EXPANDING THE EXERGY CONCEPT TO THE URBAN WATER CYCLE

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Abstract

The world is urbanizing fast and this increases the pressure on available resources. In a world of cities, it is therefore crucial to take a new look at the way urban systems function: where do the resources come from and where do the wastes end up? It is essential to find ways to minimize urban impacts on resource depletion and environmental impacts and also to improve cycles within the systems.

Energy and water cycles are vital to support urban life. Over the last decades, important advances have been made separately in the field of integrated water management and energy efficiency in urban areas. However, for urban planning purposes a shared framework is required that allows planners to model and understand the dynamics of the broader system to achieve an integrated management of the resources.

Natural energy and water cycles are modified by metabolic profiles of the cities. The metabolic profile varies with the local resource availability and the level of technological development. To cope with this complexity, the concept of Exergy, based on Thermodynamic laws, and defined as the non-used fraction of energy, has been used to understand the energy cycle in the built environment. This will lead to new approaches towards urban planning and better resources use.

This paper aims to find out if the exergy concept can be expanded to the water cycle defined as the use of the non-used water(-fraction). This way the cycle can be optimized and closed at a high efficiency level. In order to achieve this, we want to study to what extend the energy and water cycles are comparable, and how they can learn from each other in order to optimize their management.

1. Introduction

Since the beginning of history, humans have influenced and modified natural cycles. It is not clear how cities will evolve in the future. Currently more than 50 % of the world population lives in cities and projections estimate that this percentage will grow, meanwhile also world population is still growing (United Nations Population Division, 2002). Over the last century, fast urbanization and increasing living standards have created a growing pressure on resources at a global scale. Energy and water are the so called “essential or critical flows” in the cities (Timmeren et al. 2007). Energy and water are vital for human well being and for the functioning of cities. In order to guarantee reliable supply of these resources, energy and water have been the focal point of technology development. However, technological achievements are not enough to guarantee urban sustainability. Technical solutions are no longer sufficient to tackle the intricate problems we face today (Pahl-Wostl, 2007). We are facing currently an imbalance due to the short coming of cost-benefit approaches and business as usual decisions applied in most of the cities. Resources are not used efficiently and large quantities are wasted. For example, the most efficient Dutch power plant, the Eemscentrale, reaches only an efficiency-level of 55 %, and 45 % is wasted as heat (Electrabel, 2008). In the case of water, around 30 % of potable water for domestic consumption is used for toilet flushing. The urge for wasting less and saving more is growing. The outcomes of a decreasing supply of resources, dependency on politically instable countries, and conflicts about borders become more and more clear: droughts, water pollution, electricity break downs, no gas deliveries, etc.

This paper will elaborate on the importance of urban resources management as a key consideration for urban planning. Over the last years, urban planning has partly addressed energy and water resources management. This paper focuses on urban resources management as part of urban planning, with a focus

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on harvesting the urban resources. If urban planners keep resources management into mind, the growing pressure on urban resources can be tackled in a more efficient and sustainable way.

By taking stock of the resources and activities within the city, an urban scan can be performed. Next to that, research can identify an overview of existing cycles to find out hot spots, losses, inefficient processes or activities, and possible improvements. Technology development should be combined with a shift in paradigm, in which the main strategy is working towards closed cycles (Rovers, 2008). Developing a closed cycle strategy for energy in the built environment is well understood, e.g., the zero-energy buildings approach. We can improve the approach or detail it more, but the way of thinking is towards a closed cycle approach. Possible improvements are: operating with lower flow volumes, or more efficient use of the total flow quality, which can be listed as an exergy approach. A known energy approach closely related to the closed-cycles approach, is the three-step strategy of the Trias Energetica (Duijvestein, 1997; Lysen, 1996): first, prevention – limit the demand for energy through rational use; second, substitution – make use of renewable energy sources; and third, use remaining fossil fuels as efficient as possible. In comparison, Integrated Urban Water Management uses a broad range of approaches, including as well water demand reduction, water conservation and increasing efficiency. Some examples are: water sensitive planning and design, utilization of non-conventional water sources, and application of fit-for-purpose principles and a mixture of several technological solutions (Mitchell, 2006). This shows that the “Trias Energetica”-strategy and Integrated Urban Water Management aim both for an improvement in efficiency of urban cycles to optimize urban resources management.

