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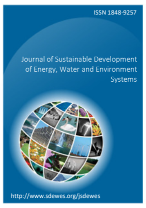

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A Nearly Net-Zero Exergy District as a Model for Smarter Energy Systems in the Context of Urban Metabolism

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ABSTRACT

The planning of urban settlements requires a targeted approach towards more sustainable energy, water, and environment systems. This research work analyses the city of Uppsala and a district that is an urban renewal project at the site of former high voltage power lines, namely Östra Sala backe, which will have a new energy concept. The latter is analysed based on proposals for two phases that aim to reach a net-zero district target based on the quality of energy (exergy). An indicator set with five main categories is introduced based on per capita values to enable a comparable basis between the scales of the city and the district, including exergy per capita as a new indicator. The present status of Uppsala is further analysed based on Sankey diagrams to provide insight into the present urban metabolism of the city. The results indicate that the best practice values of Östra Sala backe based on phase two can achieve significant savings in per capita values, which include 5.5 MWh of energy usage, 6.1 MWh of exergy consumption, 33 m^3 of water consumption, 22 kg of waste generation, and 4.2 tonnes of Carbon dioxide (CO_2) emissions. Additional scenarios for Uppsala indicate that the district can be about 10 years ahead of the city's existing performance.

KEYWORDS

Energy, Exergy, Water, Waste, CO_2 emissions, Net-zero, Urban metabolism, District.

INTRODUCTION

Smart energy systems require the purposeful integration of multiple energy carriers to enable optimized flows of energy. Smart energy systems are not confined to smart electric grids and encompass a more inclusive scope, including thermal energy [1]. In this respect, Lund *et al*. [2] introduced the concept of smart thermal grids as one of the essential components of smart renewable energy systems and defined the role of fourth Generation District Heating (4GDH) networks. 4GDH operate at low temperatures, interact with low energy buildings, and integrate renewable energy sources [2]. Especially by the year 2020, 4GDH networks are foreseen to have supply temperatures between 303 K and 343 K [2].

Studies that have analysed either realized or proposed case studies within the domain of smarter energy systems were undertaken at various levels, including districts and cities. For example, Wetterlund *et al*. [3] analysed two options to implement district heating based on biomass gasification in the Swedish city of Linköping, including the co-production of synthetic natural gas. For the same city, Difs *et al*. [4] analysed the effect that energy conserving measures in multi-dwelling buildings may have on the district heating system. Zhang *et al*. [5] analysed the feasibility of integrating concentrated solar power into a thermal power plant as a hybrid energy system for Dubrovnik-Neretva County in Croatia.

In addition, Assoumou *et al*. [6] analysed the energy system of the city of Bologna, Italy based on energy demands by fuel type and projected options for an 84% reduction in CO_2 emissions by the year 2050. Martínez *et al*. [7] determined the energy flows in the city of Bogotá in Colombia and compared changes in values of energy usage and CO_2 emissions per capita. Other studies analysed the role of photovoltaic and wind power in three cities, namely Delhi, Shanghai, and Helsinki, and aspects of surplus electricity [8]. These studies addressed the provision and use of energy in the context of urban energy systems [9].

At the national level, Mathiesen *et al*. [10] put forth the need for smart energy system configurations that merge the electricity, heating, and transport sectors to reduce primary energy spending. A 100% renewable energy system was proposed for Denmark with the use of biogas, biomass, wind power, photovoltaics, wave power, geothermal energy, solar thermal, and their interrelations [10]. Lund *et al*. [11] further compared candidate plant types of Combined Heat and Power (CHP) with the least intake of biomass resources.

From an economic point of view, smarter energy systems are expected to provide cost savings while meeting heating, cooling, and electricity demands. For example, related investments in five EU member states were found to reduce the total annual costs of the energy system by 15% while curbing energy usage by 30% and CO_2 emissions by 50% [12]. The investments included those for thermal energy savings, CHP plants, district heating networks based on excess process heat, and heat pumps [12]. Other studies conducted life cycle analyses to assess future electricity supply systems in Europe [13].

Towards smarter energy and environment systems

Beyond an energy focus, crosscutting studies addressed the need for smarter energy systems while undertaking key issues of water and environment systems. Duić *et al*. [14] developed the RenewIslands method to integrate energy and resource flows with the aim of providing guidance for sustainable communities. The method was applied to analyse the local needs for commodities, such as energy and water, the available resources, and relevant technologies. Solutions were obtained for the islands of Corvo, Porto Santo and Mljet [14].

In a related aspect, Krajačić *et al*. [15] applied the energy planning tool of H_2RES to the islands of Mljet, Porto Santo, Terceira, and Malta. The aim was to increase the integration of renewable sources and hydrogen into island energy systems. Medić *et al*. [16] analysed the island of Hvar from the aspect of self-sufficiency based on renewable sources and energy storage systems. Segurado *et al*. [17] analysed the case of the island of São Vicente in Cape Verde. The use of wind power was proposed as an integrated solution to provide for local water needs based on desalination as well as electrical energy with a penetration well above 25% of the electricity supply by the year 2020. Such cases indicate that smarter energy, water, and environment systems can co-exist to support future oriented scenarios.

Expansion of scope for assessing resource flows

The energy infrastructure of cities may be placed in a broader context to jointly assess the sustainability of energy and environment systems. In this respect, Afgan *et al*. [18] proposed the use of indicators, such as CO_2 emissions and waste, in the process of assessing energy systems. In the related aspect of urban metabolism, Ravalde *et al*. [19]

identified the need to use grey-box metrics to provide insight on specific conversion processes. Related metrics were used to compare the dependencies between energy, water, and waste flows in three cities, namely Beijing, London, and São Paulo. Sun *et al.* [20] identified key factors that affected the metabolism of the industrial city of Shenyang in China. Emergy units were used to bring energy, waste, and material flows on a common basis to formulate the new metric of emergy per capita [20]. Xia *et al.* [21] identified seven indicators based on emergy to assess the metabolic structure, density, intensity, and efficiency of Xiamen city.

Chen *et al.* [22] analysed the sectoral energy flows in Beijing based on ecological network analysis. In a subsequent study, the authors analysed the same city from the aspect of energy-related water and water-demanded energy [23]. In addition, the authors reviewed the scope of urban metabolism studies, the most frequent of which was focused on energy [24]. Tseng *et al.* [25] used a network process to assess the flow of materials or energy between the nodes of energy, waste, food, agriculture, and domestic sectors in Taipei City.

Related studies that provide an expanded scope for assessing resource flows include Kennedy *et al.* [26] who proposed a set of indicators to assess urban metabolism in megacities. The indicators included those on energy usage, water consumption, wastewater, and waste alongside urbanized area, climate, and population [26]. Mostafavi *et al.* [27] developed an analysis tool for urban metabolism to assess the impact of building location and clustering on energy, water and material flows with a geographical dimension. Conke *et al.* [28] evaluated the changes in material and energy use in the city of Curitiba, Brazil over a timeframe of 10 years up to 2010, including food, energy, and water consumption.

Venkatesh *et al.* [29] analysed the urban water and wastewater systems of Oslo based on metrics to assess the environmental impacts of resource flows. Behzadian *et al.* [30] quantified resource flows in the urban water system, including water supply, stormwater and wastewater, and the relative environmental impacts on GHG emissions, acidification, and eutrophication for a northern European city. Zhang [31] reviewed the evolution of studies to assess production, consumption, and circulation within and among components of urban systems. A trend towards a network process to assess urban metabolism was found.

Aims of the research work

The process of assessing smarter energy systems with the inclusion of environmental indicators can provide enhanced insights on sustainability. Yet there is a gap in the literature for synthesizing the analysis of specific targets for related energy concepts, such as net-zero districts, and indicators that extend beyond energy into water, waste, and CO_2 emissions. In particular, studies that combine an analysis of concepts that can support the transition to both smarter energy systems and environment systems are still limited in the literature.

Concepts based on net-zero targets can allow districts as well as cities to be the hubs for smarter energy systems. The conventional roles of urban areas as consumers of energy can be transformed with diversified local energy production based on renewable energy sources at or above the amount of annual energy usage. In contrast, studies that assess districts with net-zero targets in the context of environmental indicators are still missing in the literature.

The research work aims to expand the contextual framework for analysing net-zero targets within more sustainable energy, water, and environment systems. In particular, the performance of a district with an innovative net-zero target [32-33] is compared through per capita indicators for urban metabolism. In this way, the research work puts forth and applies an approach that has relevance to assess three objectives: the more rational use of energy based on energy quality, aspects of water, waste, and CO_2 emissions, and net-zero targets.

METHOD

Based on the aims of the research work, the method is structured to compare the performance of a district for which a net-zero target has been proposed [32, 33]. An urban metabolism indicator set with five categories is constructed as the core focus of the analyses. A per capita indicator based on the quality of energy is defined for the first time to indicate differences in using energy sources with lower versus higher grades of quality. The method is beneficial to determine any savings that can be captured by such districts.

In particular, such a method is applied to enable comparisons between two cases that are located in Uppsala Municipality in Sweden. The first case is the city of Uppsala, which is the fourth largest city in Sweden, the capital of Uppsala County, and the seat of the municipality. The population of the urban settlement of Uppsala was about 148,486 in 2014 with an average annual growth of 1.01% since 2010 [34, 35]. The second case is the planned district of Östra Sala backe that is located 2 km from the city center of Uppsala.

Östra Sala backe is the site around former high voltage power lines that were removed as part of an urban renewal project to establish better East-West linkages in the vicinity and a functional, mixed-use urban corridor [36]. Previously, the power lines had been used to transmit electric power that was generated mainly from hydropower and nuclear sources. The reclaimed site has triggered the need to advance concepts based on more locally available renewable energy sources as well as net-zero targets at the district level.

