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Neighborhood-Scale Urban Water Reclamation with Integrated Resource Recovery for Establishing Nexus City in Munich, Germany: Pipe Dream or Reality?

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Abstract: With the rapid expansion of cities due to population growth and urbanization, conventional centralized wastewater collection and treatment systems are slowly becoming a burden; expensive maintenance is required for aging plants and piping infrastructure, the cost of expanding the capacity to cover demand from population growth, and new regulations for tighter control over certain pollutants such as micropollutants. As an alternative to this system, this study discusses the feasibility of decentralized treatment systems at the neighborhood scale. Taking a Water-Energy-Food (WEF) Nexus approach, such systems can support water and energy conservation, recovery of water, energy, and nutrients as well as generation of energy from wastewater, be customized to individual water and energy requirements, and eliminate the need for lengthy pipe networks. The method employed in this study is comparing the economic feasibility of the status quo to a proposed decentralized solution. The study finds that the costs of implementing a hypothetical decentralized water reclamation with an integrated resource recovery system using an anaerobic membrane bioreactor (AnMBR) in a downtown high-density neighborhood of the city of Munich, Germany, can theoretically be recuperated within two years. This alternative system may cost 60% of what it costs to run the centralized system. By linking the AnMBR to a biogas digestor and using systematically harvested organic waste as a co-substrate, the decentralized system can generate enough energy to run itself and even feed some energy to the grid. This study is highly hypothetical, yet generating evidence such as this can support a systemic socio-technical transition towards a more circular economy with optimal resource recovery.

Keywords: water reclamation with integrated resource recovery; Water-Energy-Food (WEF) Nexus approach; climate change; wastewater management infrastructure; paradigm shift; circular economy; cities; Germany

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1. Introduction

Rapid population growth and urbanization are causing a demand for the rapid expansion of cities. This puts a large burden on existing infrastructure such as centralized wastewater collection and treatment systems, both in terms of maintaining existing aging infrastructure built 50 to 100 years ago, as well as expanding their capabilities to meet more stringent regulations and control for emerging pollutants. Furthermore, the effects of climate change are being felt increasingly intensively. This puts the burden on the cities of tomorrow to lessen their environmental footprint and become more resilient to climate change impacts and self-reliant than they are currently.

Applying the Water-Energy-Food (WEF) Nexus approach [1] offers cities a way to develop more sustainable development pathways. The approach posits that much water is needed to produce energy, much energy is needed to convey and treat water, and that much water and energy is needed to produce and supply food. Planning these "sectors" in conjunction can support the conservation of water and energy, thereby aiding climate change mitigation and adaption, and attainment of the SDGs. Conventional urban infrastructure systems tend to be planned in "silos" considering urban sectors individually and not in conjunction, and are very resource intensive and linear in how they use resources. For example, water is used once and then treated before discharging it to the natural environment from where it is re-procured.

A key Nexus opportunity is water reclamation with integrated resource recovery: this can harness "wastewater" in cities i.e., sewage and rainwater, as a valuable alternative source of water under climate change-related water scarcity, as well as being a source of energy and nutrients. Decentralized systems may be a more resilient and sustainable option than centralized sewerage systems. Whilst many technology options exist, these have rarely been implemented at a neighborhood scale in existing cities.

The aim of this study is to analyze the feasibility of implementing decentralized water reclamation with an integrated resource recovery system in an inner-city neighborhood of the city of Munich in Germany. The centralized sewerage system of Munich is over a century old and in need of costly maintenance and repairs. It is a combined sewer system that collects and treats sewage mixed with stormwater. Maxvorstadt neighborhood has a particularly dense built environment where 90% of surfaces are sealed, which is already suffering from the urban heat island effect due to the increase in heat days due to climate change. The study takes this circumstance as an opportunity to rethink the existing urban infrastructure in this neighborhood using a Nexus approach. Specifically, it aims to find out if such a system could be built and operated at a lower cost and with better resource recovery efficiency than the current centralized sewerage system. This study builds upon our previous work [2] on the potential of converting Maxvorstadt into a "green neighborhood" using the Nexus approach.

To this end, this study reviews the state-of-the-art in terms of water reclamation with integrated resource recovery using a select number of relevant best practice case studies at a neighborhood scale from across Europe. From these, lessons are derived and suitable technical components are chosen for hypothetical application in Maxvorstadt. Their application is then analyzed in terms of potential capital as well as operation and maintenance costs by comparing the decentralized option to the current centralized sewerage system, and expected benefits including water reclamation and reuse, energy generation potential, and nutrient recovery for use in urban agriculture are discussed.

2. State-of-the-Art of Water Reclamation with Resource Recovery in Europe

2.1. Jenfelder Au Quarter in Hamburg, Germany

The Jenfelder Au neighborhood is a former army barracks that is being redeveloped into an ecologically friendly settlement for 2000 people in 770 apartments [3]. Here blackwater (from toilets) and greywater (from kitchens and washrooms) are separated at the building scale. Vacuum toilets are used to convey the blackwater into the anaerobic digester for decentralized treatment with energy recovery, which is used to provide CO_2 neutral heating to the district. The final treated sludge is low on toxic organic contaminants and heavy metals as a result of greywater separation and, as such, can be used as an organic fertilizer for agriculture and landscaping [4]. Greywater is treated in a trickling filter, which is relatively simple and low in energy requirement, and then returned to the river as an environmental buffer [4].

This project shows the benefits of such an integrated and decentralized approach, as it reduces the load on the centralized treatment plant in the city [3,4]. Separation of grey- and blackwater has the following advantages: (1) reduces the load on digesters, thus lowering their required capacity; (2) boosts biogas production by about 6%; (3) allows for simple hence cheaper treatment of greywater; and (4) reduces micropollutant and heavy metal load to the final digested sludge, thus allowing its use in agriculture safely. This in turn has several benefits: it increases supply security for fertilizers especially the limited phosphorus which is imported in Germany, thus eliminating the expensive, complex and inefficient phosphorus recovery procedures that are required by law to recover phosphorus in treatment plants. Thus, it reduces the need to manufacture synthetic fertilizers which is very energy-intensive, thus providing indirect energy returns. It also provides superior plant growth availability of the nutrients due to the way phosphorus is bound to the sludge organically, thus boosting agricultural yield (Table S1 in Supplementary Materials).

