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UNIVERSIDADE Đ
COIMBRA

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MODELING ENERGY COMMUNITIES: A MULTIAGENT FRAMEWORK

PhD thesis in Sustainable Energy Systems supervised by
Professor Carlos Henggeler Antunes and Professor Marta Lopes,
submitted to the Department of Mechanical Engineering, Faculty
of Sciences and Technology of the University of Coimbra.

December 2022

Faculty of Sciences and Technology of the
University of Coimbra

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in the context of the Energy for Sustainability Initiative of the University of Coimbra and MIT-Portugal Program

Supervisors:

Professor Carlos Henggeler Antunes

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This work was supported by grants SFRH/BD/143530/2019 and by projects UIDB/00308/2020 and MAnAGER (PO-CI-01-0145-FEDER-028040), through the European Social Fund, European Regional Development Fund and the COMPETE 2020 Programs, FCT-Portuguese Foundation for Science and Technology, and the Energy for Sustainability Initiative of the University of Coimbra.

ACKNOWLEGMENTS

I would like to express my gratitude to my supervisors, Professors Carlos Henggeler Antunes and Marta Lopes, for their support since the beginning of this project and their guidance throughout the process.

A special thanks to Dr. Ivo Gonçalves for his continuous support, friendship, and countless availability. Much of the success of this journey is due to you and for that I will be eternally grateful.

A special thanks is also due to Professors Humberto Jorge, António Gomes Martins, Álvaro Gomes, and Luís Neves, who provided valuable contributions at different stages of this project and helped to define a course of action. Also, I am incredibly grateful to my lab and PhD colleagues Vahid Rasouli, Nuno Faria, Amadou Mounirah Bissiri, Bruno Cardoso, Pedro Magalhães and Pedro Carrasqueira for their support, patience, and companionship during the most difficult periods.

A formal acknowledgement is due to all the entities which either directly or indirectly supported this project. First, the Institute for Systems Engineering and Computers at Coimbra (INESC Coimbra), which provided all the resources for the development of this project. Second, the Fundação para a Ciência e Tecnologia, for its support through the grant SFRH/BD/143530/2019. Lastly, to the Energy for Sustainability Initiative of the University of Coimbra. To these and all the entities which somehow contributed to this project, thank you.

I am also deeply grateful to the Porto Energy Agency (AdEPorto) for the way I was welcomed and supported over the last months. The practical lessons on how energy communities can be materialized on the ground and the opportunity to see in practice how these initiatives can actually contribute to improving the living conditions of citizens, the ultimate beneficiaries of this entire project, made me realize the real relevance of all this work. To all my colleagues and Engineer Rui Pimenta, thank you very much.

Lastly, I would like to thank to my incredibly supportive family and closest friends for all their understanding, love, and encouragement. Thank you.

ABSTRACT

European energy and climate policies place citizens at the center of the energy transition, encouraging them to take an active role in the distributed generation of renewable energy, promoting energy communities (renewable and for citizens) as key initiatives to achieve the European climate commitments to 2030 and 2050. Energy communities are pointed as strategic tools to leverage private investment in renewable generation, increasing the share of renewable energy sources in countries' energy mix, playing a key role in balancing electricity demand and supply at a local level, in addition to envisioning a socio-technological transition with structural changes both in terms of energy systems and in the behavioral and role shift of energy consumers. However, energy communities are taking their first steps in many European countries and challenges keep coming. This thesis addresses some of these challenges, focusing on the main technical, social, and organizational dimensions underlying a collective energy project from the modeling point of view. The thesis aims to contribute to the planning of incentive programs and more effective energy policies. It analyzes collective energy projects through quantitative and qualitative lens, thus allowing to fully understand the benefits of such projects and realize:

- *What forms can energy communities take?*
- *How can they be modeled in their most diverse potential and dimensions?*
- *How can collective energy initiatives contribute to bringing and engaging all citizens in the energy transition?*