Background of the data analyses

The analysis of the existing case study of the city of Uppsala is used as the reference to compare proposals for the new district of Östra Sala backe. The planned district has ambitions to be Uppsala's most climate friendly district with sustainable solutions [36]. For the analysis of the present case of the city of Uppsala, the available statistics were used to construct Sankey diagrams of the energy, water, and waste flows of the city. Where possible, per capita statistics that were collected by city officials were utilized [37]. In other instances, values were obtained based on calculations from available data.

Proposals for the first two phases of the new district of Östra Sala backe were put forth in [32, 33] with the aim of allowing the district to reach an original net-zero target based on the quality of energy. In this research work, these proposals are subjugated to a comprehensive assessment. Levels of improvement between phases one and two of the Östra Sala backe district are compared to the existing values of the basic flows within the city of Uppsala. Initiatives for Östra Sala backe to improve the flows of water and waste are placed in the context of future scenarios with a 10 year time horizon.

Overview of the net-zero exergy target

In the prior research work of the author [32, 33], the Net-Zero Exergy District (NZEXD) target was put forth to enable an innovative energy concept for Östra Sala backe. According to the NZEXD target, a district should produce as much energy as consumed on an annual basis at the same grade and quality [32, 38]. The grade and quality of energy is measured as exergy, which is the useful work potential of a given amount of energy based on a Carnot cycle that is defined according to a reference environment temperature.

Eq. (1) provides the formulation of the NZEXD target. Here, the term AEXC is the Annual Exergy Consumption of the district. The term $\varepsilon_{\mathrm{on}}$ is the exergy that is produced from renewables within the confines of the district on an annual basis. The summation expresses the sum across all energy related units i = 1 to x in a district for all time increments $k = 1$ to $k = m$ in a year. The energy related units include buildings, industry, and transportation units:

$$\text{NZEXD} \Leftrightarrow \text{AEXC} - \sum_{i=1}^{x}\sum_{k=1}^{m} \varepsilon_{\text{on}_{i,k}} \leq 0 \qquad [\text{GWh}] \qquad (1)$$

Eqs. (2, 3) provide the expanded version of the two main variables in the NZEXD target. CF_e and CF_t are the Carnot Factors by which the energy sums $P_{i(\text{e})}$ for electrical energy and $P_{i(\text{t})}$ for thermal energy are multiplied. The sum of the related products on the demand and supply sides are used to obtain AEXC [eq. (2)] and ε_on [eq. (3)]:

$$\text{AEXC} = CF_\text{e} \cdot \sum_{i=1}^{x}\sum_{k=1}^{m} P_{i(\text{e})_{i,k}} + CF_\text{t} \cdot \sum_{i=1}^{x}\sum_{k=1}^{m} P_{i(\text{t})_{i,k}} \qquad [\text{GWh}] \qquad (2)$$

$$\sum_{i=1}^{x}\sum_{k=1}^{m} \varepsilon_{\text{on}_{i,k}} = CF_\text{e} \cdot \sum_{i=1}^{x}\sum_{k=1}^{m} P_{\text{e}_{i,k}} + CF_\text{t} \cdot \sum_{i=1}^{x}\sum_{k=1}^{m} P_{\text{t}_{i,k}} \qquad [\text{GWh}] \qquad (3)$$

In the NZEXD target, since the aim is to obtain a net-zero status, inefficiencies must be taken into account within AEXC so that the boundary conditions between the supply and demand sides are unified. Moreover, electrical energy has a CF_e of 1 since all electrical energy can be converted into mechanical energy by common convention [39]. In contrast, the CF_t for thermal energy is calculated from eq. (4). Here, T_ref is the temperature value of the reference environment that is the basis of the exergy definition, such as the ground temperature that closely resembles the average of the outdoor air temperature on an annual basis [40]. T_ex is the temperature of the energy demand or the energy resource supply for which an exergy value is to be calculated. All values are to be expressed in Kelvin (K):

$$CF_\text{t} = \left(1 - \frac{T_\text{ref}}{T_\text{ex}}\right) \qquad [\text{K}] \qquad (4)$$

To give an example, the values of CF are 0.86 for natural gas and 0.76 for biogas per 1 kWh of energy [32] based on the adiabatic flame temperatures and the reference ground temperature of Uppsala, which is 279 K [41]. For the waste heat from CHP, T_ex can be 325 K based on the return temperature in the network with the qualities of being a 4GDH.

Contextual framework of the NZEXD target

The NZEXD target can be supported by the principle of distributing the sources of exergy supply to matching levels of exergy demand. In this principle, higher exergy sources are matched with demands that require high exergy (e.g. energy resources with higher values of CF). Similarly, lower exergy sources are matched with demands that can use low exergy (e.g. energy resources with higher values of CF). Hence, the value of AEXC in eq. (2) may be reduced based on lower energy values $P_{i(\text{e})}$ and $P_{i(\text{t})}$. AEXC may further be reduced based on a greater share of lower exergy resources in the energy mix with a lower average value of CF. In addition, sources of energy that are often wasted may be better integrated into the supply side to increase the term ε_on in eq. (3).

Based on these principles, the NZEXD target is expected to be influential in reducing the values of energy and exergy per capita in the districts to which it is applied. Figure 1 overviews the contextual framework of the NZEXD target with further extensions to aspects of water and waste. Accordingly, this research work seeks to integrate analyses for the NZEXD target based on the quality of energy with those for urban metabolism. The subsequent sections describe the means of analysing related aspects for comparison.

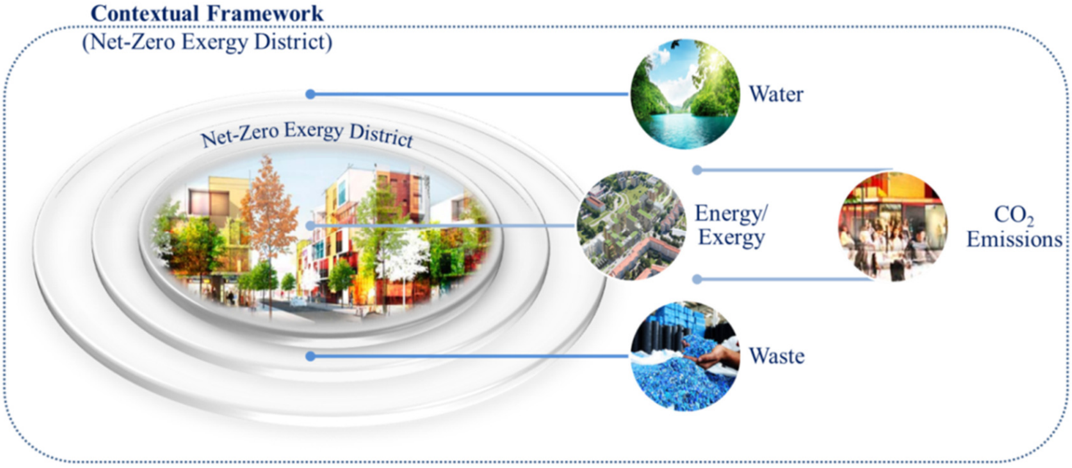


Figure 1. Contextual framework for energy, exergy, water, and waste

Determination of energy, water and waste flows

Initially, the flows of energy, water, and waste were put forth for the city of Uppsala. In so doing, the distribution of energy resources on the supply side and the points of delivered energy on the demand side are linked in an energy supply chain perspective. Eq. (5) provides the summation of these flows that are related by various efficiencies η, namely those for conversion (subscript c), transmission (tr), and distribution (d). The summations of energy E are provided for energy sources (S) and delivered energy (D). Eq. (5) may also be used for CO_2 emissions based on the application of CO_2 factors:

$$\sum E_{\mathrm{S}} = (\eta_{\mathrm{c}} \times \eta_{\mathrm{tr}} \times \eta_{\mathrm{d}}) \times \sum E_{\mathrm{D}} \tag{5}$$

In addition to the flows of energy, eq. (6) represents the flows of water G from the total amount of water that is produced in the city’s waterworks (subscript P). In eq. (6), the total amount is based on the summation of the delivered water to various sectors (O), water leakages (L), the use of water to enable energy conversion processes (E), and other internal uses (I). Hence, eq. (6) further represents an aspect of the energy-water nexus:

$$\sum G_{\mathrm{P}} = \sum G_{\mathrm{O}} + G_{\mathrm{L}} + G_{\mathrm{E}} + G_{\mathrm{I}} \tag{6}$$

The flows of waste W are analysed based on eq. (7) in which the waste that is produced (subscript P) is taken as the sum of the waste that is reused (R) or landfilled (N). Especially in the present case of Uppsala, waste is also a source for local energy production:

$$\sum W_{\mathrm{P}} = W_{\mathrm{R}} + W_{\mathrm{N}} = W_{\mathrm{R}} + \left(\sum W_{\mathrm{P}} - W_{\mathrm{R}}\right) \tag{7}$$

Eqs. (5-7) enable the attainment of key values for comparison, such as energy production per capita. Moreover, the identification of the energy flows from primary energy to end use based on Sankey diagrams enables a process of tracing the appropriate values to represent the quality of energy usage in Uppsala, which was unknown. Such Sankey diagrams were also useful to put forth the present state of energy and water usage. Codes that represent 38 entries were written and inserted into a Sankey interface [42].

