Agent-Based Modeling as an Integrative Framework for Household Energy Transition

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Abstract. This paper presents a methodological framework that resulted in two agent-based models for analyzing household heating transitions. The framework is grounded in two dedicated, nationally representative surveys in Serbia and integrates engineering data with behavioral insights to connect micro-level decisions to macro-level outcomes. Model 1 applies a compact techno-economic rule to minimize total (CAPEX+OPEX) costs under policy and price scenarios. Model 2 enriches the decision space with income, affordability constraints, and the investment history of households. Both models incorporate peer effects - each with its own specification - to capture how local adoption shapes household preferences over time. Together, the models quantify system-mix shifts, energy use, investment intensity, and emissions, and support sensitivity testing across prices, subsidies, technology availability, and social influence parameters. Overall, the framework demonstrates that ABM can serve as a bridge between technical and social perspectives, while remaining easily adaptable, upgrade-ready, and suitable for coupling with other energy models.

Keywords: Agent-Based Modeling, Energy Planning, Households

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CONTENT

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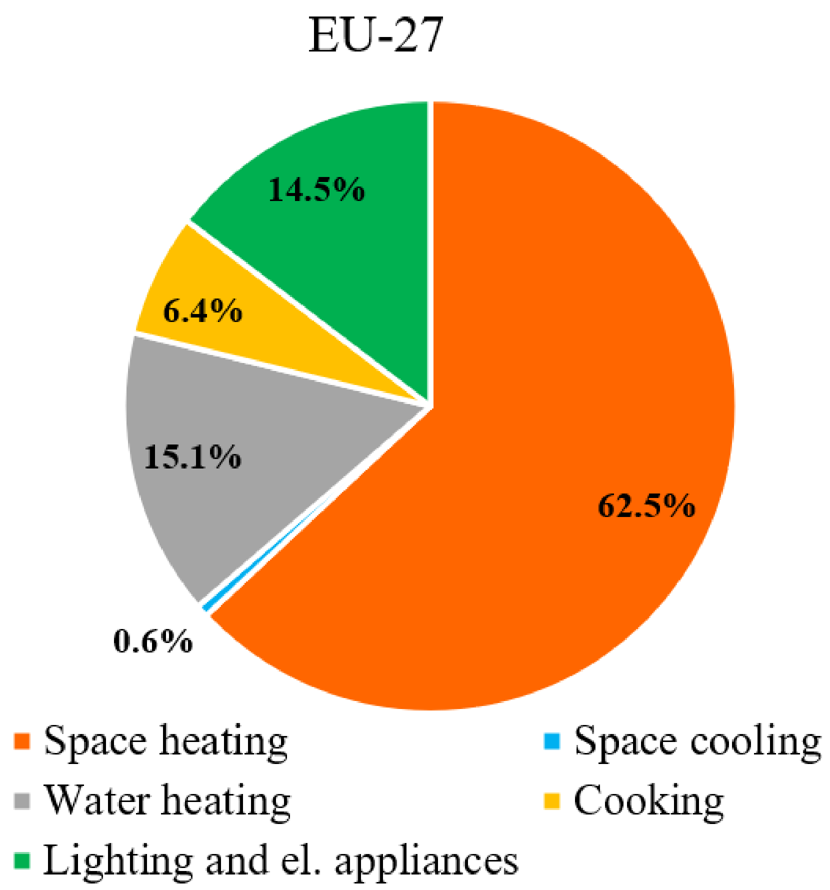
- METHODOLOGY
- RESULTS – CASE OF SERBIA
- CONCLUSION

INTRODUCTION

- The global energy transition is moving toward:
  - decarbonization,
  - higher energy efficiency, and
  - greater use of renewable energy sources.
- This process depends not only on technology and policies, but also on the behavior of final energy consumers.
- The adoption of new technologies is shaped by economic, social, and local conditions.
- A current trend: the development of more comprehensive energy transition models to provide policymakers with more realistic estimates of policy impacts before implementation.
- The **household sector** is often highlighted as a challenging area in energy transition planning.