Given the complex nature of energy communities, involving different actors occupying different roles in the electricity sector value chain (including distribution network operators, retailers, aggregators, consumers, etc.) and activities (including consumption, generation, storage, purchase and sale, etc.), and being influenced by different variables in the economic, legal, technological and social domain, a multidisciplinary approach supported by a comprehensive analysis of energy communities' context and complemented by a modeling approach is proposed. Through the exploitation of simulation and optimization methodologies addressing optimal energy resource management models, supported by social science tools to identify actors, roles, expectations, and preferences, and by analyzing business models in collective energy contexts, a multidisciplinary modeling approach is presented with a view to quantifying the energy self-sufficiency of energy communities and the energy and economic benefits unfold in such contexts. Different configurations and energy resources are exploited, using a scenario-based approach with case studies to contextualize the proposed methodology and quantify the benefits of such projects. The results indicate that energy communities can reach different energy self-sufficiency levels depending on the energy resources they have, benefiting those that exploit combined local generation, storage, and demand management strategies - an average of 73% energy self-sufficiency can be achieved in a community scenario with prosumers adopting demand management strategies based on price signals from the grid and benefiting from a collective system of renewable generation and storage. The results also show that the interaction of members with complementary demand profiles (e.g., households and companies) is beneficial for maximizing the community self-sufficiency since, due to the complementarity of those profiles, PV generation can be used more efficiently at the local level, minimizing the injection of renewable energy into the grid. Additionally, the presence of members who play different roles (e.g., consume, produce, store) and who have different individual goals to explore in a collective context (e.g., members who privilege economic savings vs. comfort standards in energy services usage) is beneficial. Having proven the advantage of the heterogeneity of profiles in a community context, this issue should be reinforced from a technical and regulatory point of view so that users and entities who, in principle, would be left out of these models (e.g., socially disadvantaged users), are included and benefit from the economic, energy and social benefits ofenergy communities.

In turn, a more qualitative analysis is performed to understand and characterize the context in which community energy projects are emerging, how are they being framed from a regulatory standpoint and how are they being designed to mitigate issues as energy poverty. This analysis allowed to draw conclusions on how policymaking should evolve to enhance the dissemination of these initiatives. Further, the analysis allowed to realize that, to fully address the potential of community energy projects, it is therefore necessary to: i) stabilize the regulatory framework; ii) clarify market agents about the role they are expected to play and what new and added-value products and services can be developed in and through energy communities, giving rise to innovative business models; iii) to strengthen and provide the power grid with smart grid functions (e.g., smart meters with bidirectional communication capability, control functions, automated demand management programs and technologies, etc.); and iv) foster the heterogeneity of participants and the inclusion of vulnerable users in collective energy projects, ensuring that the energy transition is indeed effective, inclusive and fair.

By addressing renewable-based energy communities from a comprehensive and multidisciplinary perspective, this thesis expects to have given rise to a set of conclusions to be analyzed by policy makers and project promoters, opening room to the implementation of decentralized, technically efficient, carbon neutral and accessible-to-all energy systems.

Keywords: Renewable energy communities; Citizen energy communities; Local Energy Communities; Multi-agent systems; Modeling; Optimization; Business models; Self-sufficiency

RESUMO

As políticas europeias de energia e clima colocam o cidadão no centro da transição energética, encorajando-o a assumir um papel ativo na produção descentralizada de energia renovável, promovendo as comunidades de energia (renovável e para os cidadãos) como iniciativas-chave para atingir os compromissos climáticos Europeus no horizonte 2030 e 2050. As comunidades de energia são apontadas como ferramentas para alavancar o investimento privado na produção renovável, aumentando a participação das fontes energéticas renováveis no *mix* energético dos países, desempenhando um papel fundamental no equilíbrio da procura e oferta de eletricidade a nível local, além de perspetivarem uma transição sócio tecnológica com mudanças estruturais tanto ao nível dos sistemas de energia, como do papel e comportamento dos consumidores de energia. Porém, as comunidades de energia estão a dar os primeiros passos em muitos países europeus e os desafios sucedem-se. Esta tese aborda alguns destes desafios, focando as principais dimensões técnicas, sociais e organizacionais subjacentes a um projeto coletivo de energia do ponto de vista da modelação, de modo a contribuir para o planeamento de programas de incentivo e políticas energéticas mais eficazes. Este trabalho foca três questões-chave:

- *Que formas podem as comunidades de energia assumir?*
- *Como podem ser modeladas nas suas mais diversas valências e dimensões?*
- *Como podem as iniciativas coletivas de energia contribuir para trazer e envolver todos os cidadãos na transição energética?*

Dada a natureza complexa associada às comunidades de energia, envolvendo diferentes atores que ocupam diferentes papéis na cadeia de valor no setor elétrico (incluindo operadores da rede de distribuição, comercializadores, agregadores, consumidores, etc.) e atividades (incluindo consumo, geração, armazenamento, compra e venda, etc.), e sendo influenciadas por diferentes variáveis do domínio económico, legal, tecnológico e social, é necessária uma abordagem multidisciplinar com forte ligação ao enquadramento regulatório. Através da exploração de metodologias de simulação e otimização para exploração de modelos de gestão ótima de recursos energéticos, apoiadas por ferramentas das ciências sociais para identificação de atores, papéis, expectativas e preferências, e pela análise de modelos de negócio em contextos coletivos de energia, é proposta uma abordagem multidisciplinar de modelação com vista à quantificação da autossuficiência energética de comunidades de energia e aos benefícios energéticos e económicos que podem existir nestes contextos. São exploradas diferentes configurações e recursos energéticos, utilizando uma abordagem de cenarização com casos de estudo para contextualizar a metodologia proposta.

