Sustainable long-term energy planning for a district in Suzhou City, China

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Abstract. A city district in Suzhou aims to develop a progressive, long-term sustainable energy strategy. This study examines possible energy planning pathways for the district through the development of a long-term optimization model and a range of energy scenarios until 2050. The scenarios explore different CO2 emission reduction strategies and technology mixes/parameters. Results suggest which low-carbon energy conversion technologies and efficiency measures should be adopted by the district alongside supportive local policies and targets. Photovoltaic (PV) and waste energy converters are two renewable energy technologies which are taken up at maximum possible rates in the evaluated scenarios to reduce long-term CO2 emissions. Once local renewable resources are exhausted, natural gas-based combined-cycle plants (CCP) and combined heat and power plants (CHP) are required to further reduce emissions, alongside efficiency measures in the built environment. Carbon capture and storage (CCS) technologies also demonstrate the potential to drastically reduce emissions; however, local feasibility studies are needed to support their implementation. Study results prescribe renewable energy share and CO2 emission reduction targets until 2050 for the district. Appropriate local policy and planning targets should also be accompanied by supplementary support studies, including local feasibility, renewable energy resource, and demand-side management studies.

1. Introduction

China aims to achieve net-zero CO2 emissions by 2060 [1]. In order to achieve this goal, advanced energy technology and carbon offsetting solutions will be required at all echelons of society. Cities, in particular, can play a key role in this transition. Approximately 60% of China's population currently resides in urban areas [2], with this figure expected to grow significantly by 2050 [3]. A district of approximately one million inhabitants in Suzhou City aims to become a leading, advanced sustainable energy community in China. To this end, the district will develop an energy plan to achieve low-carbon emissions through the use of sustainable energy conversion technologies, such as renewable energy technologies (RETs), storage, electric mobility, and efficiency measures, in order to meet future demand.

This study explores possible energy planning pathways for the district. We work with local stakeholders, such as the municipal utility and government, in order to develop a district-scale, long-term energy system optimization model. We also design a series of energy scenarios with varying technology and carbon policy targets towards achieving net-zero CO2 emissions in order to identify key technology investment pathways in the future, and to formulate supporting policy and planning recommendations. Learnings from this case study can benefit similar communities across China and internationally.
2. Methodology

2.1. Model Framework and Scope

A long-term, energy system optimization model of the district is developed using OSeMOSYS, an open-source, linear optimization modeling framework [4]. The entire energy conversion chain is modelled from resource acquisition to supply-side generation and end-use consumption. The developed model provides insights into cost optimal, long-term technology capacity investment and dispatch planning for the energy system under defined scenario conditions.

Key sectors and their development are represented until 2050 using 3-year time steps and sub-annual hourly profiles for typical seasonal days. Multiple competing objectives are considered that are of interest from a municipal policy perspective, including cost and carbon minimization. The district's main sectors include residential, commercial, and industrial sectors, and the main end-use demands include electricity, heating, cooling and transportation. Energy imports to the model include national/regional grid electricity, natural gas (referred to simply as gas), coal, and oil, and local renewable energy resources include solar and waste biomass. These energy carriers are of interest based on local conditions and energy access.

The modelled technology scope includes: CHP plants (coal/gas/waste), CCP plants (gas/waste), carbon capture and storage (CCS combined with gas CCP or coal IGCC), small CHP (gas/H2 fuel cell), boilers (district to building-level; coal/gas/electric/waste), PV, solar thermal heaters, water heaters (gas/electric), electric space heaters, air conditioners (ACs), heat pumps (ground/water (HPGW) and air-source (HPA)), internal combustion engine vehicles (ICEVs), battery-electric vehicles (BEVs), H2 fuel cell vehicles (FCVs), H2 generation technologies (via electrolysis or biomass gasification), H2 storage, batteries, heat storage, and network losses (district heating and electricity grids). This range of technologies has been selected based on consultation with local stakeholders and advisors, who have prioritized these technologies based on local conditions and policy goals.

Data for this study has been obtained or estimated based on a number of sources, including the local utility, literature and other publically available/published data (e.g., [5–9]). Proxy data and historical trends have been utilized from these sources to approximate and calibrate data sets. Key assumptions include the approximation of load profiles based on similar neighbouring districts and regions; and estimating demand growth based on national population projections, historical GDP growth in the district, and historical building area growth in the district. Techno-economic parameters are mostly based on international data (e.g., [10]), which are calibrated to local case conditions where possible.

2.2. Scenario Framework

Four main energy scenarios are developed which capture a range of CO2 emission reduction targets, energy technologies, efficiency measures (including new building and appliance efficiency standards), renewable energy shares, and vehicle electrification rates. The scenarios include a base case (BC), carbon policy (CP), carbon minimization (CM), and net-zero (NZ) scenario; each is described below.

