The Possible Roles of Wastewater Treatment Plants in Sector Coupling

Michael Schäfer [1],*[ID]**, Oliver Gretzschel** [1][ID] **and Heidrun Steinmetz** [2]

[1]   Institute Water Infrastructure Resources, University of Kaiserslautern, D-67663 Kaiserslautern, Germany; oliver.gretzschel@bauing.uni-kl.de
[2]   Department for Resource Efficient Wastewater Technology, University of Kaiserslautern, D-67663 Kaiserslautern, Germany; heidrun.steinmetz@bauing.uni-kl.de
*   Correspondence: michael.schaefer@bauing.uni-kl.de

Abstract: The development of a power system based on high shares of renewable energy sources puts high demands on power grids and the remaining controllable power generation plants, load management and the storage of energy. To reach climate protection goals and a significant reduction of CO_2, surplus energies from fluctuating renewables have to be used to defossilize not only the power production sector but the mobility, heat and industry sectors as well, which is called sector coupling. In this article, the role of wastewater treatment plants by means of sector coupling is pictured, discussed and evaluated. The results show significant synergies—for example, using electrical surplus energy to produce hydrogen and oxygen with an electrolyzer to use them for long-term storage and enhancing purification processes on the wastewater treatment plant (WWTP). Furthermore, biofuels and storable methane gas can be produced or integrate the WWTP into a local heating network. An interconnection in many fields of different research sectors are given and show that a practical utilization is possible and reasonable for WWTPs to contribute with sustainable energy concepts to defossilization.

1. Introduction

The energy and the water sector are both essential and vital elements of modern life. Water has to be provided and distributed to citizens, as well as discharged and treated with a substantial use of energy. On the other side, water is used to generate power and deliver or recover energy for human purposes. Due to these facts, the challenges are globally to provide these important services. Furthermore, water and energy systems are complex and strongly linked but are mostly operated independently. Facing climate change forces this water-energy nexus into a more environmentally sustainable system for a rapidly growing population on the globe. Therefore, energy efficiency, energy savings and energy recovery have become development goals all over the world. Nevertheless, every country has, on the basis of its power generation composition, its own unique chances, opportunities and obstacles to handle [1–4].

In regard to meeting the targets of the Paris Agreement of 2015 [5] or the United Nation Sustainable Development Goals [4], a system change is needed now, and the world has to act immediately. Although some countries are proactive and take a leading part in promoting renewable energy sources (RES), the actual efforts are, by far, not sufficient. Nevertheless, there are promising developments for the year 2018. The global investments in the new generating power capacity of RES exceeded that in fossil and nuclear power, with a share of 65%. In several countries, the power sector is transforming rapidly, with growth rates of over 10%, and proportions of more than 20% RES in energy production have been

reached, like in Uruguay, Germany and the United Kingdom [6]. The gradual extension of RES and the expedited abandonment of fossil and nuclear energy production results in new problems but also new opportunities for power supplies. There is a shift from demand-oriented power generation to a production-driven generation of electrical energy. In an electricity system with a high share of RES, flexibility options are needed to counterbalance fluctuating wind and solar-based power production to maintain the high standards in its supply [7]. For now, there are just a few hours of surplus energy but with proportions of more than 60% RES; times in which supply exceeds demand are increasing significantly. On this basis, there will be a high need of short-term flexibility in the near future to stabilize power grids and further integrate RES into the energy grids [8]. Short-term storage options are classified in the range of seconds up to 24 h (daily storage). These energy surpluses and deficits have to be balanced by flexible energy generators and consumers. Furthermore, long-term storage capacities are needed to provide enough energy in times of deficits on a larger scale. This is caused by longer periods of low amounts of available wind and sun. To compensate these fluctuations and store or generate energy, based on its availability, fundamentally different applications compared to short-term flexibility are required [9].

Energy has always been stored, but the focus and the technologies used have changed. Storage concepts like pumped storage plants, battery or compressed air systems are not suitable for long-term storage—too expensive or cannot provide enough capacities for an extensive use in every country [10]. Additionally, ecological issues and resource scarcity have to be considered. Unlike solar and wind-based energy production, biogas is the only RES that can be directly stored and flexibly adjusted to the production of electrical energy or heat purposes. This is possible due to a flexible power and gas production, which can be realized by biogas plants or wastewater treatment plants (WWTPs) with anaerobic sludge digestion [11–13]. The required storage technologies are available but must be re-evaluated, utilized or combined appropriately to the new challenges and obstacles, especially regarding economic feasibility during the transformation process from a fossil-based energy system to a renewable energy system [9].

Part of a solution in facing climate change could be a comprehensive use of widely spread existing infrastructure, like in the water sector. For short-term flexibility, it has been shown that WWTPs are capable of performing on energy markets without endangering system functionality to stabilize energy grids with its existing aggregates and ensure the further integration of RES into energy grids [14–16]. The capability of providing ancillary services and taking the fluctuation of the electrical energy consumption/generation pattern into account without endangering the WWTPs' systems' functionalities is shown in [16]. Such a contribution applies as well for long-term storage concepts, theoretically shown, e.g., in [15]. In the following, the focus is on practical implementations of long-term storage concepts according to sector coupling, with special focus on its interaction with WWTPs.

Sector coupling describes the interconnection between the sector's heat, gas, mobility, nonenergetic use of fossil resources (e.g., chemistry/industry) and electrical energy under the use of RES due to appropriate technologies [9]. Especially the gas sector provides with its natural gas infrastructure (NGI) a nearly infinite storage option for RES [17,18]. Similar to the NGI, large WWTPs are commonly distributed close to municipal infrastructures with significant synergies in nearly all of the targeted fields of sector coupling, which makes them preferable locations for a transposition [15,19,20].

The available literature is widely scattered across the different addressed topics, and a comprehensive compilation is missing—in particular, with special focus on the water sector and WWTPs. Therefore, the present work provides a systematic review on several fields of sector coupling and their interactions with WWTPs based on the literature. Starting from describing available and reasonable technologies, followed by analyzing the current situation, evaluating the effects of an implementation on the plant and giving examples for actual worldwide, practical applications in WWTPs, the state of the art is summarized. The objective is not only to collect and present knowledge but also provide a basis for decisions to future plant concepts due to evaluating realized projects. This paper refers to synergies, opportunities and downsides that are given to WWTPs as a local energy center in the role of sector coupling and long-term energy storage.

2. Sector Coupling with WWTPs

Sector coupling is realized by the interconnection between RE surplus and the conversion into storable energy forms and is widely called power-to-X (PtX) based on the targeted sector (e.g., power-to-heat, power-to-gas, etc.). There are a lot of Power-to-X projects on the international level, whilst countries with high shares of RES are more endeavoring, simply because they are more affected. Unsurprisingly, countries like Germany take a leading part in development and realized/planned PtX projects [21]. For the German water sector, potential analysis shows that a significant contribution can be provided in terms of ancillary services, as well as gas flow rates, for long-term storage [16,22], which applies for other countries as well.

WWTPs are ideally suited in a special way for handling different energy forms. They are not only flexible (electrical) energy consumers, with their purification aggregates (cf. [16]), but also flexible producers, with their anaerobic sludge digestion and the subsequent needs-oriented production of electrical energy (cf. [12,23]). They are also able to function as a heat sink (e.g., heating of the digestion tanks) and are capable to provide usable heat sources (e.g., waste heat from combined heat and power plant (CHP) units). Furthermore, a wide range of gases can be utilized: Despite a direct use of electrical energy generated by CHP units, the produced digestion gas supplies, with its 35% carbon dioxide (CO_2) content, a valuable and sustainable green CO_2 source for further Power-to-Gas (PtG) applications, like methanization, which enables a direct feed-in of methane (CH_4) into the local gas grid. Moreover, the produced hydrogen (H_2) can be used on the plant as well (e.g., biological methanization) instead of a mere production and feed-in into the natural gas grid. The operation of an electrolyzer for PtG can be integrated in holistic plant solutions considering different gaseous energy forms and heat. The usually unwanted by-product O_2 can also be used for aeration in the biological treatment or further treatment processes such as ozonization for removing micropollutants from the wastewater. This enables synergies and opportunities in both sectors: WWTPs are able to contribute to the energy sector and face their own new challenges in wastewater treatment at the same time (e.g., micropollutant removal).