According to a definition of “sustainable”, resources planning and management should guarantee reliable resource provision. And planning and management should maintain the state of the resource for the use of future generations. Integrated resources management should take into account all potential trade-offs and different scales in space and time (Pahl-Wostl, 2007). In present time, with the current urban planning practice, it is common to develop separately energy plans and urban water management plans. Urban planners and managers face the challenge to combine the output from different approaches used to optimize single energy and water flows. By isolation of the flows, we simplified the urban complexity, but, after studying the flows separately, the use of different approaches makes the energy and water flows not compatible. And, there is no guarantee that the sum of optimal single flows is equal to urban sustainability, due to the dependency or competition of the different flows within the urban area.

To obtain an overview of the urban metabolism, the question is: “how to combine planning practices to make the energy and water flows compatible?” The answer can be to use general definitions that are broadly applicable with similar parameters or criteria. Sustainable development implies a new paradigm based on scientifically sound concepts as exergy and exergy based methods (Wall, 1977). Dincer and Rosen (2005) stated that “an understanding of thermodynamic aspects of energy can help understand pathways to sustainable development”. Exergy can help to bridge the gap between a rational use and sustainable development (Kann et al., 2008). Exergy refers to the quality of energy (Wall, 1977; VTT, 2003): the same amount of energy, with different qualities, can be used multiple times. In that way we could define an optimal “urban exergy” design as the smart use of the urban resources – minimizing losses and optimizing use – aiming for closed cycles and sustainable urban ecosystems.

2. Background

2.1 Exergy definition

In the Netherlands a four university consortium, SREX, is developing an exergy approach for the built environment. This exergy approach aims for a more efficient use of energy, by applying the energy conservation principle. Energy is never lost, only transformed; after each use there is quality remaining that is applicable elsewhere. In a first exploring phase, the researchers found out that the exergy concept is difficult to explain to market parties. Therefore, the researchers developed a new practical definition:

“Exergy is the use of un-used energy in the conversion processes” (Gommans et al., 2007).

We can identify exergy as the rest energy in the system. Or we can also call it “the un-used quality”. The research made clear that this definition is a very useful way to illustrate the exergy – energy quality – concept. This definition makes clear that exergy refers to two main aspects: unused sources, leading to the use of multiple sources to fulfill demand, multi-sourcing; and using the remaining quality levels to fulfill other demands, cascading. Both aspects will contribute to a higher efficiency, more self-sufficiency, and a lower dependency on non-local resources. The urban area is a reservoir of unused energy sources: e.g. waste heat of power plants or industry, waste from households and municipal maintenance, or possibilities to apply renewable energy technologies, such as PV-cells.

Now the question is, when studying the closing of the water cycle, if there is anything like exergy of water? Of course, water cascading is already an old principle, but might water-exergy provide a creative new approach? And as a follow-up on this thought, can the practical exergy definition be translated for water as well, and provide a useful instrument? Based on the exergy definition, we formulated a definition for water-exergy:

“Water-exergy is the use of un-used water in the conversion processes.”

A European research program, SWITCH, will study the applicability of this water-exergy definition: when using water, it is partially polluted, but there is still an unpolluted fraction left. This fraction has some quality remaining that still could fulfill some work that requires a lower quality. For water, the urban area is also a reservoir of unused sources. Think of the application of a rainwater collection system, on roofs of buildings or on neighborhood level. Or when flushing a toilet: the water is polluted or diluted, but there is still a fresh water part in the wastewater. This part is in fact unused for its capacity to dissolve and transport waste. It is this fraction that is the unused quality of water.

2.2 Urban Harvest approach

In order to reach sustainable urban planning, it is important to study a system from the perspective of flows (Timmeren et al., 2002). So, to meet the urban need for resources – like energy and water – via a sustainable solution, we should study the total flow of resources: input, consumption, and output. This has to become a closed cycle, so in- and output are connected (Rovers, 2007; Rovers, 2008). The way people think about cities has to change: not longer just living and consuming resources, but transforming to a resource producing environment. Like said before, the urban area is a large reservoir of unused sources, but these sources have to be studied and exploited. To apply this in practice, the Urban Environment Group of Wageningen University developed the “Urban Harvest”-approach (Rovers, 2007). The researchers described this as “a strategy to investigate all possible options for re-using the full output, and the potential sources within the system itself, within the urban environment” (Rovers, 2007). The defined “Urban Harvest”-strategy focuses on:

1. Making un-used resources and flows visible;
2. Developing a model and system approach;
3. Taking stock of the harvest potentials;
4. Investigating/developing, if not available, technologies in the broad sense of the word to make them harvestable;
5. Studying optimization and adaptations of the urban environment to maximize harvests;
6. Developing integrated approaches and organizational strategies to establish harvesting in many areas.