Comparison of the city and district levels

Due to differences in scale between the city and the district, per capita values for all indicators were used as the basis of comparison for the two related case studies. Eq. (8) is used to compare the changes in the values of a set of urban metabolism indicators between the Östra Sala backe district that is seeking to near the NZEXD target and the values of the city of Uppsala. In eq. (8), the variable M is a given per capita indicator for urban metabolism as selected for the contextual framework of the NZEXD target. Here, subscripts Up and Ös represent Uppsala and Östra Sala backe, respectively:

$$\Delta M = M_{\text{Up}} - M_{\text{Ös}} \tag{8}$$

In cases where scenarios are constructed based on percentage point improvements over the existing status of Uppsala for water and waste, terms M for Östra Sala backe are found from eq. (9). The term V represents the percentage improvement over 100, which may be added or subtracted from 1 based on the specific context of the indicator. In instances where V is added, negative values in eq. (9) will indicate an improvement:

$$M_{\text{Ös}} = M_{\text{Up}} \times \left(1 \pm V\right) \tag{9}$$

Determination of NZEXD urban metabolism indicators

Figure 2 indicates the extended framework for applying the main categories of a selected set of urban metabolism indicators to the analysis of the case studies. In addition to energy per capita, a new indicator is included as exergy per capita. The latter defines a metric with specific importance for the NZEXD target. Exergy per capita represents the benefit of using lower exergy resources over higher exergy resources in a particular district. Exergy per capita has not been applied in other studies in the literature.

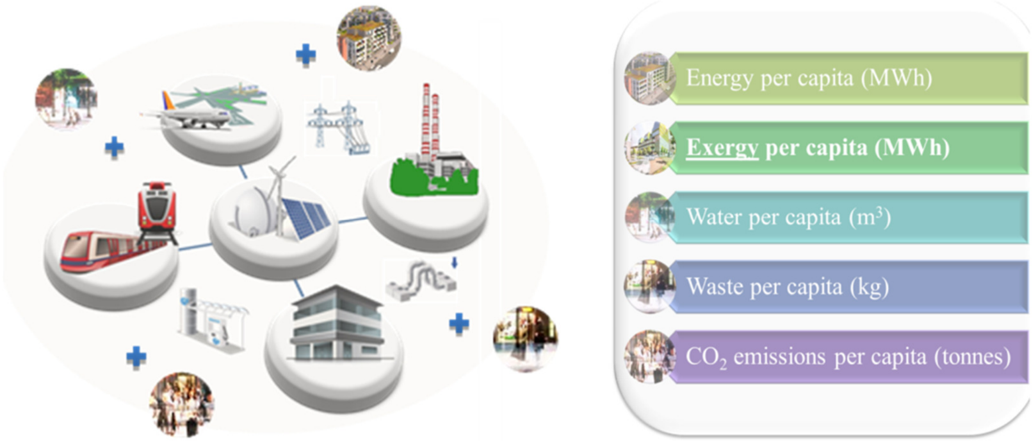


Figure 2. NZEXD urban metabolism indicator set including exergy per capita

In Figure 2, water per capita and waste per capita are other key indicators to assess the flows of other natural resources beyond energy. As the fifth indicator in Figure 2, CO_2 emissions per capita represents changes in reducing the CO_2 emissions impact of the district as a whole. The five main categories of indicators and other related indicators can be used to monitor the urban metabolism of districts seeking to reach the NZEXD target. In this study, this set is proposed to be the NZEXD urban metabolism indicator set.

In practise, the NZEXD urban metabolism indicator set can be used to support multiple aspects of planning to capture improvements in per capita values. For example, spatial planning for districts can be combined with energy and exergy planning to improve the values of the per capita indicators for energy and exergy. Environmental planning can be enhanced to reduce per capita water and waste values. The measures that are planned for Östra Sala backe provide examples of integrating such aspects to improve the performance of the district. Overall, the NZEXD target may be integrated with the planning of smart energy systems and sustainable districts that sustain both natural and human capital. Figure 3 depicts this approach involving multiple aspects of planning.

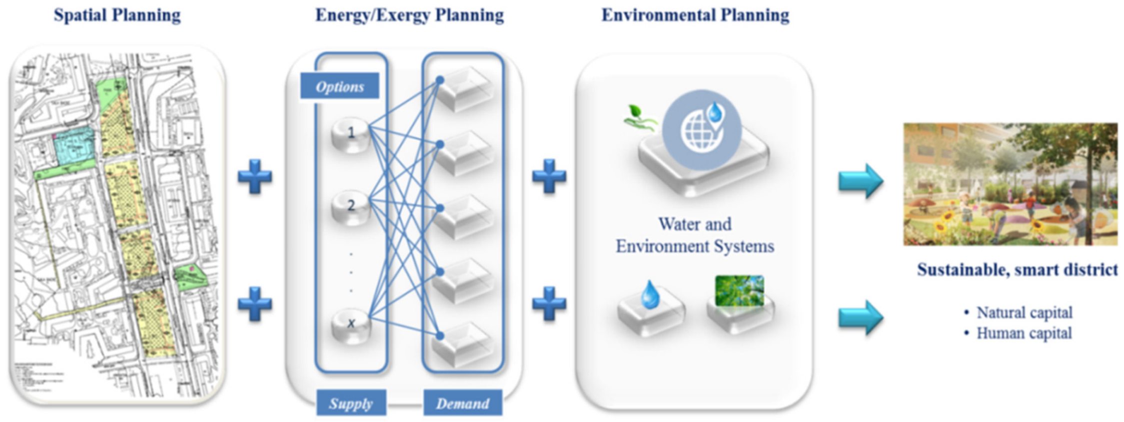


Figure 3. Integrated approach for multiple aspects of planning

At the same time, behavioural aspects and lifestyles readily impact resource spending and can undermine the ability to capture the complete savings that may be expected or given to be theoretically possible, e.g. the efficiency gap [43]. For this reason, further insight into such issues is vital in anticipating the changes that may need to take place in support of the planning processes. For example, in Uppsala, a partnership that involves the local energy provider was launched as the “One Tonne Life” project to monitor and analyse the resource spending of a household that is equipped with energy efficient technologies, a solar PV panel, and an electric vehicle [44]. The results are being integrated into future projections.

ANAYSIS OF THE PRESENT CASE (UPPSALA)

In the first aspect of the implementation of the method, the energy, water, and waste flows of the existing case of the city of Uppsala are analysed. The sections below provide these analyses alongside the results based on Sankey diagrams and per capita values.

Present energy system of Uppsala

The present energy system of Uppsala is based on a waste incineration plant, a CHP plant, and a heat pump facility that is located at the city’s wastewater works [45]. The waste incineration plant has an installed capacity of 10 MW_e of electricity and 181 MW_t of thermal energy, which includes 11 MW_t for cooling [45]. The waste incineration plant is able to intake about 52 tonnes of Municipal Solid Waste (MSW) per hour [45, 46].

The CHP plant that is based on peat and wood briquettes with a potential supply of 80 tonnes per hour has an installed capacity of 235 MW_t and 120 MW_e [45]. The briquettes are obtained from a plant in Sveg [47] in central Sweden at a distance of about 400 km from Uppsala. In contrast to wood, peat as a form of fossil fuel waste is not considered to be a form of biomass as a renewable energy resource. By the year 2020, the use of peat will be eliminated through a new CHP plant that will intake only local biomass [45]. Pollutants, including NO_x, are reduced based on processes for flue gas cleaning [45]. In the year 2014, 0.09 kg of NO_x was released per delivered MWh of district heating [45].

The heat pump facility that captures heat from the city's wastewater and directs the thermal energy to the district heating and/or cooling network has a capacity of 69 MW_t, including 24 MW_t of cooling [45]. Gas turbines and boilers are present in the local energy system as a backup for electricity generation and district heating, respectively. Unlike the city of Stockholm, Uppsala does not use seawater heat pumps to support the supply of thermal energy for district cooling due to its more inner land geography.

In the local energy system, the CHP plant is the main source of electricity generation. During the summer, the CHP is not operated and all of the electrical energy is purchased from the electrical grid. The main source of thermal energy generation is the waste incineration plant that operates on an annual basis, including for cooling in the summer.

In total, the district heating network of Uppsala is 460 km in length with a 14 km district cooling network and 7 km network for steam [45]. The CHP-based district heating network meets the heating needs of about 95% of the buildings in Uppsala [48]. A hot water accumulator is integrated into the system to facilitate fluctuations in district demand [45]. Average supply and return temperatures are about 368 K and 338 K respectively [32, 49].

Primary energy supply for local energy production. Figure 4 provides the realized primary energy supply for local energy production at Uppsala on a monthly basis in 2014. For Figure 4 only, these values exclude the purchase of electrical energy from the grid and fossil fuels for transport. Based on local convention, the energy supply for waste incineration is counted to be 60% biogenic as renewable energy and 40% as fossil fuel, which accounts for sources of plastic waste that is of fossil fuel origin [45]. This value is compliant with the excepted range of shares for heterogeneous mixture of wastes [50].

In Figure 4, fossil fuel also includes oil and coal that is used in the backup boilers that partly serve the district heating network [45]. Based on the monthly values, the total primary energy supply for local energy production is summed to be 1,841 GWh.

The greatest contribution comes from biogenic based waste at 726 GWh, which is followed by fossil fuels at 575 GWh. On a monthly basis, the highest and lowest primary energy spending is 249 GWh (January) and 50 GWh (July), respectively [45].