Os resultados indicam que as comunidades de energia podem atingir diferentes níveis de autossuficiência energética consoante os recursos energéticos de que dispõem, sendo beneficiadas as que aliam produção local, armazenamento e estratégias de gestão da procura – média de 73% de autossuficiência energética num cenário com *prosumers* que adotam estratégias de gestão da procura em função de sinais de preço do sistema elétrico e usufruem de um sistema coletivo de geração renovável e armazenamento. Os resultados mostram também que a interação de membros com perfis complementares de procura (ex. agregados familiares e empresas) é benéfica para a maximização da autossuficiência de uma comunidade de energia uma vez que, devido à complementaridade dos perfis de procura, a produção de origem fotovoltaica pode ser usada mais eficientemente a nível local, minimizando a injeção na rede. Adicionalmente, a presença de membros que desempenham papéis diferentes (ex. consomem, produzem, armazenam) e que têm diferentes objetivos individuais no contexto coletivo (ex. membros que privilegiam poupanças económicas vs. membros que privilegiam padrões de conforto no uso de serviços energéticos) é benéfica nestes modelos. Sendo comprovada a vantagem na heterogeneidade de perfis em contexto comunitário, esta questão deverá ser reforçada do ponto de vista técnico e regulamentar, para que utilizadores vulneráveis que, por princípio, ficariam à margem destes modelos (ex. utilizadores socialmente desfavorecidos ou com baixa literacia energética), sejam incluídos e beneficiem das vantagens económicas, energéticas e sociais das comunidades de energia.

Em conclusão, de modo a explorar o potencial de projetos comunitários de energia no seu todo, é assim necessário: i) estabilizar o enquadramento regulatório; ii) esclarecer os agentes de mercado acerca do papel que se espera que desempenhem e que novos produtos e serviços podem ser desenvolvidos através destes modelos coletivos, dando origem a modelos de negócio inovadores; iii) robustecer e dotar a rede elétrica de infraestruturas de redes inteligentes (contadores inteligentes com comunicação bidirecional, automatismos de controlo, programas e tecnologias de gestão automatizada da procura, etc.); e iv) fomentar a heterogeneidade de participantes e a inclusão de utilizadores vulneráveis em projetos coletivos de energia, garantindo que a transição energética é de facto eficaz, inclusiva e justa.

Palavras-chave: Comunidades de energia renovável; Comunidades de energia para os cidadãos; Comunidades Locais de Energia; Sistemas multiagente; Modelação; Otimização; Modelos de negócio; Autossuficiência

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Research paper II	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. *Business models for energy communities: A review of key issues and trends.* Renewable and Sustainable Energy Reviews, Vol. 114(7), pp. 111013, 2021. https://doi.org/10.1016/j.rser.2021.111013
Research paper III	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. *Assessing the Influence of Different Goals in Energy Communities' Self-Sufficiency—An Optimized Multiagent Approach.* Energies, Vol. 14(4), pp. 989, 2021. https://doi.org/0.3390/en14040989
Research paper IV	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. *Towards inclusive community-based energy exchanges: A multiagent framework*. Applied Energy, Vol. 307, pp. 118115, 2022. https://doi.org/10.1016/j.apenergy.2021.118115
Research paper V	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. *Collective self-consumption in multi-tenancy buildings–To what extent do consumers' goals influence the energy system's performance?* Sustainable Cities and Society, Vol. 80, pp. 103688, 2022. https://doi.org/10.1016/j.scs.2022.103688
Research paper VI	Reis, I. F. G., Pimenta, R., Gonçalves, I., Lopes, M.A.R., Antunes, C. H. *Fighting energy poverty through local energy communities: Insights from Portugal*. In Sokolowski, M. M., Visvizi, A., Energy Communities and Smart Cities, Elsevier Smart Cities Book Series (In press)
Research paper VII	Reis, I., Lopes, M.A.R., Antunes, C.H. (2018) Energy exchanges within an energy community: an agent-based modelling approach. SEST – 1st International Conference on Smart Energy Systems and Technologies; Seville, 10-12 September. DOI: 10.1109/SEST.2018.8495635
Research paper VIII	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C.H. *Residential demand-side flexibility in energy communities: a combination of optimization and agent modeling approaches*, SEST – 2nd International Conference on Smart Energy Systems and Technologies, Porto, Portugal, September 2019. DOI: 10.1109/SEST.2019.8849152
Research paper IX	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C.H. *A study of the inclusion of vulnerable consumers in energy communities with peer-to-peer exchanges*. SEST – 3rd International Conference on Smart Energy Systems and Technologies, Istanbul, Turkey, September 2020. DOI: 10.1109/SEST48500.2020.9203312
Research paper X	Reis, I. F. G., Gonçalves, I., Lopes, M.A.R., Antunes, C.H. *A multiagent framework to model the interactions of local energy communities and power systems*. SEST – 4th International Conference on Smart Energy Systems and Technologies, Vaasa, Finland, September 2021. DOI: 10.1109/SEST50973.2021.9543421

