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Empirical characterisation of agent investment behaviour to evaluate the China's residential heating transition using the MUSE-RASA model

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ABSTRACT

Energy-related investment decision-makers in the residential sector are heterogeneous in the sense that their preferences are rooted in socioeconomics, values, and perceptions, even when an ostensibly identical decision task is at hand. This study aims to address one of the challenges associated with long-term energy transition modelling by capturing the human dimension in energy system modelling. A novel multi-agent modelling approach, the MUSE-RASA model [1], is used to evaluate heterogeneous consumer-investors in the residential sector. Survey-based agent characterisation is used in the MUSE-RASA model to illustrate the difference between a single representative agent model and a multi-agent system. A survey of 1,500 Chinese families is used to generate six agents with varying investment goals, technology search strategies, and decision methods for purchasing and upgrading heating systems. The agent-based approach integrates high-resolution gridded data to geographically target the agents on a map. The results suggest that market fragmentation achievable with agent-based approaches are more powerful as closer to the real world.

Keywords: Agent-based modelling; decision making; residential heating; large survey; agent heterogeneity.

NONMENCLATURE

Abbreviations	
RS	Residential Sector
GHG	Greenhouse Gas
MUSE	ModUlar energy system Simulation Environment
RASA	ResidentiAl Spatially-resolved and temporal-explicit Agents
ABM	Agent-based modelling
Obj	Investment objective
EAC	equivalent annual cost
CAPEX	Capital costs
OPEX	Operating costs
DM	Decision method
WS	Weighted sum
SE	Same fuel
Lexi	Lexicographic
EC	Epsilon constraint
SR	Search rule
ASHeatPump	Air source heat pumps using electricity
ASHeatPumpNG	ASHeatPump using natural gas as a backup

1. INTRODUCTION

China has been increasing the energy consumed in the residential sector (RS), with a significant impact on current and future Greenhouse Gas (GHG) emissions and on meeting carbon neutrality targets [1]. To answer some questions, it is critical to include residential energy consumption in energy modelling and planning. In particular, how will the energy mix in Chinese RS change? What kinds of technologies will be prevalent in Chinese RS? What are the driving forces behind the transition to clean technologies and clean fuels in the RS? To answer these questions, while macro-level (national or regional)

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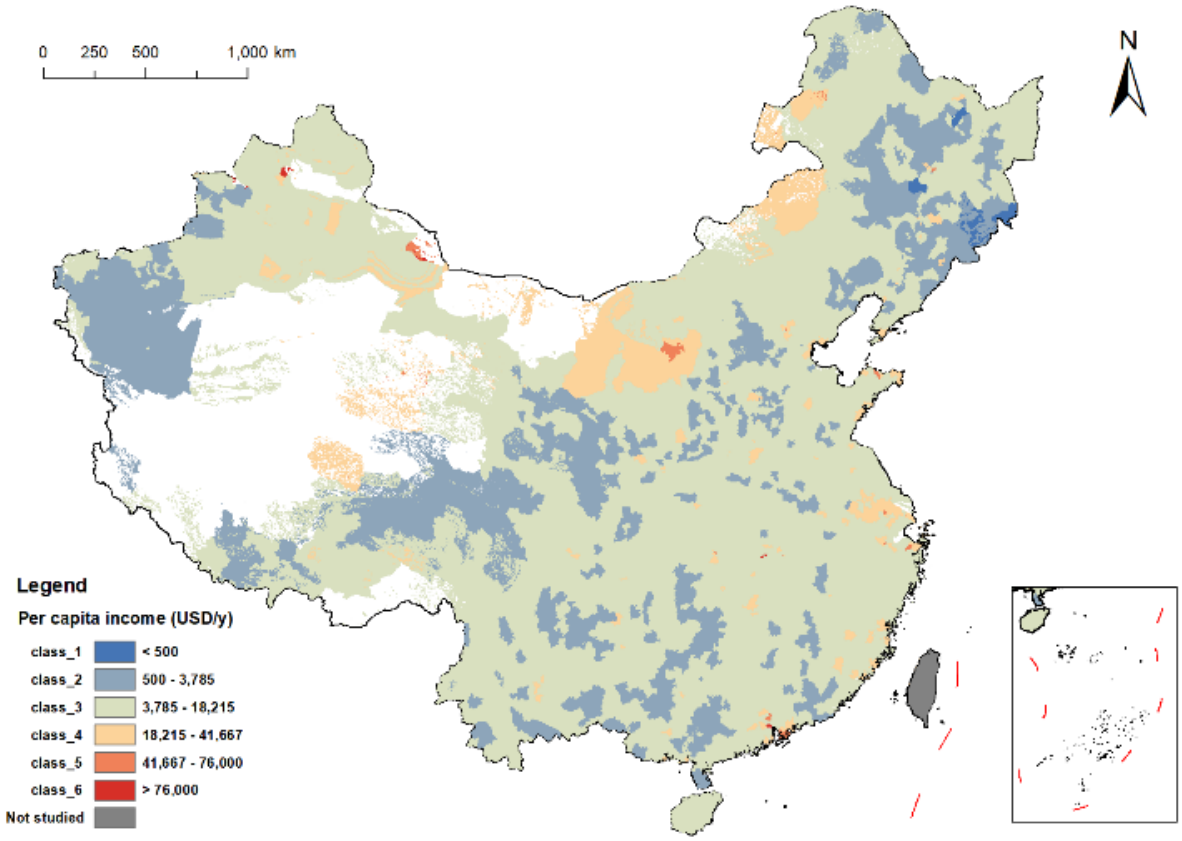

