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Multi-objective energy planning of Xiamen City considering trade-off between cost, emissions, and resilience

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ABSTRACT

The energy transition sometimes encounters challenges on balancing three competing goals, i.e., costs, emissions, and resilience (the so-called Energy Trilemma). Such trade-offs are particularly conspicuous for coastal cities, which usually have more ambitious emission reduction targets and are more likely under threat of extreme weather events, i.e., typhoon. This study develops a bottom-up optimisation framework to assess the sustainable transition of the electricity sector for a typical coastal city of Xiamen, China. The framework optimises the energy portfolio for 20-year-horizon with hourly temporal resolution considering demand-side flexibility of energy storage. By setting multiple optimisation objectives, three representative transition scenarios are evaluated: the least-cost scenario, the least-emissions scenario, and the diversity-optimal scenario. The trade-offs between competing objectives are presented as Pareto frontiers and posterior decision-making methods are further embedded to identify one superior solution and facilitate the policymaking. The optimisation results indicate that with the limited potential of solar and wind and other renewable resources, the electricity transition of Xiamen would rely on the import power to a large extent. An extra 3.9% cost than the least-cost pathway can achieve a pathway with maximum energy diversity to enhance the resilience, whereas 27% more cost than the least-cost pathway is needed to achieve the least-emissions pathway. In addition, the first 10-year modelling results are further verified by comparison with the real-world data to generate valuable insights into sustainable transition pathways of coastal cities.

Keywords: energy planning, multi-objective optimisation, Energy Trilemma, energy resilience, energy diversity, coastal cities

NONMENCLATURE

Abbreviations

HHI	Herfindahl–Hirschman Index
MOO	multi-objective optimisation
NLP	non-linear programming
PHES	pumped hydro energy storage
PV	photovoltaic
TCE	total carbon emissions
TDC	total discounted cost
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution

1. INTRODUCTION

The transition towards a low-carbon future is undergoing worldwide [1]. Technological improvement and rapid cost-reductions have led to many promising technologies, e.g., storage technologies and renewables, attractive options to achieve a sustainable energy infrastructure [2]. The electricity sector is taking action by integrating a greater amount of renewable energy and shifting to a more distributed paradigm [3]. The success of this transition is a complicated challenge that requires the joint efforts of academia, industries, and policymakers from technical, economic, and environmental initiatives [4]. Energy planning is, therefore, a decision-support tool aiding the energy policymaking at national and municipal levels.

Energy planning, based on mathematical modelling, could quantify future scenarios and optimal energy mix that meet certain goals, which can generate insights on when, where, and how to invest in energy infrastructures

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[5]. Whereas, challenges, e.g., intermittency of renewables, require energy planning models with more flexible temporal, spatial, and technical resolutions [6].

Significant efforts have been spent on developing energy planning models for different purposes, i.e., the Integrated Assessment Model, the Long-term Planning Model, and the Unit Commitment Model. The temporal, spatial, and technical resolutions vary significantly for different categories of models with different purposes. The model proposed in the present study is in-between the unit commitment model and the long-term planning model.

As a representative coastal city, Xiamen is more susceptible to extreme weather events (e.g., typhoons) with the increasingly evident climate change, meanwhile, its emissions reduction target is usually more ambitious. Therefore, it is important to investigate the energy transition pathway of Xiamen considering multiple objectives from economic, environmental, and resilience perspectives. To the best of our knowledge, few energy systems studies have evaluated the energy transition pathway at city- level considering multiple objectives simultaneously with hourly temporal resolution. Thus, a knowledge gap exists in identifying the optimal transition pathway that considers the possible trade-offs among the Energy Trilemma of cost, emissions, and resilience goals.