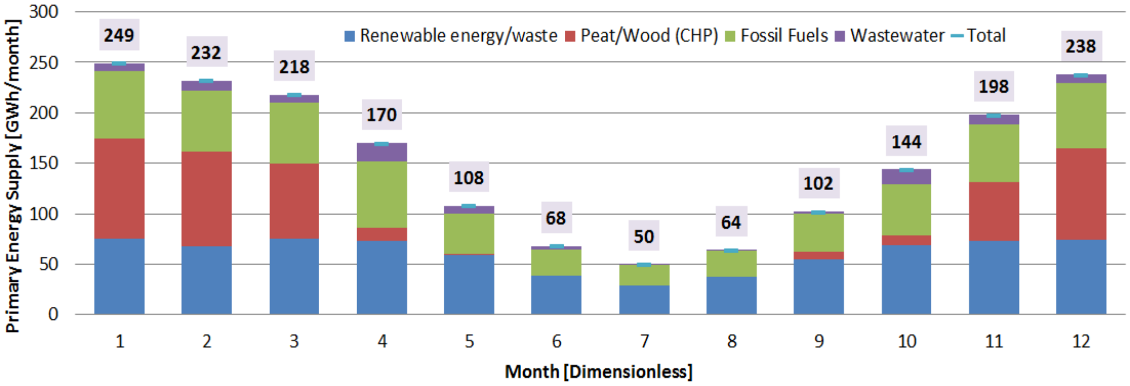


Figure 4. Primary energy supply for energy production in Uppsala [GWh/month]

Energy conversion and final energy end-use. In the local energy system of Uppsala, the average efficiency of energy conversion is given to be 93% while the efficiency of energy distribution is given to be 87% [45]. The overall energy efficiency from primary energy supply to final end use is thus about 81% [45]. For comparison to another Nordic city, the local energy system of Helsinki operates at an average primary energy efficiency of 93% [51]. The CHP plant operates yearlong with the use of absorption chillers in the summer months to utilize waste heat [51]. Yet similar to Uppsala, the city has heat pumps that capture heat from wastewater that is directed to the district energy network.

Based on the efficiency of local energy production in Uppsala, it is possible to produce about 1,719 GWh of energy in the stage of energy conversion from a primary energy supply of 1,841 GWh. Subsequently, 1,496 GWh was delivered to end-users in 2014. Of this amount, 62 GWh was used as electrical energy, 1,266 GWh was used as district heating, 40 GWh was used as district cooling, and 92 GWh was used as process steam [45]. In addition, 36 GWh of heat was supplied from boilers in island solutions.

Electrical grid and transport energy. The local production of electrical energy at 62 GWh provides 0.4 MWh of electrical energy per capita. Based on local statistics for Uppsala, 4.3 MWh of electrical energy is required per capita on an annual basis [52]. This indicates the need to purchase electrical energy from the grid to cover the load that is not covered by local energy production. Accordingly, 622 GWh must be purchased to satisfy the electrical energy load that is calculated to be 576 GWh. The distribution efficiency in Uppsala is 7.4% [48] that results in an energy loss of 46 GWh in the electrical grid.

Moreover, energy for transport must be integrated into the energy balance of Uppsala at 771 GWh. In the city of Uppsala, 5.2 MWh of transport fuel is required per capita per year directly as primary energy [53]. On average, biofuels have about a 12% share in the transport sector in Sweden [54]. In Uppsala and nearby cities, including Stockholm, bio-methane is produced in wastewater treatment plants from the anaerobic digestion of organic waste sludge and used as Liquefied Natural Gas (LPG) in private cars and city buses [55]. 679 GWh of the 771 GWh may thus be acquired from fossil fuels while 92 GWh may be acquired as bio-methane from the wastewater treatment plant of Uppsala.

Sankey diagram of the energy system. Figure 5 provides the Sankey diagram for the energy system of Uppsala. In Figure 5, the energy flows in the city are traced from energy sources and/or electrical energy purchase from the grid to the final end-use of energy. In total, 3,234 GWh of energy supply is required to satisfy the energy needs of Uppsala at 2,843 GWh, including energy for transport. The energy losses are calculated to be 391 GWh and indicate the amount of primary energy that is unavailable for final energy use.

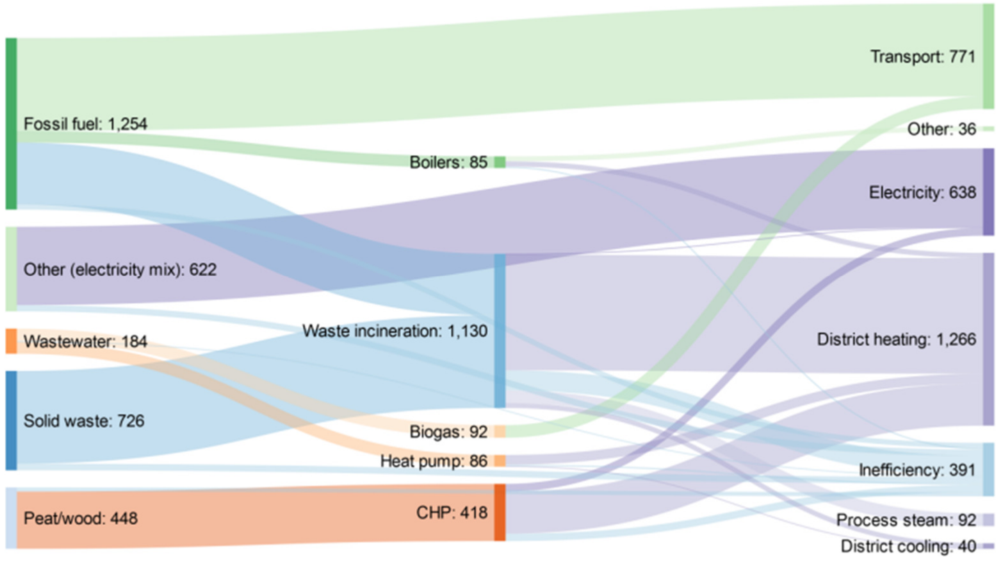


Figure 5. Sankey diagram for the energy system of Uppsala [GWh]

At the receiving end, district heating has the largest flow based on the magnitude of energy at 1,266 GWh that represents 45% of the total delivered energy in the city. Energy resources with relatively high levels of exergy, including fossil fuels, are used at the origin of this energy flow. Subsequently, however, the quality of the energy flows degrade in temperature levels from combustion towards end-use. As a result, the quality of this energy flow is not as high as those of electricity and transport. The flows from wastewater to heat pumps and biogas indicate aspects of the energy-water nexus.

Energy usage per capita. In 2014, total energy usage per capita was 19.2 MWh. This includes 9.7 MWh of thermal energy per capita at end-usage, including district heating, district cooling, steam, and other sources of heat, such as boilers. These values are lower than the reference values of Uppsala at 13.0 MWh of thermal energy and 22.5 MWh in total end-use energy per capita [53]. This result is partly due to the relatively warm winter that was recorded in 2014 [45, 56]. Recently, colder or warmer winters altered energy usage by up to 12% [57]. Based on daily average temperature records of Uppsala that is corrected for the urban effect [58], Uppsala had 4,529 Heating Degree Days (HDD) with base temperature of 18 °C in 2014. In contrast, there were 5,576 HDD in 2010.

If the total thermal energy usage is climate adjusted by a factor of 1.2, then the climate adjusted value of thermal energy usage at end-use will be about 11.6 MWh per capita. The remaining difference of 11% with the reference values may be attributed to energy saving measures in the building sector. At the same time, especially for comparison with districts that seek to near the net-zero target, it is vital to set the boundary at the stage of energy production and/or purchase of electrical energy from the grid, including the transmission efficiency, rather than end-use. Table 1 provides the respective values.

Table 1. Energy per capita values for the city of Uppsala [MWh/capita]

Energy flow/Measure	Energy per capita [MWh/capita]			
	Production/Purchase		End-usage	
Electricity	4.6	4.6	4.3	4.3
Thermal energy (Total) [a]	11.2	13.4	9.7	11.6
District Heating and Cooling (DHC)	10.9 [b]	13.1	9.5	11.4
Other (Individual boilers)	0.3	0.3	0.2	0.2
Transport	5.2	5.2	5.2	5.2
Total	21.0	23.2	19.2	21.1

[a] Under each item, the first is the 2014 value while the second is the climate adjusted value
[b] Sum of 2.4 from CHP, 0.6 from heat pumps, 7.6 from waste incineration, and 0.3 from boilers [MWh]

Present water system of Uppsala

In Uppsala, the waterworks produce 200 m^3 of water per capita of which 165 m^3 of water is consumed on the end-user side [56]. This indicates that 35 m^3 of water is wasted due to water leakages in pipelines, which is about the same as the share of water leakages in water production for Stockholm at 17% [55]. Based on the population of Uppsala, it is estimated that a total of 29,697 thousand m^3 of water was produced and 24,500 thousand m^3 of water was consumed at the end use in 2014. In addition, about 5,197 thousand m^3 of the water that was produced by the waterworks was wasted as pipeline leakages.

The water infrastructure of Uppsala includes about 620 km of drinking water pipelines and 1,080 km of pipelines for wastewater and stormwater [56]. The water quality of local water bodies is preserved by treating 100% of the used water in the wastewater treatment plant [56]. The local plant is effective in treating traces of most effluents in both stormwater runoff and incoming wastewater [59]. In 2014, the local lake received "excellent" water quality according to the EU Bathing Water Directive [60].

Overall, within the water cycle, Uppsala receives about 517 litres of rainfall per m^2 of land surface annually [36], which partly feeds the groundwater reservoirs and water bodies that are utilized by the waterworks to supply drinking water to citizens.