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Publication 1*	Bissiri, Amadou M., Reis, I. F. G., Figueiredo, N. C., Silva, P.P. *An econometric analysis of the drivers for residential heating consumption in the UK and Germany*. Journal of Cleaner Production, Vol. 228, pp. 557-569, 2019. https://doi.org/10.1016/j.jclepro.2019.04.178

Publication 2	Reis, I. F. G., Lopes, M.A.R., Antunes, C. H. *Energy literacy: an overlooked concept to end users' adoption of time-differentiated tariffs*. Energy Efficiency, Vol. 14(39), pp. 1-16, 2021. https://doi.org/10.1007/s12053-021-09952-1
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Publication 9	Reis, I. F. G., Lopes, M.A.R., Antunes, C. H. *How much demand-side flexibility can a community deliver? A multi-agent modeling approach.* eceee 2019 Summer Study on energy efficiency: Is efficient sufficient? Proceedings, Belambra Presqu'île de Giens – France. ISBN: 978-91- 983878-5-8 (online)/ 978-91-983878-4-1 (print)
Publication 10	Lopes, M.A.R., Reis, M.A.R., Antunes, C. H. *Unfolding organisational and behavioural demand response in SMEs toward smart(er) energy communities*. eceee 2019 Summer Study on energy efficiency: Is efficient sufficient? Proceedings, Belambra Presqu'île de Giens – France. ISBN: 978-91-983878-5-8 (online)/ 978-91-983878-4-1 (print)
Publication 11	Reis, I., Lopes, M.A.R., Antunes, C.H. (2018) *Dynamic tariffs: How does literacy, decision style and loss aversion influence end-users' decisions?* 5th European Conference on Behaviour and Energy Efficiency – BEHAVE 2018; Zurich, 5-7 September. DOI: 10.21256/zhaw-1370
Publication 12	Lopes, M.A.R., Antunes, C.H., Reis, I., Martins, A.G. (2018) *A Multidisciplinary approach to assess end-users´ preferences and quantify electricity demand flexibility*. 5th European Conference on Behaviour and Energy Efficiency – BEHAVE 2018; Zurich, 5-7 September. DOI: 10.21256/zhaw-1370
Publication 13	Silva, C. Oliveira, C.H. Antunes, C. Silva, D., D. Coelho, I. Reis, J. Sousa, J. L. Sousa, L. Moreira, L. Marcelino, L. Neves, M. Lopes, V. Gonçalves. (2018) *Learning with students about energy consumption behaviors*. 5th European Conference on Behaviour and Energy Efficiency – BEHAVE 2018; Zurich, 5-7 September. DOI: 10.21256/zhaw-1370

Publication 14	Lopes, M.A.R., Reis, I., Antunes, C.H. (2018) *How does literacy, decision style and loss aversion influence end-users' choice of electricity dynamic tariffs in a smart grid context?* 29th European Conference on Operational Research – EURO 2018; Valencia, 8-11 July.
Publication 15	Lopes, M.A.R., Antunes, C.H., Bernardo, H., Jorge, H., Reis, I. (2017) *Energy use feedback: A behavioural OR approach toward better decisions and more efficient energy behaviors*. 21st Conference of the International Federation of Operational Research Societies – IFORS 2017; Québec, 17-21 July.

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LIST OF ABBREVIATIONS

ABM	Agent-based models
AC	Air conditioning
AHEMS	Automated home energy management system
AI	Artificial intelligence
AMI	advanced metering infrastructure
AOP	Agent-oriented programing
BM	Business models
BMC	Business model canvas
CEC	Citizen energy community
CEI	Collective energy initiatives
CRSC	Collective renewable self-consumption
DAI	Distributed artificial intelligence
DGEG	Directorate of Energy and Geology
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
DW	Dishwasher
ECBM	Energy community business models
EE	Energy efficiency
EED	Energy efficiency directive
EPBD	Energy performance buildings directive
ERSE	Portuguese Energy Regulator
ESCO	Energy service companies
EU	European Union
EV	Electric vehicles
EWH	Electric water heater
FiT	Feed-in-tariff
G2V	Grid-to-vehicle
GA	Genetic algorithm
GD	Generation-demand ratio
HEMS	Home energy management system
ICT	Information and communication technologies
IDE	Integrated development environment
IEMD	Directive on the common rules for the internal electricity market
KPI	Key performance indicators
LC	Lean canvas
LEC	Local energy communities