2.2. Lanxmeer District in Culemborg, The Netherlands

This small district contains 250 houses as well as a hotel and a conference center where the decentralized treatment facility is integrated. The goal is to create a district as green and natural as possible, with shared open green spaces in between buildings, ponds for groundwater recharge, and a city farm to increase resilience. The settlement uses warm groundwater for both heating (geothermal energy) and drinking water purposes, as well as solar power to stay as independent from the grid as possible [5,6]. Project features include: (1) grey-, rain, and blackwater separation; (2) rainwater and water from the drinking water filters (rich in iron) are both directed to infiltration ponds. Stormwater from the streets is channeled away from the drinking water zone and allowed to infiltrate into the groundwater; (3) blackwater plus organic and green waste is treated in an anaerobic digester and the supernatant liquid is treated inside a vertically stacked living machine (a constructed wetland technology (CWT) variant) built into the glass façade in the conference center, to save space and look attractive; (4) resulting biogas is utilized in a combined heat and power (CHP) generator to generate electricity and heat the district; (5) the sludge is composted to remove odor in a confined room and the air from that room is purified before release, and then used as organic fertilizer in gardens and the city farm; (6) greywater is treated naturally via reed beds in constructed wetlands and then discharged to the nearby river.

The project shows the importance of educating and involving the community in the process e.g., residents are instructed not to use bactericides and toilet disinfectants or strong detergents as this could affect the stability of the digester. The biogas and electricity generated are not sufficient to achieve complete self-sufficiency, but nonetheless are significant and represent an important step as the concept embodies a near-closed loop cycle, from rainwater capture and reuse, to low energy decentralized waste and wastewater treatment and subsequent resource and energy recovery, which is then used in an urban farm to produce food for the neighborhood (Table S2 in Supplementary Materials).

2.3. Flintenbreite in Lübeck, Germany

This project in the neighborhood Flintenbreite in the city of Lübeck showcases an ecologically, socially, and economically sustainable urban development and buildings using green energy and natural material with minimum impact on the environment. As such, this settlement represents a holistic approach to ecological urban planning, with architecture, energy recovery, waste recycling, landscape design, and social cooperation as integral aspects. The settlement is designed to be mostly car free, with only one central parking area and project features include [7]: (1) full disconnection from the sewer and completely off-grid in terms of sewage treatment; (2) use of vacuum toilets which limit water use to 0.7–1.2 L/flush; (3) separation of black- and greywater, then using anaerobic digestion to treat blackwater plus the organic waste from kitchens to generate biogas and sludge which is then processed into fertilizer; (4) treatment of greywater using settling chambers and a vertically constructed wetland with reed beds; (5) stormwater is infiltrated to the groundwater through a system of gullies and swales; (6) high-quality insulation for buildings to minimize heating requirements; (7) utilizing solar heating and photovoltaics; and (8) full social integration and involvement of the stakeholders to ensure the project's acceptance and success (Table S3 in Supplementary Materials).

2.4. Am Römerweg in Knittlingen, Germany

The neighborhood Am Römerweg in Knittlingen has the following features [8]: (1) trainwater is stored in so-called water houses, treated with membrane technology up to drinking water standards, then used via a separate network as 'service water' for washing and laundry: this is relatively low-cost in terms of connecting existing houses, and savings in water rates exceed investment costs; (2) rainwater is stored for better protection against flooding; (3) an optional vacuum piping network, 20% of homes use it; (4) optional macerator pumps in the kitchens to shred organic waste which feeds into the vacuum system, eliminating the need for organic waste separation and collection service, while increasing the organic loads at the digester to increase biogas generation, 25% of homes use it; (5) equalization tank to even out load variations and a sedimentation tank to separate the solids from the liquid; (6) solids are directed to a high-rate digester; (7) the separated liquid is directed to an anaerobic membrane bioreactor (AnMBR) in the form of rotating membrane discs to treat it and generate additional biogas; (8) the resulting reclaimed water is pathogen-free, and can be used for irrigation as it is nutrient rich. Further, rainwater can be added to it with minimal treatment; (9) as this is a fully anaerobic treatment, the amount of generated sludge is only 10–20% of a typical aerobic treatment due to the slow rate of anaerobic bacterial growth; (10) due to the anaerobic process, operational costs are kept to a minimum; and (11) costs for piping are less than for a centralized system due to the small diameter of vacuum pipes.

Challenges of the project include [8]: (1) use of AnMBR technology is new and innovative with no large-scale plants currently in existence. Challenges of such new unproven technology include mechanical failures and difficulty to maintain membrane flux; (2) the AnMBR effluent contains 10% of the biogas in dissolved form, this needs to be air stripped before releasing the effluent to the environment as the methane present in biogas is a potent greenhouse gas; (3) use of the reclaimed irrigation water can be a challenge, as it needs to be stored, or released to rivers during rainy seasons. The high content of chemical oxygen demand (COD) and nutrients need to be dealt with and could cause bacterial growth inside storage tanks and pipes; (4) reclaimed water has a very high nitrogen content but not enough phosphorus, so the risk of contaminating groundwater is high if not applied correctly. Further, extra phosphorus needs to be added to compensate; (5) there is still a risk of heavy metals and micropollutant contamination, although most of these would normally adsorb to the sludge, so that reclaimed water effluent will have a low concentration of such pollutants; and (6) to protect soil quality, as there is a higher content of total dissolved solids found in reclaimed water, irrigation using an underground system to avoid evaporation which increases the effect of salinity (Table S4 in Supplementary Materials).

2.5. Allermöhe Settlement in Hamburg, Germany

Allermöhle neighborhood in the city of Hamburg is one of the oldest ecological settlements in Germany. Planning started in 1970 and construction in 1985. The project's focus was to establish highly efficient, ecological housing, with strong community involvement and a sense of ownership [9]. Project features include: (1) involving the users in the planning phase and for maintenance to instill a strong sense of ownership; (2) using natural insulating material to be as efficient and ecologically friendly as possible; (3) compact homes with high renewable energy utilization such as solar panels; (4) greywater separation and urine and feces are mixed using waterless toilets which also helps saving a significant amount of water; (5) house designs are adapted to waterless toilet use; (6) waterless toilets are connected to vertical wide chutes (30 cm in diameter) to prevent odor; (7) 80% of the urine is evaporated and carried out via the ventilation pipe, the rest is diverted by a urine diversion channel; (8) food and organic waste are disposed of directly in the toilet, the addition of toilet paper adds structure to the compost; (9) the chutes are connected to a composter in the basement where feces, urine, organic waste and toilet paper are composted, together with grass from gardens, raising the temperature of the compost; (11) maintenance labor from mixing the compost and adding food and organic waste is around 1 h/month and is done by the owners or by community volunteers; (12) greywater is separated and directed to an underground Imhoff tank for settling particles and grease separation. Subsequently, it is released in intervals to a vertical flow CWT with a required area of 1.7 m^2/person, followed by a polishing pond and then to a river; (13) the system is completely disconnected from the municipal sewers in order to recirculate resources (nutrients) internally. However, in case of system failure, the wetlands have an emergency overflow system which connects them to the municipal sewage, thus avoiding river contamination; (14) rainwater is either stored in cisterns for green spaces irrigation or directed to ditches and allowed to infiltrate to the groundwater. Some homes also collect rainwater for use as service water in washing machines due to its low hardness level which allows for use of fewer detergents (Table S5 in Supplementary Materials).

