Sébastien Rauch · Gregory Morrison
Stefan Norra · Nina Schleicher *Editors*

Urban Environment

Proceedings of the 11th Urban Environment Symposium (UES), held in Karlsruhe, Germany, 16-19 September 2012

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Preface

The 11th Urban Environment Symposium (11UES) was held in September 2012 in Karlsruhe, Germany. The UES series is run by Chalmers University of Technology and the 11UES was organized in collaboration with the Karlsruhe Institute of Technology.

UES was initiated by Professor Ron Hamilton at Middlesex Polytechnic (now University) in the early 1980s and had the title "Highway Pollution". The initial aim was to measure and assess challenges in highway pollution, with a strong emphasis on urban photochemical smog, ozone formation and particle release. After the first symposium, the emphasis on air pollution issues continued through to Munich in 1989 where diesel particulate issues and the relevance to health through measurements of PM10 emerged. The focus on air quality issues was also strengthened by the co-organisation of the symposium with Professor Roy Hamilton at the University of Birmingham from 1986 to 1998. In parallel, the symposium started to receive an increasing number of scientific contributions from the area of urban run off, indeed to the extent that the title of the symposium was changed to "Highway and Urban Pollution". Also at this time the importance of science in support of policy was emerging as a key aspect of the symposium.

The 8th edition of the symposium was held in Nicosia, Cyprus in 2006 and was hosted by the Cyprus Institute. For this symposium, we decided to evolve the name of the series to "Highway and Urban Environment" to provide a positive view of our common future looking to a positive environment. That said, paper addressing pollution issues in the highway and urban environment remain a central part of the symposium as they help to raise awareness around issues to be solved. The 8th symposium was also marked by an organizational change with Chalmers University of Technology taking over the organization of the symposium series. For the first time, the proceedings were published as a book by Springer. The following symposia were held in Madrid, Spain and Gothenburg, Sweden. The 10th symposium was marked by a further name change with the term "highway" being dropped.

For 11UES we aimed at continuing to provide a forum for exchange and discussion on all aspects of the urban environment. Presentations covered air, soil and water contamination, pollution control technologies, management and mobility, urban ecosystems, urban climate and climate change. The symposium was opened by Peter Fritz, Vice-President of KIT, and Gisela Splett of the State Government of Baden-Württemberg. Plenary presentations were given by Jean-Louis Morel from the University of Lorraine, France; Stefan Emeis from KIT, Germany; Christiane Weber from the University of Strasbourg, France, and Timon McPhearson from the New University, USA. The best poster prize was awarded to Lucas Reid of KIT.

The following facts provide a background of 11UES:

90 delegates from 26 countries
138 abstracts accepted for papers and posters
95 oral and poster presentations

We would like to take this opportunity to thank all who have contributed to the success of 11UES. We would especially like to acknowledge Andrea Friedrich at KIT whose organizational skills were essential to the success of this symposium. Cecilia Rossing is acknowledged for editorial work on the proceedings. The Organizing and Scientific Committees thank the following partners for financial support: PALAS, the Stadtwerke Karlsruhe, the KIT Center for Climate and Environment, the Ministry of Traffic and Infrastructure of Baden-Württemberg, and the Karlsruhe Municipality. Finally we would like to thank the delegates for the many valuable contributions and a highly enjoyable symposium.

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Part I
Urban Management and Spatial Planning

Overview of Material and Energy Flows in Water Infrastructures in Context of Urban Metabolism

Eve Menger-Krug, Jutta Niederste-Hollenberg and Thomas Hillenbrand

Abstract Urban water and wastewater infrastructures (UWIS) are an essential part of every city. They manage large flow streams of water, organic substances and nutrients from urban areas. Management of flow streams has a considerable energy demand, while there are large opportunities for energetic reuse of wastewater resources, which are not yet sufficiently exploited. Energetic reuse of wastewater resources can contribute to more sustainable urban energy systems. UWIS are also hot spots for emission of anthropogenic pollutants to the environment. On the way to a sustainable metabolism of cities, restructuring energy systems and reducing emission of anthropogenic pollutants are two important challenges. Both involve UWIS. This paper analyses material and energy flows in UWIS in Germany and explores their contribution to urban metabolism. We conclude by highlighting potential improvements by new technologies.