To fill the knowledge gap, we develop a bottom-up optimisation model, which is structured with the hourly temporal resolution considering the demand-side flexibility, and able to assess the impacts of multi-objective on the energy transition pathway. Notably, we consider the electricity storage and technological diversity in our model to enhance system resilience, and we evaluate multiple scenarios, e.g., the least cost, the least emission, and the maximised diversity scenario. For each scenario, the energy mix and dispatch strategy would be optimised simultaneously. Furthermore, we validate the modelling results with the real-world condition and generate valuable insights from both political and methodological perspectives.

2. METHOD

2.1 *Outline of the proposed framework*

This study addresses a city-level energy planning problem by proposing a bottom-up optimisation model, which optimises an energy portfolio and hourly operation strategy for given constraints. Fig. 2 shows schematic of the proposed model, by which different transition pathways satisfying the energy demand are identified according to three competing objectives. Inputs of the model include energy demand, energy resource, and technology details; subject to constraints of supply-demand balance, emissions control, and technology operations. The whole model is developed based on non-linear programming (NLP), and solved by the NLP engine. Several specific features of the proposed model are described as follow,

(1) Various supply and demand-side technologies are considered and classified into sets for the ease of model development and further model extension.

(2) Hourly dispatch capturing the demand-side flexibility are formulated and the transition pathway over the 20-year horizon are optimised simultaneously.

(3) Multi-objective optimisation and posterior decision-making are enabled to assess the trade-offs of the Energy Trilemma.

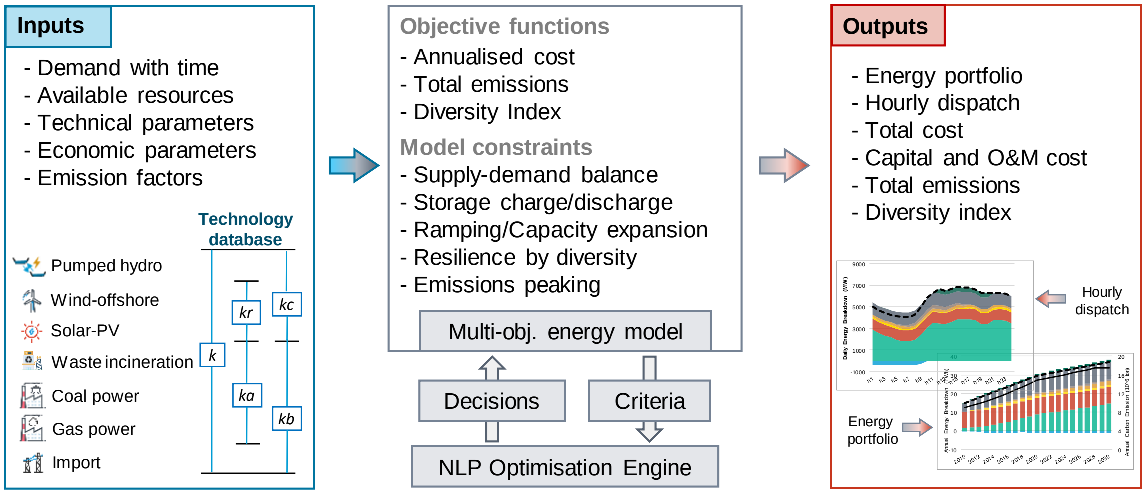

Fig 1 Outline of proposed energy planning framework.

2.2 *Model assumption*

To tackle the research question and minimize the computational expense, the following assumptions have been made in the model formulation:

(1) The model assumes the perfect foresight over the entire planning horizon;

(2) Each year during the planning horizon are sliced into certain representative slots;

(3) We model the targeted system as one node and can purchase electricity from the wider national grid while cannot feed power back to the grid; surplus can be stored to PHES if available;

(4) We model the installed capacity of each technology as a continuous variable considering the computational expense caused by the nonlinearity for modelling the diversity;

(5) We take the high-level master planning perspective.