3. Decentralized Water Reclamation with Resource Recovery Application in Maxvorstadt

As the above case studies show, a plethora of technology options exist for water reclamation with integrated resource recovery. To choose systematically which technology options are suitable for Maxvorstadt, we need to review its individual characteristics and resource requirements.

Maxvorstadt is a densely built-up neighborhood in central Munich of the urban block fabric type, with a population density of 12,000 people/km^2. Munich can source plenty of freshwater from the Alpine foothills through a gravity system virtually energy-free. Thus, water reclamation potential would need to address a particular water need in order to potentially become attractive for decision-makers. Now, climate change predictions for Munich entail growing water scarcity and an increasing number of heat days in summers as well as a significant increase in precipitation and strong rain events in winters by 2050. The amount of water falling on Munich in one year will stay roughly the same, but there is a significant seasonal shift [10]. At the same time, due to a very high density of the built environment and around 90% of surfaces being sealed, the urban heat island (UHI) effect is already a public health risk particularly for the elderly and young children in Maxvorstadt due to its high built-up density [2]. In a hypothetical Munich of the future, the city will have to find ways of integrating more green infrastructure into the urban fabric of neighborhoods like Maxvorstadt to counter UHI. As energy and food prices are also on the rise, we may consider urban farming in connection with a Sponge City concept a key Nexus opportunity. In a sponge city, as many surfaces as possible are desealed in order to be able to absorb and infiltrate rain- and stormwater, thus countering the risk of flooding and supporting the storage of valuable water in local groundwater aquifers. The soil provides filtration of this urban run-off water which will be polluted by contaminants from building roofs and facades such as heavy metals, oils, and microplastics from road surfaces, etc. These unsealed surface areas provide an opportunity for integrating green infrastructure also in form of urban agriculture into the urban fabric to produce vegetables and fruits, which are often imported at high energy costs, locally. As energy prices are also rising, a further selling point for a decentralized approach could be the potential to generate energy at the neighborhood scale. Maxvorstadt's key characteristics are summarized in Table 1.

Table 1. The study area Maxvorstadt in the city of Munich. Source: [2,11].

Parameter	Unit	Remarks
Population in 2014	51,642 people	Of this, 48,474 people live in 136 housing blocks (in 2011)
Water consumption	6.01 million L/day, of which 1.64 is for toilet flushing	Based on a population of 46,960 which excludes children less than 3 years of age, who consume less water and energy [2]
Dry sewage generated in 2015	3,870,913 m^3/year	Average dry sewage (excluding stormwater) generated was around 82.43 m^3/capita/year, for a population of 46,960 [11]

3.1. Synthesis of the Literature Review

To operationalize water reclamation with resource recovery in Maxvorstadt taking its individual circumstances into account, the following approach is chosen. In view of climate change, rainwater harvesting, water reclamation and reuse, energy recovery, and urban agriculture will become important elements in the future urban development of Munich.

Thus, the feasibility of using these alternative water resources for various water demands is assessed, including toilet flushing and urban agriculture irrigation. For the treatment of this "wastewater", an AnMBR (microfiltration) system is chosen. This will enable treating sewage to a level when it is safe to apply as irrigation water in urban farming as pathogens are retained by microfiltration (MF) membranes. Further, many micropollutants and heavy metals will mostly be retained by the membrane as they adsorb to suspended solids. Removal rates of AnMBR systems have been demonstrated at Am Römerweg and a similar pilot project in China [12] (Tables S7 and S8 in Supplementary Materials).

To further ensure a safe reclaimed water quality, a multiple barriers strategy is employed where different treatment units target the same pollutant (namely pathogens and COD). To use the reclaimed water provided by the AnMBR units for urban agriculture, further treatment is needed including a nitrifying trickling filter (NTF). This process is passively aerated and thus can oxidize ammonia into nitrate. After this, the effluent is mixed with some COD from the head of the plant and directed towards a slow sand filter (SSF) to provide denitrification as well as COD removal and pathogen reduction. Final disinfection is achieved by UV irradiation. This would result in reclaimed water with significantly lowered COD, thus making it easier to store.

In terms of energy generation potential, blackwater and greywater separation inside buildings may only slightly increase biogas yield, up to 6% [4], and would be relatively difficult to implement in Maxvorstadt. AnMBR systems of a certain size linked to a biogas digester, however, can boost biogas production by as much as 160% [8]. It is important to strip the biogas from the AnMBR effluent as 10% of methane gas is usually dissolved in the liquid [8]. Releasing this gas to the environment is not only a waste, but methane is also a potent greenhouse gas (GHG). Energy generation potential for both heat and electricity will be assessed using a combined heat and power turbine (CHP).

For nutrient recovery, the resulting final sludge must then be tested for suitability for agricultural application, but generally is a high-quality organic fertilizer that can reduce the need for chemical fertilizers which also have associated GHG emissions. The excess nutrients, especially in seasons where agricultural water is not needed, can be recovered from the AnMBR effluent using the MAP chemical precipitation and ion exchange processes mentioned earlier [13]. The suggested treatment train is shown in Figure 1 below.

3.2. Captial Costs and Operation and Maintenance Estimates of the Two Systems

The first step was to calculate the costs imposed by continuing the use of the current centralized treatment plant via a collection of data from the plant's operator the Munich City Public Works Department (MSE) and analyzing them for short and long-term maintenance and expansion costs. After which, estimating the feasibility of establishing decentralized treatment systems at a neighborhood scale was performed. To achieve this goal, the data from the case studies as well as the current situation can be used, to roughly estimate the costs involved as well as the potential benefits via scaling and extrapolation. Using the collected data, as well as the treatment processes suggested above, a cost estimation for each component, in terms of both capital and operational costs, and a comparison between the decentralized and the existing centralized system is carried out.

3.2.1. The Status Quo

According to Munich Public Works Department [11], there are about 1.77 million people connected to the sewerage network in Munich and its suburbs. This sewer network consists of 2413 km of piping (at the end of 2015) with 4 km being built in 2014 alone. An additional 918 km of piping is also connected to the plant from syndicates and adjacent communities. The total capacity of Munich's two wastewater treatment plants is 3 million people equivalents (PE) with WWTP Gut Großlappen covering 2 million PE and WWTP Gut Marienhof covering 1 million PE.