In addition, water is used in the energy system to enable local energy conversion processes. This aspect includes the use of water in cooling towers and circulating water in the district energy network. The energy provider of Uppsala indicates that 290 litres of water was used per delivered MWh of energy in the energy plants in 2014 [45], which is equivalent to 290 m^3 of water per delivered GWh of energy. This value results in about 434 thousand m^3 of water that is used in the local energy production in Uppsala and 614 thousand m^3 of water when the purchase of electrical energy from the grid is included. In this scope, the energy-water nexus results in at least 4.1 m^3 of water usage per capita.

Sankey diagram of the water system of Uppsala. The Sankey diagram of Figure 6 puts forth the water flows in Uppsala from the stages of water production to end use by sector. The water use profile of the nearby region indicates that households consume about 62% of the delivered water while businesses and the public sector consume about 10% and 20%, respectively [55]. At the same time, the share of water that is used internally in plants is given to be about 9% [55]. Accordingly, households may receive about 15,207 thousand m^3 of water. This is followed by business and the public sector at 2,323 m^3 and 4,858 m^3, respectively (see Figure 6). In an aspect of the energy-water nexus, water usage for energy processes at 614 thousand m^3 is 29% of the total internal water use. Figure 6 is thus useful to compare the flow of water resources for various purposes in Uppsala.

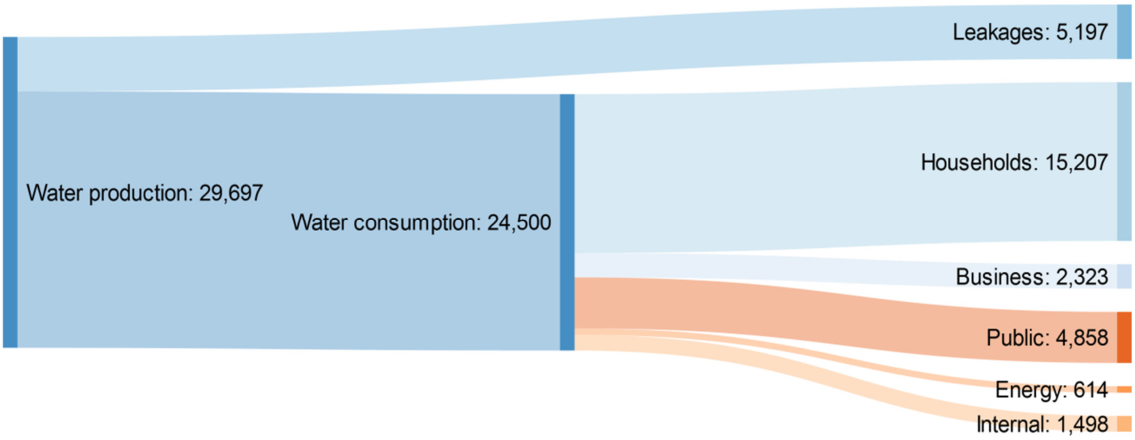


Figure 6. Sankey diagram for the water system of Uppsala [thousand m^3]

The water flows in the city, however, are not limited to those as represented in Figure 6. Used water is sent to the wastewater treatment plant, which partly becomes a source of energy based on heat pumps and biogas as indicated previously within Figure 5.

Present waste system of Uppsala

At the city level of Uppsala, 219 kg of solid waste, which includes plastics, glass, and organic waste, is produced per capita of which 85 kg is sent to the landfill [61]. This indicates that solid waste was produced in an amount of 32,519 tonnes of which 12,682 tonnes was sent to the landfill. As indicated in Figure 7 for the flows of waste in Uppsala, the remaining amount of 19,836 tonnes is split between waste incineration at 14,146 tonnes and material recycling at 5,691 tonnes. The shares of waste incineration and material recycling in total waste production are 44% and 18%, respectively [61].

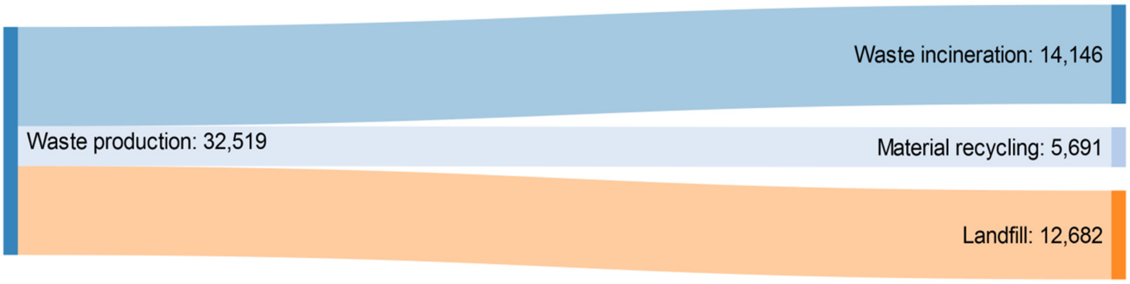


Figure 7. Sankey diagram for the waste system of Uppsala [tonnes]

Beyond the flows that are depicted in Figure 7, sludge from the wastewater treatment plant and residue from the heating plant is directed to the waste plant of Uppsala at Hovgårdens [45]. Alongside combustible waste, these flows become a source of energy supply. Here, it is estimated that 17 kg of solid waste or 9 kg of sludge can produce 1 MWh [45]. Based on the data in Figure 7 for waste and Figure 5 for energy, the amount of energy that is converted from 14,146 tonnes of waste was 1,130 GWh. Hence, an average of 12.5 kg of waste produced 1 MWh in the waste-to-energy scheme of Uppsala.

ANALYSIS OF FUTURE CASES (ÖSTRA SALA BACKE)

Based on the ambition of Östra Sala backe to be Uppsala's most climate friendly district [36], the planned district must provide improvements over the benchmark of the present status of the city of Uppsala. As of 2016, phase one of the district is under construction and the planning of phase two is under consultation [62]. At the same time, due to the magnitude of scale between the city of Uppsala and the phases of Östra Sala backe, the two scales must be compared on a common basis irrespective of the difference in population. As indicated in the method, the common basis is satisfied based on per capita indicators for energy, water, waste, and CO_2 emissions, as well as the quality of energy as exergy. The sections below provide comparisons between the two scales.

Once completed, Östra Sala backe is planned to be a district with mixed residential, commercial, and municipal functions that will host about 20,000 people by the year 2030 [63]. For this reason, each of the four phases can be taken to host about 5,000 additional people to reside, work, and/or study in the district. The set of planned smart energy measures include biomass-based CHP with District Heating and Cooling (DHC), District Heating Driven White Goods (DHDWG), smart home automation and systems including sensors, efficient lighting and electric appliances with energy labels of A+++ where possible, large scale Ground-source Heat Pumps (GSHP) that are driven based on renewable energy, and bioelectricity driven public transport [32]. The average return temperature in the district heating network will be about 325 K based on a 4GDH network [32].

The spectrum of these measures represents an energy systems perspective that recognizes the need to consider the entire energy supply chain prior to and including the stage of meeting energy services in the district. Measures such as DHDWG decrease the electricity load since the thermal energy that is circulating in the district loop will be extracted by heat exchangers to heat the process water in white goods. Other measures that decrease the electricity load are smart home automation, efficient lighting, and A+++ labelled appliances as defined in Directive 2010/30/EU [64]. The district minimizes the need for electricity while finding some of the most efficient means of its usage. This includes public transport that has a lower energy usage per passenger kilometre than other forms of transport. Grid electricity is included only to support the loads as needed. These measures were determined based on a NZEXD option index in the previous stages of the study, including variables for the payback period and level of penetration [32].

In the aspect of spatial planning, Östra Sala backe emphasizes the proximity of residential, educational and cultural zones, as well as businesses for compact urban form [65, 66]. The zoning of the district, especially phase one, is completed based on these principles. In addition, land will be allocated to businesses based on criteria that are used to evaluate sustainability practices [65]. Once completed, apartments will pay a fixed monthly cost of car pool to reduce the demand for individual car travel and parking [65].

Proposal for the energy system of Phase 1

The NZEXD status for the first phase of the pilot district was calculated by the author in [32]. Reference values of energy usage per capita in Uppsala were used as the basis of the planning. Table 2 summarizes the results of phase one based on the total energy and exergy values for each of the eight measures that have been proposed. For ease of referral with eq. (1), Table 2 sorts the inputs by the demand and supply sides.

In Table 2, the measures on the demand side amount to 113 GWh of energy and 54.3 GWh of exergy. The same amount of energy is satisfied by the measures on the supply side while the energy value of the grid electricity at 4.6 GWh is not included in the column for ε_{on} since it is not part of the exergy that is produced on-site. Accordingly, only 108.4 GWh of energy and 49.7 GWh of exergy are produced locally in phase one. Based on eq. (1), the NZEXD status is 4.6 GWh, which indicates a nearly NZEXD status since the value is close to the target value of being less than or equal to zero.

Table 2. Net-zero exergy district analysis of the proposed phase one [32], [GWh]

	Proposed measure	Demand side [GWh]		Supply side [GWh]	
		Total P_i [a, b]	AEXC [c]	Total P_i [b]	ε_{on} [c]
Demand side	District Heating and Cooling (DHC)	60.3	7.5	-	-
	District Heating Driven White Goods (DHDWG)	6.7	0.8	-	-
	Smart home automation and systems	0.5	0.5	-	-
	Efficient lighting (Buildings and industry)	9.2	9.2	-	-
	A+++ electric appliances	13.3	13.3	-	-
	Bioelectricity driven transport	23.0	23.0	-	-
Supply side	Biomass-based CHP (Electricity component)	-	-	36.8	36.8
	Biomass-based CHP (Thermal component)	-	-	53.2	7.5
	Renewable power coupled GSHP [d]	-	-	18.4	5.4
	Grid electricity	-	-	4.6	0.0
	Total	113.0	54.3	113.0	49.7
	NZEXD status [eq. (1)]	4.6 (Nearly NZEXD status)			

[a] Includes embedded inefficiencies prior to end-usage at the stage of energy production or purchase
[b] The total values in this column is for $P_{i(e)}$ and/or $P_{i(t)}$ in eq. (2) or (3)
[c] The Carnot Factors are $CF = 0.14$ for the thermal component of the CHP and 0.06 for ground source heat
[d] Takes a Coefficient of Performance (COP) of 3 based on the renewable power

In the GSHP option, COP is taken to be 3 based on a renewable power input at 4.6 GWh that provides a thermal output of 13.8 GWh. Such an output provides a 21% share in the thermal energy in the DHC loop that is mainly based on the output of the CHP. Based on eq. (4), values of CF_{t} that result in the differences between energy and exergy values are 0.14 for the CHP and 0.06 for the GSHP [32].