LEM	Local energy market
LM	Laundry machine
MAS	Multiagent systems
MCDA	Multi-criteria decision aiding
MTB	Multi-tenancy buildings
NECP	National energy and climate plans
NSGA-II	Non-dominated sorting genetic algorithm II
P2P	Peer-to-peer
PBM	Physically controlled models
PPA	Power purchase agreement
PSM	Problem structuring methods
PV	Photovoltaic
REC	Renewable energy community
RED-II	Renewable Energy Directive
SCME	Self-consumption management entity
SMEs	Small and medium size enterprises
SoC	State-of-charge
SS	Self-sufficiency
SSM	Soft systems methodology
TCL	Thermostatically controlled loads
TD	Tumble dryer
ToU	Time-of-use
V2G	Vehicle-to-grid
VFT	Value-Focused Thinking

1. INTRODUCTION[A]

This section introduces the local energy communities' topic, frames the research questions, and describes how the document is organized.

1.1. BACKGROUND AND MOTIVATION

As part of the European Green Deal, the European Union (EU) set a compulsory target of achieving climate neutrality by 2050. This ambition requires that, by that date, at least 75% of the total energy demand comes from renewable sources and around 16% of the electricity generation has its origins in collective projects (Kampman et al. 2016; EC 2018a). By that time, almost half of all European households must be involved in renewable energy generation[1], 37% of which should be engaged in collective energy projects (Kampman et al. 2016; REScoop.EU 2018). As a midway step, in July 2021, the EU proposed the "Fit for 55" package, to revise and push some of its targets (net 55% emissions reduction in 2030 compared to 1990 levels instead of the previous 40% reduction target) and policy initiatives as it was concluded that the previously policy framework was insufficient to reach carbon neutrality by 2050 (EP 2021). More recently, in May 2022, the European Commission launched the REPowerEU package which sets the scene for the independence of the EU from Russian fossil fuels (EC 2022). Under this package, the EU Solar Strategy is one of the most expected measures as it unfolds a massive solar photovoltaic (PV) deployment in Europe, setting the goal of 320 GW_{ac} (400 GW_{dc})[2] by 2025 of PV capacity installed and almost 600 GW_{ac} (750 GW_{dc}) target for 2030 (EC 2022). With the EU Solar Strategy, the EU aims to: 1) facilitate and accelerate the deployment of solar PV and the access to sustainable solar products, both through the shortening and simplification of permitting procedures; 2) create a skilled labor force and an EU solar industry capable of producing, installing and maintaining the solar systems; 3) push building owners to take action by enforcing rooftop solar energy production in all new public and commercial buildings with useful floor area larger than 250 m^2 by 2026, all existing public and commercial buildings with useful floor area larger than 250 m^2 by 2027, and all new residential buildings by 2029; and 4) boost municipalities to participate in the energy transition by ensuring that, by 2025, every EU municipality with a population higher than 10,000 people will have at least one renewable energy community in place (EC 2022). These new EU targets place greater focus on distributed renewable energy generation and set the pace towards the EU energy transition where end-users are active players contributing to the management of the power grid as asset holders, investment decision-makersand participants in demand response (DR) programs. This changing paradigm empowering end- users allows for new business models and energy infrastructure ownership configurations to emerge (Rae and Bradley 2012). In this setting, local energy communities (LEC) and collective renewable self-consumption (CRSC), in which end-users become prosumers and prosumagers[3], are gaining momentum both in the literature (Klaimi et al., 2017; Koirala et al. 2018) and in the EU's regulatory framework (CECCE 2018).

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[a] Chapter based on Research Paper I, II and III.

[1] In the scope of this document, only electricity is addressed. Therefore, hereafter, unless otherwise stated, the term energy will be used to refer to electricity.

[2] ac/dc means alternate/direct current, respectively.

[3] Prosumers are users who are consumers and producers of energy whereas prosumagers are users who consume, produce and store energy (Schill et al. 2017).

LEC have been a component of the EU's energy landscape for a long time. North-Western European countries have a long-lasting tradition of implementing renewable-based energy cooperatives to solve supply issues (electricity and heat) in rural and isolated areas (Braunholtz-Speight et al. 2018; Caramizaru and Uihlein 2020). Despite this practice, only recently these initiatives were brought to the EU political agenda due to the pressure exerted by groups of active prosumers aiming to scale up and participate in energy markets (Hahnel et al. 2019). In order to make this possible, while leveraging private investment to hasten the energy transition, the *Clean energy for all Europeans* legislative package, proposed for the first time a formal definition for LEC through the Renewable Energy Directive (RED-II) (Directive 2018/2001/EU) (EC 2018b) and the Directive on the common rules for the Internal Electricity Market (IEMD) (Directive 2019/944/EC) (EC 2019a). These directives were updated to boost the EU's climate and energy policy framework for 2030 providing the first definitions for 'renewable energy communities' (REC) and 'citizen energy communities' (CEC), respectively and setting new rules for individual and collective self-consumption. In both documents, LEC, hereafter used to refer to both REC and CEC, are based on the voluntary participation of shareholders and members, which can be households, small and medium sized enterprises (SMEs) or local authorities (EC 2018b; EC 2019a).

