiles. Moreover it can be used as a row materials for production of cement, concrete, mortal, and lightweight materials, etc.

It is also possible and economically profitable to recover from the ashes that remain after burning sewage sludge, such valuable elements as copper, silver or gold [23]. Researchers at the world's leading technical universities also conduct research work on biotechnology for wastewater treatment, giving the opportunity to produce biodegradable plastics from polyhydroxyalkanoates (PHA) accumulated in biomass developing in wastewater treatment reactors [24]. Similarly, attempts are made to directly generate electricity during the process of removing contaminants from waste water using Biological Fuel Cells (BFCs) [25].

3. Wastewater Treatment Plants in SMART Cities

Circular economy is aimed on optimization of circle system functions by reduction of resources escaping from the system [26]. Moving toward more CE can help to deliver assumptions of the resource efficiency agenda established under the Europe 2020 Strategy for smart, inclusive and sustainable growth.

Smart cities concept is pragmatic and balanced combination of social, economic, ecological, and other important field for perfect sustainable development. Ecological cities worldwide share a common goal: "to enhance the well-being of citizens and society through integrated urban planning and management that fully harnesses the benefits of ecological systems, and protects and nurtures these assets for future generations".

WWTPs slow become an important nexus of SMART city. Figure 1 shows the intelligent wastewater system concept in which WWTPs not only treat wastewater with efficiency that allows effluent reuse but also generate energy and produce fertilizers [27,28]. More and more cities around the world are implementing SMART concepts in their area. An example is Sweden where the City of Borås, has developed project in which WWTP will be collocated with the local power plant and will contribute renewable fuel for a city power plant [29]. The aim of this recycling model is to convert the energy of the city's waste streams into renewable valuables, and create a city free from fossil fuels.

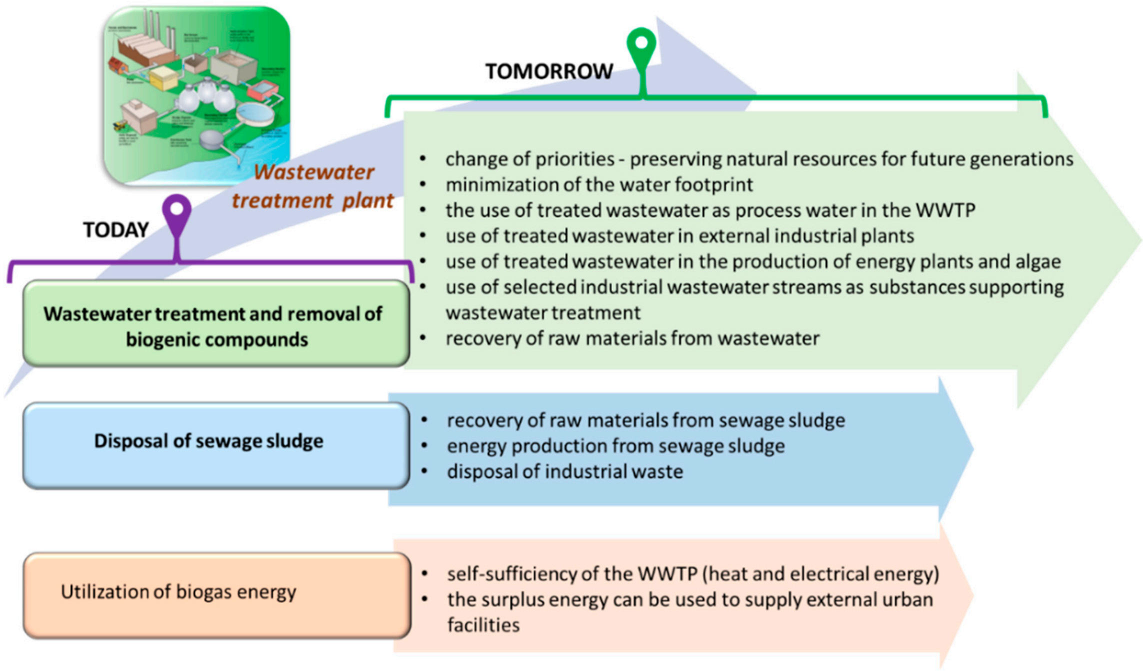

Figure 1. WWTP today and in the future.

4. Challenges of the Future

It is clear that priority is that implementation of a cost-effective and high-performance wastewater treatment system [29,30]. But if we think of WWTP as an important nexus in the cities of the future, the priorities of wastewater treatment plants must expand (Figure 2).