Fig. 1. Spatial distribution of the six agents classified by per capita income.

research can only contribute to the overall planning and design of energy transitions, these changes will be the result of the human behaviour which can be captured in micro-level modelling. While the two approaches are typically separate because of modelling and data availability, this work bridges such a knowledge-gap proposing a modelling framework integrating macro with micro-level modelling using a spatially-resolved and survey-grounded agent-based modelling of the transition of the RS in China.

The novelty of this approach is the consideration of real-world decision-making factors to define agent dynamics in energy modelling and planning with a focus on the residential sector. This research is unique in comparison with previous studies in that heterogeneous characteristics, diverse socioeconomic attributes, and evolving macroeconomic drivers shape the decision-making process of individual agents under exogeneous constraints. This novel approach collects primary data from a nationwide survey and combines it with gridded data to be used as inputs in the novel MUSE-RASA model [2].

This research parametrizes agent decision-making from a large survey to be used as inputs within the MUSE (ModUlar energy system Simulation Environment) framework presented in [2], which outlines the MUSE-RASA* model (*ResidentiAl Spatially-resolved and temporal-explicit Agents). The primary goal of this research is to characterize consumer agents for household heating/cooling system investment in China. In particular, the large-scale questionnaire survey provides a realistic basis for agent-based modelling (ABM) which considers the heterogeneity of decision-makers using socio-demographic factors and subjective criteria (e.g., investment motivation choices) to determine preferences for energy technologies (e.g., renewables, efficient, and low cost). The proposed model structure allows for a more detailed investigation of technology adoption by identifying the factors influencing the decision-making process of agents.

The work is organised as follows. Section 2 presents a review of the literature on energy use behavior in RS, as well as the use of ABM for energy transition assessment and surveys to characterise consumer agents. The ABM framework and questionnaire design used in this study are presented in Section 3. Section 4 presents the results in terms of agent classification and location, as well as agent characterisation for future RS transition ABM in China. Finally, Section 5 concludes the study.

Table 1. Agent characterization from the national survey in China.

Type	Agent	Obj1	Obj2	Obj3	ObjW1	ObjW2	ObjW3	SR	DM	Budget MUSD/PJ
New	1	efficiency	EAC	OPEX	0.41	0.29	0.30	S	Lexi	13
	2	efficiency	EAC	OPEX	0.39	0.32	0.29	S	Lexi	10
	3	efficiency	EAC	OPEX	0.37	0.35	0.27	S	Lexi	6
	4	efficiency	EAC	environment	0.35	0.35	0.30	S	Lexi	1.5
	5	efficiency	EAC	fixed costs	0.33	0.33	0.33	S	WS	0.5
	6	EAC	CAPEX	environment	0.44	0.23	0.33	S	Lexi	0.4
Retrofit	1	efficiency	EAC	OPEX	0.29	0.34	0.36	S	WS	14
	2	efficiency	EAC	OPEX	0.38	0.32	0.29	S	Lexi	9
	3	efficiency	EAC	OPEX	0.39	0.32	0.30	S	Lexi	5
	4	efficiency	EAC	fixed costs	0.40	0.32	0.28	S	Lexi	1.3
	5	efficiency	EAC	fixed costs	0.29	0.34	0.37	S	Lexi	0.4
	6	EAC	environment	efficiency	0.43	0.25	0.32	E	EC	0.3