Although LEC and CRSC can encompass several components of the value chain (e.g., generation, distribution, supply, aggregation), in their most elementary forms they are mainly involved in local energy generation and consumption (REScoop.EU 2018). More recently, innovative business models have started to emerge, providing integrated solutions to LEC participants, favoring self-consumption and enabling the combined use of storage, local energy trading, and exchanges with the grid (Caramizaru and Uihlein 2020). Thus, the emergence of collective energy initiatives (CEI) (encompassing both LEC and CRSC) creates the prospects for a social change by shifting the role played by traditional end-users, who have now the opportunity to actively participate in local energy markets. CEI also promote collaborative social transformation by leading local communities to pursue common goals (e.g., energy costs reduction and energy self- sufficiency) (Van Der Schoor and Scholtens 2015), playing a relevant role in local economic growth and job creation, boosting smart grid infrastructures, and providing valuable flexibility services tobe traded in emerging markets, thus speeding up the transition to a low-carbon economy (Koirala et al. 2016).

The activities developed in CEI are expected to advance energy efficiency in households and promote the diffusion of renewable technologies while contributing to mitigate poverty through reduced energy consumption and lower supply tariffs (Caramizaru and Uihlein 2020). The innovation brought by CEI is expected to strengthen the citizens environmental and energy awareness, their willingness to invest and profit from local energy at the same time as local energy resilience is promoted (Caramizaru and Uihlein 2020). CEI have the capability to mitigate energy poverty by facilitating the access of vulnerable consumers to cheaper energy (REScoop.EU 2018; Sloot et al., 2019). Additionally, the full rollout of smart metering as well as the reinforcement and modernization of information and communication (ICT) structures, is key to handle and keep track of the large data flows created in CEI (Aguero et al. 2017). CEI are also expected to reduce power system losses and mitigate grid congestion issues. Thus, the value proposition of CEI is diversified, including local and sustainable energy supply, energy self- sufficiency, active participation of citizens in the energy context, social cooperation, assistance to vulnerable consumers and energy poverty mitigation (Caramizaru and Uihlein 2020). These initiatives are, therefore, often described as drivers of a socio-technological transition since beyond the technological modernization of power systems, social innovation is also fostered (Caramizaru and Uihlein 2020).

The primary purpose of these arrangements is to "provide environmental, economic or social benefits" for their members “rather than financial profits” (EC 2018b; EC 2019a). Although social and environmental benefits are often pointed out as very relevant in engaging community members, the economic benefits are particularly attractive for members’ engagement (Bauwens 2019). As participants are usually financially involved in the creation of these projects, the return of investment, either through self-consumption and bills reduction or by economically benefiting from the sale of surplus generation, is anticipated (Interreg Europe 2018). Additionally, the enabling framework fostered by both IEMD and RED-II is expected to boost innovative business models and attract private and public investment, allowing CEI to become increasingly commercial. CEI are able to diversify their revenue streams by proposing novel energy services in addition to local energy generation, while intermediating entities, alliances, and collaborative relationships among initiatives are promoted (Hall and Roelich 2016; Mirzania et al. 2019). Still, so far, the information on possible and most likely business models to emerge in these contexts is scattered and a comprehensive view of the value proposition, the entities involved, and the value streams is necessary.

In addition to the economic benefit, energy self-sufficiency, perceived as the ability of an energy system being able to run autonomously from the power grid, is a key motivation for end-users to be engaged in CEI (Dóci and Vasileiadou 2015; Engelken et al. 2016; Rae and Bradley 2012; REScoop.EU 2018). In such settings, energy self-sufficiency can be achieved by managing local power generation, storage, and demand, taking advantage of the flexibility of power utilization profiles (Rae and Bradley 2012). Currently, CEI are mainly created by groups of grid-connected private households, located nearby, owning small-scale PV systems (Hahnel et al. 2019). Although the drop in prices of PV in recent years has triggered the dissemination of these systems and the emergence of prosumers, this technology is progressively being complemented with storage systems, both static and mobile (as electric vehicle (EV) batteries), for maximizing residential self-consumption due to the time lag between the periods of solar radiation availability and the residential consumption (McKenna et al. 2019). Demand-side management (DSM) programs can be exploited in these settings to encourage end-users to modify their electricity utilization patterns, in combination with energy storage (Strbac 2008). In general, changes in consumption patterns are triggered by price signals (tariff schemes are designed to penalize consumption in grid congestion periods and less renewable energy availability), end- users’ behavioral changes or automated control over loads (Gelazanskas and Gamage 2014). The benefits of DSM programs are two-fold: end-users may reduce their energy bills by adjusting the timing and amount of electricity utilization, while the energy system can benefit from the shifting of consumption from peak to non-peak hours, reducing congestion. The flexibility of non- residential activities can also be exploited in CEI settings with positive contributions for self-sufficiency due to the complementarity of energy use profiles, which allows for optimizing the use of locally generated energy resources. So far, the distinctive energy consumption patterns of non-residential actors have been neglected and few works have assessed the demand-side flexibility of diversified communities (Voulis et al., 2017).

