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Modelling smart energy systems in tropical regions

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ABSTRACT

A large majority of energy systems models of smart urban energy systems are modelling moderate climate with seasonal variations, such as the European ones. The climate in the tropical region is dominated by very high stable temperatures and high humidity and lacks the moderate climate's seasonality. Furthermore, the smart energy system models tend to focus on CO_2 emissions only and lack integrated air pollution modelling of other air pollutants. In this study, an integrated urban energy system for a tropical climate was modelled, including modelling the interactions between power, cooling, gas, mobility and water desalination sectors. Five different large scale storages were modelled, too. The developed linear optimization model further included endogenous decisions about the share of district versus individual cooling, implementation of energy efficiency solutions and implementation of demand response measures in buildings and industry. Six scenarios for the year 2030 were developed in order to present a stepwise increase in energy system integration in a transition to a smart urban energy system in Singapore. The economically best performing scenario had 48% lower socio-economic costs, 68% lower CO_2e emissions, 15% higher particulate matter emissions and 2% larger primary energy consumption compared to a business-as-usual case.

1. Introduction

Climate change has become one of the most important topics in political discussions among nations and cities around the world in recent years. Energy production and consumption are responsible for two-thirds of the world's greenhouse gas (GHG) emissions, making the energy sector one of the main contributors to the man-made climate change [1]. In order to tackle that problem, 195 countries worldwide signed the Paris agreement in 2015 [2]. The countries committed themselves to increase its efforts to cut CO_2e emissions with the aim of keeping the projected growth in global average temperature below 2 °C. An important part of those efforts is changing local and national energy systems from using fossil fuels towards using renewable energy sources (RES). Coastal cities are especially vulnerable to the climate change due to the sea level rise potential, stronger storms and other unexpected weather events.

Cities will be among the major contributors in this transition process. Today, 54% of the world's population lives in cities and the United Nations forecasts that the share is expected to continuously grow, resulting in 66% of the world's population being urban in 2050 [3]. Cities are also facing the challenge of increasing energy consumption per capita, as urban energy use in the last 25 years has grown more than the urbanisation rate [4]. Cities can therefore easily become hotspots of air pollution, as they concentrate people, traffic, construction activity and energy use [5]. The World Health Organisation (WHO) states that more than 80% of the global urban population is exposed to air quality levels that are below WHO recommendations [6]. Particularly interesting in this context are cities in tropical climates. While heating demand accounts for a predominant part of the total energy consumption in moderate and cold climates, tropical climates are experiencing an ever growing cooling demand, as they are dominated by humid air and high temperatures throughout the year [7]. It is therefore important to analyse future energy systems in cities located in tropical climates, with a special emphasis on residential cooling.