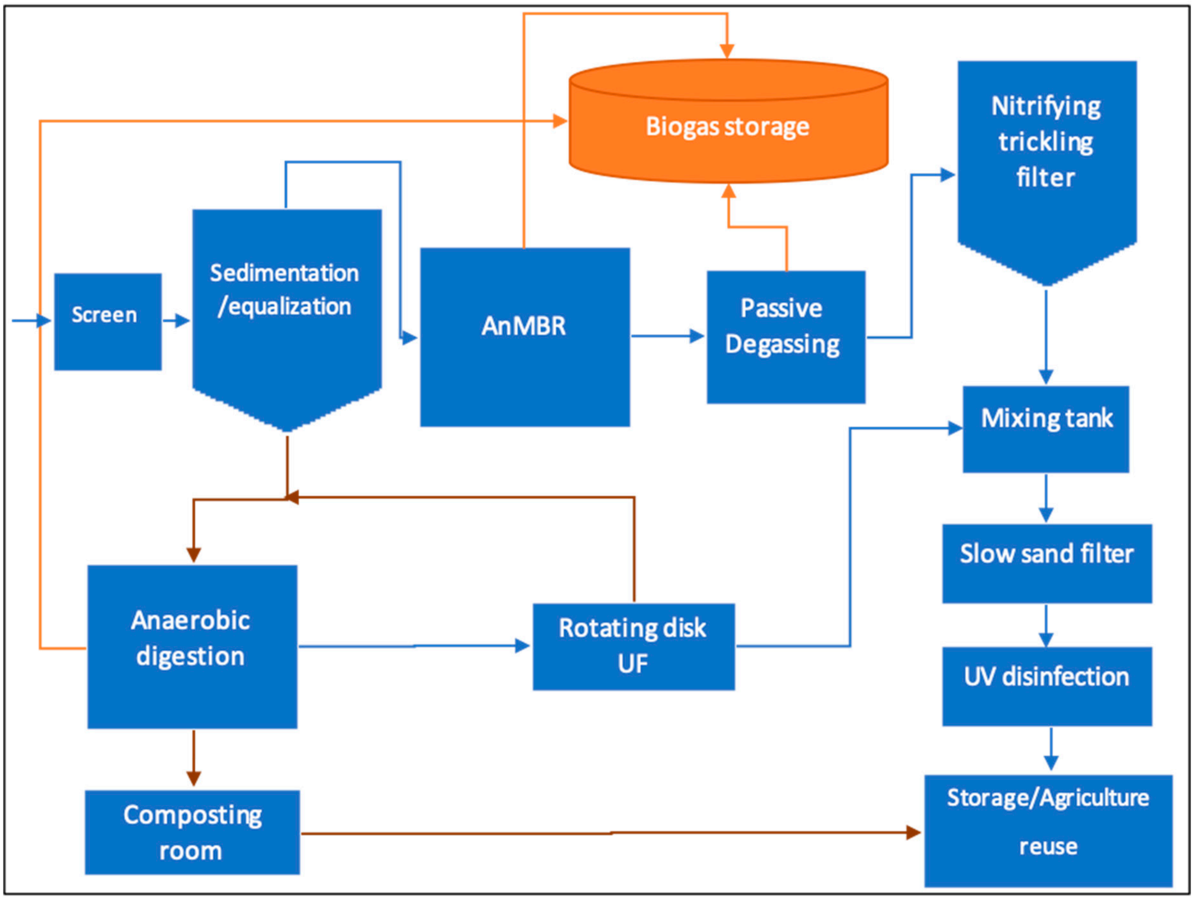

Figure 1. Suggested treatment train for the selected blocks in Maxvorstadt.

Munich's entire sewer network is designed as a mixed sewerage system in which rainwater is collected and mixed with municipal sewage. The collection system functions mainly by gravity so it has a very low energy demand. The system has 14 reservoirs and 2 collection channels underground that hold rainwater during strong rain events, and release it slowly to treatment plants afterwards, with a total retention capacity of 703,000 m^3. Furthermore, the sewerage system in Munich received 165.5 million m^3 of mixed wastewater in 2015 with 145.9 million m^3 under dry weather conditions that is excluding rain- and stormwater [11]. This means that 19.6 million m^3 of rainwater was mixed with sewage and due to this pollution was in need of additional treatment, which incurred additional energy costs. The city charges 1.3 €/m^2 per year of sealed surface area for rainwater disposal [11]. These costs can be saved and re-allocated by retaining rainwater on-site and reusing it.

Further, there are costs for maintaining the existing infrastructure and upgrading it. Projects to maintain and expand the piping network cost around 192.3 million € since the year 2000, and projects to improve and maintain the two existing treatment plants are estimated at 288.45 million € until 2021 [11]. Additionally, the landfill 'North' which was used to dispose of the sewage sludge from 1982 until 2005 needs maintenance to avoid leachate and groundwater contamination requiring an additional 48 million € till 2017 [11]. In summary, the total costs for maintaining this centralized wastewater management system were 528.75 million € in the past 20 years, or around 14.94 €/capita, year. Most of these costs occurred between the years 2015 and 2021. Actual cost over a longer period could be much higher. The question is whether this is feasible economically in the long-run, or if a transition to a hybrid system with decentralized components is a better option, despite the initial capital costs for building an alternative infrastructure. In the existing system, over half of the cost is dedicated to maintaining and expanding the existing sewer network, with the added inconvenience of lengthy construction works and closing of streets due to construction. A decentralized system providing reused water locally can reduce the need for lengthy sewer networks (Table S6 in Supplementary Materials).

3.2.2. Expected Capital Costs of the Decentralized System

In order to simplify an estimate for a decentralized system, it is assumed to cover the entire Maxvorstadt neighborhood. According to the study by [12], capital costs for the AnMBR system can be divided into the following components. To this, the components of the treatment train of the proposed system are added (Figure 1). All costs are converted into € and adjusted for inflation [14]:

Reactor tanks: Approximately 3,870,913 m^3/year of wastewater is generated in Maxvorstadt (Table 1: [11]). This amounts to an hourly flowrate of 442 m^3/h. This stream contains around 1–2% of solids [8], which would be treated in the anaerobic digester. Assuming a solids content of 1.5% results in 6.63 m^3/h, and at an SRT of 7 days, the dimensions of the digester will be around 1114 m^3. Taking 15% for head space [12], this yields a final digester volume of about 1281 m^3.

The AnMBR tanks treat the remaining 98.5% of the influent that is not settled in the primary sedimentation tank (435.37 m^3/h). After a startup period of 12 days, an HRT of 10 h was selected based on the study of [12]. Thus, 4353.7 m^3 is required, plus 15% head space, equating to a final reactor volume of 5006.8 m^3. The primary sedimentation tanks receive the full quantity of the influent, that is 442 m^3/h. Detention time ranges from 1.5–2.5 h [15]. Considering 2 h, a volume of 884 m^3 is required, or 972.4 m^3 with a head space of 10%. Furthermore, for the nitrifying trickling filter, based on [16], for an influent flow of 435.37 m^3/h, a volume of around 320.5 m^3 is needed. The cost for an MBR tank is around 189 €/m^3 [17]. This price is assumed for all reactors and tanks in the system, resulting in a total combined capacity of 7580.7 m^3 and a capital cost of about 1.63 million €. Such tanks usually have a life time of 30 years [12].