Figure 1 gives an overview of the multiple utilization paths and the complex interactions with different sectors and the WWTP. This demonstrates that WWTPs are reasonable energy centers, which are located at nearly every urban area. In the following, the focus is on new findings and realized projects in the field of sector coupling explicitly concerning and interacting with WWTPs for the different sectors.
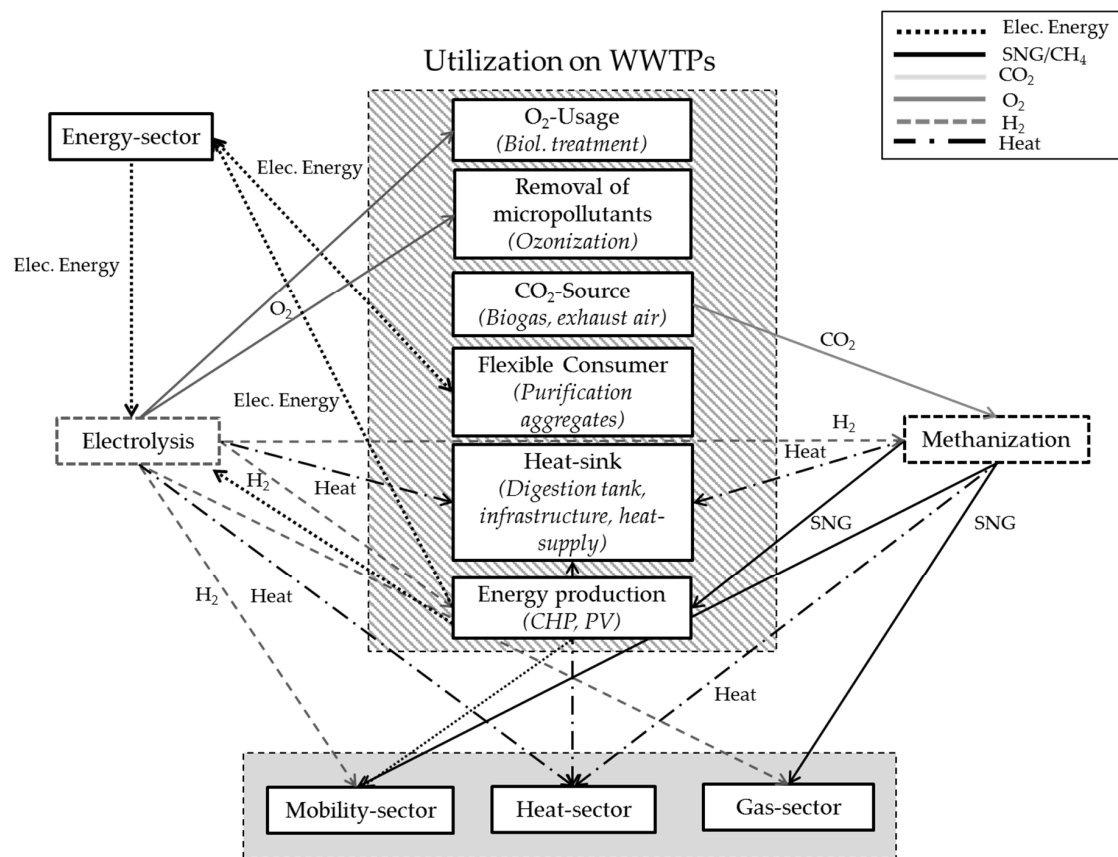
Figure 1. Interaction of wastewater treatment plants (WWTPs) with different technologies and sectors. Reproduced from [16], Technische Universität Kaiserslautern: 2019.

3. Gas-Sector

3.1. Power-to-Gas in WWTPs

A capable long-term storage concept for renewable surplus energy is the transformation into gaseous energy carriers, like H_2 and CH_4, called power-to-gas (PtG). With that technology, energy can be stored and, later on, used again for power production to compensate energetic deficits on a large scale. In a first step, H_2 is produced by the utilization of surplus energy via an electrolyzer, which splits water (H_2O) into H_2 and oxygen (O_2). In a further step, the produced H_2 can be upgraded with CO_2 to CH_4 (Sabatier process). Thus, PtG is divided in two classes: PtG-H_2 and PtG-CH_4. A general comparison of the two concepts is given in Table 1. The core process thereby is the electrolysis, with three different suitable processes: alkaline water electrolysis, polymer-electrolyte membrane electrolysis (PEM) and high-temperature steam electrolysis. Further information and more detailed descriptions on different electrolyzer types can be taken from the report [24]. Whereby the PEM electrolysis seems to be the best-suited option in this framework due to technical advantages regarding fast load changes, good partial-load operations and a good scalability, especially in small-scale implementations (usually below 1 megawatt connected load), like in WWTPs [15,25].

Table 1. General comparison of Power-to-Gas (PtG)-H$_2$ and PtG-CH$_4$ concepts (adapted and extended from [9,18,26]).

	Power-to-Gas(-H$_2$)	Power-to-Gas(-CH$_4$)
Chemical equation (simplified)	$2H_2O \xrightarrow[\text{Electrolyzis}]{} 2H_2 + O_2$	$2H_2O \xrightarrow[\text{Electrolyzis}]{} 2H_2 + O_2$ $4H_2 + CO_2 \xrightarrow[\text{Methanization}(CO_2)]{} CH_4 + 2H_2O$
Efficiency *	54%–84%	49%–79%
Advantages	• Easier direct use in the mobility sector due to higher market penetration • No CO$_2$ source needed (more independent in location selection) • Higher efficiency than PtG-CH$_4$ • Contribution to decarbonization in the industry and mobility sectors due to more customer availability	• Accessible infrastructure available for all fields using natural gas • Easier to compress, to store and to transport due to a triple-higher energy density than H$_2$ • Nearly infinitely storable due to the NGI • No additional gas treatment needed due to biological methanization
Drawbacks	• Limited feed-in capacity of the NGI (2%–10% volume) • H$_2$ infrastructure hardly developed	• Additional transformation step needed (higher costs and loss in efficiency rate) • Slightly lower efficiency than PtG-H$_2$ • Constrains due to available CO$_2$ sources (e.g., restrictions in location selection, green CO$_2$ source, etc.)

* Efficiency may vary due to the type of storage, the pressure and the used technology (further information is given in [9]). NGI: natural gas infrastructure.

Nevertheless, the produced gas needs to be stored. The NGI is a huge, easily accessible and well-distributed storage system for long-term storage and providing natural gas to customers. Furthermore, it is one of the best-developed and accessible infrastructures in most countries. A part of the produced H$_2$ can be directly stored in the NGI (e.g., 2°–10% volume in Germany), and for the CH$_4$, the storage capacities are nearly infinite due to almost identical chemical attributes of the gases [10,18]. With this background, the surplus energy can be stored, distributed and is accessible for months up to years to compensate seasonal fluctuations in the energy production without building one's own distribution/storage system [9,26].

Therefore, PtG plants have to be located close to the gas grid. As biogas plants are mostly located in rural areas, large WWTPs are present in nearly every urban location, mostly close to the NGI. This makes WWTPs favorable as a PtG location. Another big advantage of WWTPs with anaerobic digestion as a possible location for a PtG plant is the already existing gas infrastructure on-site and the existing know-how on handling gases. On plants with anaerobic sludge digestion, a suitable infrastructure is available in terms of digestion tanks, gas storages and combined heat and power plants (CHP). Furthermore, one of the biggest challenges for PtG(-CH$_4$) is the lack of an appropriate CO$_2$ source ("green carbon") [9]. This is a major benefit of WWTPs due to an easily accessible and sustainable biogas with a high CO$_2$ content of nearly 35% volume [27]. To use the CO$_2$, it is possible to extract it from the biogas (biogas treatment) or use the raw biogas directly to upgrade the CH$_4$ content to feed-in quality for the NGI. A techno-economical study of state-of-the-art of such methanization concepts for PtG was conducted by [28] and showed that, especially, biological methanization has a great potential for further development. For WWTPs, a utilization is possible by directly inserting H$_2$ into the digestion tank or upgrade the biogas to a feed-in quality with a special external reactor [28–31].

Basic plant concepts for PtG implementations in WWTPs and the theoretical feasibility are shown in [15], characteristic values and a feasibility study for upgrading biogas with H$_2$ are given in [31]. A large-scale practical demonstration for a two-year operation is located at the Avedøre WWTP, Denmark [32] and for a biogas plant in Pirmasens, Germany [30]. Both implementations could demonstrate a successful upscaling from a laboratory scale to a nearly full scale. A continuous feed-in

of the produced CH_4 with a high level of flexibility of the biological processes could be established and is running in a stable operation. Nevertheless, an implementation of PtG requires a high control of real-time data and complex coordination of the different parameters, like the CO_2 supply, power supply, operation of the electrolyzer, storage of intermediate gases and utilization of oxygen and heat [32].

Although PtG in WWTPs is technologically possible, much remains to be done. Especially regarding optimization in the coordination of the different material flows and embedding the system in the whole WWTP operation business to gain the full benefits of the synergies. Due to the complexity of process engineering of big WWTPs itself, implementing PtG concepts are quite challenging. However, the greatest problems in implementing are not technology driven but the legal and regulatory framework, which makes the systems so far not feasible without funding (e.g., for Germany: cf. [15,31]). Better conditions would lead to dropping prices, a needed market penetration and faster development for full-scale application.

It can be stated that WWTPs are able to implement PtG systems and can ensure an efficient methanization due to a constant and viable CO_2 source. In addition, it provides a supplement flexibility option for energy grids as a flexible RES. Furthermore, a sustainable and beneficial utilization path for oxygen is given, which leads to unique location advantages for WWTPs.

3.1.1. CH_4 Utilization

Reaching an "energy-positive WWTP" is the proclaimed goal of many operators of anaerobic sludge digestion plants, which can be primary realized by reducing energy consumption, mostly due to efficiency measures, and increasing biogas production. Therefore, the produced digestion gas is mostly used in CHP units in WWTPs to produce electricity. The present literature shows that increasing self-sufficiency is still the dominant topic rather than an interest in holistic and overarching utilization of the different energy forms (e.g., [33–35]). This is mostly caused by missing incentives and the regulatory framework and taxes, which makes selling gas/electricity not economically viable in contrast to a use on-site (e.g., in Germany; [9]). The economic feasibility of anaerobic digestion in WWTPs is highly dependent on the legal framework conditions. A large-scale study of the feasibility of a conversation from aerobic to anaerobic stabilization was conducted in [36]. It could be shown that it is feasible even for WWTPs at sizes of 20,000 PE_{120} under fitting circumstances (for Germany). Furthermore, the boundary conditions favoring conversation were evaluated, but it was also shown that, especially, taxation systems have a huge impact, and feasibility has to be examined individually for each plant and each country's framework [36].

In a future RE-dominated system, biogas should be used to generate electricity with the CHP units if the RE production in the grid is lower than its demand and vice versa. If the demand is below the actual production, the CHP unit would be shut down, and the electrolysis is used to convert the energy surplus into CH_4 and stored in the NGI afterwards. Another possibility of a holistic gas usage could be a more centralized than decentralized electricity production for the CH_4. The (electric) efficiency of modern CHP units in WWTPs is around 43%, with an electrical power scale in the range of 100 up to 1000 kW_{el} [37]. At the same time, big natural gas power plants reach up to 60% [38]. Under a holistic point of view, the overall benefit from the utilization of the gas would be much higher to feed the (green) gas into the NGI and utilize it in large power plants. This would increase the electric energy output from the same gas by ~ 17% and replace fossil natural gas in the NGI at the same time.

