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# Energy system analysis of a pilot net-zero exergy district

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ABSTRACT

The Rational Exergy Management Model (REMM) provides an analytical model to curb primary energy spending and $CO_2$ emissions by means of considering the level of match between the grade/quality of energy resources (exergy) on the supply and demand sides. This model is useful for developing forward-looking concepts with an energy systems perspective. One concept is net-zero exergy districts, which produce as much energy at the same grade or quality as consumed on an annual basis. This paper analyzes the district of Östra Sala backe in Uppsala Municipality in Sweden as a pilot, near net-zero exergy district. The district is planned to host 20,000 people at the end of four phases. The measures that are considered include an extension of the combined heat and power based district heating and cooling network, heat pumps driven on renewable energy, district heating driven white goods, smart home automation, efficient lighting, and bioelectricity driven public transport. A REMM Analysis Tool for net-zero exergy districts is developed and used to analyze 5 scenarios based on a Net-Zero Exergy District Option Index. According to the results, a pilot concept for the first phase of the project is proposed. This integrates a mix of 8 measures considering an annual electricity load of 46.0 GW $h_e$ and annual thermal load of 67.0 GW $h_t$. The exergy that is produced on-site with renewable energy sources is 49.7 GW h and the annual exergy consumed is 54.3 GW h. The average value of the level of match between the demand and supply of exergy is 0.84. The paper concludes with advice for a more efficient usage of energy resources in the energy systems of net-zero exergy districts of the future.

## 1. Introduction

The redesign of future energy systems must better integrate renewable energy sources and reduce primary energy spending while substantially lowering $CO_2$ emissions. This requires more innovative changes in the energy system, possibly with districts being the agents of change. Studies in the literature focus on research questions related to the design of district heating networks, the maximum integration of renewable energy sources, and the role of energy efficient and/or energy producing buildings within these systems. For the purposes of this paper, this literature is grouped into four headings, which define stages of an energy supply chain leading to the delivery of more sustainable energy services, namely production and conversion, distribution networks, energy storage, and end-usage. The main highlights of the literature under these headings are given below while Fig. 1 presents an overview.

### *1.1. Production and conversion on the supply side*

On the supply side, Münster et al. compare district heating grid expansion to individual heating and determine that district heating networks should cover about two thirds of heat consumption in Denmark [1]. Lund et al. find a similar share while proposing that there should be a gradual expansion of district heating over individual heat pumps [2]. Finney et al. focus on the expansion of the district heating network for the UK city of Sheffield while considering options for future heat sources [3]. Østergaard et al. propose a 100% renewable energy system for the Danish city of Frederikshavn by integrating low-temperature geothermal energy for district heating with other supply side technologies, such as off-shore wind power, large-scale solar collectors, and local waste incineration [4]. It is seen that primary energy consumption can be sustainably reduced based on changes in the production system even before savings in end-usage [4]. For the Swedish city of Linköping, Wetterlund et al. analyze two options for district heating based on biomass gasification, including the co-production of synthetic natural gas [5]. Chow et al. analyze a district cooling system for a new urban development in Hong Kong based on direct seawater cooling [6]. Haiwen et al. compare an electricity-driven

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## Nomenclature

| | |
|---|---|
| $AEXC$ | annual exergy consumption of the district in Eqs. (5) and (6), GW h |
| $CF$ | Carnot factor based on a reference environment temperature, dimensionless |
| $c$ | net calorific $CO_2$ content of on-site ($i$) or energy mix ($j$) resources, kg $CO_2$/kWh |
| $M$ | set of measures for the process of scenario construction, dimensionless |
| $max$ | maximum value of an indicator considering all measures in a scenario |
| $min$ | minimum value of an indicator considering all measures in a scenario |
| $N$ | set of penetration levels for the process of scenario construction, dimensionless |
| $P$ | energy load, may be electrical ($e$) or thermal ($t$) energy, GW h |
| $V$ | value of indicators in the NEDOI Index, used in Eq. (9) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | variable weights in index, dimensionless |
| $\Delta$ | indicator in the NEDOI Index, used together with subscripts |
| $\varepsilon$ | exergy, may be exergy demand, supplied or destroyed in the district, GW h |
| $\varepsilon_{on}$ | exergy that is produced on-site within the district in Eq. (5) and (7), GW h |
| $\eta$ | energy efficiency, dimensionless |
| $\rho$ | payback period, years |
| $\sum CO_{2i}$ | compound $CO_2$ emissions in the energy system in Eq. (4), kg $CO_2$ |
| $\Phi$ | binary variable for the presence of a measure in index, dimensionless |
| $\psi_{Ri}$ | rational exergy management efficiency, dimensionless |
| $\Omega$ | penetration level score of a given measure in a district, dimensionless |