3. Energy and water cycles

On earth, energy and water flows are crucial to maintain ecosystems equilibrium. According to thermodynamic laws, energy is never lost, only transformed into one with a lesser quality (Wall, 1977; VTT, 2003). When analyzing the water cycle, it seems that the situation is similar: water changes of state and composition, but it is never lost. Different activities use energy and water, but they are not consumed completely, only transformed.

When analyzing the cycles, the scale is determining the main characteristics. When studied on a global scale, energy and water resources are present on earth in vast amounts: solar energy, geothermal energy, oceans, rivers, groundwater, etc. However, when we look at a local scale, cities face problems like water scarcity, energy crisis, etc.

3.1 Global scale

Let us first look at the natural flows, sunlight and rain. The main source of energy in our world comes from the sun. And it happens that water falls from above as well. Let us start exploring the relation of the two at a very broad level: earth and space. At this level the earth can be considered more or less in balance between receiving energy from outer space from the sun, and losing energy by infrared radiation. This balance in general, over billions of years, is losing energy: the earth is cooling down and solar radiation decreases. The balance will be shifting to much cooler levels as we know today: the system earth increases entropy. Within a more modest time range of thousands of years the system can however be regarded as “in balance”. The system is in balance, except for some minor or more severe fluctuations, as for instance due to man made climate changes, via increased absorption of solar radiation – reduced losses of infrared radiation.

Nevertheless, the system is a, nearly, closed system, with one inflow channel – solar radiation, and one outflow channel – infrared losses. At first sight this seems already to disturb up the idea of a similar approach and process, because water is not going in or out that system in the same way. However, here we introduce a slightly different system border, and fix this border at 500 meter above and under ground level. This system includes all human activity and area of influence, except for some high towers. With these borders set, we can have a look at the natural flows within that system, for both energy and water.

In a general and rough way, we can state that energy, in the form of radiation, goes through the system. Some energy is reflected before reaching the ground, some is reflected at ground level, some absorbed, and some stored and released at a later stage. For water the general picture is similar: some is reflected before reaching ground level – evaporated, some is reflected instantly when reaching ground on warm surfaces, creating fog for instance, and some is absorbed or stored and released at a later time. See figure 1.

Similarities of energy and water can also be observed in other aspects, like resources stocks. For instance lakes can be similar to oil or gas reserves: both lakes and oil/gas reserves are deposits of resources and they can be depleted.