Isolated feed-in endeavors of WWTPs are made, e.g., at Hamburg WWTP [39] or Pfaffenhofen WWTP [40]. First efforts of rethinking for plants larger than 30,000 PE_{120} of feeding in the biogas as a suitable alternative to CHP usage on a countrywide scale are made in Switzerland [19,41]. In 2019, a guideline [42] for the plant operator and planner was published, giving specific advice for decision-making and implementations in WWTPs. Both systems got their advantages and drawbacks shown in Table 2. Finally, decision-making will be determined economically and differ widely due to local boundary conditions. Compared to both options, revenues of selling energy (gas, electrical

energy and heat) and energy trading on energy exchanges (e.g., control energy and load-management) have to exceed the incurring costs for construction, machinery, energy, maintenance and legal authorizations [42].

Table 2. Advantages and disadvantages of using digestion gas on-site and feeding into the natural gas infrastructure (NGI) (adapted and extended from [42]). WWTP: wastewater treatment plant.

Electrical Energy Production on-Site	Feeding into the NGI
(+) use for self-sufficiency purposes (reduced fees in power purchasing)	(+) full use of the energy content of the digestion gas
(+) heat demand of the WWTP fully covered	(+) substitution of fossil CH_4 in the NGI
(+) local production of renewable energy	(+) separated CO_2 due to the gas treatment as a green CO_2 source for PtX systems
(+) usable surplus heat for local district heating	(+) new opportunities for alternative heat concepts
(+) emergency power generation	
(+) providing control energy for energy grids	
(−) excess heat possibly not usable	(−) gas treatment installations required
	(−) new heat management required
(−) lower efficiency than utilization in bigger power plants	(−) higher costs for electricity purchase due to not fitting taxation systems
(−) no incentives for a utilization of otherrenewable heat sources (e.g., heat recovery)	(−) highly dependent on the local boundary conditions (e.g., connection and distance to the NGI)

(+) Advantage; (−) Drawback.

The waste heat from the CHP units usually covers the heating demand of the digester tanks and the operating buildings. Abandoning the standard of using the CHP waste heat could lead to a higher energy demand for heating purposes due to a feed-in instead of an on-site utilization of the gas. However, this fact may be the missing incentive for plant operators to integrate new renewable heat solutions, like heat recovery from wastewater. Furthermore, the most digestive tanks lack a proper insulation. Improving the reduction of heat losses could lower the thermal energy demand significantly, down to a manageable amount even without CHP units. For conventional WWTPs with fitting feed-in conditions, it is presumed that implementing PtG concepts are a considerable addition to trigger additional synergies and improve the overall efficiency. The authors of [32] showed that it is possible that the missing waste heat can be substituted by the heat production of an electrolyzer and the methanization reactor as well. Additionally, the produced metabolic by-water during the methanization process can be used in the digestion tanks to enhance biogas production [32].

3.1.2. O_2-Utilization: Usage of O_2 From Electrolysis in Wastewater Treatment

Another synergy for PtG in WWTPs is the use of O_2 from the electrolyzer. PtG systems are usually focused on H_2 production, thus O_2 is—as an unintended by-product—usually just vented-off due to a missing application [26]. During the different wastewater treatment steps, O_2 is needed in the aeration tanks for the biological degradation of carbon and nitrogen (nitrification) and can also be utilized to produce ozone (O_3) for micropollutant removal or sludge disintegration.

The intake of O_2 for biological treatment is usually realized by inserting compressed air (blowers/compressors) into the system and supplying the bacteria with the needed oxygen. This part of wastewater treatment is the biggest energy consumer, with 50%–70% of the overall energy consumption [43,44]. Based on that fact, it is often claimed that big energy savings could be achieved due to a reduced gas volume needed, caused by higher O_2 rates (pure O_2 got a five-times higher O_2 content than air). However, there are contradictory scientific evidences for the actual feasibility and impacts of an implementation beyond theoretical considerations. Especially, the benefits of a pure O_2 system in comparison to a conventional municipal system on a large scale are insufficient [45]. Based on a market analysis conducted in [46], using pure O_2 is usually more interesting in treating industry wastewater than for municipal WWTPs.

The major benefits and drawbacks of using pure O_2 instead of compressed air to enhance wastewater treatment are shown in Table 3.

Table 3. Benefits and drawbacks for using pure oxygen for aeration purposes in wastewater treatments.

Benefits	Drawbacks
• Reduction of the needed gas volume due to a five-times higher O_2 content of pure O_2 than compressed air [47] • Better O_2 transfer rate and higher dissolved O_2 concentrations due to higher possible biomass concentrations [48] • Smaller and more compact basin constructions are possible for locations with limited spatial conditions [46] • Better sludge sedimentation is possible, lower specific sludge production and better sludge volume index [49] • Pure O_2 is usable to support aeration processes as an additional system and compensate peaks in O_2 demand caused by, e.g., tourism regime or viticulture [47,50] • Good short/medium-term reconstruction measures for capacity increases in purification quality [51]	• Reduction of the pH level due to insufficient CO_2 stripping, which can inhibit nitrification processes [46,47] • An additional mixing system is required because of the reduced gas flow rates [47,48] • Higher demands on material quality and safety measures [48,52] • Problems with sludge sedimentation could occur [48,51] • Usually, higher operation costs, if no other synergies, are used [32,46,48]

In the following, promising conductions related to enhanced purification quality and/or energy savings are summarized.

One of the first worldwide electrolyzer implementations in WWTPs for O_2 utilization was conducted in 2002 in Barth (Germany) to support the biological treatment during high-load phases and avoid capacity extensions. The annual average load amounts to 10,000 PE_{120}, but during tourism season, the loads peak up to 24,000 PE_{120}, and the plant was not able to handle those peaks with the existing plant configuration. With the electrolyzer-driven supportive O_2 system, the seasonal influence was manageable, and no capacity extension was needed [50,53]. The PEM electrolyzer was used from 2002–2007, and since 2009, an alkaline electrolyzer generates O_2 for treating the wastewater. However, the H_2 utilization path (fuel-cell bus) was abandoned due to two major break-downs and the lack of further funding [53].

Regarding purification quality, approaches for a pure O_2 system in Spain showed no significant increase in COD (chemical oxygen demand), BOD (biochemical oxygen demand) or TN (total nitrogen) removal, whilst energy savings were assumed [54]. In contrast, a study in Germany showed that, in comparison with a conventional system, an additional reduction of up to −20% for COD and TN is possible, but no energy savings could be achieved [47]. At the Nürnberg WWTP (Germany), pure oxygen is successfully used for years as the first biological treatment step for COD removal [55], and at the Lynette WWTP (Copenhagen, Denmark), pure O_2 was used to support the biological treatment step for 15 years. In Neustadt (Germany), a pure oxygen system was implemented and used for years to handle and ensure the legal discharge values due to high viticulture-related load peaks of nearly 100% compared to the usual loads [51].

At the PtG implementation in Avedøre (Denmark), it is shown via laboratory experiments that the use of pure O_2 is possible, and purification processes are not inhibited by the use of pure O_2. Furthermore, the already pressurized O_2 from the electrolyzer is able to displace the corresponding air blower operation to supply the aeration basins [32]. The implementation of an O_2 utilization would increase the overall system economy but was not implemented in full scale due to high investment costs caused by misfitting local plant circumstances. Nevertheless, in combination with an above-described PtG system, the feasibility in WWTPs could be reached towards a single investment (cf. [32]).

For pure oxygen systems, an additional mixing system is required, and deeper basins are favorable due to a longer contact of the O_2 bubbles with the media. The authors of [46,47] showed that shallow basins or volatile fill levels might cause losses in the purification quality. Furthermore, the reduced gas volume of the pure O_2 system is insufficient for mixing the media and preventing sludge settling in common aeration tanks. This also causes a lower CO_2 stripping, which could result in a reduced pH level for wastewater with low buffer/acid capacity and inhibited nitrification processes at pH levels

under 6.6. To solve this problem, it could be required to add chemicals (e.g., milk of lime; cf. [47]) or add additional aeration times for the system (cf. [46]) to sustain the biological treatment. This issue could also occur with aeration tank depths of 6 meters or deeper [56]. Other cost savings could thereby be offset, leading to similar or higher total operating costs for the use of pure O_2 systems. Claimed reduced overall basin volume or smaller basins must be viewed critically as well, because sludge concentration is not limited by the O_2 input but of the thickening in the secondary clarifier. Nevertheless, due to the needed deeper basin construction, the space requirements are reduced and favorable for, e.g., very limited field conditions. Whilst [49] claims better sludge characteristics like sedimentation properties or sludge volume indices, in contrast, [48,51] could not observe a similar effect. Additionally, for an implementation of an O_2 system, an expensive O_2 storage and piping infrastructure is needed, with special arrangements regarding corrosion, higher fire risk and a special safety concept due to dealing with pure O_2 [48]. Further instructions regarding handling O_2 in WWTPs are given in [52].

In summary, the results of the evaluated scientific papers are partially contradictory, e.g., enhanced purification quality or space requirements. However, the long-term experiences of several WWTPs with supportive O_2 utilization show that it is even on a large scale possible and reasonable if the local boundary conditions are fitting or require special arrangements. However, no economic statements were given in those publications. The popular claim that using pure O_2 will result in energy (and cost) savings for the WWTP could not be proven in any practical implementation, but higher operating costs were mentioned in [51]. Nevertheless, it can be stated that at least similar or better purification results could be achieved with the use of pure oxygen regarding COD, BOD and NH_4-N (e.g., [47,54]) and energy savings are theoretically possible (e.g., [32]).