Background: Metabolism of Cities

Urban futures for a sustainable world is the title of the symposium. With increasing urbanization, a sustainable metabolism of cities is one important prerequisite for a sustainable world. It is the physical base of urban sustainability. The term was coined by Wolman [49] to describe the sum of material and energy flows in and out cities. The urban metabolism is an important feature of urban ecosystems or the astysphere [33]. Today, the flow streams are managed mainly in a linear way, characterized by large resource inputs, e.g. Energy, Water, Food, Products; and large outputs or emissions to the environment. The function depends on resource availability and capacity of (local to global) hinterland to absorb wastes/emissions. The following Fig. 1 shows an illustration of the urban metabolism. For increased sustainability, minimized resource input, maximized on site cycling and minimized emissions to the environment are important steps. Ultimately, the *sustainability* of resource input need to be maximized and the *negative effects* of emissions need to be minimized. The on site cycling should be organized to mirror natural ecosys-

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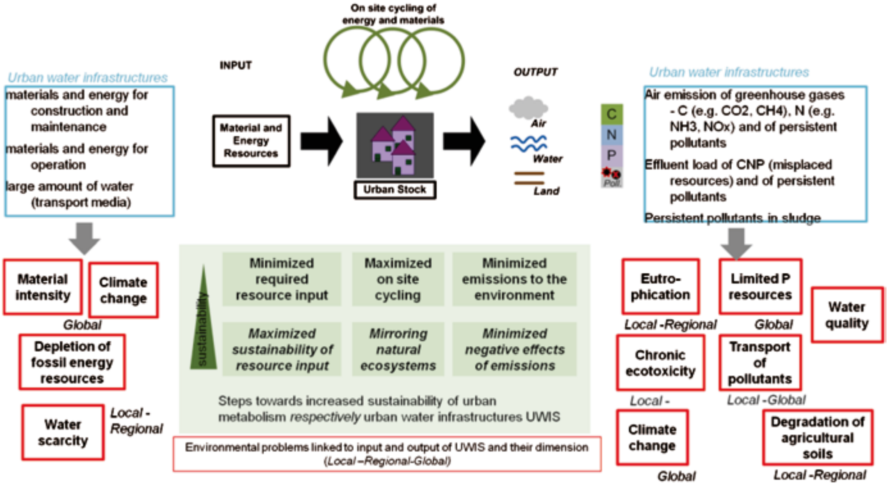

Fig. 1 Urban metabolism with input and output (emission) side, steps towards increased sustainability (*green*), input and output of urban water infrastructures (*blue*) and associated environmental problems (*red*)

tems, which use material and energy in cascades with the flow streams in balance with the surrounding ecosystems. But this is a long way ahead for present cities with their linear metabolism.

Metabolism of Urban Water and Wastewater Infrastructures (UWIS)

Urban water and wastewater infrastructures (UWIS) are an essential part of every cities metabolism. Their main function is to guarantee public health and safeguard water resources. But due to the resource consumption and the emission of UWIS, they are connected to many environmental problems (red boxes in Fig. 1). This includes energy related problems, such as the depletion of fossil energy resources and climate change, as well as water quality and quantity related problems, such as eutrophication and persistent pollutants.

Wastewater flow streams contain large amounts of “resources”: Water, Carbon C, Nitrogen N and Phosphorus P. This provides an opportunity for water and nutrient recycling and energy harvesting (reuse of “internal” resources). Currently these opportunities are not fully exploited. There are large non recovered potentials.