Proposal for the energy system of Phase 2

The proposal for phase one provided a foundation to scale-up the best practices into the second phase of the project and further improve the proximity to the NZEXD target. In this respect, the gap of 4.6 GWh in phase one was initially reduced to 3.5 GWh in the proposal for phase two and further reduced to 1.8 GWh as the result of a stepwise approach with four steps that was developed in [33]. The stepwise approach exemplified the process of exergy transition planning for districts that aimed to near the NZEXD target phase by phase.

Table 3 provides the proposal for phase two based on the results of the process of exergy transition planning. According to the results, 88.4 GWh of energy is required to be supplied for phase two on an energy basis. On an exergy basis, 42 GWh of AEXC is consumed in the district and 40.2 GWh of ε_{on} is produced in the district. The biomass-based CHP provides the most significant contribution to the supply side of the local energy system.

Table 3. Net-zero exergy district analysis of the proposed phase two [33], [GWh]

	Proposed measure	Demand side [GWh]		Supply side [GWh]	
		Total P_i [a]	AEXC	Total P_i	ε_{on}
Demand side	District Heating and Cooling (DHC)	46.7	5.8	-	-
	District Heating Driven White Goods (DHDWG)	6.1	0.7	-	-
	Smart home automation and systems	0.4	0.4	-	-
	Efficient lighting (Buildings and industry)	7.1	7.1	-	-
	A+++ electric appliances	10.3	10.3	-	-
	Bioelectricity driven transport	17.7	17.7	-	-
Supply side	Biomass-based CHP (Electricity component)	-	-	30.1	30.1
	Biomass-based CHP (Thermal component)	-	-	42.1	5.9
	Renewable power coupled GSHP [b]	-	-	14.3	4.2
	Grid electricity	-	-	1.9	0.0
	Total	88.4	42.0	88.4	40.2
	NZEXD status [eq. (1)]	1.8 (Nearly NZEXD status)			

[a] Includes embedded inefficiencies prior to end-usage at the stage of energy production or purchase

[b] 3.6 GWh is electrical energy that is used to produce 10.7 GWh of thermal energy (COP = 3 as in Table 2)

Comparison of Phases 1 and 2 per measure

Table 4 provides the per capita values of the total magnitudes of energy and exergy in Tables 2 and 3 for the phases of the project based on the demand side of the measures. The *CF* values are also given based on the quality of energy that is used in each measure. The use of the DHDWG option lowers the return temperature in the district heating loop.

Table 4. Per capita values of energy and exergy per measure and *CF* values

Proposed measure	Energy per capita [MWh/capita]		Exergy per capita [MWh/capita]		*CF* [a]
	Phase 1	Phase 2	Phase 1	Phase 2	
District Heating and Cooling (DHC)	12.1	9.3	1.5	1.2	0.12 [b]
District Heating Driven White Goods (DHDWG)	1.3	1.2	0.2	0.2	0.12 [b]
Smart home automation and systems	0.1	0.08	0.1	0.08	1.0
Efficient lighting in buildings	1.8	1.4	1.8	1.4	1.0
A+++ electric appliances	2.7	2.1	2.7	2.1	1.0
Bioelectricity driven transport	4.6	3.5	4.6	3.5	1.0

[a] Represents *CF* based on eq. (4) for thermal energy. The *CF* of electricity is 1 [Dimensionless]

[b] The *CF* of thermal energy is based on shares of 0.14 for CHP and 0.06 for GSHP

According to Table 4, there is a decrease in energy and exergy usage per capita in the proposed measures of DHC and DHDWG between phases one and two. In particular, in the first phase, the total value for both of these measures was 13.4 MWh of energy and 1.7 MWh of exergy per capita. In contrast, the extension of the same measures into phase two is based on 10.5 MWh of energy and 1.4 MWh of exergy per capita.

Comparison of Östra Sala backe and Uppsala

The indicator set for assessing urban metabolism in the context of the NZEXD target was applied to phases one and two of the district of Östra Sala backe. The per capita values of these indicators were compared to those of Uppsala based on eq. (8) using inputs from eqs. (5-7) for energy, water, waste and CO_2 emissions as needed. The results of the urban metabolism indicator set as put forth and analysed herein are presented in Tables 5-10, including respective comparisons. In particular, the results are provided in Table 5 for energy per capita, Tables 6-7 for exergy per capita, Table 8 for water per capita, Table 9 for waste per capita, and Table 10 for CO_2 emissions per capita.

Comparison of urban metabolism indicators for energy. Table 5 provides the values of the urban metabolism indicators for the category of energy for Östra Sala backe. Based on the shifting of energy flows between sectors, some flows are not directly comparable with Uppsala. As one example, the use of district heating rather than electricity for white goods has had an effect on increasing thermal energy usage per capita. In addition, the use of smart home automation may also be integrated with the off-peak charging of any private electric vehicles in homes, which will increase electrical energy per capita at the domestic level. In contrast, incentives for the reduced use of individual car travel and the spatial planning of the city is expected to lower energy use for transport.

Table 5. Comparison of urban metabolism indicators for energy [MWh/capita]

Energy per capita	Östra Sala backe [MWh/capita]			
	Phase 1	ΔM [a]	Phase 2	ΔM [a]
Electrical energy per capita	4.6	0.0	3.6	1.0
Thermal energy per capita	13.4 / 12.1 [b]	0.0 / 1.3 [b]	10.6	2.8
Transport energy per capita	4.6	0.6	3.5	1.7
Total energy per capita	22.6	0.6	17.7	5.5

[a] For thermal energy per capita, climate adjusted value is taken from Table 1 at the same boundary
[b] The second value is based on the comparison of the DHC component without DHDWG only

Table 5 includes the comparison of phase one of Östra Sala backe and Uppsala based on eq. (8) in which all four indicators for energy have improved or similar values. Total energy reduces by 0.6 MWh per capita in comparison to the climate adjusted value of Uppsala at the same production boundary. Electrical energy per capita in Östra Sala backe is the same as the respective value in Uppsala. Due to energy savings in buildings, thermal energy per capita remains the same despite the addition of the load for DHDWG. When compared to the heating of buildings in the DHC network only, an improvement of 1.3 MWh per capita is evident. Transport energy reduces by 0.6 GWh per capita.

In phase two, all four variables have improvements over the respective values of Uppsala as indicated within Table 5. Total energy per capita is 17.7 MWh in phase two that represents a 5.5 MWh reduction based on more stringent energy saving measures. The most significant contribution to this energy savings comes from reductions in thermal energy at 2.8 MWh per capita, which represents a 21% reduction over the value of 13.4 MWh per capita in Uppsala. Reductions in phase two based on electrical energy and transport energy per capita are 1.0 MWh and 1.7 MWh, respectively.

Comparison of urban metabolism indicators for exergy. For a basis of comparison, the values of the exergy indicators for Uppsala are first calculated based on the values of *CF* in Table 6. The existing DHC network of Uppsala is not at the level of the network that is proposed for Östra Sala backe. As a result, the value of *CF* for the waste heat of the CHP is 0.17 for Uppsala rather than 0.14 for Östra Sala backe. In contrast, the energy resources that supply the DHC network contain components other than the waste heat of the CHP. The weighted average of *CF* as indicated in Table 6 is thus used. Accordingly, the corresponding thermal energy is calculated to be 5.5 MWh per capita in Uppsala. The exergy value for the transport energy is based on the shares of biogas and fossil fuels. Based on the components in Table 6, 14.6 MWh of exergy was consumed per capita.

Table 6. Calculation of exergy per capita and *CF* values for Uppsala

Components of energy	Uppsala		
	Energy per capita [MWh/capita]	Exergy per capita [MWh/capita]	*CF* [Dimensionless]
Electrical energy	4.6	4.6	1.0
Thermal energy	13.4	5.5	0.41 [a]
Transport energy	5.2	4.5	0.87 [b]
Total per capita values or *CF*	23.2	14.6	0.62 [c]

[a] Includes 0.86 for boilers and/or equivalents, 0.24 for waste based DHC, 0.04 for wastewater heat pumps

[b] *CF* is 0.88 for gasoline based on an adiabatic temperature at about 2,138 K [67] and 0.76 for biogas [68]

[c] The average value is based on the quotient of 14.6 MWh of exergy and 23.2 MWh of energy in Table 6

Table 7 compares the exergy values of Uppsala with the exergy values of the phases of Östra Sala backe. For Östra Sala backe, the exergy per capita values of the energy components are aggregated from Table 4. In total, both phases one and two of the district have lower exergy spending per capita than Uppsala at 10.9 MWh and 8.5 MWh per capita. Based on eq. (8), the difference in the values of Uppsala and the phases of Östra Sala backe represent 3.7 MWh and 6.1 MWh of exergy per capita, respectively.