2.3 *Temporal resolution*

The temporal resolution of the proposed model is shown in Fig. 3, where the modelling horizon is 2010~2030 and the model has finer season-day-scenario-hour resolutions to as to model the demand-side flexibility and engagement of storage technologies. Three representative seasons, i.e., summer (Apr. 15th to Oct. 15th), winter (Dec. 15th to Feb. 15th), and the transition season (the rest of days) are considered; and further represented by two typical days, i.e., weekday (Monday to Friday) and weekend (Saturday and Sunday). For each kind of typical day, four scenarios representing the fluctuation of solar and wind profiles are considered with hourly resolution. Hence, each year is sliced into 576 temporal slots. Investment decisions are made annually; whereas operation decisions are made at hourly resolution.

The solar and wind profiles fluctuate each day over the time horizon as shown in Fig. 3(b and c). The k-means clustering approach is applied to generate representative profiles for wind and solar as shown in Fig. 3(d). The whole set of hourly weather data is firstly sorted by representative days. Then, for each type of typical day, the array of data points is clustered into the pre-defined number of clusters (i.e., 2 in this case), such that the Euclidean distance between the data points and the corresponding cluster centroid is minimised. For each cluster, a representative profile can be chosen by collecting the cluster centroids of that cluster and is further weighted by the frequency of occurrence for the data points in that cluster. Hence, for each kind of typical day, two representative profiles (i.e., high profile and low profile) are chosen for wind and solar, respectively. The detailed procedure of k-means clustering is explained in Ref. [7].

2.4 *Model framework*

The mathematical formulation of the proposed model as outlined below.

min obj1 = Total Discounted Cost (TDC)

min obj2 = Total CO2 Emissions (TCE)

min obj3 = Diversity Index (HHI) by

S.T. Energy balance

Capacity expansion constraints

Operation constraints

Pumped hydro energy storage constraints

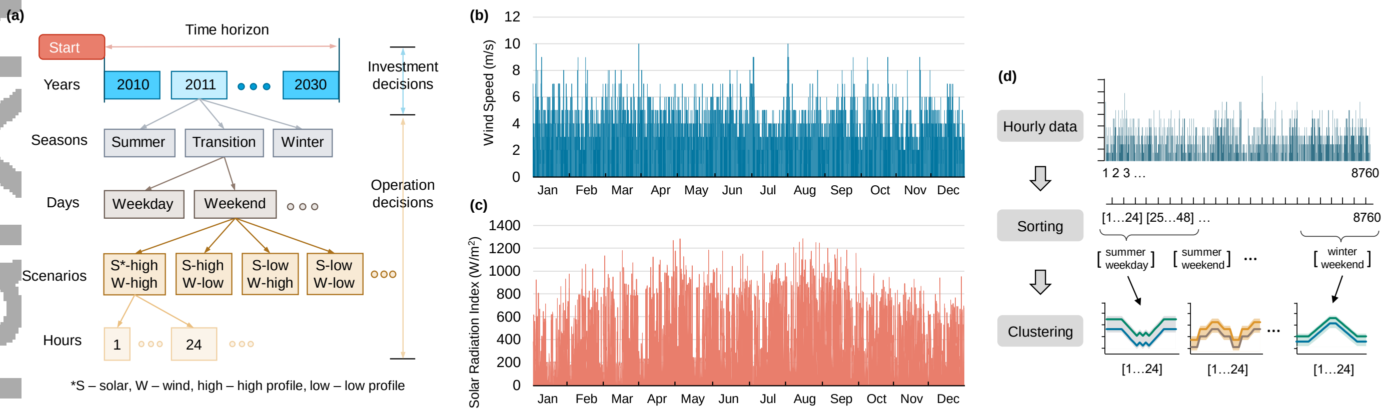

Fig 2 Model temporal resolution (a), wind fluctuating profile (b), solar fluctuating profile (c), and process of generating representative profile (d). (b) and (c) show the hourly distributions and variation of wind and solar radiation based on three-year (2013-2015) historical data obtained from online sources. (d) shows the k-means clustering approach for generating representative profiles for solar and wind.