The base case scenario reflects baseline conditions with a cost minimization goal and no explicit emission reduction or renewable energy targets. It assumes an average uptake of efficiency measures and electrification rates in the transportation sector, and considers all technologies except for CCS. The BC scenario serves as a benchmark for comparative purposes.

The remaining three scenarios (CP, CM and NZ) implement sustainable energy planning targets to varying degrees with respect to emission reduction targets and increased efficiency measures, renewable energy targets, and transportation electrification rates compared to the base case, based on municipal priorities and targets. The carbon policy scenario assumes a gradual reduction in CO2 emissions according to national guidelines, with peak emissions occurring in 2020 followed by a 15% relative reduction by 2040 [11]. Additionally, higher building efficiency standards are assumed (based on national building standards [12]); RETs assume 8% of the local electricity mix by 2026 (based on provincial recommendations); and 40% and 70% of transportation demand is supplied by electric drivetrains by 2025 and 2050, respectively (based on municipal fleet electrification targets).

In contrast, the CM scenario minimizes carbon emissions over the modeling horizon cost optimally, while maintaining the same technology mix, efficiency measures, and vehicle electrification rates as in the CP
scenario. This carbon minimization target is driven by the local policy priority to achieve carbon neutrality within the scope of conventional conversion technologies.

A third, more aggressive carbon minimization scenario is also of interest to the municipality in order to identify carbon neutral development pathways. The NZ scenario strives towards net-zero emissions by 2050 by allowing for investment in CCS technologies (which are not available in any other scenario). It also allows for higher electrification rates of transportation compared to other scenarios, if optimal. Similar to CM, this scenario cost optimally minimizes CO2 emissions over the modeling horizon.

All scenarios have base assumptions in common in accordance with current municipal energy plans. These include closure of an existing coal power plant in 2021, commissioning a new gas CHP plant in 2021, and upgrading an existing waste incineration plant to a CHP plant by 2023. The newly upgraded and commissioned power plants are assumed to operate until at least 2035.

Assumptions with respect to renewable energy resources include long-term estimates of approximately 2 GW of PV and 1 GW of solar thermal potential, based on district characteristics [13]. Biomass is primarily sourced from municipal waste, and is assumed to scale with population growth.

3. Modeling Results

The generation shares across electricity and heat generation technologies are exemplarily illustrated over the modeling horizon for the CP scenario in Figure 1. Here, a gradual increase in PV uptake is accompanied by a shift towards decentralization with respect to waste technologies from centralized CHP to decentralized industrial boilers to satisfy the district's significant industrial heat demand. Gas CHP and CCP play a key role in reducing emissions in the intermediate term, and the majority of heat supply in the residential and service sectors is met by air-source heat pumps.

![Figure 1](image.png)

**Figure 1:** CP scenario - electricity and heat production. Legend sector descriptors: I: industrial, R: residential, S: services

Figure 2 compares analogous electricity and heat generation shares across all scenarios in key years. The total generation share from RETs is noted in green text above each column. Several trends emerge through this comparison. As CO2 emission reduction targets become more aggressive across scenarios, RET shares increase, driven by the uptake of PV and solar thermal technologies. PV is deployed at maximal rates across non-BC scenarios beyond 2035, while waste is maximally deployed across all scenarios over the modeling horizon. Solar thermal heaters and ground/water-source heat pumps are also deployed at maximum rates by 2035 in carbon minimization scenarios (CM and NZ).
Natural gas CCP and CHP technologies play an essential role in meeting CO\textsubscript{2} minimization targets as well. Natural gas conversion technologies are maximally deployed and replace comparatively high-emission grid imports until 2050 in CM and NZ scenarios. The NZ scenario achieves further emission reductions through CCS technologies. Gas CCP with CCS is found to be the most cost- and carbon-optimal CCS solution, followed by coal IGCC CCS.

Figure 3 illustrates net CO\textsubscript{2} emissions in each scenario for key years. Net emission reductions are reduced by 23\%, 41\%, and 93\% in 2050 compared to 2020 in the CP, CM, and NZ scenarios, respectively. The majority of emissions are attributed to grid electricity imports, which can only be fully replaced in the NZ scenario using CCS.

Within the transportation sector, electrification rates reach 100\% by 2050 in the NZ scenario due to the availability of near net-zero carbon electricity. However, only battery-electric vehicles are selected as these are found to be both cost- and carbon-optimal compared to FCVs. This is owing to the additional costs and conversion losses associated with hydrogen generation (e.g., using electrolysis) for FCVs. Unless hydrogen
can be sourced from a lower-emission and -cost pathway, FCVs are suboptimal compared to BEVs across all scenarios for the given district.

A sensitivity analysis was also performed to identify critical model assumptions and input data. One key finding was that gas technology investments are highly sensitive to assumed regional grid emission factors. As the grid emission factor increases, gas technologies (i.e., CCP and small CHP) represent a significantly higher share of the local electricity mix. Investments in gas, PV, and waste technologies are also highly sensitive to assumed bounds/estimated potentials in the model. However, RET investments were not found to be sensitive to capital cost assumptions in the long-term.