Gas storage tank: Various retailers online for medium to large size steel storage tanks can be found with price ranges from 4300 to 17,500 € for tanks ranging from 3.5 m^3 to 20,000 m^3. In this study, maximum gas yields are estimated to be around 3817 m^3/day (detailed calculations in Section 4.2). Costs are assumed to be 15,000 € for simplification and a 15 years lifetime is assumed.

Pumps: Liquid pumps cost 51.68 €/m^3/h [12]. However, until there is a design in place, it is difficult to estimate how many pumps will be needed. It is safe to assume that one will be needed to feed the digester, another to pump out the permeate, one for the trickling filter, and one for the slow sand filtration system. To be conservative, assume that around five times the influent will be pumped, in total 2176.85 m^3/h. This will cost around 126,100 €. These pumps have a life time of 5 years [12].

Membrane area needed: Flux is found to be very dependent on the consistency of the mixed liquor suspended solids (MLSS), which can vary between 5–15 L/m^2 h, and can even reach 25–30 L/m^2 h [12]. In this study, a flux of 15 L/m^2/h is assumed. For the influent flow of 435.37 m^3/h calculated above, a membrane area of 29,025 m^2 is needed. Flat sheet membranes cost 43 €/m^2 [12], so this amounts to around 1.4 million €. These have a life time of 10 years [12].

Screening: According to [12], this equation can be used for the calculation of the costs for the screens needed to protect the membranes from damage (60,000 + 60,000 × Qi/5000), where Qi is the influent flowrate. Taking 442 m^3/h calculated previously, this results in 73.200 €. These have a life time of 15 years [12].

Control boards and other equipment needed: According to [12], the total costs for all of this is 2 × (20,000 + 10 × Qi), where Qi is the influent flowrate. This results in around 54.700 €. Control boards have a life time of 15–30 years [12].

Gas scouring for membrane fouling control: Pumping costs for 2.5 m maximum head, according to calculations on the data from [12], are 32.99 €/m^3/h, and the costs for gas diffusers are around 0.58 €/m^3/h. The specific air demand per unit of permeate needed ranges from 5–30 $m^3{}_{air}/m^3{}_{permeate}$, with 10 $m^3{}_{air}/m^3{}_{permeate}$ considered ideal [12]. Assuming the same value for this study also, this results in 4354 m^3/h of gas, and this costs around 161.000 € and 2.800 € for the blowers and the diffusers, respectively. These have a lifetime of around 5 years [12].

Nitrifying trickling filter (NTF) for post-treatment: The cost for the tank itself was already calculated above, and the bed packing material, according to calculations following data from [18], would cost around 12.100 € and assuming a lifetime of 15 years.

Slow sand filter for polishing: According to [19], the cost of sand filters can be estimated using the following formula: Cost [$] = 9120 × $A^{0.49}$, where A is the surface area. Assuming a filtration rate of 0.15 m/h [19], this yield in a required surface area of around 2903 m^2. Setting this in the equation results in around 626.200 €. Assuming 15 years for the packing material and 30 years for the constructed tank.

UV disinfection: According to [20], the cost of UV disinfection is estimated at 200,000 €.

CHP microturbine: According to the calculations detailed later in Section 4.2, a turbine with a capacity of around 943 kW is needed. According to [21], a microturbine with a maximum capacity of 950 kW would cost 2280 €/kW. This means the capital expense for the turbine would be around 2.1 million €.

TOTAL: Final costs involved will be those of land, extra equipment needed as well as pipes, and retrofitting buildings to use recycled water. Estimation of these costs is difficult and beyond the scope of this study, thus it will roughly be assumed to be 4 million €. This brings the total estimated capital costs to around 10.4 million €, detailed as follows (Table 2):

Table 2. Summary of the capital costs of the proposed system.

Item	Capital Cost (€)
Reactor tanks	1.630.000
Gas storage tank	15.000 €
Pumps	126.100
Membrane	1.400.000
Screening	73.200
Control boards	54.700
Gas scouring	163.800
Nitrifying trickling filter	12.100
Slow sand filter	626.200
UV disinfection	200.000
CHP microturbine	2.100.000
Other costs (land, extra equipment, building retrofitting)	4.000.000
TOTAL	10.400.000

3.2.3. Expected Operational Costs

The operational costs stem mostly from the energy expenditure, sludge handling, and chemicals used, and would be divided between the plant and the urban agriculture application costs:

Gas scouring: Gas scouring requires 0.015 kWh/Nm^3 of biogas [12]. As calculated in the previous section, the system would need 4354 m^3/h of biogas to keep the membranes from fouling, hence this would require 572,076 kWh/year. The price of electricity in Munich is 0.25 €/kWh [22]), so the costs for gas scouring are around 146.400 €/year.

Influent and permeate pumping: The energy required can be estimated to be 0.02 kWh/m^3 and 0.03 kWh/m^3 for influent and permeate, respectively [12]. To be conservative, 0.03 kWh/m^3 will be assumed for both. As assumed in the previous section, 2177 m^3/h of influent and effluent need to be pumped, requiring around 533,937.8 kWh/year. At 0.25 €/kWh [22], this will cost around 136.600 €/year. This cost covers the trickling filter and the slow sand filter as well.

Chemicals and sludge handling: Chemicals are needed to regularly clean the membranes, and chemical additives are also used to enhance operation. Further, sludge needs to be treated with chemicals, hygienized, and moved to storage or incineration. Ref. [12] estimated that chemical costs and sludge handling costs are around 40% of the total cost for the AnMBR. Thus, multiplying the costs for scouring and pumping (283,029 €/year) with a factor of 0.4 results in around 113.200 €/year.

Anaerobic digester thermal demand: According to [23], for a plant size of around 50,000 population equivalent (PE) about 191 kW_th is needed for a thermophilic digester (+70 °C), and about half of that for a mesophilic digester (37 °C). Since the suggested digester is mesophilic, this would mean 95.5 kW_th over the year is needed, or in terms of energy, 836,580 kWh_th/year. For simplicity, a consumption of 800,000 kWh_th/year will be assumed to keep the digester at 37 °C. The price of thermal energy according to [24] is 0.04 €/kWh_th, resulting in around 36.600 €/year.

Maintenance and personnel: Maintenance depends heavily on the degree of implementation. However, in the case of Am Römerweg, a similar system was proposed to be fully automated and controlled online to minimize costs, hence they will be assumed as 10% of the total costs thus far (432,800 €/year), i.e., around 43.300 €/year.