Also, to develop successful local governance strategies, a comprehensive policy framework based on the deep understanding of the role the different stakeholders involved in CEI will play, their motivations and expectations, must be designed. The diffusion of CEI may encompass several difficulties due to the large investments required, the cost of reverting decisions, and the long- term consequences for a wide range of players, whose support and cooperation is key for the prosecution of plans (Elzen and Wieczorek 2005). In an initial implementation stage and in countries with little experience in CEI, as is the case of Portugal – the country which a large part of this project will focus on - the courses of action may not yet be completely clear to stakeholders, hampering and delaying their decision processes. In this context, traditional assessment models (e.g., cost-benefit analysis) may not be suitable since, on the one hand, the lack of real projects makes it difficult to quantify decision variables and, on the other hand, some of these variables will not be easily quantifiable in monetary units (e.g., social value) (Rosenhead 2013). This explains why assessment alternatives must be explored to guarantee that all the points of view expressing goals, motivations and expectations raised by the actors involved are properly considered. Therefore, assessing collective and individual objectives, translating the different stakeholder interests, as well as evaluating the barriers faced when trying to put projects into motion, is a relevant step for the design of more effective policy frameworks.

1.2. RESEARCH QUESTIONS

As the regulatory framework on CEI is still evolving, new business models are emerging, and different legal forms and governance models must be evaluated. In this setting, the pros and cons of centralized models (i.e., having an intermediate entity) vs. fully decentralized configurations must be assessed to anticipate the computational modeling effort and the real-world implications. Thus, the first research question is:

RQ1: *What is the best configuration of the energy community from a modeling and a real implementation point of view considering the current regulatory framework and the emerging business models?*

The regulatory context determines the activities performed in CEI settings by the different participants and their individual expectations and objectives. Collective participants face decision-making processes that can be complex, since, in addition to individual decisions, they should also consider the project collective objectives. Such decisions can be even more complex if, in addition to all the remaining characteristics of the collective energy system, dynamic pricing schemes are considered to trigger users' cost sensitivity and influence their willingness to participate and perform DR actions. Therefore, the stakeholders of CEI, their expectations, roles as well as individual and collective goals should be clearly identified as they influence the entire energy system development. These issues gave rise to the second and third research questions:

RQ2: *What decisions should be taken individually by each of the agents and what decisions should be taken at community level?*
RQ3: *How can conflicting agents' preferences and goals be incorporated into the modeling process?*

In a renewable-based system aiming to achieve a certain level of self-sufficiency, it becomes relevant to assess which demand flexibility profiles are more interesting to be exploited from the energy system point of view and how the participants having less flexibility (as is the case of residential vulnerable consumers) can be accommodated without compromising the overall system performance. As CEI allow households, SMEs, and public entities to actively participate as members, understanding the extent to which complementary flexibility profiles can be efficiently managed and how can they influence the energy system sufficiency allows for the design of more resilient energy systems. This framework triggered the formulation of the fourth research question:

RQ4: *What is the influence of different demand-side flexibility profiles on the overall collective energy initiative performance?*

To address the gaps identified and the research questions established, a bottom-up modeling approach, based on multi-agent systems (MAS) is developed to exploit the behavioral dimension associated with the decision processes, the organizational dimension related to SMEs and the technical and social dimensions related to managing multiple entities interacting in collective settings. MAS modeling and optimization techniques are combined to simulate and optimize energy use and the available local energy generation, considering end-users' goals, preferences, behavioral practices, and organizational constraints.