Besides the resources, wastewater flow streams also contain a multitude of pollutants. The wastewater pollutant load is a mirror of society: it contains heavy metals and organic micropollutants, such as disinfecting and impregnating agents, flame retardants, pharmaceuticals. Some of them have persistent, bioaccumulative or toxic properties. They are not fully biodegradable with the current technical setup

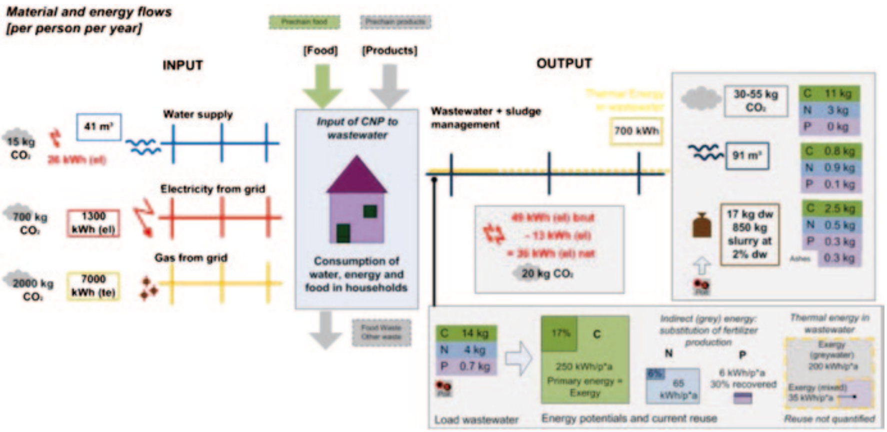

Fig. 2 Urban metabolism: household consumption of water, electricity and gas (thermal energy te) and associated CO2 emissions, energy demand for water treatment (input side); energy demand for wastewater and sludge treatment; material input to wastewater (CNP), energy potentials and current reuse; emission to the environment: generation of wastewater sludge and on site CO2 emissions

employed in wastewater treatment. They are transferred to the environment via effluent, air or stabilized sludge. These are important pathways for many pollutants. The presence of pollutants is a challenge for water and nutrient recycling. Wastewater is also an important pathway for antibiotic resistent pathogens.

On the way to a sustainable metabolism of cities, restructuring energy systems and reducing emission of anthropogenic pollutants are two important challenges. Both involve UWIS.

We now take a closer look at the energy balance of UWIS in context of urban metabolism. For a holistic picture of the current situation of the energy balance, we need to include: direct energy consumption and generation at the different stages of UWIS, as well as an estimate of the internal energy potentials of flow streams, and the proportion which is currently reused *resp.* not reused.

The following Fig. 2 shows the material and energy flows in UWIS in context of urban metabolism. The system boundaries include:

1. The extraction, treatment and distribution of drinking water and the associated energy consumption,
2. Energy use in households: electricity consumption and consumption of gas (thermal energy) for heating and for hot water preparation
3. The transport and treatment of wastewater and the use of biogas from anaerobic digestion, and the associated energy consumption and generation
4. The transport, processing and end use of stabilized sludge generated during wastewater treatment including sludge incineration, and the associated energy consumption and generation.

Extended Energy Balance of UWIS

The inventory and results of the energy balance and associated substance flow analysis is taken from earlier work of the authors [28]. Main data sources for the external energy balance are Haberkern et al. [14], Hansen et al. [15], Agis [1], Lingsten et al. [23], Olsson [34], ATT et al. [3], DWA [10, 11], Houillon et al. [19], UBA [47], MUNLV [31], Stillwell et al. [43], Hong et al. [18], Manara and Zabaniotou [26], for the quantification of TEP: Heidrich et al. [16], Shizas and Bagley [42], Svardal and Kroiss [45] and Olsson [34], Lal [21], Dockhorn [9], Maurer [27]. For the SFA: DWA [10, 11], Ekama [12], Henze et al. [17], Bischofsberger et al. [6], Bengtsson et al. [5], Rosso and Stenstrom [40].

The weighted average of net consumption on the level of UWIS is 62 kWhel/p*a and 7 kWhthermal/p*a. Current reuse covers 18 % of brut electricity demand and 84 % of brut demand for thermal energy. On a primary energy base, net consumption adds up to 189 kWh/p*a (including fuels for sludge transport).

To extend the usual approach to energy balances, we included the theoretical energy potentials (TEP) of resources in flow streams. We base our quantification of the TEP of carbon (C) on a study with bomb calorimeters using freeze dried samples [16]. With 14 kg C/p*a and the derived TEP factor, theoretical energy potential of C resources is 254 kWhprimary/p*a. With 35 % electrical efficiency, 89 kWhel/p*a can theoretically be generated from C resources in wastewater, covering current brut electricity consumption on the level of water and wastewater infrastructures.