CHP microturbine: The cost of operation of a turbine with a maximum output of 950 kW is around 0.01 €/kWh [21]. The biogas in Maxvorstadt would generate around 8258 MWh/year in total (detailed calculation in Section 4.2), so the operation and maintenance costs of this would amount to around 82.600 €/year. However, this would not be part of the calculated system costs as the price of energy is already included in the calculations above. Furthermore, the price of operation for the CHP would be later included in the calculation of the energy generation feasibility.

With 3,870,913 m^3/year of wastewater generated in Maxvorstadt (Table 1), dividing the yearly operational cost of the treatment train calculated till now—476,080 €/year, excluding the CHP operating costs as mentioned above—by this amount results in around 0.12 €/m^3.

Agriculture application: By scaling the results of [25] to Maxvorstadt, costs for operation (storage, pumping and distribution, etc.) as well as maintenance of urban agriculture irrigation will be around 0.75 €/m^3.

TOTAL: This brings the total expected operational cost to 0.87 €/m^3. However, costs of reinvestment due to the life time of the components must also be considered. Taking a lifetime of 20 years (for the sake of comparison with the current system), a reinvestment cost of about 5.9 million €/20 years is needed, and not taking into account discount rates, this amounts to 293.200 €/year. For the population in Maxvorstadt, this means around 6.2 €/capita year. Taking the generated dry sewage (82.43 m^3/capita/year) based on calculations from ([11]; Table 1), means an additional 0.08 €/m^3. Thus, the real operational cost in terms of the life cycle is approximately 0.95 €/m^3.

4. Comparison between the Status Quo and the Suggested Decentralized System

The current sewage treatment plants are still operational. However, as shown in Table S6 in Supplementary Materials, for the span of 20 years, these plants cost 528.8 million € just to repair and upgrade [11], i.e., around 26.4 million €/year or 14.9 €/capita year, assuming the population figure in 2015 of 1.77 million people connected to the system [11]. This is much higher than the 6.2 €/capita year calculated for the decentralized system. Further, as mentioned earlier, this is a rather conservative estimate. The real cost of maintaining the existing system could be a lot higher.

4.1. Rainwater Harvesting and Water Reuse Potentials

The municipality charges 1.3 €/m^2 per year for rainwater discharge into the mixed sewerage system [11]. In Maxvorstadt, the residential blocks are 90% sealed and the total sealed area in the blocks is 175.5 ha [2]. Around 94% of the population lives in those blocks as the rest of Maxvorstadt are non-residential buildings (museums, universities, shops, etc.). This means if one assumes that 46,960 people live in the neighborhood [2], then 44,142 people live in the blocks, and the cost for rainwater discharge is 51.68 €/capita per year.

In a hypothetical future world geared towards maximum resource recovery, 87 ha of these 175.5 ha could be de-sealed and used for rainwater infiltration, and all roofs steeper than 15° that cannot be used for urban farming can be used to harvest 783,000 m^3/year of rainwater [2]. At a price of 1.3 €/m^2/year, this would mean a saving of 1.13 million €/year for the rainwater no longer entering the sewerage system.

This rainwater can be used for various water demands, e.g., the 35 L/capita/day [26] or 600,000 m^3/year used for toilet flushing can be met using rainwater, leaving 183,000 m^3/year for other uses such as laundry or showering [2]. The price of freshwater in Munich is 1.68 €/m^3 [27]. Thus, rainwater harvesting could hypothetically save the neighborhood about 1.3 million €/year.

Finally, the discharge fee for regular sewage is 1.56 €/m^3 [11]. In 2015, 145.9 million m^3 of dry sewage was generated [11]. Taking 1.77 million inhabitants, this means 82.43 m^3/capita year in Munich or around 128.6 €/capita year. When compared to the operational cost, the cost of the decentralized system calculated above of 0.95 €/m^3 is clearly much less than the 1.56 €/m^3 the municipality is charging for dry sewage in the current system. Taking 0.95 €/m^3 for decentrally treating 82.43 m^3/capita year of dry sewage gives 78.2 €/capita year, which means a saving of around 50.4 €/capita year with the decentralized system. Thus, for the 46,960 people in Maxvorstadt, a total of around 2.4 million €/year is saved. This reused rainwater will also need to be treated in the decentralized system. At a cost of 0.95 €/m^3, this will be about 740.500 €/year, enabling net savings of 389.500 €/year. Thus, the total amount saved by decoupling the wastewater treatment in Maxvorstadt will be around 2.8 million €/year. This amount can be invested into the neighborhood each year. However, the cost of storing the harvested rainwater has not been estimated as this is beyond the scope of this study.

4.2. Biogas and Energy Generation Potential

In terms of energy generation potential, it can be assumed that by using sewage and organic waste as a co-substrate for anaerobic co-digestion to generate biogas, the suggested decentralized system would obtain yields similar to the rotating disk AnMBRs in Am Römerweg, where 8000 L/day or 45.7 L/capita day of biogas is being generated which is around half the maximum theoretical biogas yield of 80 L/capita/day (Table S4 in Supplementary Materials) [8,13] due to underloading of the system and load variations. For Maxvorstadt with its much larger population density, less load variation and a biogas yield closer to the theoretical maximum can be assumed.

Extrapolating this to Maxvorstadt's population of 46,960, 2146 m^3/day of biogas can be generated, with a theoretical maximum yield of 3757 m^3/day. Munich's sewage treatment plants (STPs) also generate biogas, but only 38.68 L/capita day [11], which is lower than in Am Römerhof, not to mention the theoretical maximum yield. In Munich, around 25 million m^3/year of biogas is used to generate 45.774 MWh_el/year of electrical energy for 1.77 million users, resulting in 0.02 kWh_el/capita year [11]. This is very low when compared with Jenfelder Au 339.7 kWh_el/capita year is estimated.

This can be explained as follows. At Jenfelder Au, the biogas yield is 465.75 L/capita day, i.e., ten times higher than in Am Römerweg, mostly due to adding 9000 m^3/year of fat [4]. Further, the CHP unit installed there is new and of high efficiency. Munich's STPs on the other hand rely mainly on sludge incineration for energy generation rather than biogas. Thus, adding fat and organic waste from industries, restaurants, and kitchens as a co-substrate could be significant for energy generation via anaerobic digestion. Maxvorstadt has many restaurants and households, and oils and organic matter could be collected from these. At the moment these wastes are not systematically harvested in Munich, but macerators could be installed on kitchen sinks to collect food remains, or containers provided to collect used oil, which can then be added to the digester. This can boost the production of biogas, and improve compost quality for use in agriculture. According to [28] a restaurant in Salt Lake City, USA, outputs around 1.154 m^3/year of fats. If we assume that Maxvorstadt has around 500 restaurants, 577 m^3/year of fats could be harvested. At Jenfelder Au, 340,000 m^3/year of biogas were generated using 9000 m^3/year of added fats [4], or 37.78 m^3 of biogas produced for each m^3 of added fat. Applying this to Maxvorstadt can increase the biogas yield by 21.800 m^3/year. Adding this to the maximum theoretical yield gives a total biogas potential of around 1.4 million m^3/year or 3.800 m^3/day.