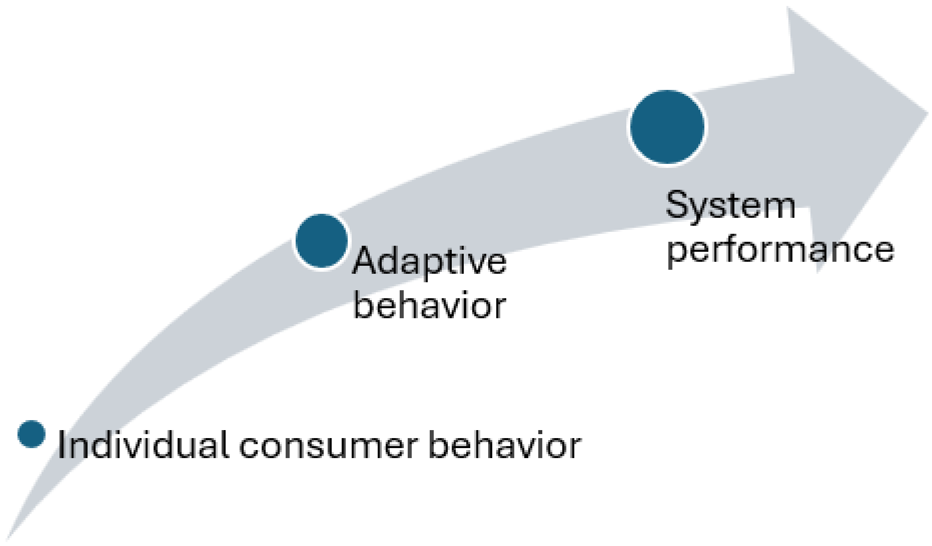
INTRODUCTION

- In 2023, household sector, represented 26.2% of final energy consumption in the EU.
- Disaggregated final energy consumption in households:

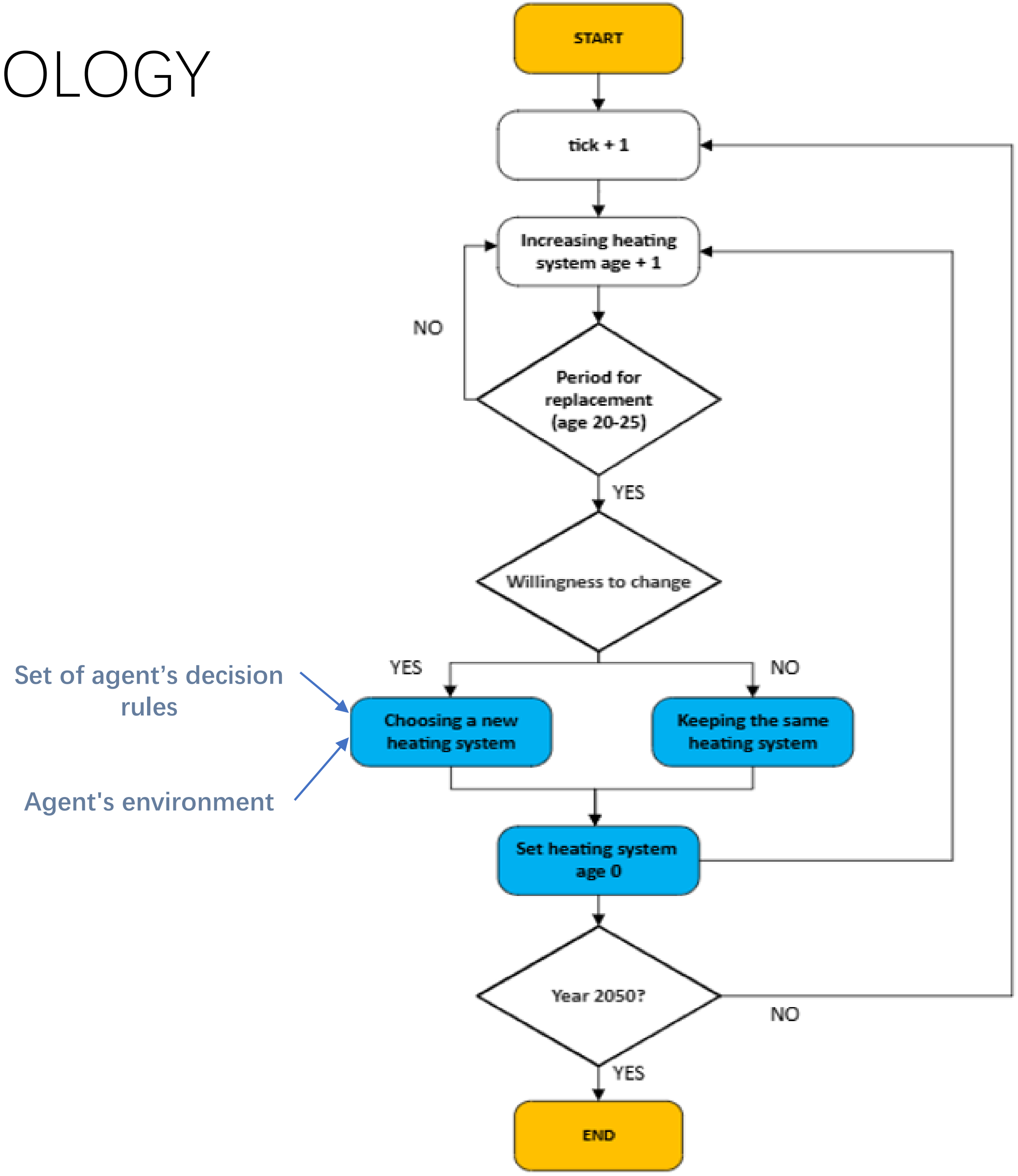


OBJECTIVE

- The main objective of the research – to develop an approach that can support energy planning by simulating household behavior in terms of heating, based on a rich set of empirical household data and a bottom-up simulation design.
- Agent-based modeling approach is used – simulation approach where individual agents (households) make decisions based on their characteristics and interactions, allowing complex system behavior to emerge.
- The simulation:



METHODOLOGY



Household-Level Input Variables

Category	Model 1: Variables	Model 2: Variables
Identity and Network	agent ID (R) linked neighbors (R)	agent ID (R) linked neighbors (R) number of neighbors with modern heating (R)
Location	urban (S) rural (S) extra urban (S)	urban-rural (binary) (S) ad-dhs (district heating system coverage) (S)
Heating System	heat-system (S) system-age(S)	heat-system (S) system-age (S) modern-system (yes/no) (S)
Housing Characteristics	house-size (S) (3 classes)	house-size (S) (4 classes, indexed for CAPEX lists)
Economic Variables	house-wtp (S) (willingness-to-pay factor)	house-wtp (S) house-income (S) pv-solar-willingness (S)
Energy Use and Efficiency	annual energy demand (kWh) (S) system efficiency (S)	annual energy demand (kWh) (S) system efficiency (S) energy efficiency (EE)-measure history (S)
Behavioral Factors	unwilling-to-change (S) neighboring-effect (R)	unwilling-to-change (S) neighboring-effect (R) behavioral response by income threshold (S)
Policy and System Dynamics	DHS migration embedded via annual assignment (R) EE improvements assumed historically (R)	Eligibility for EE upgrades based on survey responses (S)

Decision Logic

Cost per option j:

$$C_j = (\text{CAPEX}_j \times (1 - s_j) + p_j \times \frac{E}{\eta_i}) \times w_j$$

Where:

- CAPEXj = Investment cost of system j
- s_j = Subsidy rate (applied only to modern systems)
- p_j = Fuel or electricity price for option j (EUR/kWh)
- E = Annual heat demand (kWh/year)
- η_j = System efficiency of option j; for heat pumps,
- w_j = willingness to pay more if option j is a modern system