3. XIAMEN CASE STUDY

Xiamen is a typical coastal city in Fujian Province, which is on the southeast coast of the People's Republic of China (see Fig. 3).

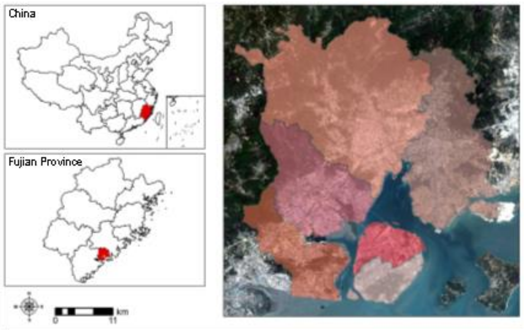

Fig 3 Location map of Xiamen.

The energy system of Xiamen city has the following features. Due to emission concerns, no more coal-fired power plant is further planned; the natural gas supply is sufficient; waste incineration power plant is a promising solution considering the growing amount of municipal waste produced. Building-integrated photovoltaic (BiPV) pilot projects have been initiated as one of the demonstration cities for energy-efficient urban retrofit with annual availability of 2200~3000 solar hours but relatively limited available rooftop space. The average wind speed of 2.7 m/s; whereas relatively limited potential sites available for both off-shore and on-shore considering the land-use and the landscape constraints. Other than local power generations, Xiamen's electricity supply has a strong dependence on imported electricity from the provincial grid of Fujian province, where the proportion of nuclear and wind power increase gradually and is sufficient to feed Xiamen. In addition, Xiamen has a geographical advantage to develop pumped hydro energy storage with a potential of 1,400 MW.

4. RESULTS AND DISCUSSION

4.1 Trade-off between cost and diversity/emissions

Fig. 4 indicates a trade-off between cost and diversity, as well as the trade-off between cost and CO2 emissions. We present such a trade-off by the Pareto frontier, each solution on the Pareto frontier denotes a certain scenario with the optimal system design and dispatch strategy accordingly. In Fig. 4(a), the diversity-optimal scenario maximises the diversity of energy mix with the least diversity index (HHI). Since the renewable energy potential (Wind, WI, and PV) is limited (less than 10% in total), the import power, coal power, and gas power are three main suppliers, which account for approximately 1/3 of the energy mix, individually. From the diversity-optimal scenario to the cost-optimal scenario (i.e., the least-cost solution), the proportion of import power increase gradually with the drop of gas power share, while the coal power share stays constant. This is due to the cost of domestic coal power is the lowest among all energy technologies, and the price of import power is lower than the cost of domestic gas power in this case. Compared the diversity-optimal scenario with the cost-optimal scenario, 3.9% more cost is required. This cost difference is mainly caused by the cost difference between import power and domestic gas power as well. Meanwhile, the PHES technology is only been enrolled when the requirement for diversity is high. Its potential on cost-saving or providing flexibility has not been fully explored unless the import power price difference on peak/off-peak would be more significant.

Fig. 4(b) shows that, in the emissions-optimal scenario (i.e., the least emissions solution), the coal power is completely phased out, and the import power is the biggest contributor with roughly 45% share, gas power is the second-largest contributor with 40% share. This is due to the emission factor of the utility grid is assumed to decline gradually, gas power has lower emissions factor than coal power, and the limited resource for other clean renewable energy. In the meantime, as the cheapest coal power is phased out, 27% more cost has to be spent on the emissions-optimal scenario compared to the least-cost scenario.

In general, due to the limited potential of renewables, the import power, coal power, and gas power are three major drivers for balancing the Energy Trilemma of Xiamen. In the trade-off between cost and diversity, the import power and the gas power are competing with each other. While in the trade-off between cost and emissions, the coal power and gas power are two major competitors. In addition, a superior solution on the Pareto frontier has been specified for Fig. 7(a) and (b) individually by the TOPSIS posterior decision-making approach. The identified superior solution is with the maximal rationality for representing the trade-off between conflicting objectives, and for the ease of policymaking if needed.