Note that the added fats in the case of Maxvorstadt did not cause a massive increase in biogas yields as it did in Jenfelder Au. Here, a much larger proportion of fats was added, i.e., 9000 m^3/year for a population of 2000 which means 4.5 m^3/capita year. To put things into perspective, an average McDonald's branch in London disposes of around 3.75 m^3/year ("McDonalds.co.uk," 2013). Applying the same ratio to Maxvorstadt, for 46,960 people, 211,320 m^3/year of fat would be needed, i.e., the estimated fat waste of 189,120 regular restaurants or 56,352 McDonald's. Such a large amount would indeed yield a respectable additional 7,983,247 m^3/year of biogas. Harvesting this amount of fat in Munich, however, is unrealistic, thus its contribution in our hypothetical study in Maxvorstadt is not as high as in the literature.

According to (Hamburg Wasser, 2013), 360,000 m^3/year of biogas can be used to generate 700 MWh_el/year and 1470 MWh_th/year. With a CHP efficiency of 34% electric and 55% thermal (89% total efficiency), an energy yield of 1.94 kWh_el/m^3 and 4.08 kWh_th/m^3 can be achieved. These results are consistent with the findings of [8], at a total potential of around 6.85 kWh/m^3. Assuming a similar conversion efficiency for the 1.4 million m^3/year biogas generated in Maxvorstadt, 2660 MWh_el/year and 5599 MWh_th/year can be estimated.

This will not be the net output, as the equipment and systems will require some of the electrical energy and the digester would require thermal energy to operate properly. Referring to the calculations performed in Section 3.2.3, the expected electrical and thermal consumption are 1217 MWh_el/year and 800 MWh_th/year respectively, after adding 10% extra electrical consumption for the additional equipment.

This gives a net produced energy of about 1444 MWh_el/year or 30.74 kWh_el/capita/year, and 4799 MWh_th/year or 102 kWh_th/capita/year. These figures are much higher than what is being generated from the central treatment plants in Munich, which is only around 0.03 kWh_el/capita per year. However, as mentioned previously, these plants rely on incinerating the sludge for energy and data was not available.

According to [22,29], the electricity costs in Munich are 0.25 €/kWh_el and 0.0457 €/kWh_th with a fixed service fee of around 90–100 €/household/year depending on the contract type. Furthermore, in a typical block of 138 apartments in Maxvorstadt the energy cost per apartment is 56.84 €/household year. This represents the block's vital services (external lighting, ventilation, pumps, etc.), and does not include the electrical consumption of the residents. A typical Munich household with two adults consumes 2500 kWh_el/year [22], this would cost a total of 729.75 €/household year (including the mentioned 90 €/household year fixed fees), bringing the total electricity cost up to 786.586 €/household/year or 393.284 €/capita year. This translates to a total consumption of around 1361 kWh_el/capita per year.

Furthermore, heating and warm water costs are on average 1310 €/household year or 655 €/capita year for a typical household. Using Munich's tariffs [29], this corresponds to a consumption of around 28,670 kWh_th/household year. This is higher than the typical value of 20,000 kWh_th/household year for Germany [22]. Thus, to round off errors, a value of 25,000 kWh_th/household year will be assumed or 12,500 kWh_th/capita year for a typical household.

Extrapolating this to Maxvorstadt with its 46,960 people shows that the neighborhood consumes 63,912.6 MWh_el/year and 587,000 MWh_th/year. Thus, the CHP plant would supply around 2.26% of the electrical demand, and 0.82% of the heat and warm water demand. However, to calculate the savings achieved one must consider the fact that the electrical costs for the system were already included in Section 3.2.3, so to avoid double counting, the total generation of the CHP was considered here, i.e., 2660 MWh_el/year and 5599 MWh_th/year. This would amount to around 936,608 €/year, however, the operational costs for the CHP are calculated in Section 3.2.3 to be 82,589 €/year, so net savings would be lower at around 854.000 €/year.

4.3. Nutrient Generation and Recovery Potential

In this study, the nutrient generation potential of Maxvorstadt focuses on urban agricultural production. Regarding agricultural water demand, according to [2], vegetables require 2 L/day/m^2 during the planting season, which if we consider all the unsealed surfaces and roofs with an inclination of less than 15° that are suited for urban agriculture leads to a water consumption of 1.84 million L/day between the months of May to October. While agriculture irrigation demand is usually met by rain in Germany, in case of hot dry summers, the vegetables would need to be watered frequently. Using the described system would generate around 12.75 million L/day of reclaimed water, which is more than enough to cover potential irrigation demand in Maxvorstadt. This could be an encouraging factor to expand the urban farming concept to the areas surrounding Maxvorstadt.

In terms of nutrient generation potential, the total amount of sludge potentially generated by the proposed decentralized system has not been estimated in this study. Yet we can assume that there would be a lot of it, and it would potentially be a very valuable source of organic fertilizer for urban farming. In any case, it would not have been possible to factor in any numbers for this in the calculations, as at the moment there is no market for organic fertilizer produced from sewage and organic waste in Germany.

4.4. Total Potential Savings by Implementing the Proposed System and Amortization

To summarize, by adding the costs estimated above, namely saving on freshwater usage due to rainwater harvesting (1.3 million €/year), savings due to decoupling wastewater treatment (2.8 million €/year), and saving due to local energy generation (0.854 million €/year), a total annual saving of around 5 million €/year can potentially be achieved. Since the capital costs were estimated to be around 10.4 million €, the system will amortize itself in around two years.

5. Discussion about Implementation of the Decentralized System and Its Co-Benefits

Maxvorstadt has 136 residential blocks, each covering an area of around 1 ha, where 94% of the population lives [2]. Assuming the population figure of 46,960 people above 3 years old, around 325 people live in each block. The suggested system can be installed on a block-by-block basis, or several blocks can be joined together via abstracting their sewage to be treated in one of the blocks.

In an existing neighborhood like Maxvorstadt, substantial changes in infrastructure may be very difficult or even not realistically feasible to implement. A multiple barrier approach to eliminating pathogens as well as the COD that causes regrowth is employed in the system, so as to ensure the safety of the people coming in contact with the urban agricultural areas as well as to protect the groundwater quality. As the centerpiece of the system, an AnMBR was chosen as it is relatively compact in terms of a spatial requirement compared e.g., to constructed wetlands technology, which can achieve very high removal rates but has a huge space requirement. In fact, to treat the "wastewater" of Maxvorstadt may require an area similar to that of Maxvorstadt. The AnMBR also has a high treatment efficiency at a relatively low energy cost compared to established technologies. Further, the system minimizes undesirable side-effects that may hamper implementation, such as unpleasant smells.