3.1.3. O_2 Utilization: Micropollutant Removal via Ozone Produced from Renewable O_2

At present, removing micropollutants is getting more and more important for the water sector. In Switzerland, it is even ordered by law for municipal WWTPs above 80,000 PE_{120} [57]. This is discussed in several other countries as well (e.g., Germany, [58]), or additional steps for micropollutant removal are set up on plants unsolicited (e.g., WWTP Mannheim, Sindelfingen, etc.; Germany). Besides adsorption on activated carbon, oxidation of the micropollutants is a suitable removal process. This leads to another future benefit in operating an electrolyzer in WWTPs by upgrading O_2 to O_3, which could be used in a further treatment step. This additional process stage will result in a substantially higher energy demand for WWTPs, e.g., for a 100,000 PE_{120}, WWTP 22.5 kWh/(PE*a) to 58.3 kWh/(PE*a) (cf. [59]). In a future holistic WWTP concept, O_2 is produced by a RE-driven electrolyzer and closes another loop of resource and overall efficiency. In the next steps, O_3 is produced and the water treated, followed by a biological treatment step to remove the by-products due to the ozonization process to ensure the effluent quality [60]. Using the ozone to remove micropollutants is a commonly used technology in WWTPs [61,62]. Guidelines for the preinvestigation, design and operation are described in, e.g., [63]. This makes ozonization a preferable option for removing micropollutants in combination with PtG systems, leading to more feasibility for both applications. Like dealing with O_2, O_3 requires special precautions in handling as well, which should not be underestimated in daily business. Those are, for instance: use of specific materials, needed O_3 detectors, ventilation systems and safety concepts [64]. First approaches in the form of feasibility studies for a full-scale application for such a system are conducted at WWTP Mainz (Germany) with a planned start in 2021 [65,66].

4. Heat-Sector

PtH describes technologies that transform the electrical surplus energy of RES into heat. The scarce available publications on that topic substantiate that using electrical energy to utilize and store heat in a PtH concept is not an issue and not state-of-the-art in WWTPs so far. The dominant topics in the heat sector are mostly regarding internal optimization concepts using the waste heat for building heating, sludge treatment and in anaerobic sludge digestion (cf. [67]), as well as heat recovery from the

sewer system or influent/effluent of the WWTP (cf. [68,69]). Nevertheless, PtH and heat concepts hold a respectable potential for sector coupling, even if they are not in the actual focus for plant operators.

In addition to a high electricity demand, WWTPs with anaerobic sludge digestion usually also have a high demand for heat of 30 to 50 kWh/(PE*d) with big seasonal fluctuations [70]. Compared to electrical energy, heat is an even more complex field to manage. This is caused by the different parameters, which have to match in terms of the amount of needed heating energy, time of demand, different temperature levels, various possible technologies and the nearly unique framework of each WWTP. Heat supply is usually handled as a by-product from the production of electrical energy from the CHP units and, therefore, not demand-driven and in competition with on-site electricity production [70]. Further information in this regard and specific proposals for the implementation of optimized heat and cooling concepts for WWTPs are given in [67].

Typical heat sources in WWTPs are exhaust gases from the CHP units and other combustion processes (e.g., pyrolysis and hydrothermal carbonization); waste heat from aerators/blowers and drying processes or heat recovery from wastewater [71]. Typical heat sinks are given in forms of sludge treatment (e.g., preheating, sludge drying and thermal disintegration); building heating and hot water preparation and heating of the digestion tank [67].

Especially, the digestion tanks are a reasonable heat sink, which is interesting for further investigations. They are usually operated on a mesophilic temperature level of 34 °C to 38 °C; however, a thermophilic temperature level of 48 °C to 55 °C is possible as well [72]. As a biological process, minor fluctuations are not harmful for the system, but effects in biogas production are possible, depending on the rate of increasing the temperature due to a needed adaptation time for the microorganisms. The authors of [73] showed that temperatures up to even 50 °C (change to thermophilic temperature level) are possible without losses in biogas quantity and quality with stable processes in the digestion tank. In this regard, existing studies show different effects concerning methane yield, methane concentrations and needed adaptation time (cf. [73–75]). Thereby, a gradual temperature change is advisable and should not exceed 2 °C per week [76], whilst a direct heating within 24 h could result in a drop of methane yield and methane concentration [74]. Under the approach of using the digestion tanks for PtH purposes, a calculated raise or lowering of the usual operation temperature level is intended, and the digestion tank is used as a "hot water storage". The potential of this storage option is huge: with an average digestion tank volume of 50 l/PE [72] and a specific heat capacity of water of 4.19 kJ/(l*K), the specific energy storage results in 58.2 kWh/(K*PE) or nearly 17.5 GWh for a 100,000 PE_{120} WWTP for a temperature rise of 3 K.

A PtH concept can be implemented directly via heating rods/boilers or indirectly via different types of heat pumps. However, electrode boilers are commonly used for PtH on an industrial level due to the need of a high-temperature process heat. It is possible to integrate such a system into existing heat cycles, but it depends highly on the local boundary conditions. Requirements are an all-the-year heat sink and a power grid connection with sufficient electrical power reserve [9].

Published practical implementations on a scientific level for "classic" PtH concepts in WWTPs are hardly available. Nevertheless, some holistic approaches in local energy concepts demonstrate promising interconnections between WWTPs and the heat sector. The authors of [77] showed for a commercial district located in Milan (Italy) that a PtH system complemented by sewage heat recovery is competitive to individual, distributed heat pumps. In addition, WWTPs are able to participate in local heat supply systems by feeding-in surplus heat [35,70,78,79]. This is realized, e.g., at the Hamburg WWTP, which is feeding heat into the district heating systems for the container terminals of the port of Hamburg. Furthermore, the Hamburg WWTP is testing an aquifer storage by using the groundwater to store heat surplus during the summer to compensate for seasonal fluctuations and save heating energy in the winter [79,80]. The aquifer storage is located beneath the WWTP and includes heat of the nearby industry as well—summing up to nearly 400 GWh/a. By using 100% green energy, this system is able to provide CO_2-free district heating with economically acceptable costs of avoiding CO_2 emissions below 100 € per ton and year [80].

Thermal energy potentials of the Austrian WWTPs are stated in [81], showing that WWTPs are able to contribute significantly in local district heating concepts by recovering energy from digester gas production and wastewater effluent. Based on that, the authors of [78] proposed a set of methods to integrate the potentials into local energy concepts, considering spatial, environmental and economic issues. It is shown that the heat generation from WWTPs offers an alternative to conventional heat generation at competitive costs.

Besides heat, cooling concepts are also an interesting approach to using energy surplus. Cooling is needed in WWTPs for the air conditioning of the operation buildings and cooling down the processed heat (e.g., blowers for aeration and digestion gas) [35]. This can be realized due to, e.g., sorption chillers, which work like heat pumps but just the other way around. Whereas, in heat pumps, a lot of heat is to be dissipated at a higher temperature, in chillers, the aim is to absorb as much heat as possible at a low temperature and, thus, provide cooling [9]. Further information regarding different cooling technologies are given in [82].

Regarding economic feasibility, it can be stated that single-handed PtH systems (even on an industrial level) were in the past, just in combination with high revenues from the control energy market profitable. On the basis of significantly decreasing prices, new business cases have to be found [18]. Nevertheless, compared to other general storage concepts (e.g., batteries, load-shifting, etc.), thermal storages are cheaper, even if prices for other technologies are dropping [9]. However, even if a single implementation of classic PtH systems is not yet feasible, the chances to utilize surplus thermal energy from WWTPs are given but considerably underestimated or unknown. The actual benefit may not be using surplus energy from the subordinate energy grids but taking a more significant role in the local energy system. Integrating WWTPs in local district heating is possible without high investment costs compared to new developments in the vicinity of towns due to an intelligent use of the existing and surrounding infrastructure, provided that the spatial framework is suitable. In addition, thermal energy from WWTPs is a continuous and reliable source of energy, which can be substantially used in district heating, substituting fossil energy sources and reducing greenhouse gas emissions (cf. [78,81]).

5. Mobility Sector and Power-to-Fuel

The mobility sector is one of the most relevant factors and affected by the biggest challenges in reducing greenhouse gas emissions and energy consumption [83,84]. In perspective, it is predicted that, especially, road transport will rise even more and double in terms of CO_2 emissions from 2010 to 2050, up to 14–18 Gt CO_2 [85]. Therefore, a change in transport is mandatory to achieve climate protection goals. In fact, to reduce greenhouse gas emissions, decrease dependencies from crude oil imports and emissions of pollution and noise in cities, the mobility sector has to be nearly completely decarbonized [86]. The potential of RES is huge, e.g., using H_2 in vehicles: 1.0 kWh H_2 is able to replace 1.5 to 2.2 kWh fossil fuel in transport and prevents 465–680 $CO_{2\text{-eq}}$ [9].

To realize defossilization under the use of RES in the transport sector, different types of technologies, types of drive and fuels are available, each with different technology levels and market penetration rates. These include e-mobility, fuel-cell cars and combustion engines using fuel made from renewables. The comparison of the efficiency of drive concepts shows advantages for battery electric vehicles [87]. That is one reason why many car companies actually focus on this concept. Nevertheless, the comparison of total life-cycle greenhouse gas emissions shows that the difference is not as relevant as it seems when only comparing efficiency. All type of drives have advantages and disadvantages, and the assessment of life-cycle greenhouse gas emissions depends heavily on the assumed boundary conditions (e.g., battery size, range and RES) of the individual considered study [88]. Therefore, all types of drive will find its application area and will be part of a mix of technologies in the mobility sector. This variability will be needed to progress in achieving climate protection goals (cf. Table 4).

Table 4. Different types of drives and used renewable fuels [87].

Type of Drive	Type of Fuel	Efficiency of Drive Concept (%)	Life-Cycle Greenhouse Gas Emissions * (g $CO_{2\text{-eq}}$/km)
Battery electric vehicle + battery	Electrical energy	75–85	40–80
Fuel cell + electric vehicle	Hydrogen	25–35	50–70
Combustion engine	Synthetic fuel	10–20	-
Combustion engine	Biofuel	-	-

* [88]: overall driving performance of 150,000 km, battery 60 kWh and further assumptions.

Though, advanced biofuels and biomethane are still represented just in small shares; especially biomethane is growing rapidly in some countries [6].