Putting current reuse of C resources for electricity generation in relation to TEP gives an average reuse rate of 17 % for Germany. This means that 83 % of TEP of C resources in wastewater is not recovered.

Other than C resources, nutrients in wastewater cannot be used for generation of electricity and heat. But reuse on agricultural lands gains indirect energy credits by substitution of energy-intensive fertilizer production. Fertilizer production via Haber-Bosch requires 60 MJ/kg of N [9, 21]. For P, energy intensity for mining and processing is estimated at 29 MJ/kg P [27]. For N, there are no limitations in resource availability as N2 is abundant in the atmosphere. But P resources are limited and energy demand for processing is expected to rise, as good quality resources decline. For our model, we assume a TEP factor of nutrients of 60 kJ/g N and 29 kJ/g P. This represents the grey energy of nutrient provision.

With 4 kg N/p*a, TEP of N is 66 kWhprimary/p*a, which is lower by a factor of 4 than TEP of C. Again lower is TEP of P with 6 kWhprimary/p*a for 0.7 kg P/p*a. Current energetic reuse of N and P equals the load in sludge applied to agricultural land, taking into account average plant availability. Results of a substance flow analysis (SFA) shows that the weighted average of energy credits for fertilizer substitution is currently 6 % of TEP for N (4 kWh/p*a) and 30 % for P (1.7 kWh/p*a). Energy credits for reuse of N are more than twice as high as for P, despite the lower reuse rate. Fertilizer consumption in Germany is 19 kg N and 1.3 kg P per capita in average (on a elemental base, [8]). 20 % (N) resp. 58 % (P) of this amount can theoretically be supplied by nutrients in wastewater, underlining the importance of nutrient reuse.

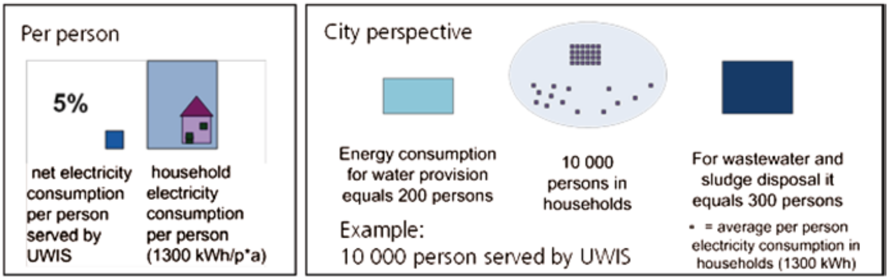

Fig. 3 Electricity demand for UWIS vs. household electricity demand on a per person base and seen from city perspective (10,000 person served as an example)

It is noteworthy, that the non recovered TEPs of CNP add up to 272 kWh/p*a on a primary energy base. This is considerably larger than the current net energy demand of infrastructures with 189 kWh/p*a. C resources in wastewater can theoretically supply enough electricity to cover demand of infrastructures, but currently only 17 % of the theoretical potential is used for electricity generation. By optimizing biogas use and incineration of sludge, reuse can be increased to 43 % of the theoretical potential. Further increase requires minimization of losses occurring during conventional aerobic wastewater treatment. Today, more than one third of C energy is lost at this treatment step. Energy balances of UWIS stand on two important pillars: energy efficiency—reducing external energy consumption; as well as resource productivity—maximizing energetic reuse of internal resources.

It can be seen in the figure above, that energy consumption in households is considerably larger than on the level of UWIS on a per person base. Hot water preparation and heating in households consumes approximately 7000 kWh/p*a [7]. Electricity use averages 1300 kWhel/p*a [41]. Therefore, electricity demand for UWIS equals only 5 % of household electricity demand.

Emission Balance of UWIS

On the output side, emissions to air, water and land need to be considered. Effluent load is mostly in focus of public and politics, as it is a prime goal of UWIS to protect water resources (receiving waters). The effluent load of CNP can cause eutrophication (misplaced resources).