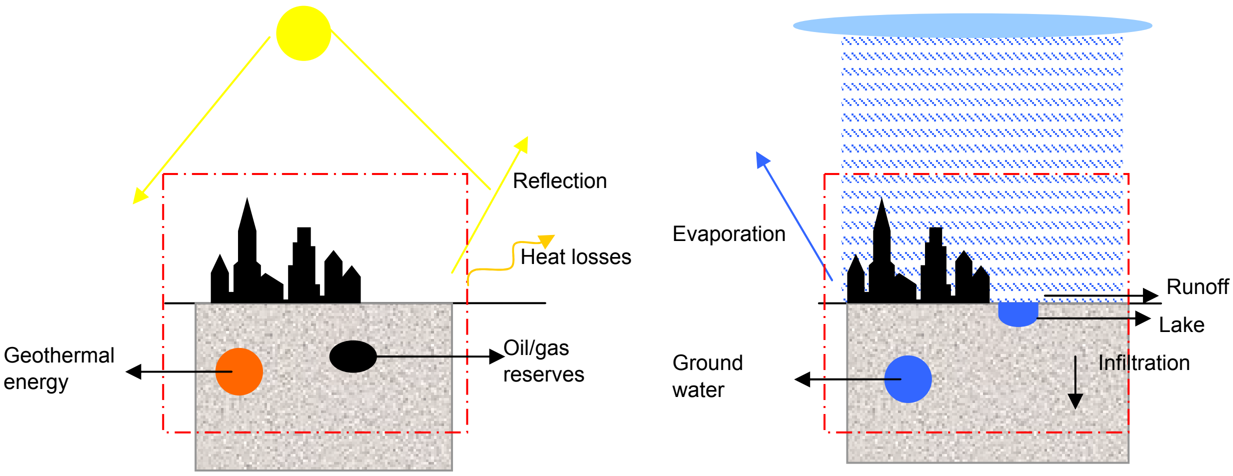

Figure 1 Energy and water cycles at global scale

Disruption in the cycles can create similar consequences. Energy can concentrate or dilute at certain geographic areas, creating heat or cold waves – in fact a negative heat wave. For water, a flooding is comparable to a heat wave and a negative flooding, a drought, is comparable to a cold wave.

3.2 Local scale

Even though the amount of resources is not a problem on a global scale, cities face resources scarcity. This is due to disparity in distribution of resources, lack of technology to harvest available resources, or due to old technologies and paradigms for resources exploitation. Both, energy and water natural cycles are disrupted by urban environment. Land coverage, building typology, intensive extraction and use of resources, and emissions to the environment, among others, affect the energy and water flows. The increasing population and rising living standards influence urban energy and water cycles as well. The urban energy and water systems, in general, can be described as open systems, starting with a generator or extractor that supplies the resource at a given quality – input. This supply is usually at the highest quality required by urban activities: in the case of water, this is water of drinking water quality, and in the case of energy, this is electricity. Within the city, the urban activities transform/use the resources, and finally emissions discharge – output.

Comparing the two grids at city level, we found more similarities. Infrastructure and grids upgrade quality, distribution re-allocates resources within the built environment, and after consumption or transformation, waste is discharged into the environment. In a schematic view, we could describe urban energy and water systems as shown in figure 2.

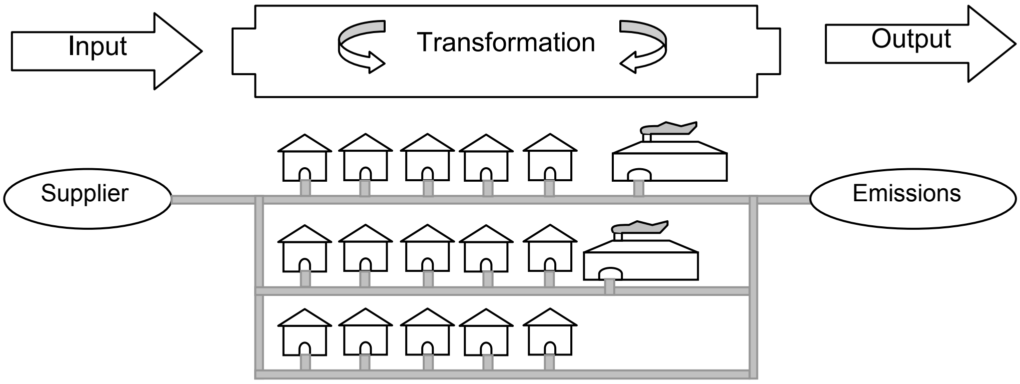

Figure 2 Schematic view of energy and water urban systems

Looking in detail to the quality of resources, we can describe the actual system as shown in figure 3. For the supply side, different exploited sources provide energy or water at different qualities; however, the grid must be fed with a certain quality. To reach this quality levels, conversion steps are involved between sources and distribution, e.g. water purification or energy transformers. Each conversion step consumes energy and can influence the efficiency of the system. Analyzing the demand, different activities require different resource qualities. Because the grid can provide only a single quality, some of the activities will get a higher quality than needed – they have a surplus of quality. After performing a given activity, some remaining water or energy quality is available – an unused quality. In an open system with emissions, remaining qualities will be waste. In the closed cycle approach a flow with a lower quality can be useful to perform a certain activity, which has a lower quality requirement.