The production of fuels for the mobility sector in WWTPs is not state-of-the-art but demonstrated in several projects (e.g., [45,89]). Besides providing electrical energy for e-mobility, there are basically two types of fuels usable: gaseous fuels (H_2 and CH_4) and liquid fuels (biofuel and synthetic fuel).

The production of gaseous fuels (CH_4 and H_2) by WWTPs using RES was discussed before in the PtG section of this paper. The utilization of these fuels in the mobility sector is successfully demonstrated in several practical implementations (e.g., [50]). The Henriksdal WWTP in Sweden produces and upgrades biogas for 280 buses used in public transportation [90]. Furthermore, the PtG plant at the Pfaffenhofen WWTP (Germany) will serve as a CH_4-fuel provider for 250 buses as of 2020 [91]. Further small-size mobility studies (1 to 6H_2 buses) are conducted in Barth, Kaisersesch and Sonneberg, Germany [45,50,92]. Another way to produce H_2 is possible via gas reformation from the biogas and was tested in Bottrop (Germany), as well as methanol synthesis (power-to-liquid), but not continued due to missing profitability whilst the technical feasibility could be shown (cf. [89,93]). Another way to produce H_2 is the fermentative conversation of organic mass like sewage sludge or molasses, called "dark fermentation" (cf. [94]).

Besides WWTPs as power-to-mobility locations, there are a lot of ongoing and planned projects given in [21] related to the use of H_2 and CH_4 for transportation in Europe.

WWTPs are able to produce liquid biofuels as well (state-of-research), e.g., through microalgae using wastewater as a nutrient source. This offers a (theoretically) efficient way to remove nutrients than conventional tertiary treatment together with a biomass production that does not use agricultural land or compete with food crops but still lacks feasibility on a large scale [95]. The drawbacks are a high demand of light and a subsequent poor performance during the wintertime for European climatic conditions. This would result in needed technical lighting and big basins, which can offset any feasibility.

Furthermore, the economic production of H_2 and synthetic fuel from sewage sludge is examined in Rosenheim, Germany [96]. Advantages of synthetic liquid fuel and CH_4 (as a natural gas substitute) is the usability in existing and established combustion technologies, which can be used as interim solutions to a future, e.g., H_2-based mobility that differs substantially in the forms of the types of drive and needed infrastructure from the conventional system [97]. WWTPs are able to accompany that transformation by providing the currently required type of fuel and reducing the construction of interim solutions.

At first sight, fuel-based vehicles seem concurrent to electric vehicles. However, the existing energy system cannot provide enough capacity for a full-scale private e-mobility, especially not-controlled charging in local electric distribution grids. Furthermore, battery-driven vehicles are not suitable for transportation vehicles [98]. As a result, a mix of fuel-based mobility for long distances and transportation of goods, as well as electric vehicles for individual mobility in the cities, could be a suitable solution.

Apart from technical issues, the high demand of special raw materials for batteries and fuel cells raise additional ecological problems, which have to be taken into account. The authors of [99] state that

tolerable environmental effects, working conditions in mining areas and violations of fundamental rights, as well as the needed amount of raw materials on a large scale, are not given for an abrupt transformation in transportation. Along with technical progress, the conditions of mining, the needed materials and their supply chains have to be developed gradually at the same time. This is transferable to other sectors, like catalysts in the electrolyzer or battery-storage systems.

From a realistic point of view, the capacities of WWTPs compared with the entire demands of fuel are just a contribution to a future solution. However, the authors of [45] showed that the provided H_2 by WWTPs corresponds with the amount of needed fuel in the respective urban area with the size of the WWTP. Therefore, a WWTP of 50,000 PE_{120} that generates O_2 for aeration purposes via a PtG system comprises the H_2 potential of more than an average-sized filling station. The technical proportions between the PtF-concepts and WWTPs fit, but implementations are mostly in combination with other reasonable energy concepts. Nevertheless, this fact is no disadvantage, and WWTPs offer considerable opportunities to take a part in the local sector of mobility as a fuel provider in terms of production and location for filling stations. Combining fuel production and public transport, especially in combination with other synergies, seems reasonable.

6. Conclusions

The evaluation in this paper illustrates the wide spectrum of interactions and possibilities for WWTPs. It is shown that the water sector is capable of taking part in sector coupling in many ways and generates multiple synergies and advantages towards a stand-alone solution of the different applications. The scale of an implementation in WWTPs is mostly much lower than on an industrial level but with a transferability to a high number of suitable locations and individual solutions. For many cases, a quantitative statement from literature/reports is not transferable due to the laboratory scale. Mostly, just the opportunity and feasibility could be evaluated, but in the end, it has to be tested individually on the considered plant. First, practical implementations are realized by small, local networks taking environmental protection as a top priority for their own local policy development, even without funding.

Across all the literature, obstacles and challenges resemble one another. Technological feasibility is mostly given, but the most relevant obstacle is the lack of economic viability driven by a regulatory framework that does not fit to a fast-changing energy environment. That relates, e.g., to Germany, from not fitting the taxation treatment of energy storage systems and power purchases to inconsequential funding mechanisms and other regulatory backgrounds, which lag behind the technological progress for a fast energy transition [6]. There is a need for establishing a framework for sector coupling regarding the special, manifold and complex interactions of the many affected sectors with each other. This includes a further development and coordination of norms and standards across the national level as well.

Furthermore, WWTP operators have to be supported in day-to-day businesses to handle additional tasks caused by sector coupling. Key objectives of the plants will always be treating wastewater as the main priority. Especially, smaller WWTPs are often not able to provide the needed financial and human resources for additional activities in such a variety of tasks outside the usual disciplines. New business models for operating innovative technologies have to be found and to make use of as much of the synergies as possible. WWTPs would switch from locations of just treating wastewater to local energy and resource facilities, with all their benefits and drawbacks. In conclusion, the water sector is a notable and reasonable player in the field of sector coupling, especially in times of changes to a renewable energy system.

7. Outlook and Further Approach

To implement such innovative technologies in WWTPs, a holistic analysis of the available resources on the plant is necessary, e.g., energy production, flexibility options and gas flow rates. These have to match with the surrounding infrastructure (industry, public transportation system and energy

grids) and the energetic environment (local heat demands, available energy surplus, etc.). For the Mainz WWTP (400,000 PE_{120}; Germany), a wide-range sector-coupling analysis was carried out, which includes an overall analysis followed by a detailed feasibility study for the most promising results [65,66]. In the following, based on these conductions, the findings that are necessary to prepare and realize such an implantation are presented:

- The upcoming needed technical knowledge of every sector is very diverse and causes many interconnections. This requires interdisciplinary expertise, with challenging tasks for every specialist in his field, which cannot be handled by a single player.
- Whilst every expert group can handle their specific field the best, the interconnections can rise up to major problems due to missing experiences and require a very close cooperation.
- Coordination and handling of the utilization path among each other of the competing available resources and their data management is very challenging in terms of gas flow rates, energy production, heat demands and storage management.
- Linking new components with significant impacts on plant processes to existing systems is difficult, e.g., coordination of the electrolysis gases: O_2 production, O_3 generation and O_3 demand for wastewater treatment or the use of H_2 by supplying public transportation and feeding into the NGI.
- The plant operators and the political decision-makers have to be involved and convinced from the start to carry out and promote such big municipal implementations and investments.
- Only a motivated and reliable team is able to keep up with a challenging and difficult regulatory environment.
- Local and/or federal funding is up-to-now mandatory to use the potential of sector coupling in WWTPs.

Assembling a responsible interdisciplinary team is therefore a prerequisite for working on such a diversified project. This includes at least one of the following experts: general planner for large construction measures, plant operator, energy supplier, grid operator, scientific support and various engineering expertise depending on the targeted sectors. This team should develop a practicable and technical-economic feasible concept based on the local situation. After selecting and specifying a preferred variant to be implemented, the funding situation needs to be clarified before finally deciding on the implementation.

In the meantime, at the Mainz WWTP, the political and technical decision-maker has given their consent, and the positive notification of federal funding has arrived. The project will start in 2020 with further regulatory preparations, assessments and the invitation of tenders. The start of implementation is planned for 2021.

References

1. Friedrich, E.; Pillay, S.; Buckley, C.A. Environmental life cycle assessments for water treatment processes—A South African case study of an urban water cycle. *Water SA* **2009**, *2009*, 73–84. [CrossRef]
2. U.S. Department of Energy. The Water-Energy Nexus: Challenges and Opportunities. 2014. Available online: https://www.energy.gov/downloads/water-energy-nexus-challenges-and-opportunities (accessed on 13 March 2020).
3. Beca Consultants Pty Ltd (Beca). Opportunities for Renewable Energy in the Australian Water Sector. 2015. Available online: https://arena.gov.au/assets/2016/01/Opportunities-for-renewable-energy-in-the-Australian-water-sector.pdf (accessed on 13 March 2020).

4.　Economic and Social Council, United Nations. Special Edition: Progress Towards the Sustainable Development Goals. 2019. Available online: https://undocs.org/E/2019/68 (accessed on 13 March 2020).

5.　UNFCCC. Paris Agreement. 2016. Available online: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf (accessed on 13 March 2020).

6.　Renewable Energy Policy Network for the 21st Century (REN21). Renewables 2019—Global Status Report. 2019. Available online: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf (accessed on 13 March 2020).

7.　BNetzA. Flexibilität im Stromversorgungssystem. Bestandsaufnahme, Hemmnisse und Ansätze zur Verbesserten Erschließung von Flexibilität. 2017. Available online: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/BNetzA_Flexibilitaetspapier.pdf?__blob=publicationFile&v=1 (accessed on 13 March 2020).

8.　Deutsche Energie-Agentur GmbH (DENA). dena-Netzflexstudie. Optimierter Einsatz von Speichern für Netz- und Marktanwendungen in der Stromversorgung. 2017. Available online: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9191_dena_Netzflexstudie.pdf (accessed on 13 March 2020).

9.　Sterner, M.; Stadler, I. *Energiespeicher—Bedarf, Technologien, Integration*; 2.Auflage 2016; Springer: Berlin, Germany, 2016; ISBN 978-3-642-37379-4.