Air emissions from UWIS are also gaining attention. Besides the emissions related to energy use (off site emissions) emissions of greenhouse gases from the flow streams can be considerable. For example, CO2 emissions originating from renewable C in the flow streams (42 kg/p*a) are larger than the off site (fossil) CO2 emissions from energy use of UWIS (35 kg/p*a). The on site CO2 emissions are renewable, as they mainly originate from food and cannot be avoided, as they are inherent components of the flow streams. But their magnitude underlines the importance of energetic reuse of the C resources in flow streams for a minimized CO2 intensity of bioelectricity generation at UWIS.

Other greenhouse gases may also be emitted from the flow streams, e.g. CH4, NH3 and NOx.

Besides the resources, wastewater can contain a multitude of pollutants, such as heavy metals and synthetic organic substances [13, 20, 50]. In general, most of the chemicals used everyday in modern society—flame retardants, plasticizers, disinfection and impregnation agents, pharmaceuticals, and many more—can be found in waste water or sewage sludge. Some of them have persistent, bio-accumulative or toxic properties. Due to their persistent nature, they are not biodegradable with the current technical setup of WWTPs and remain in large parts in effluent and/or sludge or are transferred to air e.g. as aerosols. These micro pollutants are a growing concern for WWTPs: a 4th treatment stage for effluent, as recently introduced in Switzerland, is discussed; sludge use on land has shown a decreasing trend in the last years in Germany due to concerns about soil contamination [47] and air emissions of persistent pollutants from UWIS are also gaining attention.

Energy Balance of UWIS in City Perspective

Even though electricity demand for UWIS equals only 5 % of household electricity demand, UWIS are still an attractive target for measures for improved energy balances, due to the following reasons. Firstly, there are large potentials for energetic resource reuse, as laid out above. Secondly, measures at facilities such as water and wastewater treatment plants, do not affect the users e.g. they require no change in user habits. Also, most companies in Germany are community owned allowing direct political influence. Thirdly, seen from the city perspective, facilities are large single consumers. As shown in the figure below, energy consumption is concentrated there, while households are distributed with different densities over the city area. Taking rather small facilities with 10,000 person served as an example, consumption equals 200 households on the water provision side and 300 households on the wastewater and sludge management side. For the same impact on urban energy balance as a 10 % reduction in external electricity consumption at the wastewater treatment plant, e.g. by increased biogas use, successful reduction measures in 300 households (each 10 %) are required. For larger facilities the value proportionally increases. Often, the wastewater treatment plant is the largest single electricity consumer in a particular city.

Eco Innovations in UWIS: Microalgae Systems for Bioenergy Production

Based on the analysis of the Status Quo of Energy and Emission Balances, we would like to outline a promising approach to improve energetic reuse of wastewater resources, while reducing the emissions of persistent pollutants: Integration of microalgae systems for bioenergy production at WWTPs. The idea of integrat-