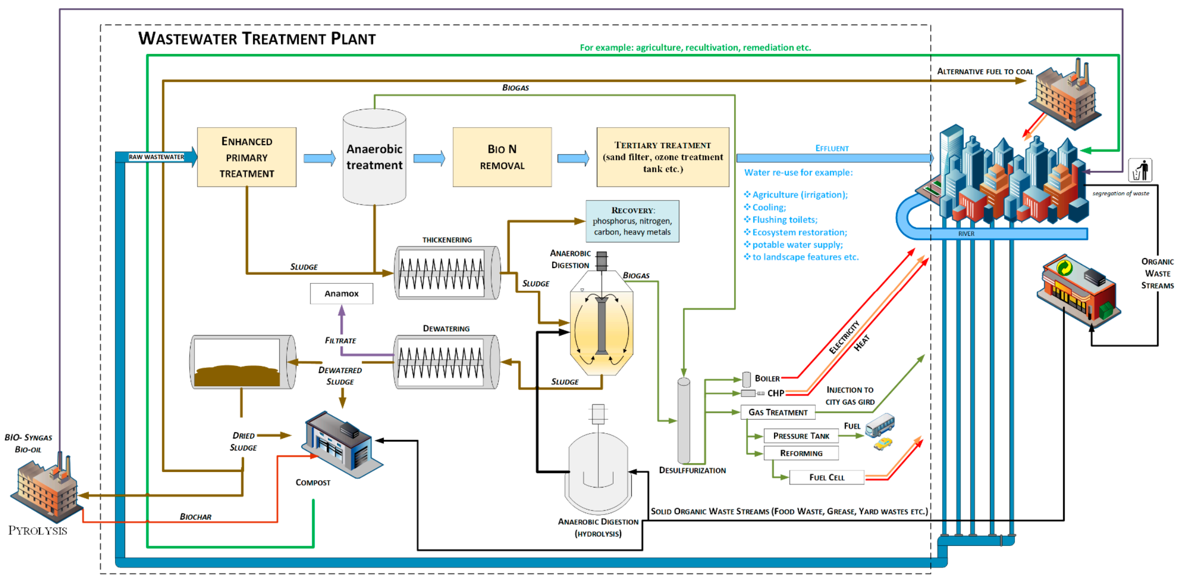

Figure 2. WWTP place in Smart City in the future.

5. Conclusions

Municipal wastewater treatment plants can ply important role in helping cities toward a sustainable future, characterized by circular flow of water, waste, material and energy. WWTPs are beginning to be perceived not only in the traditional role of wastewater and sewage sludge treatment, but also in the new role associated with resources and energy recovery. WWTPs in the near future are to become "ecologically sustainable" technological systems and a very important nexus in SMART cities.

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References

1. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32, doi:10.1016/j.jclepro.2015.09.007.
2. Rashidi, H.; GhaffarianHoseini, A.; GhaffarianHoseini, A.; Sulaiman, N.M.N.; Tookey, J.; Hashim, N.A. Application of wastewater treatment in sustainable design of green built environments: A review. *Renew. Sustain. Energy Rev.* **2015**, *49*, 845–856, doi:10.1016/j.rser.2015.04.104.
3. Mo, W.; Zhang, Q. Energy–nutrients–water nexus: Integrated resource recovery in municipal wastewater treatment plants. *J. Environ. Manag.* **2013**, *127*, 255–267, doi:10.1016/j.jenvman.2013.05.007.
4. Commission Staff Working Document. Summary of the Responses to the Consultative Communication on the Sustainable Use of Phosphorus [COM(2013) 517]. Available online: http://ec.europa.eu/ environment/natres/pdf/phosphorus/SWD(2014)263%20final.pdf,accessed (accessed on 20 February 2018).
5. Cordell, D.; Drangert, J.O.; White, S. The story of phosphorus: Global food security and food for thought. *GEC* **2009**, *19*, 292–305, doi:10.1016/j.gloenvcha.2008.10.009.
6. EU Reference Scenario 2016 Energy, Transport and GHG Emissions Trends to 2050. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf (accessed on 20 February 2018).
7. WssTP. Water and Energy: Strategic Vision and Research Needs. The Water Supply and Sanitation Technology Platfor. Available online: http://www.danishwaterforum.dk/activities/WssTP_Water_ and_Energy_Publication%2009_2011.pdf (accessed on 20 February 2018).
8. Cantwell, J.; Dunning, J.H.; Lundan, S.M. An evolutionary approach to understanding international business activity: The co-evolution of MNEs and the institutional environment. *JIBS* **2010**, *41*, 567–586.
9. Zhang, Q.; Hu, J.; Lee, D.J.; Chang, Y.; Lee, Y.J. Sludge treatment: Current research trends. *Bioresour. Technol.* **2017**, *243*, 1159–1172, doi:10.1016/j.biortech.2017.07.070.
10. Eurostat. 2017. Available online: http://ec.europa.eu/eurostat/web/products-datasets/product?code =env_ww_spd (accessed on 20 February 2018).
11. Hukari, S.; Hermann, L.; Nättorp, A. From wastewater to fertilisers—Technical overview and critical review of European legislation governing phosphorus recycling. *Sci. Total Environ.* **2016**, *542*, 1127–1135, doi:10.1016/j.scitotenv.2015.09.064.
12. Kabbe, C.; Kraus, F.; Remy, C. Review of promising methods for phosphorus recovery and recycling from wastewater. In Proceedings of the International Fertiliser Society, London, UK, 23–24 June 2015; pp. 1–29.
13. Batstone, D.J.; Hülsen, T.; Mehta, C.M.; Keller, J. Platforms for energy and nutrient recovery from domestic wastewater: A review. *Chemosphere* **2015**, *140*, 2–11, doi:10.1016/j.chemosphere .2014.10.021.
14. El-Shafai, S.A.; El-Gohary, F.A.; Nasr, F.A.; Van Der Steen, N.P.; Gijzen, H.J. Nutrient recovery from domestic wastewater using a UASB-duckweed ponds system. *Bioresour. Technol.* **2007**, *98*, 798–807, doi:10.1016/j.biortech.2006.03.011.
15. Becerra-Castro, C.; Lopes, A.R.; Vaz-Moreira, I.; Silva, E.F.; Manaia, C.M.; Nunes, O.C. Wastewater reuse in irrigation: A microbiological perspective on implications in soil fertility and human and environmental health. *Environ. Int.* **2015**, *75*, 117–135, doi:10.1016/j.envint.2014.11.001.
16. Lyu, S.; Chen, W.; Zhang, W.; Fan, Y.; Jiao, W. Wastewater reclamation and reuse in China: Opportunities and challenges. *J. Environ. Sci.* **2016**, *39*, 86–96, doi:10.1016/j.jes.2015.11.012.
17. Pintilie, L.; Torres, C.M.; Teodosiu, C.; Castells, F. Urban wastewater reclamation for industrial reuse: An LCA case study. *J. Clean. Prod.* **2016**, *139*, 1–14, doi:10.1016/j.jclepro.2016.07.209.
18. Bertanza, G.; Canato, M.; Laera, G. Towards energy self-sufficiency and integral material recovery in waste water treatment plants: Assessment of upgrading options. *J. Clean. Prod.* **2018**, *170*, 1206–1218, doi:10.1016/j.jclepro.2017.09.228.