Note: Six agents were identified to invest in new technologies and upgrade current ones. SR, search rule; S, same system; E, same energy; DM: Decision Method, WS: Weighted Sum, Lexi: Lexicographic, EC: Epsilon constraint.

2. METHODOLOGY

Using an empirical methodology, the paper embeds heterogeneity in the investment for heating and cooling in Chinese households proposing: a systematic survey to characterize residential agents as real-world decision-makers, a spatial distribution of residential agents based on high-resolution gridded economic data.

A nationwide questionnaire survey was conducted in China to characterize agentsm. Each questionnaire survey included at least one professional response to ensure the validity of the data. Agents were classified based on their income using statistical analysis of the data. Finally, the survey was used to extract the agent characteristics and define the decision-making process. This research consisted of four major steps: (1) a review of the literature on agent characterization, (2) the design and implementation of a survey, (3) survey-based agent classification, and (4) agent characterization.

To describe the investment behavior of a region's population, several representative agents are defined and endowed with a set of attributes, as explained by Giarola, et al. [3], Sachs et al. [4] and Moya, et al. [5]. The framework of MUSE-RASA model is used in the study, which is a geospatial agent-based Modelling framework based on both (i) Shaikh's Theory of Real Competition developed in [6] and (ii) Crooks' framework to combine GIS with ABM developed in [7] and [8]. The MUSE-RASA model has been applied to assess the long-term transition of the climate-energy-economy system, with a focus on the residential sector of China and its impact on reaching the mid-century NZE target. The MUSE-RASA model is an enhanced version of the MUSE model developed for the residential sector in [4] and the industrial sector in [9]. The complete MUSE framework can be found in [3].

3. RESULTS AND DISCUSSION

3.1 Agent classification and location

Figure 1 shows how the Chinese population was divided into six categories, classes, based on per capita income. The data were obtained from [10] and calibrated with [11] for 2019. Class 1 has a per capita income of less than $500 USD per year and is primarily concentrated in Northwest and Northeast China. Other classes can be found in the whole country.

3.2 Agent description

Table 1 presents the nine characteristics of each agent as obtained from the analysis of the surveyed data. The population is divided into households needing new heating/cooling systems, as well as agents who need to upgrade or maintain (retrofit) their existing heating/cooling systems. Several investment objectives (Obj) were identified (EAC–equivalent annual cost, technology efficiency, CAPEX–capital costs, OPEX–operating costs, fixed costs, environemnt–environmental costs) and prioritized based on the decision method (DM) to which each agent responds.