4. Discussion & Recommendations
Several trends and recommendations emerge for sustainable energy planning for the district based on the modeling results.

4.1. Towards Net-Zero CO$_2$ Emissions - Key Technologies
Multiple technology pathways enable the district to achieve drastic CO$_2$ emission reductions in the long-term. On the supply-side, key renewable energy technology investments include PV and waste energy converters (i.e., waste CHP or boilers). The total PV potential of 2 GW is deployed by the mid- to late-2030s under the range of evaluated sustainable scenarios. Larger PV investments and faster rollout would be optimal if these bounds were feasible/relaxed. Waste biomass is fully utilized in every year of every scenario. This is a valuable resource for the district which should be fully exploited and expanded if possible (e.g., by importing underutilized waste from neighbouring districts).

Natural gas-based CCP and small CHP are also vital to decarbonize the district's energy mix, after limited renewable energy resources/technology potentials have been exhausted. These technologies are used to offset grid emissions and demonstrate higher and earlier investments in scenarios with high CO$_2$ reduction targets or if regional grid emissions are comparatively high. However, it is also worth noting the impact of the China's net-zero emissions target on local natural gas technology planning. If higher regional grid decarbonization occurs than currently assumed in the model, the role of natural gas in the district will be reduced (i.e., as decarbonization shifts to the regional grid).

CCS technologies are needed in order to achieve more drastic emission reductions in the district. In the NZ scenario, CCS resulted in reducing CO$_2$ emissions by 70% compared to the CM scenario. However, CCS technologies cannot be recommended without detailed local engineering and economic feasibility studies. Implementation costs for CCS projects, particularly demonstration projects, are notoriously high and uncertain; therefore, these technologies must be considered with care before planning decisions are made.

Efficiency measures are an important demand-side measure for reducing energy demand and corresponding emissions as well. For example, the considered new building and appliance efficiency measures yielded 5% lower CO$_2$ emissions in the CM scenario compared to BC. Additional measures should be considered to expand upon this potential; for example, efficiency measures in the industrial and service sectors; renovations in the existing building stock; the rollout of residential smart-metering programs; and increased public transportation.

4.2. Policy and planning recommendations
Several policy measures and planning targets can be adopted by the district in order to support long-term sustainable development. The results for moderate to aggressive carbon scenarios (i.e., CP, CM and NZ) suggest that renewable energy (electricity and heat) generation share targets for the district should be targeted between at least 21-24% by 2035, and 23-30% by 2050. Similarly, a CO$_2$ reduction target should be set to at least 11-32% in 2035 and 23-41% in 2050 relative to 2020 CO$_2$ levels (not considering CCS). This target increases to over 90% by 2050 if CCS technologies are deemed feasible in the district. The exact target settings will ultimately depend on local sustainability objectives and resource availability, including financing, technical feasibility, and support by higher-level governmental authorities (i.e., from a city to national scale).

The district should commission, encourage, or otherwise support additional studies to inform and support the development of a sustainable long-term energy plan as well. Supplementary studies are needed to
determine the potential of demand-side management solutions (including efficiency measures); to determine
the feasibility of technologies such as CCS and water-source heat pumps while considering environmental
restrictions/objectives; and to quantify renewable energy potentials in more detail (i.e., regarding waste
resource and solar/heat pump technology installation potentials in the long-term, and to identify potentially
untapped or underutilized local renewable energy resources).

Energy policymakers should also work closely with urban planners to minimize energy demand through
urban design, particularly for newly developing areas. In the transportation sector, for example, energy
demand may be reduced through increased public transportation access, bicycle lanes, and urban planning to
minimize commuter distances. High building and appliance efficiency standards should also be enforced in
newly developed areas.

5. Conclusion

The given city district has an opportunity to become a leading community in sustainable energy planning in
China. In this work, we developed a district-wide, energy system optimization model to support this
sustainability goal. Based on the insights gained, we propose several possible pathways towards achieving a
low-carbon and secure energy future for the district, while include a range of energy conversion technology
solutions, efficiency measures, and supporting policies.

Overall, the district is encouraged to implement policies that maximize the deployment of PV and waste
technologies, as well as high efficiency standards for buildings and electrical devices. Given the limited
potential of these technologies, however, supplementary natural gas-based CCP and CHP technologies are
needed to decarbonize the energy mix in the long-term as well. Results support the establishment of a CO2
emission reduction target by the district of at least 23% in 2050 compared to 2020, should CCS technologies
not be feasible in the area.

The district is advised to commission additional support studies in the next planning stages, including
technical feasibility studies for recommended technologies (particularly the feasibility of CCS to achieve
more drastic CO2 emission reductions); detailed renewable energy resource assessment; and other demand-
side management solutions.

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