19. Zhen, G.; Lu, X.; Kato, H.; Zhao, Y.; Li, Y.Y. Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives. *Renew. Sustain. Energy Rev.* **2017**, *69*, 559–577, doi:10.1016/j.rser.2016.11.187.
20. Hagos, K.; Zong, J.; Li, D.; Liu, C.; Lu, X. Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. *Renew. Sustain. Energy Rev.* **2017**, *76*, 1485–1496, doi:10.1016/j.rser.2016.11.184.
21. Culha, O.; Gunerhan, H.; Biyik, E.; Ekren, O.; Hepbasli, A. Heat exchanger applications in wastewater source heat pumps for buildings: A key review. *Energy Build.* **2015**, *104*, 215–232, doi:10.1016/j.enbuild.2015.07.013.
22. Frijns, J. Intervention Concepts for Energy Saving, Recovery and Generation from the Urban Water Sytems D45-1. KWR Watercycle Reasearch Instutute. 2014. Available online: https://www.researchgate.net/profile/Nelson_Carrico/publication/275213940_Intervention_concepts_for_energy_saving_recovery_and_generation_from_the_urban_water_system/links/553576530cf20ea35f10d908.pdf (accessed on 15 February 2018).
23. Smol, M.; Kulczycka, J.; Henclik, A.; Gorazda, K.; Wzorek, Z. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *J. Clean. Prod.* **2015**, *95*, 45–54, doi:10.1016/j.jclepro.2015.02.051.
24. Bengtsson, S.; Karlsson, A.; Alexandersson, T.; Quadri, L.; Hjort, M.; Johansson, P.; Magnusson, P.A. Process for polyhydroxyalkanoate (PHA) production from municipal wastewater treatment with biological carbon and nitrogen removal demonstrated at pilot-scale. *N. Biotechnol.* **2017**, *35*, 42–53, doi:10.1016/j.nbt.2016.11.005.
25. Pandey, P.; Shinde, V.N.; Deopurkar, R.L.; Kale, S.P.; Patil, S.A.; Pant, D. Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. *Appl. Energy* **2016**, *168*, 706–723, doi:10.1016/j.apenergy.2016.01.056.
26. Gaur, A.; Scotney, B.; Parr, G.; McClean, S. Smart city architecture and its applications based on IoT. *Procedia Comput. Sci.* **2015**, *52*, 1089–1094, doi:10.1016/j.procs.2015.05.122.
27. Papa, M.; Foladori, P.; Guglielmi, L.; Bertanza, G. How far are we from closing the loop of sewage resource recovery? A real picture of municipal wastewater treatment plants in Italy. *J. Environ. Manag.* **2017**, *198*, 9–15, doi:10.1016/j.jenvman.2017.04.061.
28. Xie, M.; Shon, H.K.; Gray, S.R.; Elimelech, M. Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction. *Water Res.* **2016**, *89*, 210–222.
29. Swedish Utility Selects Veolia for Wastewater to Energy Project. Available online: https://www.metering.com/news/swedish-utility-selects-veolia-for-rollout-of-wastewater-project/ (accessed on 15 February 2018).
30. Gu, Y.; Li, Y.; Li, X.; Luo, P.; Wang, H.; Robinson, Z.P.; Li, F. The feasibility and challenges of energy self-sufficient wastewater treatment plants. *Appl. Energy* **2017**, *204*, 1463–1475.