5. CONCLUSIONS

In this work, we propose a municipal-level optimisation framework with bottom-up structure, hourly temporal resolution, and demand-side flexibility, and apply it to explore the sustainable transition pathways for the electricity sector of Xiamen City. Various scenarios caused by the trade-offs among the

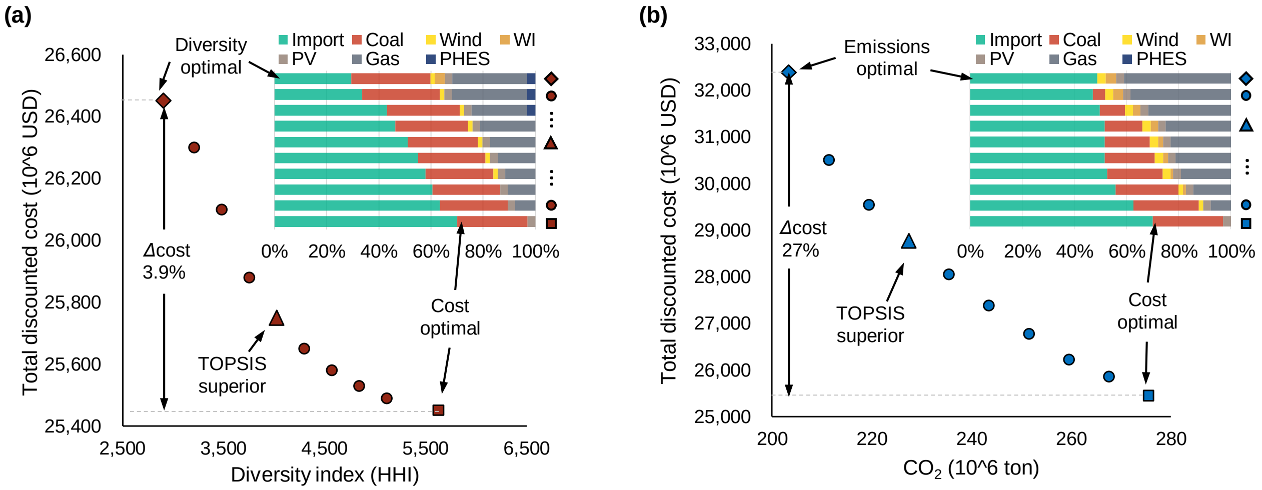

Fig 4 Pareto frontier representing the trade-off between cost and diversity (a); the trade-off between cost and CO2 emissions (b). The total discounted cost is the overall cost of 20-years horizon, the set of bar chart on the up-right corner represents the energy mix at 2030 for each optimal solution on the Pareto frontiers. Abbreviations: WI – waste incineration power, PV – photovoltaic, PHES – pumped hydro energy storage.

Energy Trilemma, i.e., cost, emissions, and resilience, have been captured and analysed by multi-objective optimisation and decision-making approaches. The modelled scenarios are further verified by the real-world condition. The key findings are concluded as follows,

(1) Compared to the least-cost scenario, 3.9% more cost could lead to a most-diverse solution for energy resilience consideration; and 27% more cost is required to achieve a least-emission solution as the natural gas price is relatively high.

(2) Coal power is still a cost-efficient technology. Meanwhile, with the limited potential of renewables locally, the natural gas power and the import power play key roles in the low-emission and high-diversity electricity transition of Xiamen. Besides, as a demand-side technology, the pumped hydro energy storage is only adopted when optimising the diversity index while not contribute to the goals of minimising cost or emissions.

(3) The non-linearity caused by the diversity significantly increases the computational expense, more computationally efficient way of formulating energy resilience will be developed in future works.

In general, this study provides valuable insights into the sustainable transition of the electricity sector for similar coastal cities considering the Energy Trilemma.

The main conclusions of the study may be presented in a short Conclusion section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

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