10.　Müller-Syring, G.; Henel, M.; Köppel, W.; Sterner, M.; Höcher, T. Entwicklung von Modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz. 2013. Available online: https://www.dvgw.de/medien/dvgw/forschung/berichte/g1_07_10.pdf (accessed on 15 April 2020).

11.　Lensch, D.; Schaum, C.; Cornel, P.; Lensch, D.; Schaum, C.; Cornel, P. Examination of food waste co-digestion to manage the peak in energy demand at wastewater treatment plants. *Water Sci. Technol.* **2016**, *73*, 588–596. [CrossRef] [PubMed]

12.　Seier, M.; Schebek, L. Model-based investigation of residual load smoothing through dynamic electricity purchase: The case of wastewater treatment plants in Germany. *Appl. Energy* **2017**, *205*, 210–224. [CrossRef]

13.　Mauky, E.; Weinrich, S.; Jacobi, H.-F.; Nägele, H.-J.; Liebetrau, J.; Nelles, M. Demand-driven biogas production by flexible feeding in full-scale—Process stability and flexibility potentials. *Anaerobe* **2017**, *46*, 86–95. [CrossRef] [PubMed]

14.　Schäfer, M.; Hobus, I.; Schmitt, T.G. Energetic flexibility on wastewater treatment plants. *Water Sci. Technol.* **2017**, *76*, 1225–1233. [CrossRef]

15.　Schmitt, T.G.; Schäfer, M.; Gretzschel, O.; Knerr, H.; Hüesker, F.; Kornrumpf, T.; Zdrallek, M.; Salomon, D.; Bidlingmaier, A.; Simon, R.; et al. Abwasserreinigungsanlagen als Regelbaustein in intelligenten Verteilnetzen mit Erneuerbarer Energieerzeugung—arrivee. 2017. Available online: www.erwas-arrivee.de (accessed on 25 June 2018).

16.　Schäfer, M. Ein Methodischer Ansatz zur Bereitstellung Energetischer Flexibilität Durch Einen Anpassungsfähigen Kläranlagenbetrieb. Ph.D. Thesis, Technische Universität Kaiserslautern, Kaiserslautern, Germany, February 2019. Available online: https://nbn-resolving.org/urn:nbn:de:hbz:386-kluedo-56084 (accessed on 13 March 2020).

17.　ASUE. Power to Gas. Erzeugung von Regenerativem Erdgas. 2014. Available online: https://asue.de/sites/default/files/asue/themen/umwelt_klimaschutz/2014/broschueren/07_06_14_Power_to_Gas.pdf (accessed on 13 March 2020).

18.　Forschungsstellefür Energiewirtschaft e.V. (FfE). Kurzstudie Power-to-X. Ermittlung des Potenzials von PtX-Anwendungen für die Netzplanung der Deutschen ÜNB. 2017. Available online: https://www.netzentwicklungsplan.de/de/ermittlung-des-potenzials-von-power-x-anwendungen-fuer-die-netzplanung-zu-kapitel-251 (accessed on 13 March 2020).

19.　Peyer, T.; Rene, N.; Thomas, H.; Monika, R. Kläranlagen-Ideal für Power-to-Gas: Swisspower identifiziert 100 Kläranlagen in der Nähe von Gasnetzen. *AQUA GAS* **2016**, *7–8*, 42–46.

20.　Schäfer, M.; Gretzschel, O.; Schütz, S.; Schuhmann, E.; Raabe, T. The natural gas grid infrastructure as a suitable storage for renewable energy produced by wastewater treatment plants. In Proceedings of the 10th International Renewable Energy Storage Conference (IRES), Düsseldorf, Germany, 15–16 March 2016.

21.　Wulf, C.; Linßen, J.; Zapp, P. Review of Power-to-Gas Projects in Europe. *Energy Procedia* **2018**, *155*, 367–378. [CrossRef]

22. Schäfer, M.; Gretzschel, O.; Schmitt, T.G.; Knerr, H. Wastewater Treatment Plants as System Service Provider for Renewable Energy Storage and Control Energy in Virtual Power Plants—A Potential Analysis. *Energy Procedia* **2015**, *73*, 87–93. [CrossRef]

23. Hien, S. Approaches for Supportive Prediction of Biogas Production Rate and Control Strategies to Provide Flexible Power Production. Ph.D. Thesis, University of Luxembourg, Esch-sur-Alzette, Luxemburg, May 2017. Available online: http://hdl.handle.net/10993/31245 (accessed on 13 March 2020).

24. Smolinka, T.; Günther, M.; Garche, J. Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien: NOW-Studie: Kurzfassung des Abschlussberichts—Redakionsstand: 22.12.2010 (Revision 1 vom 05.07.2011). 2011. Available online: https://www.tib.eu/de/suchen/id/TIBKAT%3A872387518/Stand-und-Entwicklungspotenzial-der-Wasserelektrolyse/ (accessed on 16 March 2020).

25. DENA. *Power to Gas. Eine Innovative Systemlösung auf dem Weg zur Marktreife*; Deutsche Energie-Agentur GmbH, DENA: Berlin, Germany, 2013.

26. Graf, F.; Götz, M.; Henel, M.; Schaaf, T.; Tichler, R. Technoökonomische Studie von Power-to-Gas-Konzepten. 2014. Available online: https://www.dvgw.de/medien/dvgw/forschung/berichte/g3_01_12_tp_b_d.pdf (accessed on 16 March 2020).

27. DWA. *DWA-M 363—Herkunft, Aufbereitung und Verwertung von Biogasen*; DWA, Ed.; DWA: Hennef, Germany, 2010; ISBN 978-3-941897-52-6.

28. Graf, F.; Krajete, A.; Schmack, U. Techno-ökonomische Studie zur Biologischen Methanisierung bei Power-to-Gas-Konzepten. 2014. Available online: https://www.dvgw.de/themen/forschung-und-innovation/forschungsprojekte/dvgw-forschungsbericht-g-30113/ (accessed on 16 March 2020).

29. Reuter, M. Power-to-Gas: Biological methanization; first at a municipal sewage plant. In Proceedings of the 8th International Renewable Energy Storage Conference, Düsseldorf, Germany, 18–20 November 2013.

30. Dröge, S.; Pacan, B. Erfahrungen mit der Power-to-Gas Pilotanlage im Energiepark Pirmasens-Winzeln. In Proceedings of the Fachgespräch, Biologische Methanisierung, Berlin, Germany, 25 April 2017.

31. Trautmann, N.; Nelting, K.; Vogel, B.; Weichgrebe, D.; Stopp, P.; Cuff, G. Methan aus Erneuerbaren Energien—Biologische Umwandlung von Wasserstoff aus der Elektrolyse zu Methan. 2018. Available online: https://www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-33505-01.pdf (accessed on 16 March 2020).

32. Lardon, L.; Thorberg, D.; Krosgaard, L. Biogas valorization and efficient energy management—Technical and economic analysis of biological methanation. In *Powerstep: Your Flush, Our Energy*; Kompetenzzentrum Wasser Berlin: Berlin, Germany, 2018; Available online: http://powerstep.eu/system/files/generated/files/resource/d3-2-technical-and-economic-analysis-of-biological-methanationdeliverable.pdf (accessed on 16 March 2020).

33. Gandiglio, M.; Lanzini, A.; Soto, A.; Leone, P.; Santarelli, M. Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems. *Front. Environ. Sci.* **2017**, *5*, 221. [CrossRef]

34. Wang, H.; Gu, Y.; Li, Y.; Li, X.; Luo, P.; Robinson, Z.P.; Wang, X.; Wu, J.; Li, F. The feasibility and challenges of energy self-sufficient wastewater treatment plants. *Appl. Energy* **2017**, *204*, 1463–1475. [CrossRef]

35. Pinnekamp, J.; Schröder, M.; Bolle, F.-W.; Gramlich, E.; Gredigk-Hoffmann, S.; Koenen, S.; Loderhose, M.; Miethig, S.; Ooms, K.; Riße, H.; et al. Energie in Abwasseranlagen. Handbuch NRW. 2018. Available online: https://www.umwelt.nrw.de/fileadmin/redaktion/Broschueren/energie_abwasseranlagen.pdf (accessed on 16 March 2020).

36. Gretzschel, O.; Schmitt, T.G.; Hansen, J.; Siekmann, K.; Jakob, J. Sludge digestion instead of aerobic stabilisation—A cost benefit analysis based on experiences in Germany. *Water Sci. Technol.* **2014**, *69*, 430–437. [CrossRef]

37. ASUE. *BHKW Kennzahlen 2014/2015. Module, Anbieter, Kosten. Arbeitsgemeinschaft für Sparsamen und Umweltfreundlichen Energieverbrauch e.V.*; ASUE: Berlin, Germany, 2014.

38. Strauss, K. *Kraftwerkstechnik. Zur Nutzung Fossiler, Nuklearer und Regenerativer Energiequellen, 7. Auflage*; Springer Vieweg: Berlin/Heidelberg, Germany, 2016; ISBN 978-3-662-53029-0. [CrossRef]

39. Erbe, V.; Kolisch, G.; Feldmann, N. Studie zur Aufbereitung und Einspeisung von Faulgas auf Kommunalen Kläranlagen. 2011. Available online: https://www.lanuv.nrw.de/landesamt/forschungsvorhaben/sonstiges?tx_cartproducts_products%5Bproduct%5D=741&cHash=baebeccab6c9a99fb823b8f435fc00a2 (accessed on 16 March 2020).

40. Electrochea. Electrochea Realisiert Power-to-Gas-Anlage für ein Nachhaltiges Pfaffenhofen. 2017. Available online: http://www.electrochaea.com/wp-content/uploads/2017/11/20171113_PM-Electrochaea_PtoG_fuer_Pfaffenhofen_DE_FIN.pdf (accessed on 16 March 2020).