Table 7. Comparison of urban metabolism indicators for exergy [MWh/capita]

Exergy per capita values	Östra Sala backe [MWh/capita]			
	Phase 1	ΔM	Phase 2	ΔM
Electrical energy	4.6	0	3.6	1.0
Thermal energy	1.7	3.8	1.4	4.1
Transport energy	4.6	–0.1	3.5	1.0
Total exergy per capita	10.9	3.7	8.5	6.1

As indicated in Table 7, the greatest contributor to reducing exergy per capita in the phases of Östra Sala backe is the thermal energy component. This result is partly due to the elimination of the direct combustion of energy resources to satisfy the low exergy demands of space heating and cooling in the district through a CHP based DHC network. It is also the result of the inclusion of a fourth generation DHC network that represents a lower exergy energy infrastructure. The reduction of exergy per capita based on thermal energy values was 3.8 MWh and 4.1 MWh per capita in phases one and two, respectively.

The use of biogas from the wastewater treatment plant in transport that constituted a 12% share of the total energy usage for transport may have been considered as one of the best practices of Uppsala. In Östra Sala backe, however, renewable energy resources are not used for direct combustion in the transport sector as discussed in [32]. Instead, renewable energy resources are directed to the CHP plant to produce both heat and power. As a result, as proposed in [33], the transport sector is thereby expected to be highly electrified in the new district. Although the amount of energy spending in the transport sector is lower than in Uppsala as indicated in Table 5, the use of a *CF* value at 1.0 for electrical energy indicates that the transport sector is using more high quality energy. As a result, ΔM has an exergy value of –0.1 MWh per capita in Table 7 based on eq. (8).

Comparison of urban metabolism indicators for water. In addition to proposals for the NZEXD target, Östra Sala backe is currently committed to pursuing a high standard for environmental management. For example, the district has planned to increase permeable surface layer materials to enhance rainwater infiltration [69]. Green spaces are distributed throughout the district and between buildings for water management and biodiversity. Vegetation will be selected based on water requirements and biological values [69]. The amount of water savings for these and other related measures are unknown. As a result, proposals for the first two phases of Östra Sala backe are based on normative targets to improve the values of Uppsala in the near future. The percentage values of possible improvements are provided within Table 8. Here, water leakages have higher targets. The new sum of water produced per capita is calculated based on the sum in eq. (6).

Table 8. Comparison of urban metabolism indicators for water

Water per capita	Östra Sala backe [m^3/capita]					
	V [a]	Phase 1	ΔM [b]	V [a]	Phase 2	ΔM [b]
Water produced per capita	0.12	176	24	0.22	157	44
Water consumed per capita	0.10	148	17	0.20	132	33
Water leakages per capita	0.20	28	7	0.30	25	11

[a] Represents normative targets that are set for improvements in the water indicators [dimensionless]

[b] Values for Uppsala are 200 m^3, 165 m^3, and 35 m^3 per capita in the order of indicators in Table 8

According to the normative targets in Table 8, phase one can reduce water produced per capita to 176 m^3 while phase two may further obtain a value of 157 m^3 per capita. In comparison to the values of Uppsala based on eq. (9) for ΔM, there are savings of 24 m^3 and 44 m^3 in water produced per capita in phases one and two, respectively. These values may guide the design of water saving measures to meet or exceed the targets.

Comparison of urban metabolism indicators for waste. In the aspect of waste, Östra Sala backe is on track for attaining materials based on principles of green procurement. Various incentives to repair and reuse waste within the community are also planned [66]. As a whole, these initiatives are designed to maximize the separation and recycling of waste [69]. As normative targets, such initiatives may involve improvements in the waste per capita values of Uppsala as indicated within Table 9. Due to the nature of indicators, the value V is subtracted in eq. (9) to reduce waste produced per capita while it is added in the case of waste reused per capita. Relatively small percentage changes in these indicators have a leveraging effect on reducing the flows of waste to landfill. Targets V are set for the first two indicators. The third indicator is found from eq. (7).

Based on Table 9, the first phase of Östra Sala backe may produce 11 kg of less waste per capita. Such a value may further increase to reductions of 22 kg of waste per capita in phase two. In addition, while the waste to landfill ratio was 39% in Uppsala, it may reduce to 32% in phase one and 25% in phase two, respectively.

Table 9. Comparison of urban metabolism indicators for waste

Waste per capita	Östra Sala backe [kg/capita]					
	V [a]	Phase 1	ΔM [b]	V [a]	Phase 2	ΔM [b]
Waste produced per capita	0.05	208	11	0.10	197	22
Waste reused per capita	0.05	141	−7	0.10	147	−13
Waste to landfill per capita	0.21	67	18	0.42	50	35

[a] Represents normative targets that are set for improvements in the water indicators [dimensionless]

[b] Uppsala values are 219 kg, 134 kg, and 85 kg per capita in the order of indicators in Table 9

Comparison of urban metabolism indicators for CO_2 emissions. The scope of CO_2 emissions are taken to include the CO_2 emissions of the energy sector, which further includes municipal solid waste due to the energy infrastructure of the city of Uppsala, and the CO_2 equivalent of CH_4 emissions from domestic wastewater. The energy provider of Uppsala indicates that 223 kg of CO_2 is emitted per MWh_t of delivered district heating [45]. In Sweden, the standard emission factor for consumed electricity is 23 kg of CO_2 per MWh_e [70]. For transport, 249 kg of CO_2 is emitted per MWh of gasoline [70]. Based on IPCC guidelines, biogas is given to emit 197 kg of CO_2 per MWh while biomass based on wood waste is given to emit 403 kg of CO_2 per MWh [71]. In contrast, both sources may be taken to have zero CO_2 emissions if sustainability criteria are met [70]. For CH_4 emissions from wastewater, it is estimated that about 16 kg CH_4 is emitted from domestic wastewater per capita in Sweden [72], which results in 411 kg of CO_{2e} per capita when converted based on global warming potential [73]. Based on these inputs, Table 10 compares the values of Uppsala and Östra Sala backe based on tonnes of CO_2 emissions.

Table 10. Comparison of urban metabolism indicators for CO_2 emissions

Main components of CO_2 emissions	CO_2 emissions per capita [tonnes CO_2/capita] [a]				
	Uppsala	Östra Sala backe			
		Phase 1	ΔM	Phase 2	ΔM
Energy related CO_2	4.2 [b]	0.02	4.0	0.01	4.1
Electrical energy	0.1	0.02 [c]	0.08	0.01 [c]	0.08
Thermal energy	3.0	0.0	3.0	0.0	3.0
Transport energy	1.1 [d]	0.0	1.1	0.0	1.1
Wastewater related CO_{2e}	0.4	0.4	0.0	0.4	0.0
CO_2 emissions per capita	4.6	0.4	4.2	0.4	4.2

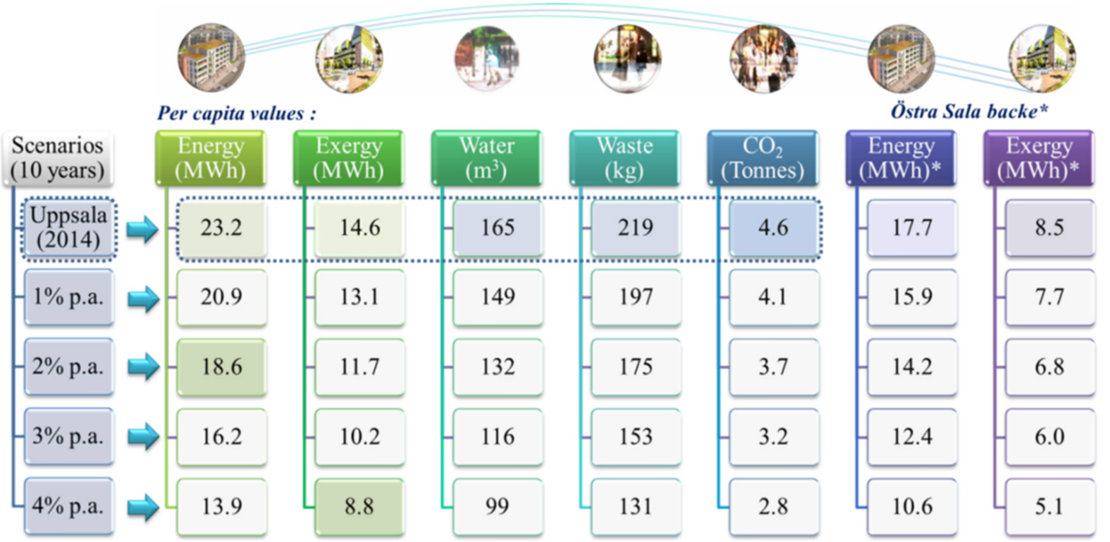
[a] Values are based on the product of CO_2 emission factors and the energy values in Tables 1 and 5
[b] The calculated value is validated by the reported total energy related CO_2 emissions in Uppsala [53]
[c] CO_2 emissions of grid electrical energy grid at 0.9 MWh/capita (Phase 1) and 0.4 MWh/capita (Phase 2)
[d] Considers 12% of transport energy as zero emissions based on the use of biogas in Uppsala

Based on Table 10, Uppsala is found to have a value of 4.6 tonnes of CO_2 emissions per capita of which 4.2 tonnes is based on energy related CO_2 emissions and 0.4 tonnes is based on wastewater related CO_2 emission equivalents. Considering that Östra Sala backe obtains sources of biomass that meet sustainability criteria as further envisioned in the long-term plans of the local energy provider [45], energy related CO_2 emissions will be confined to grid sourced electrical energy. For this reason, the main component of local CO_2 emissions in Östra Sala backe will be from wastewater related emissions.