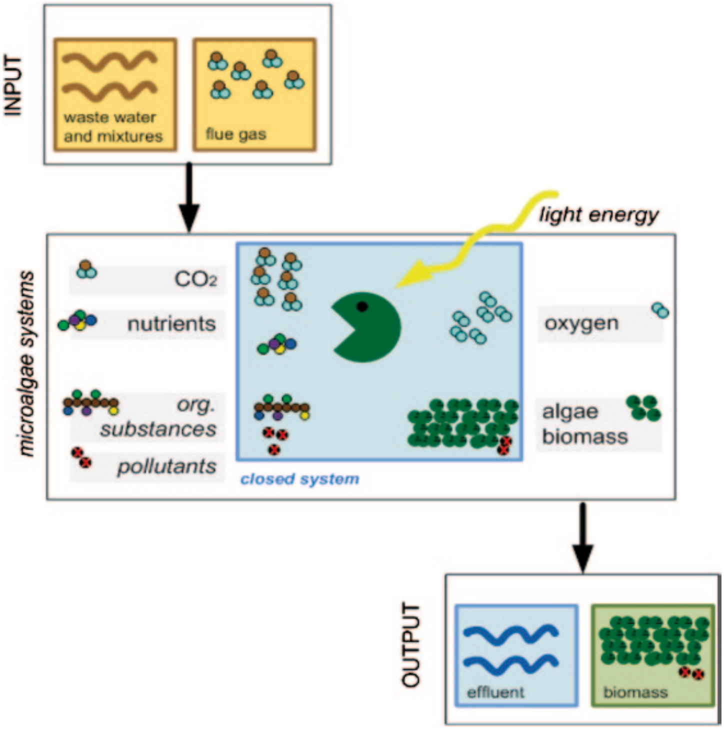

Fig. 4 Substance flows in microalgae systems for bioenergy production at WWTPs

ing microalgae systems and wastewater treatment dates back to the 1950s [35, 36] and offers many potential synergies. In theory, all resources required for algae growth are available at WWTPs (see figure). Wastewater provides a growth medium rich in macro and micro nutrients and CO_2 can be supplied from flue gas on site [24, 46] fig. 4.

Another synergy is the energy offset from (partial) wastewater treatment, as algae remove nutrients from wastewater during growth. Harvested biomass can be used energetically for production of biofuels, or for electricity generation via biogas or direct combustion. Despite these potential synergies, only a few pilot projects of microalgae systems running with wastewater have been described, mainly located in the US [24, 44] and New Zealand [37–39]. They confirm the technical feasibility of the concept.

In an earlier study [29], we proposed a process design for integration of microalgae systems and wastewater treatment, which relies solely on resources from wastewater for microalgae cultivation, with no external input of water, fertilizer or CO_2. Algae grow in flat basins (high rate algae ponds HRAP, [37–39] with CO_2 supply from biogas combustion. For nutrient provision, a mixture of process water (from sludge dewatering) and primary treated wastewater is fed to algae systems.

Harvested biomass is co-digested with sludge. The whole process chain, from cultivation to production of bioelectricity, takes place at the WTP [29].

Integration of microalgae systems considerably improves energy balance of WTPs. With full exploitation of the CO_2 available on site, enough bioelectricity is produced to run WTP energy-neutral during the vegetation season, or even to generate surplus bioelectricity. While effluent quality meets limit values, integration of microalgae systems increases loads of nutrients in effluent, mainly due to the contribution of non-harvested biomass. Important parameters for energy and emission balances are harvesting efficiency and anaerobic digestibility.

To recap, 20 % (N) *resp.* 58 % (P) of fertilizer consumption in Germany can theoretically be supplied by nutrients in wastewater, underlining the importance of nutrient reuse. But besides the resources wastewater can contain a multitude of persistent pollutants. With regard to these pollutants, algae systems offer considerable advantages: On the one hand side, algae systems can be designed in a way to minimize risk of emission of pollutants to the environment, while achieving the same areal productivities as (open) "conventional" bio energy systems (e.g. corn or canola). Microalgae grow in (semi-)closed systems (ponds) and nutrients from wastewater can thus be reused in a safe way. The problem of groundwater pollution and eutrophication, which often accompanies intensive "conventional" bio energy systems, is abolished with algae systems.

On the other hand side, algae systems have the potential to reduce loads of heavy metals and organic micro pollutants in effluent. Processes such as bio-oxidation, bio-sorption or assimilation can remove heavy metals [25] and other persistent organic pollutants [34], supported by a long hydraulic retention time of 4–6 days in aerated environment. Eliminated micro pollutants from wastewater are degraded or transferred to algae biomass *resp.* sludge, making it unsuitable for non-energetic reuse such as animal feed or soil conditioner. Potential to eliminate micro pollutants is well described for laboratory studies, but remains to be proven in pilot projects. If proven in practice, algae systems could provide a cost and energy efficient option to reduce loads of micro pollutants in effluent, while producing energy. This would provide a strong additional incentive for WWTPs to integrate algae systems

Integration of algae systems is interesting for WWTPs striving for improved energy balances, with land resources available in the surroundings. As algae have higher areal energy yields than other energy crops, the area for production of a specific amount of bio-energy can be expected to be smaller [48]. Free digester capacities are available at many WWTPs in Germany, due to safety reserves, and faster digestion in summer. Demographic change with decreasing population, especially in rural areas, contributes to free capacities. Co-digestion of algae biomass to increases biogas production can also move down the threshold for economic feasibility of anaerobic sludge stabilization, allowing smaller plants to switch to anaerobic sludge stabilization.