41. Zutter, R.; Nijsen, R.; Peyer, T. Studie Potential zur Effizienzsteigerung in Kläranlagen mittels Einspeisung oder Verstromung des Klärgases. 2015. Available online: https://swisspower.ch/themen-und-standpunkte/potential-zur-effizienzsteigerung-in-kl%C3%A4ranlagen-mittels-einspeisung-oder-verstromung-des-kl%C3%A4rgases (accessed on 16 March 2020).

42. Ryser Ingenieure AG. Klärgas-Verstromung oder Aufbereitung und Einspeisung. Entscheidhilfe für Betreiber und Planer. 2019. Available online: http://www.infrawatt.ch/sites/default/files/2019_02_20_Energie%20in%20ARA_Kap._Kl%C3%A4rgas%20Verstromen%20oder%20Einspeisen.pdf (accessed on 16 March 2020).

43. Kolisch, G.; Taudien, Y.; Osthoff, T. Projekt Nr. 2: Verbesserung der Klärgasnutzung, Steigerung der Energieausbeute auf kommunalen Kläranlagen (Zusatzbericht). 2014. Available online: https://www.lanuv.nrw.de/fileadmin/forschung/wasser/klaeranlage_abwasser/2014_Abschlussbericht_TP2.pdf (accessed on 16 March 2020).

44. Maktabifard, M.; Zaborowska, E.; Makinia, J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. *Rev. Environ. Sci. Biotechnol.* **2018**, *17*, 655–689. [CrossRef]

45. Jentsch, M.; Büttner, S. Dezentrale Umsetzung der Energie- und Verkehrswende mit Waserstoffsystemen auf Kläranlagen. *gwf Gas + Energie* **2019**, *6*, 28–39.

46. Rudolph, K.-U.; Müller-Czygan, G.; Bombeck, M. Reinsauerstoffbelüftung auf kleinen Industriekläranlagen—Energieeinsparpotenziale und Kapazitätssteigerungen am Beispiel der Kläranlage der Fa. Emsland Frischgeflügel GmbH: Meschede, Germany. Available online: https://www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-26353.pdf (accessed on 15 April 2020).

47. Büttner, S.; Jentsch, M.; Hörnlein, S.; Hubner, B. Sektorenkopplung im Rahmen der Energiewende—Einsatz von Elektrolysesauerstoff auf kommunalen Kläranlagen. In *Nutzung Regenerativer Energiequellen und Wasserstofftechnik 2018*; Luschtinetz, T., Lehmann, J., Eds.; Fachhochschule Stralsund: Stralsund, Germany, 2018; pp. 22–41. ISBN 978-3-9817740-4-7. Available online: https://www.hochschule-stralsund.de/storages/hs-stralsund/FAK_ETI/Dateien/REGWA/TagungsBaende/Tagungsband_2018-11-04.pdf (accessed on 16 March 2020).

48. CETAQUA. Greenlysis—Final Report. 2013. Available online: https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=LIFE08_ENV_E_000118_AfterLIFE.pdf (accessed on 16 March 2020).

49. Schmid-Schmieder, V. Alternative Energiequellen auf Kläranlagen: Elektrolytische Wasserstoff- und Sauerstoffnutzung auf Kläranlagen—Wasserstoffproduktion aus Faul- und Biogas. In *wwt Wasserwirtschaft Wassertechnik*; HUSS-Verlag: Munich, Germany, 2007; Volume 11–12.

50. Haas, F.; Jain, A.; Lehmann, J.; Luschtinetz, O.; Schefler, R. The hydrogen-oxygen project in Barth. *Int. J. Hydrog. Energy* **2004**, *30*, 555–557. [CrossRef]

51. Hansen, J.; Steinmetz, H.; Zettl, U. Betriebsergebnisse zum Einsatz der Reinsauerstoffbegasung zur weitergehenden Stickstoffelimination bei einer Anlage mit Weinbaueinfluß. *Abwassertechnik* **1996**, *2*, 32–36.

52. Margot, J.; Urfer, D. Sicherheitsaspekte zum Umgang mit Sauerstoff auf Kläranlagen. 2016. Available online: https://www.micropoll.ch/fileadmin/user_upload/Redaktion/Dokumente/02_Faktenblaetter/Faktenblatt_Sauerstoff_DE_FINAL_21112016.pdf (accessed on 16 March 2020).

53. Strässle, M. Anwendungspotentiale der Wasserstofftechnologie auf Kläranlagen. Master's Thesis, Leibnitz University Hannover, Hannover, Germany, October 2017.

54. CETAQUA. GREENLYSIS—Hydrogen and Oxygen Production via Electrolysis Powered by Renewable Energies to Reduce Environmental Footprint of a WWTP 2012. Available online: http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=3416 (accessed on 16 March 2020).

55. SUN. Das Klärwerk 1 in Nürnberg. Eine Kurzbeschreibung. 2017. Available online: https://www.nuernberg.de/imperia/md/sun/dokumente/sun/kw1_kurz.pdf (accessed on 16 March 2020).

56. DWA. *DWA-A 131—Bemessung von Einstufigen Belebungsanlagen, Juni 2016*; Deutsche Vereinigung für Wasserwirtschaft Abwasser und Abfall: Hennef, Germany, 2016; ISBN 978-3-88721-331-2.

57. Gewässerschutzverordnung. Schweizerische Bundesrat. GSchV, 2018. Law Text (AS 1998 2863). Available online: https://www.admin.ch/opc/de/classified-compilation/19983281/index.html (accessed on 28 September 2018).

58. Hillenbrand, T.; Tettenborn, F. Empfehlungen des Stakeholder-Dialogs "Spurenstoffstrategie des Bundes". An die Politik zur Reduktion von Spurenstoffeinträgen in die Gewässer. 2017. Available online: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Binnengewaesser/spurenstoffstrategie_policy_paper_bf.pdf (accessed on 16 March 2020).

59. Pinnekamp, J.; Bolle, F.-W.; Palmowski, L.; Veltmann, K.; Mousel, D.; Mauer, C.; Eckers, S. Energiebedarf von Verfahren zur Elimination von organischen Spurenstoffen. Final Report. 2011. Available online: https://www.lanuv.nrw.de/fileadmin/lanuv/wasser/abwasser/forschung/pdf/Abschlussbericht_ENVELOS.pdf (accessed on 20 March 2020).

60. Schäfer, M.; Schmitt, T.G.; Gretzschel, O.; Steinmetz, H. Integration of fluctuating Renewable Energies on WWTPs to remove micropollutants due ozonation. In Proceedings of the 12th International Renewable Energy Storage Conference—IRES 2018, Düsseldorf, Germany, 13–15 March 2018.

61. UBA. Maßnahmen zur Verminderung des Eintrages von Mikroschadstoffen in die Gewässer 85/2014. 2014. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_85_2014_massnahmen_zur_verminderung_des_eintrages_von_mikroschadstoffen_in_die_gewaesser_0.pdf (accessed on 16 March 2020).

62. DWA. *Möglichkeiten der Elimination von Anthropogenen Spurenstoffen*; DWA, Ed.; DWA: Hennef, Germany, 2015; ISBN 978-3-88721-210-0.

63. Wunderlin, P.; Abegglen, C.; Durisch-Kaiser, E.; Götz, C.; Joss, A.; Kienle, C.; Langer, M.; Peter, A.; Santiago, S.; Soltermann, F.; et al. Abklärungen Verfahrenseignung Ozonung. Available online: https://www.micropoll.ch/fileadmin/user_upload/Redaktion/Dokumente/03_Vollzugshilfen/Abkl%C3%A4rungenVerfahrenseignungOzonung_DE_FINAL_20042017.pdf (accessed on 16 March 2020).

64. Margot, J.; Urfer, D. Sicherheitsaspekte zum Umgang mit Ozon auf Kläranlagen. 2016. Available online: https://www.micropoll.ch/fileadmin/user_upload/Redaktion/Dokumente/02_Faktenblaetter/Faktenblatt_Ozon_DE_Final_09092016.pdf (accessed on 16 March 2020).

65. Steinmetz, H.; Schmitt, T.G.; Schäfer, M.; Gretzschel, O.; Krieger, S.; Alt, K.; Zydorczyk, S.; Bender, V.; Pick, E. Konzeptstudie. Klimafreundliche und ressourceneffiziente Anwendung der Wasserelektrolyse zur Erzeugung von regenerativen Speichergasen kombiniert mit einer weitergehenden Abwasserbehandlung zur Mikroschadstoffelimination auf Kläranlagen. Unpublished work. 2018.

66. Steinmetz, H.; Schmitt, T.G.; Schäfer, M.; Gretzschel, O.; Krieger, S.; Alt, K.; Zydorczyk, S.; Bender, V.; Pick, E. Ergänzende Betrachtungen zur Konzeptstudie. Unpublished work. 2019.

67. DWA KEK-10.4. *Wärme- und Kältekonzepte auf Kläranlagen: Arbeitsbericht der DWA-Arbeitsgruppe 10.4 "Wärme- und Kältekonzepte auf Kläranlagen"*; Arbeitsbericht. Korrespondenz Abwasser, Abfall; DWA: Hennef, Germany, 2016; pp. 704–713.

68. AWEL—Amt für Abfall, wasser, Energie und Luft. Baudirektion Kanton Zürich. Heizen und Kühlen mit Abwasser. Leitfaden für die Planung, Bewilligung und Realisierung von Anlagen zur Abwasserenergienutzung. 2010. Available online: https://awel.zh.ch/internet/baudirektion/awel/de/energie_radioaktive_abfaelle/waermenutzung_ausuntergrundwasser/abwasser/_jcr_content/contentPar/downloadlist/downloaditems/1596_1433140855118.spooler.download.1433141005406.pdf/Heizen_Kuehlen_Abwasser.pdf (accessed on 16 March 2020).