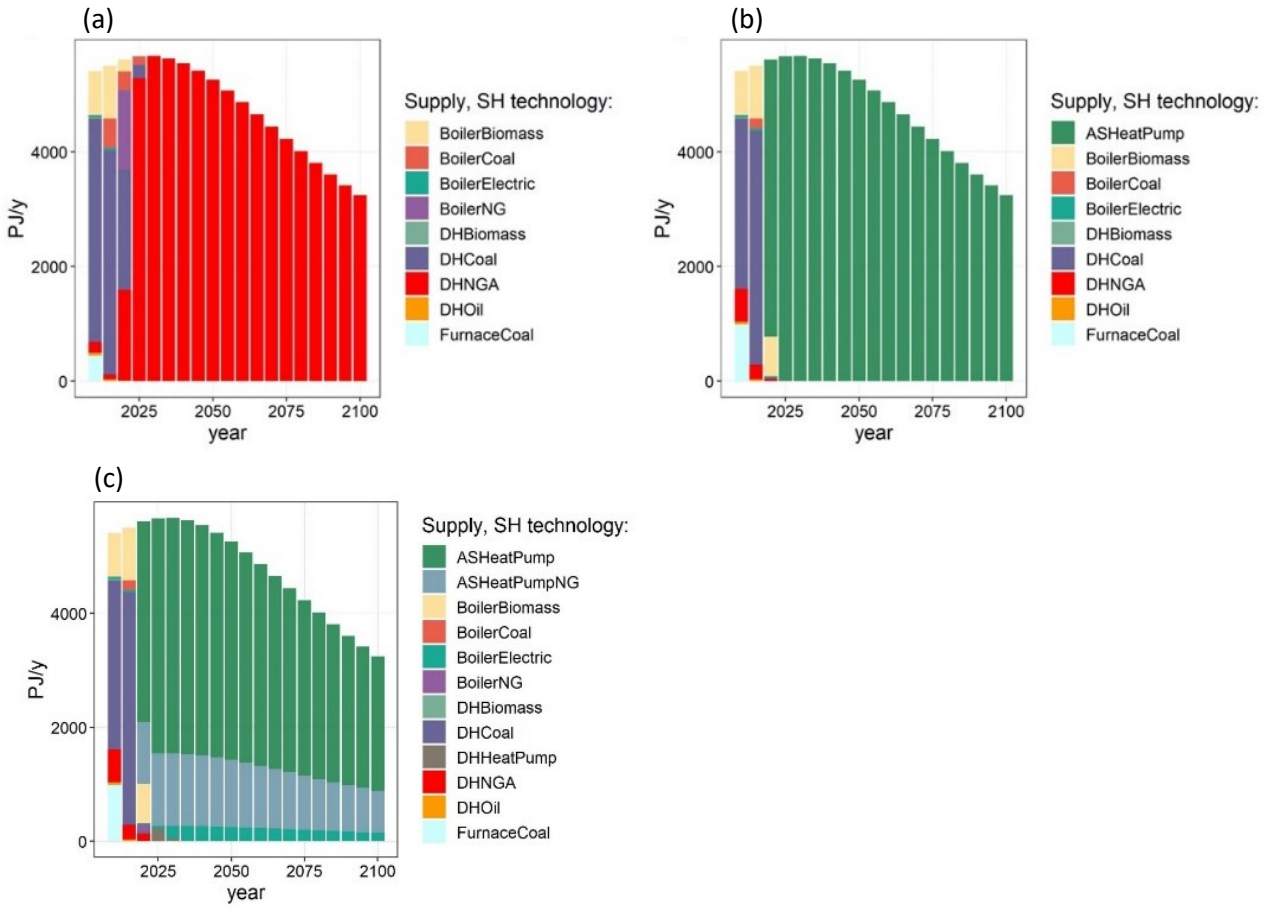

Fig. 2. Long-term technology supply in the Chinese residential sector services when considering a single representative: (a) hyper-rational agent without carbon price, (b) hyper-rational agent with carbon price as exogenous constraints and (c) six bounded rational agents under a carbon price scheme as an exogenous constraint.

The DM can weigh the objectives (WS), or sort them (Lexi), or maximise the first subjected to conditions on the next two (EC). Agents could allocate a maximum budget to the investment they make, measured in MUSD/PJ of delivered energy. A search rule represents how new heating/cooling technologies are bought, either preferring the same type of technology (SS, e.g. boiler, stove) or the same fuel (SE) as the previous investment made.

3.3 Agent simulation and validation

Fig.2(a), (b) and (c) compare an approach based on a single agent with one based on multiple agents applying a survey-informed decision-making for heating/cooling investments. A more realistic decision-making produces a smoother transition to a wider technology portfolio. In the single-agent scenario, there is a single technology that dominates the market. In presence of multiple consumers, electric boilers, air source heat pumps using electricity (ASHeatPump), and ASHeatPump using natural gas as a backup (ASHeatPumpNG) were dominant in the long-term transition. The higher market fragmentation, although an approximation of the real-world, is deemed closer to real market behaviours.

4. CONCLUSIONS

This research has demonstrated the relevance of heterogeneous decision-making in the residential sector. In comparison with a single-agent (consumer) market, a disaggregated market would lead to a varied technology portfolio where not a unique technology would dominate the market.

Future research should consider a deeper disaggregation of the six agents used to represent Chinese households and a more accurate estimation of the technology stock. A major limitation would be the data availability, as no comprehensive database would provide such information and could be overcome extending the breadth of the data gathered in a next survey campaign.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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