*Chemical symbols*

| | |
|---|---|
| $CO_2$ | carbon dioxide |

*Subscripts*

| | |
|---|---|
| $dem$ | demand, as in exergy demand in Eq. (1) |
| $dst$ | destroyed, as in exergy destroyed in Eq. (2) |
| $e$ | electrical energy |
| $ex$ | temperature relevant to the specific exergy calculation in Eq. (3) |
| $i$ | energy consuming units in the district, dimensionless |
| $j$ | energy producing unit(s) in the energy system |
| $k$ | number of time increments, dimensionless |
| $L$ | level of penetration of the measure in the scenario |
| $m$ | the total number of time increments $k$ in one year |
| $n$ | normalized value using the min-max method |
| $R$ | rank of measure based on the value of the parameter $\psi_{Ri}$ |
| $s$ | number of measures in a net-zero district, dimensionless |
| $sup$ | supplied, as in exergy supplied in Eq. (1) |
| $t$ | thermal energy |
| $x$ | the total number of energy consuming units in the district, dimensionless |
| $z$ | the total number of measures in a net-zero district, dimensionless |

*Abbreviations*

| | |
|---|---|
| AEXC | annual exergy consumption, used as a variable in Eqs. (5) and (6) |
| CHP | combined heat and power |
| COP | coefficient of performance |
| DHC | district heating and cooling |
| DHDWG | district heating driven white goods |
| EEI | energy efficiency index in Directive 2010/30/EU |
| GSHP | ground-source heat pump(s) |
| IPCC | Intergovernmental Panel on Climate Change |
| LED | light emitting diode |
| NZEXD | net-zero exergy district, as formulated by Eq. (5) |
| NEDOI | Net-Zero Exergy District Option Index, as formulated by Eq. (8) |
| OE | original entry in the REMM analysis tool for net-zero exergy districts |
| REMM | Rational Exergy Management Model |

seawater heat pump system and a central boiler system as district heating options for coastal areas in China, such as Dalian [7]. Kwon et al. analyze the concept of a district heating system that is driven by the recovery of waste heat from urban facilities (e.g. water treatment plant, industrial waste heat, subway waste heat) based on a large-scale, two-staged compression heat pump system [8].

### *1.2. Distribution networks for the delivery of energy services*

Other than a focus on supply side technologies that support district heating networks, Pirouti et al. analyze issues related to distribution, such as a variable supply temperature operating strategy [9]. Tol et al. compare pipe dimensioning methods, substation types, and network layouts in low-temperature district heating systems, including looped and branched network layouts [10]. In another study [11], a network layout with connection to low-energy buildings in a new, suburban settlement area in Trekroner, Denmark is proposed with an operating supply temperature of 55 °C (328 K). As a result, these and other studies address the more working level issues of future district heating networks, which are required for their efficient operation.

### *1.3. Energy storage for enhanced flexibility*

Another factor of concern for the design of future district heating networks is energy storage. Verda et al. take the Italian district of Turin as a case study to show that thermal storage can increase primary energy savings in district heating networks [12]. This is based on increases in the annual operating hours of combined heat and power units that serve district heating systems, which reduce the usage of individual boilers [12]. Nuytten et al. couple thermal energy storage with a combined heat and power system to increase the flexibility in matching the supply and demand of thermal energy loads in Flanders [13]. Krajačić et al. determine the role of smart energy storage in allowing the energy system of Croatia to become a 100% independent energy system [14]. The scope of smart energy storage includes thermal storage with phase change materials to better facilitate the use of options for low temperature heat generation.

### *1.4. Improvements in end-usage on the demand side*

The impact of energy efficient and/or energy producing buildings on future district heating networks have been questioned in