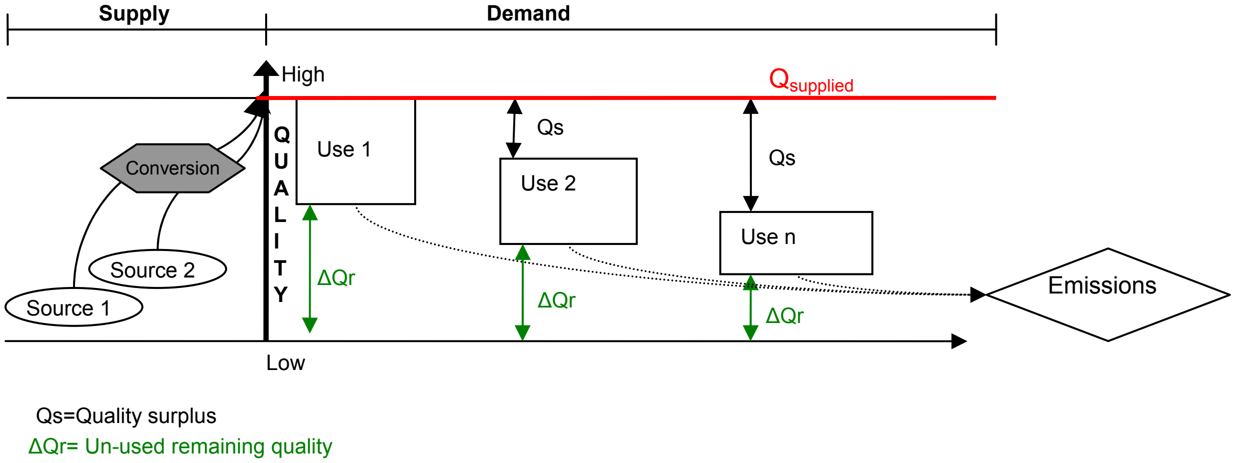

Figure 3 Schematic view of energy and water qualities within the urban systems

Like explained in the text and shown in figure 3, this linear system is not efficient. Sources have to be upgraded to higher qualities, and functions do not always need these higher qualities or unused qualities remain. There are possibilities to improve the current systems. Therefore, we think that it is better to work towards a more efficient, circular system for energy and water. If we keep the Urban Harvest approach in mind, cities are like forests, filled with harvestable primary and secondary resources. Within a multisource strategy, several sources offer resources at different qualities, which can be coupled for fitting the demand of different urban functions. In our approach also remaining qualities are seen as new sources, of lower quality levels. Figure 4 shows this more efficient, circular system for energy and water. It is a system that handles the input more efficiently – conversion technologies handled more efficiently, a system that captures and transforms more incoming resources, and a system that limits the output – runoff/reflection, and looks for ways to recycle the remaining qualities of the output. What figure 4 shows is that planning is important when applying remaining qualities. The functions have to be planned in a stepwise order, a cascade of energy or water. The function that demands the highest quality has to be located highest in the cascade. The remaining quality can be high enough to fulfill the demand of another function. And this process can go on until only a very low quality is remaining (Dobbelsteen et al., 2006).