However, even in a hypothetical world, it will very difficult to modify the Maxvorstadt blocks to be able to implement such a system. The system can be installed in the basement of one or more buildings or underground in the courtyards. To gain an understanding of how this could work, spaces, power, and safety requirements would have to be assessed in detail, and all of these again will entail associated costs which however are outside the scope of this study.

Further, it will be a huge challenge to store vast amounts of rainwater as suggested in this study in Maxvorstadt. These numbers are included for the purpose of demonstrating how costs associated with rainwater harvesting could potentially factor into a decentralized system cost-benefit analysis. Although [2] estimated that the underground structures in Maxvorstadt, such as building basements and underground parking garages, if used as cisterns, have the hypothetical capacity to store this rainwater. However, equipping these spaces to function as cisterns would entail huge costs. Rainwater would also need to be treated and disinfected before being used even for toilet flushing. An advantage of using rainwater for showering or laundry is that it requires less harmful detergents due to the very soft rainwater compared to Munich's relatively hard water supply.

Source separation may also be something to consider in an increasingly water-stressed future. Separating blackwater from toilets may not be able to support a substantial increase in biogas yield, as pointed out above. However, separating it from the greywater from kitchens and baths would make the recycling of greywater much simpler and may justify the initial investment in a source separation piping system. Implementing a dual piping system in the blocks to be able to reuse service water would also be very difficult in the existing urban fabric, and entail huge costs for storage, piping, and pumping, etc.

As for the biogas storage and CHP generator, they can either be for a few blocks or the entire neighborhood, so as to provide a decent biogas yield. Again, the actual implementation will be a big challenge.

For nutrient recovery, the resulting final sludge must be tested for suitability for agricultural application, but generally is a high-quality organic fertilizer that can reduce the need for chemical fertilizers, which also have associated GHG emissions.

To summarize, as mentioned above, this study is very hypothetical. The inaccuracy of results is caused by various hypotheses and scale differences as follows: the best practices listed above are all of different scales and none are of exactly the same scale as our case study in Maxvorstadt. Hence the costs in terms of construction, operation, and maintenance cannot be transferred directly to our case study. Further, these case studies are located in different geographical regions, which will add inaccuracy to the results as costs may vary considerably regionally even within Europe depending on local markets. Nonetheless, best practice examples were chosen that came as close as possible to the case study in their specifications. Hence, the cost estimate has been done as thoroughly and comprehensively as possible using the available literature. For a more correct cost estimate, the alternative technology scenario would have to be put to a real engineering firm for a detailed cost estimation. However, this step would have defied the boundaries of this study. Even with such an estimate moreover, we may anticipate that many unexpected costs might occur during actual implementation.

All of the above would require huge engagement with the community to adapt the functions of existing spaces to be able to implement the decentralized systems infrastructure components. Functions of existing spaces required to implement the envisioned decentralized system such as courtyards at the moment filled with parking garages, parking lots and workshops, or basements used for storage, etc., will need to be very significantly modified. Costs of large-scale awareness and acceptance campaigns that would be needed also would entail. All of these points are however outside the scope of this study.

6. Conclusions

The proposed decentralized system aims to employ a near closed-loop concept, to enable water reuse, rainwater harvesting, generation and use of bio-energy, and nutrient recovery for urban agricultural production on a significant scale. The key highlights of this alternative decentralized system are as follows.

The capital costs can be recuperated in a little over two years as a result of cost effectiveness. The required costs of treating a cubic meter of wastewater using the proposed decentralized system are potentially only around 60% of the current costs incurred by the users of the centralized system.

Saving on water consumption by using rainwater as service water offered a large saving even in a city with an abundance of water resources like Munich. Harvesting rainwater decentrally can theoretically take pressure off the sewer network during strong rain events and potentially mitigate flooding. As the storage of such rainwater for reuse however presents a big hurdle, we can also imagine a different scenario. In a theoretical future where decentralized systems gain traction for the treatment of sewage, if the centralized system proves too expensive and unsustainable to maintain it could be partially retired and used mainly for stormwater drainage and flood prevention. The piping network would still have to be maintained to ensure its functionality in terms of flood mitigation.

In terms of treating sewage at the neighborhood scale, a densely populated neighborhood like Maxvorstadt can relieve pressure on the centralized system. Using reclaimed water for urban agriculture also has benefits, as it is rich in nutrients, and reusing it offers resiliency in the face of climate change when summers are expected to become increasingly dry.

Energy generation potential covered only 2.26% of the electrical demand and 0.82% of the heating demand inside Maxvorstadt. This does not seem much, but is indeed very significant. The proposed decentralized system is energy-autonomous, i.e., generating enough energy to run itself. Further, it is energy positive, i.e., can feed electricity to the grid. This can help save costs and reduce the CO_2 footprint of the neighborhood. Biomass can easily be stored and accrues locally, but is continuously under-highlighted in policy and academic literature as a valuable source of renewable energy.

This is a very preliminary feasibility study with many broad assumptions made. Despite this, the study aims to show that devoting more research to this topic is worthwhile, including detailed cost-benefit analyses. Ideally, a pilot project could be installed to concretize costs and economy of scale.

Large-scale urban transformation as envisaged in this study, e.g., through modification of existing spaces such as parking lots, will need to be linked to a high-level policy push for zero-carbon urban development. This push needs substantial support through incentives such as subsidies and tax rebates, and tariffs, e.g., raising the costs for parking and sealed surfaces, and curbing harmful substances entering the water cycle in the first place. This again will need to be linked to a paradigm shift in how we value water as a society.

However, a "tipping point" has not yet been reached in Munich. The structures of its urban planning and infrastructure departments and related decision-making are not conducive to a dialogue on the Nexus approach. Yet, generating evidence like this is a first step to supporting a systemic socio-technical transition toward a more circular economy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources11070064/s1, Table S1. Project statistics in the neighborhood Jenfelder Au [3,4]; Table S2. Available project statistics in the neighborhood of Lanxmeer [5,6]; Table S3. Available project's statistics in the neighborhood of Flintenbreite [7]; Table S4. Available project's statistics in the neighborhood of Knittlingen [8]; Table S5. Project statistics in the neighborhood of Allermöhe [9]; Table S6. Summary of the current situation [11,26]; Table S7. Demonstration plant statistics in Am Römerweg between Nov. 2009 and July 2010, the values between the brackets are the min and max values, the value outside the bracket is the average for the observed period [8]; Table S8. Results from the pilot project in the study of [12].

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