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Exergy transition planning for net-zero districts

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ABSTRACT

Future energy systems need to synthesize a mix of solutions to reduce energy spending and CO_2 emissions. The NZEXD (net-zero exergy district) target can guide districts in better using the useful work potential (exergy) of energy resources. This paper develops a four step analysis approach to bring districts closer to two net-zero targets: NZEXD and NZCED (net-zero compound CO_2 emissions district). Step 1 requires the modeling of the initial net-zero exergy status. Step 2 involves the modeling of the exergy matches in the district and its compound CO_2 emissions in the energy system. Step 3 considers scenarios based on the decision-making tools of the REMM (Rational Exergy Management Model) Analysis Tool and a multi-criteria index. Step 4 finalizes the approach based on the selection of a scenario to start implementation. The four steps are applied to the second phase of Östra Sala backe in Uppsala, Sweden that will host 20,000 people by 2030. The paper concludes with a proposal for the second phase. The energy system configuration has an energy load of 88.4 GWh, NZEXD status of 1.8 GWh, and NZCED status of −7.6 Gton. The results are useful for IEA (International Energy Agency) Annex 64 and assisting local decision-makers to integrate exergy into energy plans to support an exergy transition.

1. Introduction

Future energy systems need to synthesize a mix of solutions on the supply and demand sides to reduce primary energy spending and CO_2 emissions. The local level provides an active unit of analysis for such exploratory endeavors into future energy systems. At the local level, studies that seek to address this challenge propose energy system configurations for districts, islands, and regions. These units of analysis are often seen as pilot cases that can lead to changes at larger scales in the energy system. For the purposes of this paper, we divide the literature into those studies that analyze local case studies with existing tools (Section 1.1), propose or review analysis methods and tools (Section 1.2), or provide a mixture of both (Section 1.3). This sample provides insight into emerging research trends to optimize local energy system performance.

1.1. Local case studies

Table 1 overviews a sample of 14 case studies that are analyzed based on measures that are implemented or proposed for their energy systems. Multiple cases are analyzed with EnergyPlan [1] that seeks to aid the design of 100% renewable, smart energy systems. This section describes the cases of districts, cities, and municipalities while cases of islands are given in Section 1.3.

For Danish local cases, Østergaard et al. [2] analyzed a scenario with low-temperature geothermal heat, wind, and biomass for Aalborg Municipality. Supply side measures were integrated with electric vehicles, light-rail, and thermal energy storage. For the city of Frederikshavn, Østergaard et al. [3] proposed a 100% renewable energy system. Low-temperature geothermal energy based district heating was integrated with other supply side technologies, such as off-shore wind power, large-scale solar collectors, and local waste incineration. These changes in the production system reduced primary energy consumption even before savings in end-usage. Based on the same city, Sperling et al. [4] combined end-usage energy savings and district heating expansion to improve the overall system efficiency. For a new, suburban settlement area in Trekroner, Tol et al. [5] proposed a network layout with connection to low-energy buildings with an operating supply temperature of 55 °C (328 K).

For the UK city of Sheffield, Finney et al. [6] focused on the expansion of the district heating network and considered options for expanding future heat sources to buildings. Nuytten et al. [7] coupled thermal energy storage with a CHP (combined heat and power) system to increase the flexibility of matching the supply and demand of thermal energy loads in Flanders, Belgium.

For the Swedish city of Linköping, Wetterlund et al. [8] analyzed two options to implement district heating based on biomass

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Nomenclature

AEXC	annual exergy consumption of the district in Eqs. (1) and (2), GWh
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
max	maximum value of an indicator considering all measures in a scenario
min	minimum value of an indicator considering all measures in a scenario
OE	original entry in the NEDOI index, as in Eq. 13
P	energy load, may be electrical (*e*) or thermal (*t*) energy, GWh
S	scenario entry in the NEDOI index, as in Eq. 13
T	temperature values in Eq. 4, K
V	min-maxed value of indicators in the NEDOI index, used in Eqs. (14) and (15)
v	data entries of a data set into Eqs. (14) and (15) for min−max normalization

Greek letters

α	variable weights in index, dimensionless
Δ	subscript in the NEDOI index, used together with V
$\Delta\sum CO_{2i}$	savings in compound CO_2 emissions of the scenario, kg CO_2
ε	exergy, may be exergy demand, supplied, or destroyed in the district, GWh
ε_{on}	exergy that is produced on-site within the district in Eqs. (1) and (3), GWh
η	energy efficiency, dimensionless
ρ	payback period, years
$\sum CO_{2i}$	compound CO_2 emissions in the energy system in Eq. (9), kg CO_2
ψ_{Ri}	rational exergy management efficiency, dimensionless
Ω	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. 5
dst	destroyed, as in exergy destroyed in Eq. 6
e	electrical energy
ex	temperature relevant to the specific exergy calculation in Eq. 4
i	energy consuming units in the district, dimensionless
j	energy producing unit(s) in the energy system
k	number of time increments, dimensionless
m	the total number of time increments *k* in one year
n	data set of an indicator in the NEDOI index, as in Eqs. (14) and (15)
ref	reference environment temperature
s	number of measures in a net-zero district, dimensionless
sup	supplied, as in exergy supplied in Eq. (5)
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. (1) and (2)
CHP	combined heat and power
COP	coefficient of performance
DHC	district heating and cooling
DHDWG	district heating driven white goods
EBC	Energy in Buildings and Community Program
GIS	Geographical Information Systems
GSHP	ground-source heat pump(s)
IEA	International Energy Agency
LED	light emitting diode
NZEXD	net-zero exergy district, as formulated by Eq. 1
NZCED	net-zero compound CO_2 emissions districts, as formulated in Eq. 8
NEDOI	net-zero exergy district option index, as formulated by Eq. 13
REMM	Rational Exergy Management Model
SEAP	Sustainable Energy Action Plan

gasification, including the co-production of synthetic natural gas. Difs et al. [9] analyzed the effect that energy conserving measures in multi-dwelling buildings may have on the district heating system. Åberg et al. [10] found that any reduced heat demand due to higher energy efficiency in buildings primarily decrease heat-only production.

Verda et al. [11] took the Italian district of Turin as a case study to show that thermal energy storage can increase primary energy savings in district heating networks. This is based on increases in the annual operating hours of CHP units that serve district heating systems and a reduction in the usage of individual boilers. In contrast, Ravindra et al. [12] examined the case of a microgrid implementation and proactive demand response in the urban residential community of Vijayanagar, Bangalore in India. The proposed microgrid is based on CHP and is designed to enable demand and supply matching at a community or even the individual consumer level.

For the city of Asan-si, South Korea, Kwon et al. [13] analyzed the concept of a district heating system driven by the recovery of waste heat from urban facilities based on a large-scale, two-staged compression heat pump system. Haiwen et al. [14] compared an electricity-driven seawater heat pump system and a central boiler system as district heating options for coastal areas in China, such as Dalian. Chow et al. [15] analyzed a district cooling system for a new urban development in Hong Kong based on direct seawater cooling. Yamaguchi et al. [16] analyzed the Yodoyabashi district in Japan as a sustainable urban energy system case.

1.2. Analysis methods and tools

Another cluster of research work focuses on hybrid energy systems, which combine one renewable energy source with a conventional source of energy or involve multiple renewable energy sources [17]. As intermediary steps towards 100% renewable energy systems, hybrid energy systems require detailed analysis of all system components, including energy storage.

Perera et al. [18] developed a multi-step decision-making process to evaluate the system design of hybrid energy systems. The