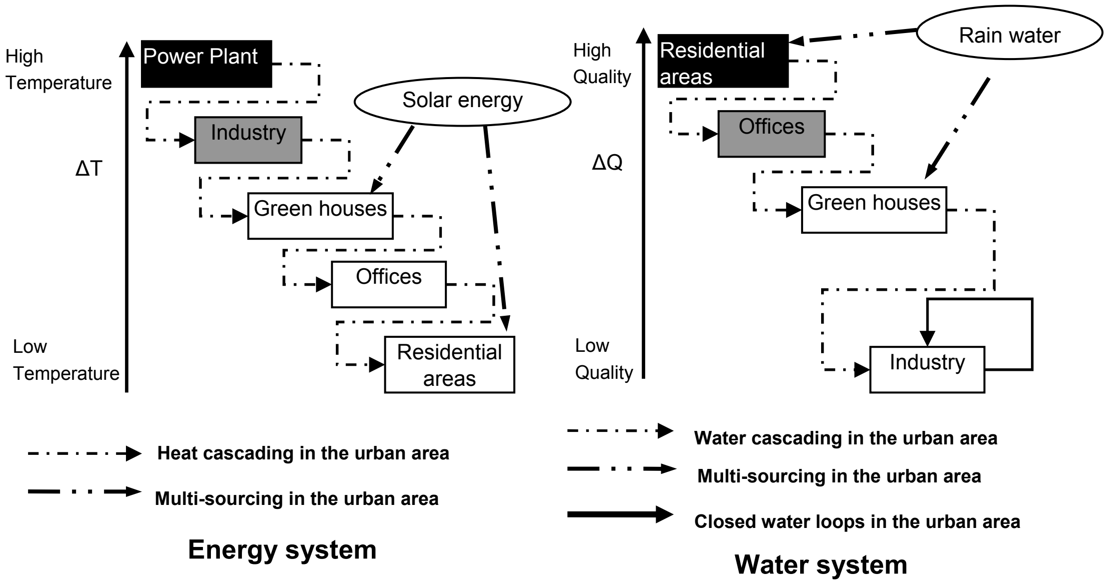

Figure 4 Schematic views of possibilities to optimize resource management by coupling supply and demand based on quality parameters

3.3 Sub-local scale

We described until now comparisons of energy and water cycles on a global scale and on a local scale. Next to that, there is a smaller scale. At sub-local scale, the border of the system is the building plot: e.g. individual houses, streets or neighborhoods. The systems for providing energy and water to this sub-local units can be decentralized. On this smaller scale this may prove to be more efficient than a centralized system. For example, a central electricity grid supplies the building plots, but the required quality can be fulfilled with another – lower quality – source. Similarly, the central drinking water grid supplies the building plots, but some purposes demand only water of a lesser quality. A decentralized system can tackle these differences in quality in a more efficient way. For energy, technologies, e.g. PV-panels, can be applied to supply the building plots with the required electricity of a certain quality. The electricity via the grid is upgraded to fulfill several purposes, but this upgrading is not necessary for all household appliances. PV-panels deliver a better quality matching form of electricity. For water, an on-site rainwater collection system is an application of using a lesser quality source to fulfill a lower quality demand, e.g. toilet flushing. These examples show opportunities for self-sufficient, autarkic building plots. A self-sufficient building plot will not depend on external inputs. It will be a more efficient system in the sense that it needs a lower input, because it can provide its demand from within the system.

An example of a project that applies these ideas of coupling flows on a sub-local scale is “Zonneterp” in the Netherlands (Mels et al., 2006). This combination of greenhouses with houses couples energy, water and waste flows to optimize the total system. This system also refers to the cascading principle, because “Zonneterp” combines two urban functions and the remaining quality of one function is the required quality of another function.

4. Urban – energy and water – planning

Over the years, planning has been a flexible science changing according the new emerging problems in urban areas. Urban planning has evolved with the increasing complexity of urban areas. And specifically, when referring to energy and water infrastructure. When looking at existing urban infrastructures, the current situation is a consequence of past planning practices, for instance sewer systems being replicated in cities, or use of fossil fuels used as main electricity generator. Complex, expensive and long lasting centralized systems, developed to supply cities needs, have the disadvantage of pathway dependency in which developments focus on trying to improve existing systems. And those developments do not focus on studying several solutions to existing problems.

Currently urban areas extract resources from external areas and after consumption emissions are released to the local or global environment. Cities face strong dependency on other areas, meanwhile overlooking local possibilities of self-producing resources. Within our approach we see the city as an “urban forest”, with multiple potentials to harvest primary and secondary untapped resources. In this way, we aim to achieve a strategic urban-resource management. It is essential to separate the various components, and therefore different qualities in flows. And it is also important to optimize or minimize the quantities. Mixing qualities of different urban resources is unsustainable, exergy principles should be the basis of every solution (Timmeren et al., 2002).

However, within resource management, not only isolated cycles are studied but also their interactions and their implications. Regarding urban infrastructure systems – water, energy, transport, and communication – are actually dependent systems that rely on each other, and have co-evolved over time (Dupay, 1991 in Mitchell et al. 2004). Infrastructure linkages are increasingly apparent and some links provide synergistic opportunities (Mitchell et al., 2004). A strategic resources management should not only involve supply and demand characteristics, namely quality and quantity, but also spatial and temporal implications. For this purpose, exergy defined as: the quality of energy - in place, level and time (Timmeren et al., 2002), can create the link between spatial planning, urban infrastructure and resources management. Thus, the exergetic approach necessitates a synergy between spatial planning and infrastructure (Timmeren et al., 2002).