Cooling systems have been the main focus in many research

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Nomenclature

abs_{DC}	Cold production for district cooling (DC) from single phase absorption units, MWh_c
air_poll_j	Costs of air pollution emissions, €/kg
$air\_poll_{inten,j}$	Air pollution intensity of a certain technology or energy within the system boundaries, kg/MWh
B_y	Binary variable (0 or 1) used for modelling the choice of the refurbishment scenario
bio_cap	Maximum allowed biomass consumption in the modelled system, MWh
$chiller_{DC}$	Production of cold in DC from centralized electric chillers, MWh
$COP_{DC_{chiller}}$	Coefficient of performance of chillers in DC
$chiller_{individual}$	Production of cold from individual electric chillers, MWh
$cool_{en,ef}$	Reduced cooling energy demand due to the increased energy efficiency, MWh
$cool_{demand,total}$	Total cooling demand, MWh
$COP_{individual}$	Coefficient of performance of individual chillers
COP_{abs}	Coefficient of performance of absorbers
$CO2\_cap$	Maximum amount of emissions allowed in the system, ton
$CO2\_inten_j$	CO_2 intensity of a certain technology or energy within the system boundaries, ton/MWh
$CO2_{intenk}$	CO_2 intensity of a certain technology or energy coming in or out of the system boundaries, ton/MWh
$CO2_j$	Costs of CO_2 emissions, €/ton
DC_{demand}	DC demand, MWh
dis_rate_i	Discount rate of the technology i, %
el_dem	Electricity demand, MWh
ela	Elasticity of willingness to pay with respect to income
$ele_{transport}$	Electricity demand for electrified part of the transport sector, MWh
$fix\_O\&M_i$	Fixed operating and maintenance costs of energy plants, €/MW
$flex$	Reduced electricity demand due to the load shifted in industry or buildings sector, MWh
$flex_{ch}$	Additional demand for electricity due to the shifted load demand, MWh
$fuel_j$	Fuel cost of specific energy type, €/MWh_{fuel}
gas_dem	Gas demand, MWh
gas_imp_k	Price of import or export of gas in a specific hour, €/MWh
$gas_{synthesis}$	Synthetic natural gas production from syngas using gas synthesis, MWh
$geothermal_{DC}$	Cold production for DC from geothermal waste heat, MWh
$heat\_level_r$	Heating energy content stored in the energy storage, MWh
$heat\_dem_t$	Heat demand in district energy grid t, MWh
i	Energy technology index
ind_cool_{demand}	Individual cooling demand, MWh
inv_i	Total investment in technology i, €
$inv_{en,ef,y}$	Investment cost of a certain building energy efficiency scenario, €
j	Energy technologies that consume fuels and have emissions
lev_inv_i	Levelized cost of investment over the energy plant lifetime, €/MW
$lifetime_i$	Lifetime of the technology i, years
MEC_{Sing}	Marginal external cost of air pollution in Singapore, €/ton
MEC_{UK}	Marginal external cost in the United Kingdom, €/ton
$methanol$	Methanol production via synthesis from syngas, MWh
$petr\_dem$	Gasoline demand, MWh
$petr\_imp_k$	Price of import of gasoline in a specific hour, €/MWh
RO	Fresh water production from sea water desalination using reverse osmosis (RO), m^3
$SOEC$	Hourly production of syngas from solid-oxide electrolysers, MWh
$SOFC$	Hourly production of electricity from solid-oxide fuel cells, MWh
t	Hour, h
$var\_O\&M_j$	Variable operating and maintenance costs of energy plants, €/MWh
$water_{demand}$	Demand for fresh water production from sea desalination via RO, m^3
x_i	Capacity variables of energy plants and gas grid, MW
x_j	Generation capacities of energy plants (8760 variables for each energy plant, representing the generation in each hour during the one year), MWh
$x_{j,EL}$	Hourly generation of technologies which generate electricity, MWh
$x_{j,EL,biomass}$	Hourly generation of technologies which generate electricity and are driven by biomass, MWh
$x_{j,EL,gas}$	Hourly generation of technologies which generate electricity and are driven by gas, MWh
$x_{j,EL,other}$	Hourly generation of technologies which generate electricity and are driven by other fuel types, or are not fuel-driven (Photovoltaics (PVs) and wind turbines), MWh
$x_{j,battery,storage_{ch}}$	Hourly charge of vehicles battery storage, MWh
$x_{j,battery,storage\_dis}$	Hourly discharge of electricity of vehicles battery storage, MWh
$x_{j,battery,storage\_grid\_dis,r}$	Hourly discharge of electricity of vehicles battery storage to the power grid (vehicle-to-grid (V2G)), MWh
$x_{j,grid_{battery},storage_{ch}}$	Hourly charge of electricity grid battery storage, MWh
$x_{j,grid\_battery,storage\_dis}$	Hourly discharge of electricity grid battery storage, MWh
$x_{j,heat,storage\_ch,t}$	Hourly charge of heat to the heat storage operated in the district cooling (DC) system t, MWh
$x_{j,heat,storage\_dis,t}$	Hourly discharge of heat from the heat storage operated in the DH system t, MWh
x_{j,an_dig}	Generation of gas after CO_2 removal in anaerobic digester, MWh
$x_{j,wasteheat,l}$	Heat generation needed for absorption chillers; from gas, biomass, waste CHPs, solar thermal or waste heat from data centres, MWh
x_k	Import or export across the system boundaries of different types of energy (8760 variables per one type of energy, representing the flow in each hour during the one year), MWh
y	Chosen refurbishment scenario (out of several predefined ones), integer value
Y_{Sing}	Gross national income per capita at purchasing power parity in Singapore, $
Y_{UK}	Gross national income per capita at purchasing power parity in the United Kingdom, $
η_j	Efficiency of technology, MWh_{energy}/MWh_{fuel}