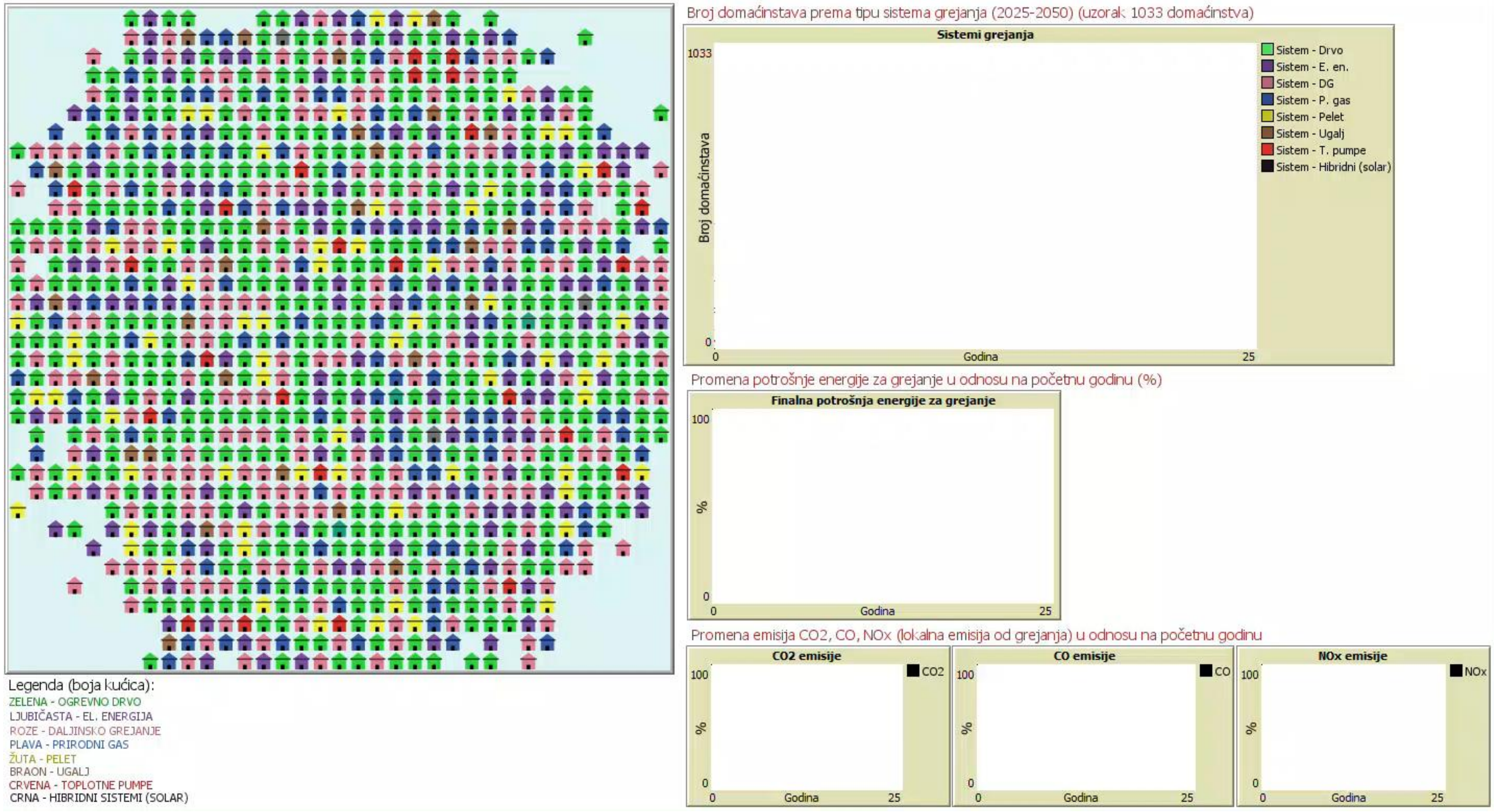
Affordability condition (only Model 2):

$$\textit{Affordable if: } CAPEXj \times (1 - sj) \leq B$$

Where:

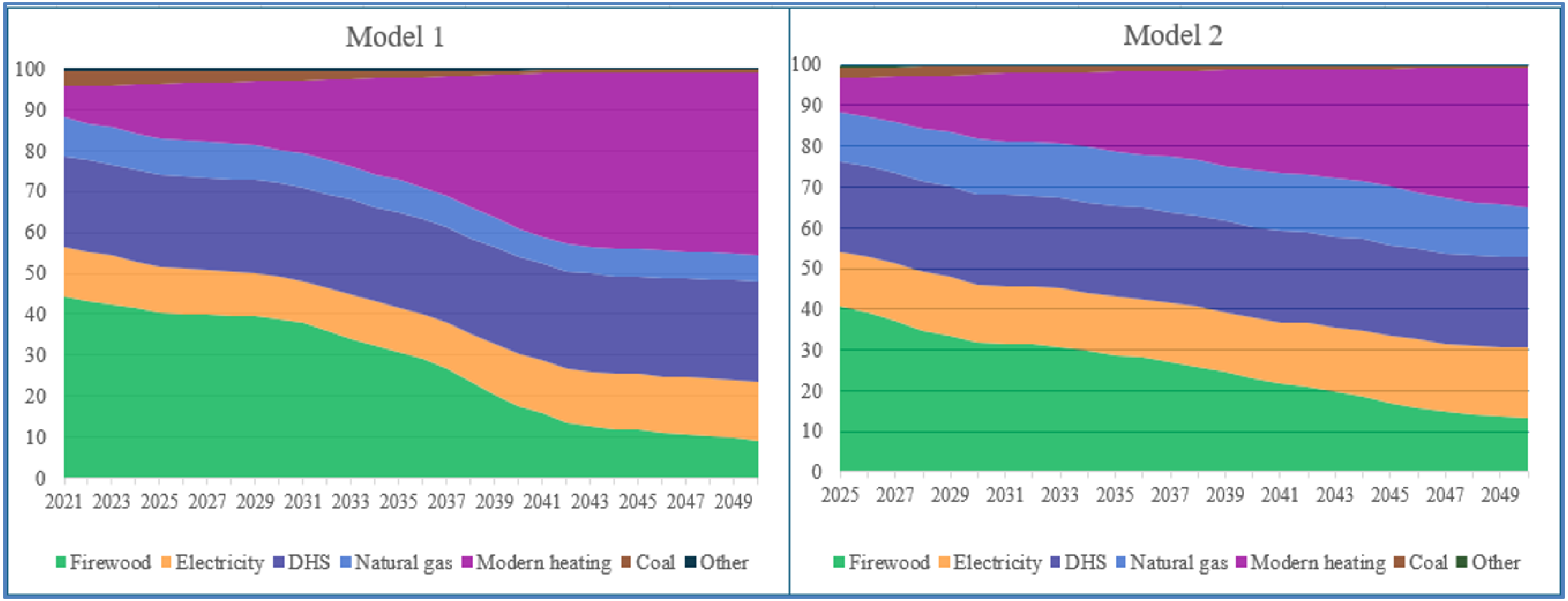
- B = household's available budget for investment (e.g. savings or credit capacity)

RESULTS



Legenda (boja kućica):
ZELENA - OGREVNO DRVO
LJUBIČASTA - EL. ENERGIJA
ROZE - DALJINSKO GREJANJE
PLAVA - PRIRODNI GAS
ŽUTA - PELET
BRAON - UGALJ
CRVENA - TOPLOTNE PUMPE
CRNA - HIBRIDNI SISTEMI (SOLAR)
Broj domaćinstava prema tipu sistema grejanja (2025-2050) (uzorak 1033 domaćinstva)
Sistemi grejanja
1033
0
Broj domaćinstava
0
Godina
25
Sistem - Drvo
Sistem - E. en.
Sistem - DG
Sistem - P. gas
Sistem - Pelet
Sistem - Ugalj
Sistem - T. pumpe
Sistem - Hibridni (solar)
Promena potrošnje energije za grejanje u odnosu na početnu godinu (%)
Finalna potrošnja energije za grejanje
100
%
0
0
Godina
25
Promena emisija CO2, CO, NOx (lokalna emisija od grejanja) u odnosu na početnu godinu
CO2 emisije
CO2
100
%
0
0
Godina
25
CO emisije
CO
100
%
0
0
Godina
25
NOx emisije
NOx
100
%
0
0
Godina
25

RESULTS



Model 1
100
90
80
70
60
50
40
30
20
10
0
2021 2023 2025 2027 2029 2031 2033 2035 2037 2039 2041 2043 2045 2047 2049
Firewood Electricity DHS Natural gas Modern heating Coal Other
Model 2
100
90
80
70
60
50
40
30
20
10
0
2025 2027 2029 2031 2033 2035 2037 2039 2041 2043 2045 2047 2049
Firewood Electricity DHS Natural gas Modern heating Coal Other

Conclusion

- Household diversity matters
- Beyond cost: perceived standard of living, social factors, technical and local conditions, environmental awareness, etc.
- Combining approaches in the same ABM framework
- No single “best” model
- Better data → better realism
- ABM complements other models
- Scalable to other countries

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GreEN
Fast Forward Green

Thank you for your attention!

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