Discussion on city and district level comparisons

The comparison of the city of Uppsala and the district of Östra Sala backe based on selected urban metabolism indicators in the contextual framework of the NZEXD target provides an original approach in the literature. These indicators have covered aspects of energy, water, waste, and CO_2 emissions as well as exergy. As a whole, this process has enabled the process of benchmarking proposals for the first two phases of the district to the city in which it will be established. As a district that aims to be a pioneering example of greater urban sustainability, the district shall provide improvements over the existing status of the city. Based on Östra Sala backe, the city of Uppsala will be establishing a living laboratory to test more sustainable production and consumption systems.

Future oriented 10 year scenarios for Uppsala. Figure 8 summarizes the use of the benchmarked data for a two way comparison between Uppsala and Östra Sala backe. Figure 8 includes per capita values for energy and exergy usage, water consumption, waste generation, and energy and wastewater related CO_2 emissions. The first numerical row provides the present values of the per capita indicators for Uppsala. For comparison, the last two columns provide best practice values from the phase two proposal for Östra Sala backe for energy and exergy. The subsequent rows are based on alterations in these values in a 10 year timeframe. Accordingly, four scenarios are represented in Figure 8 such that there is a 1%, 2%, 3% or 4% improvement in the values of the indicators each year as the value of V in eq. (9) for 10 years. As a result, these scenarios represent improvements of 10%, 20%, 30%, and 40% from present values at the end of 10 years.



	Per capita values :					Östra Sala backe*	
Scenarios (10 years)	Energy (MWh)	Exergy (MWh)	Water (m^3)	Waste (kg)	CO_2 (Tonnes)	Energy (MWh)*	Exergy (MWh)*
Uppsala (2014)	23.2	14.6	165	219	4.6	17.7	8.5
1% p.a.	20.9	13.1	149	197	4.1	15.9	7.7
2% p.a.	18.6	11.7	132	175	3.7	14.2	6.8
3% p.a.	16.2	10.2	116	153	3.2	12.4	6.0
4% p.a.	13.9	8.8	99	131	2.8	10.6	5.1

* Phase 2 best practice values

Figure 8. Scenarios for the NZEXD urban metabolism indicators

Already, the best practice values from the phase two proposal for Östra Sala backe exceeds one of these scenarios based on annual improvements in the present values of Uppsala. For example, the energy usage per capita at 17.7 MWh in phrase two exceeds the corresponding value in the 2% per annum scenario in which Uppsala would improve energy usage per capita to 18.6 MWh (see shaded area in Figure 8). In contrast, exergy consumption per capita at 8.5 MWh in phase two exceeds the respective value in the more ambitious 4% per annum scenario based on a reduction of 42%. In this scenario, Uppsala would attain exergy consumption per capita at 8.8 MWh.

From the perspective of these scenarios, Östra Sala backe may be considered to be about 10 years ahead of Uppsala given the specified rates of improvement on an annual basis. The strategy of Östra Sala backe in limiting the use of high exergy energy resources in the process of nearing the NZEXD target also represents the leap that is made under the exergy per capita indicator. The energy system configuration involves a greater share of lower exergy resources. At the same time, annual improvements in the indicators are also possible for Östra Sala backe. For this reason, both Uppsala and Östra Sala backe may record further improvements.

Based on the values in Tables 5-10, the envisioned reductions in water consumption and waste generation for Östra Sala backe would enable a performance that meets or exceeds either the 10% or 20% improvements in the 10 years scenario for Uppsala. In the aspect of water consumption, the targeted values at 148 m^3 and 132 m^3 per capita for phases one and two are better than or equal to the 10% and 20% scenarios, respectively. In the aspect of waste generation, only the targeted value for phase two at 197 kg per capita exceeds the 10% scenario for Uppsala. In contrast, based on the values in Table 10, Östra Sala backe exceeds the values of all scenarios in CO_2 emission per capita.

Figure 9 puts forth the vision for Östra Sala backe in which the district is able to have savings in aspects of energy, exergy, water, waste, and CO_2 emissions when compared to its surrounding urban environment. The left inset provides images from Östra Sala backe [62] with foreseen low energy consuming building designs. The improvement of energy and exergy savings to meet or near the NZEXD is taken to be a key aspect of improving urban metabolism. These savings may be realized based on better exergy matches in the energy system for high and low exergy requiring energy demands, a more efficient water system network, a better waste management system, and increased renewable energy penetration.

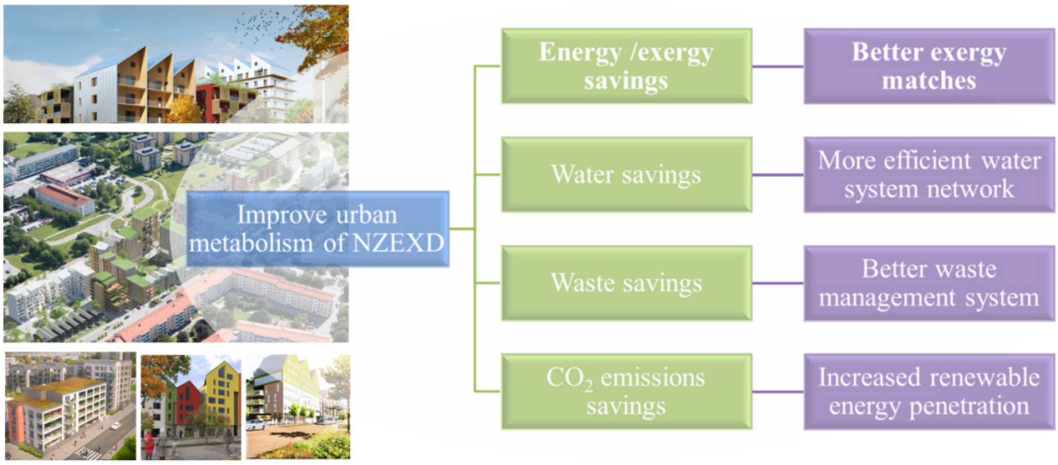


Figure 9. Improving the urban metabolism of NZEXD

CONCLUSIONS

The planning of urban settlements requires a targeted approach to improve aspects of more sustainable energy, water and environment systems. This research work has analysed these aspects at the embedded levels of the city of Uppsala and the district of Östra Sala backe, which is currently being established within the city. The comparison of the proposed phases one and two of the Östra Sala backe project has indicated that the district is on track to obtain various levels of savings over the performance of Uppsala. In particular, existing proposals for the district can achieve savings in per capita values at 5.5 MWh of energy usage and 6.1 MWh of exergy consumption based on the best practice values of phase two. In addition, 33 m^3 of water consumption, 22 kg of waste generation, and 4.2 tonnes of CO_2 emissions are the calculated savings per capita for the other indicators. These five values represent savings of 24%, 42%, 20%, 10%, and 91% when compared to the corresponding present values of Uppsala. Exergy consumption and CO_2 emissions per capita mark the greatest savings. The choice of energy resources with lower exergy values and the switch to renewable energy resources in the process of nearing the NZEXD target have led to these results.

This research work contributes to the literature based on the placement of the NZEXD target in the contextual framework of urban metabolism indicators, including the use of a new indicator as exergy per capita. As a whole, the five indicators can enable an integrated approach to plan for more sustainable urban settlements. These indicators synthesize the analysis of the NZEXD target with indicators that extend beyond energy into water, waste, and CO_2 emissions. The integrated approach can support the basis to combine spatial planning, energy and exergy planning as well as environmental planning in districts that may seek to reach the NZEXD target in the future. Regions that may have less locally available endowments of renewable energy than others may further benefit from any excess process heat from the nearby industry, if any. In the future aspects of the research work, the urban metabolism indicators can also be associated with any cost savings based on energy and water prices as well as the social cost of CO_2 emissions.

The research work further indicates that districts with proposals for net-zero exergy targets may be model cities for the sustainable development of energy systems. In particular, smarter energy systems in these districts can apply the guiding principle of matching diverse demand and supply profiles based on exergy. Districts can further seek to optimize the resource flows for water usage, waste generation, and CO_2 emissions. The scenarios as considered in this research work indicate that Östra Sala backe may be a model district for the NZEXD target as well as the improvement of urban metabolism. The transition from a site that was characterized by power lines to a more sustainable district with increased local energy solutions can inspire other examples in the future.

NOMENCLATURE

AEXC	annual exergy consumption	[GWh]
CF	carnot factor (dimensionless)	[-]
E	energy [eq. (5)]	[MWh] or [GWh]
G	water [eq. (6)]	[m^3]
M	specific per capita indicator [eqs. (8-9)]	[-]
NZEXD	net-zero exergy district target [eq. (1)]	[GWh]
P	energy production	[GWh]
T	temperature	[K]
V	percentage improvement [eq. (9)] (dimensionless)	[-]
W	waste [eq. (7)]	[tonnes]

Greek letters

ε	exergy	[GWh]
η	efficiency (dimensionless)	[-]

Subscripts

c	energy conversion
D	delivered energy
d	energy distribution
E	water for energy conversion
e	electrical energy
ex	exergy
I	internal uses of water
i	energy units
k	time increments
L	water leakages
m	total time increments
N	landfilled waste
O	delivered water
on	produced on-site
Ös	Östra Sala backe (District)
P	water or waste produced
R	waste reused
ref	reference temperature
S	energy sources
t	thermal energy
tr	energy transmission
Up	Uppsala (City)

x	total energy units

Abbreviations

4GDH	Fourth Generation District Heating
NZEXD	Net-Zero Exergy District

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