To apply the exergetic planning approach for urban energy and water flows, it is necessary to define those four parameters – quantity, quality, location and time – for each source and each demand to couple them optimally (Rovers, 2008). Quality and quantity can be addressed by multi-sourcing and cascading; meanwhile, location and time have implications on transport/distribution and storage. They all have implications on planning. Some guiding planning principles that build upon this knowledge can be:

1. Avoid converters, each conversion consumes energy;

2. Promote cascading;

3. Prefer local resources.

5. Discussion

Urban energy and water cycles are interconnected. It is important to be aware of the interactions between them because they can influence each other. For instance, energy is required when implementing wastewater treatment to upgrade water quality. On the other hand, water can be an energy carrier in the form of heat or potential energy.

This paper studied the expansion of the exergy concept to urban water cycles. Our exergy definition supports the comparability of energy and water cycles within the urban area. Both cycles show unused primary and secondary resources with remaining, applicable qualities. If we study the urban energy cycle, it may seem that energy has not a waste stream, like water has. Heat losses in buildings or losses in installations are kind of energy waste streams. They are not as visible as waste water streams, because they are carried away by free air.

Another point of comparison is the unused fraction at a lesser quality level. The exergy concept, referring to quality of energy, shows this for energy. But also for water, we see an unused fraction available in urban flows. An example for energy is: in a gas boiler system, about half of the produced heat is wasted. An exergy approach tries to capture and transport the wasted heat, unused quality, to a place where there is a need for heat. For water, the conversion of drinking water into grey water leads to an unused fraction. This fraction is still capable to dissolve and transport waste, and can be re-used, for instance, for toilet flushing. In other words, this shows that energy and water have both unused fractions that can be applied for other purposes. Using grey water for toilet flushing shows the idea of using a remaining lower quality for a lower quality demand, a better quality match. And it is comparable to the use of residual heat for heating houses.

Our comparison of the cycles for energy and water on different scales – global, local and sub-local - indicates further that energy and water are comparable. On a local scale, the main focus of this paper, energy and water flows work as a system with an input, transformation and use within the city, and an output. On this scale, our exergy definition, for energy and water, becomes visible: in a linear system remaining qualities or unused fractions are lost. On the contrary, a circular system cascades remaining qualities and utilizes unused fractions. On a smaller scale we also see similarities and the applicability of combinations. Autarkic systems both apply technologies to supply energy and water on a small scale, e.g. onsite rain water collection, and PV-panels. Combinations are possible to make the whole system even more efficient, by cascading and using remaining qualities.

At the global scale, we explained that the energy and water cycles are comparable. And the amount of resources is not a problem at this scale. The most relevant scale for urban planning is the local scale, the scale of cities. Cities face scarcity of resources. So, cities should look for possibilities to harvest own potentials, become more self-sufficient and less dependent on non-local resources. Our paper states that urban energy and water planning should be tackled together and with a similar approach. We identified four main parameters for planning, which are the same for energy and water: quality, quantity, time and location. City planners should study the full potential and all available remaining and unused qualities within the city. In order to plan efficiently, planners have to account for the time and location at which those unused sources are available. On the sub-local scale, we mention possibilities for autarky on single housing level or street/neighborhood level. However, urban planning does not have too much impact on these levels.

During the last decades, urban energy and water planning have been facing a similar transition phase. Basically, both aim for a paradigm shift, trying to overcome similar problems – high consumption rates, resources scarcity, dependency on non-local inputs, etc. Comparing their principles and planning parameters we can see more similarities than differences. By using similar approaches to study both systems, they can learn from each other, cooperate and provide an integrated urban planning.

6. Conclusions

Urban energy and water flows are comparable. There are possibilities for urban planners to learn from resources management theories to guarantee cities sustainability. Similarities regarding quantity and quality valuation and principles for resources allocation show that the exergy concept can be extended from energy to water with some adjustments or adaptations. The use of a common approach to deal with urban energy and water flows within the urban planning practice is feasible. However, further research is needed to study the real applicability of this concept and its translation into real planning practice. A proposed direction to follow is to develop detailed planning rules to maximize the potential harvest of urban resources by using exergy principles.

Further research is also needed, to study the applicability of the exergy concept in other urban flows such as materials, or nutrients, in order to use a unique system to study the complexity of the different flows within the built environment.

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