69. Alekseiko, L.N.; Slesarenko, V.V.; Yudakov, A.A. Combination of wastewater treatment plants and heat pumps. *Pac. Sci. Rev.* **2014**, *16*, 36–39. [CrossRef]

70. Mitsdoerffer, R. Wärme- und Kältekonzepte auf Kläranlagen, München. 2017. Available online: https://www.gfm-ingenieure.de/fileadmin/Daten/Referenzen/Klaeranlage/Energie/Vortrag-Mitsdoerffer-20170115-mi.pdf (accessed on 16 March 2020).

71. DWA. *DWA-M 114—Abwasserwärmenutzung. Merkblatt, Entwurf September 2018*; Deutsche Vereinigung für Wasserwirtschaft Abwasser und Abfall: Hennef, Germany, 2018; ISBN 978-3-88721-635-1.

72. Seyfried, C.F.; Kroiss, H.; Rosenwinkel, K.-H.; Dichtl, N.; Weiland, P. *Anaerobtechnik. Abwasser-, Schlamm- und Reststoffbehandlung, Biogasgewinnung*; 3., neu bearbeitete Auflage; Springer Vieweg: Berlin, Germany, 2015; ISBN 978-3-642-24895-5.

73. Hubert, C.; Steiniger, B.; Schaum, C.; Michel, M.; Spallek, M. Variation of the digester temperature in the annual cycle—Using the digester as heat storage. *Water Pract. Technol.* **2019**, *14*, 471–481. [CrossRef]

74. Bousková, A.; Dohányos, M.; Schmidt, J.E.; Angelidaki, I. Strategies for changing temperature from mesophilic to thermophilic conditions in anaerobic CSTR reactors treating sewage sludge. *Water Res.* **2005**, *39*, 1481–1488. [CrossRef]

75. Barrington, S.; Ortega, L.; Guiot, S.R. Thermophilic adaptation of a mesophilic anaerobic sludge for food waste treatment. *J. Environ. Manage.* **2007**, *88*, 517–525. [CrossRef]

76. DWA. *DWA-M 368—Biologische Stabilisierung von Klärschlamm*; DWA, Ed.; DWA: Hennef, Germany, 2014; ISBN 978-3-944328-60-7.

77. Aprile, M.; Scoccia, R.; Dénarié, A.; Kiss, P.; Dombrovszky, M.; Gwerder, D.; Schuetz, P.; Elguezabal, P.; Arregi, B. District power-to-heat/cool complemented by sewage heat recovery. *Energies* **2019**, *12*, 364. [CrossRef]

78. Kollmann, R.; Neugebauer, G.; Kretschmer, F.; Truger, B.; Kindermann, H.; Stoeglehner, G.; Ertl, T.; Narodoslawsky, M. Renewable energy from wastewater—Practical aspects of integrating a wastewater treatment plant into local energy supply concepts. *J. Clean. Prod.* **2016**, *155*, 119–129. [CrossRef]

79. Hamburg-Wasser. Unterirdischer Waermespeicher Erfolgreich Getestet. 2017. Available online: https://www.hamburgwasser.de/privatkunden/unternehmen/presse/unterirdischer-waermespeicher-erfolgreich-getestet/ (accessed on 16 March 2020).

80. Hansen, G.; Giese, T. "Mach 3": Umweltwärme aus Wasser für eine erneuerbare Fernwärmeversorgung in Hamburg—ein Projekt mit vielen Möglichkeiten. In Proceedings of the 31th Hamburger Kolloquium zur Abwasserwirtschaft: Themenschwerpunkte: Mikroschadstoffe, Mikroplastik, Antibiotikaresistenzen; Industrieabwasserbehandlung; Niederschlagswasser, Umweltwärme; Klärschlammentsorgung, Gewässerschutz, Hamburg, Germany, 18–19 September 2019; Available online: https://cgi.tu-harburg.de/~{}awwweb/downloads/TagungsbandAbwasserkolloquium2019.pdf (accessed on 16 March 2020).

81. Neugebauer, G.; Kretschmer, F.; Kollmann, R.; Narodoslawsky, M.; Ertl, T.; Stoeglehner, G. Mapping Thermal Energy Resource Potentials from Wastewater Treatment Plants. *Sustainability* **2015**, *7*, 12988–13010. [CrossRef]

82. BHKW-Infozentrum. Grundlagen der Kraft-Wärme-Kälte-Kopplung. Available online: https://www.bhkw-infozentrum.de/allgemeine-erlaeuterungen-bhkw-kwk/kwkk-grundlagen.html (accessed on 6 April 2020).

83. IPCC. Climate change 2014. Synthesis Report. Available online: https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf (accessed on 16 March 2020).

84. IEA. World Energy Outlook. 2018. Available online: https://webstore.iea.org/download/summary/190?fileName=English-WEO-2018-ES.pdf (accessed on 16 March 2020).

85. Pietzcker, R.C.; Longden, T.; Chen, W.; Fu, S.; Kriegler, E.; Kyle, P.; Luderer, G. Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy* **2014**, *64*, 95–108. [CrossRef]

86. Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). Initiative klimafreundlicher Straßengüterverkehr. Fahrplan für einen klimafreundlichen Straßengüterverkehr. 2017. Available online: https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/initiative-klimafreundlicher-strassengueterverkehr.pdf?__blob=publicationFile (accessed on 16 March 2020).

87. Unnerstall, T. Verkehr—Die Zukunft des Autos. In *Energiewende verstehen: Die Zukunft von Autoverkehr, Heizen und Strompreisen*; Unnerstall, T., Ed.; Springer: Berlin, Germany, 2018; pp. 57–69. ISBN 978-3-662-57786-8.

88. Sternberg, A.; Hank, C.; Hebling, C. Treibhausgas-Emissionen für Batterie- und Brennstoffzellenfahrzeuge mit Reichweiten über 300 km: Studie im Auftrag der H2 Mobility. Available online: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/news/2019/ISE_Ergebnisse_Studie_Treibhausgasemissionen.pdf (accessed on 11 March 2020).

89. Bolle, F.-W.; Genzowsky, K.; Gredigk-Hoffmann, S.; Reinders, M.; Riße, H.; Schröder, M.; Manja, S.; Wöffen, B.; Illing, F.; Jagemann, P.; et al. WaStraK NRW "Einsatz der Wasserstofftechnologie in der Abwasserbeseitigung"—Phase I. Band I: Kompendium Wasserstoff. 2012. Available online: https://www.lanuv.nrw.de/landesamt/forschungsvorhaben/klaeranlage-abwasserbeseitigung?tx_cartproducts_products%5Bproduct%5D=654&cHash=f6ef363dd1a75575207fe2fa142d5e95 (accessed on 16 March 2020).

90. Scandinavian Biogas. Henriksdal and Bromma, Sweden. Available online: http://scandinavianbiogas.com/en/project/henriksdal-and-bromma/ (accessed on 16 March 2020).

91. Schattenhofer, S. Pfaffenhofen gibt Gas—erneuerbar: Neues Projekt der Bürger-Energiegenossenschaft: Überschüssiger Öko-Strom wird Biomethan. 2017. Available online: https://www.donaukurier.de/nachrichten/wirtschaft/lokalewirtschaft/Pfaffenhofen-Pfaffenhofen-gibt-Gas-erneuerbar;art1735,3569895 (accessed on 16 March 2020).

92. Meier, B. Kläranlage Kaisersesch soll Wasserstofftankstelle speisen. Rhein-Zeitung. 2017. Available online: https://www.rhein-zeitung.de/region/aus-den-lokalredaktionen/kreis-cochem-zell_artikel,-klaeranlage-kaisersesch-soll-wasserstofftankstelle-speisen-_arid,1606117.html (accessed on 29 January 2018).

93. Bolle, F.-W.; Reinders, M.; Riße, H.; Schröder, M.; Bernhard, W.; Illing, F. WaStraK NRW "Einsatz der Wasserstofftechnologie in der Abwasserbeseitigung"—Phase I. Band II: Methanolsynthese. 2012. Available online: https://www.lanuv.nrw.de/landesamt/forschungsvorhaben/klaeranlage-abwasserbeseitigung?tx_cartproducts_products%5Bproduct%5D=654&cHash=f6ef363dd1a75575207fe2fa142d5e95 (accessed on 16 March 2020).

94. Mariakakis, I. A Two Stage Process for Hydrogen and Methane Production by the Fermentation of Molasses. Ph.D. Thesis, Stuttgarter Berichte zur Siedlungswasserwirtschaft, Stuttgart, Germany, 2013.

95. Chen, G.; Zhao, L.; Qi, Y. Enhancing the productivity of microalgae cultivated in wastewater toward biofuel production: A critical review. *Appl. Energy* **2015**, *137*, 282–291. [CrossRef]

96. 2synfuel. Turning Sweage Sluidge into Fuels and Hydrogen. 2018. Available online: http://www.tosynfuel.eu (accessed on 16 March 2020).

97. Energbieangentor.NRW Wasserstoff—Schlüssel zur Energiewende. Beispiele aus Nordrhein-Westfalen von der Herstellung bis zur Nutzung. 2018. Available online: https://broschueren.nordrheinwestfalendirekt.de/broschuerenservice/energieagentur/wasserstoff-schluessel-zur-energiewende-beispiele-aus-nordrhein-westfalen-von-der-herstellung-bis-zur-nutzung/2833 (accessed on 16 March 2020).

98. Wietschel, M.; Plötz, P.; Pfluger, B.; Klobasa, M.; Eßer, A.; Haendel, M.; Müller-Kirchenbauer, J.; Kochems, J.; Hermann, L.; Grosse, B.; et al. *Sektorkopplung—Definition, Chancen und Herausforderungen. Working Paper Sustainability and Innovation No. S 01/2018*; Fraunhofer ISI: Arlsruhe, Germany, 2018.

99. Reuter, B.; Hendrich, A.; Hengstler, J.; Kupferschmid, S.; Schwenk, M. Rohstoffe für innovative Fahrzeugtechnologien. Herausforderungen und Lösungsansätze. 2019. Available online: https://www.e-mobilbw.de/fileadmin/media/e-mobilbw/Publikationen/Studien/Material-Studie_e-mobilBW.pdf (accessed on 16 March 2020).