1.3. THESIS OUTLINE

This document encompasses seven chapters. Chapter 1 introduces the research problem, the objectives and research questions, and describes the thesis contribution. Chapter 2 reviews the literature on CEI, focusing on definitions, the regulatory framework, the relevant stakeholders, and the need to assess their expectations and perspectives on collective energy projects dissemination as well as the anticipated business models emerging in such settings. In this chapter, the contribution of collective energy initiatives for energy poverty alleviation is also discussed. Chapter 2 also discusses the most common modeling approaches used in collective settings and emphasizes the aptitude of MAS to model distributed energy systems, as is the case of CEI and list the main literature gaps, highlighting the research contribution. Chapter 3 presents the problem structuring methodology used to unveil stakeholders' perspectives and the factors hindering community energy implementation as well as the simulation approach used to model different energy community configurations. The local resources to be managed, the objectives and preferences of community agents and the optimization problems to be solved by agents playing distinct roles in the modeling are fully presented and discussed in this chapter. In Chapter 4, the decision setting in which energy community projects are being promoted as well as the perspectives of different stakeholders are presented and discussed, and simulation results of distinct illustrative cases are described. Lastly, conclusions are drawn on how this thesis answered the initial research questions identified, and future research directions are outlined in Chapter 5.

2. ENERGY COMMUNITIES

This section is divided in two. The first part reviews the literature on energy communities, namely concerning: (i) the existing definitions and regulatory framework, (ii) the enablers and challenges of a successful implementation, (iii) the existing and prospective energy community business models, and (iv) the role of energy communities in energy poverty alleviation. The second section overviews how modeling approaches are being applied to solve CEI problems, focusing on MAS.

2.1. DEFINITIONS AND REGULATORY FRAMEWORK

Already pointing to the 2030 and 2050 horizons, the European Commission launched in November 2016, the so-called *Clean Energy for all Europeans* legislative package which encompasses eight legislative acts presented in Fig.1. The Governance Regulation imposed each Member-State to define 10-year national energy and climate plans (NECPs) for the period 2021 -2030, reflecting a long-term energy and climate view towards 2050. The recasts of the Energy Performance of Buildings Directive and the Energy Efficiency Directive impose more challenging limits on the energy consumption of buildings and equipment. In turn, the reformulation of RED-II and the IEMD, one of the dossiers of the Electricity Market Design package, has brought significant changes to the energy paradigm by enhancing CRSC and establishing REC and CEC, being the first time that the energy community concept was framed from a regulatory point of view. In the scope of this thesis, a special attention is paid to the RED-II and IEMD due to their contribution to boost REC and CEC, respectively, and special attention is paid to LEC due to their diversified range of activities and scope of action.

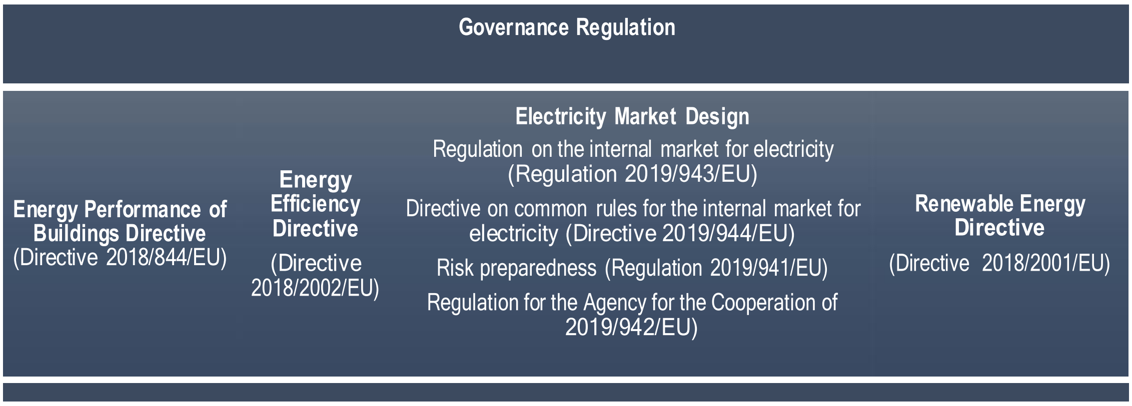

Fig. 1 Clean Energy for all Europeans legislative package (based on https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans).

In November 2018, the European Parliament published the RED-II to boost the spread of renewable energy sources. The Art. 2 of this document defines a REC as "*a legal entity: (a) based on open and voluntary participation, autonomous, and effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity*" (EC 2018b). Although this first regulatory step boosted by RED-II has been important for the promotion of LEC at the European level, many operational issues were still to be defined.

Some of these issues were somehow dissipated by the IEMD. In the Art.2 of this directive, the word "citizens" is introduced in conjunction with "energy communities", highlighting the importance of consumers involvement. CEC, differing from REC presented by RED-II, are also defined as legal entities based on voluntary and open participation of members or partners (EC 2019a). Like REC, the main objective of these initiatives is to provide environmental, economic, and social benefits to its members rather than generating financial incomes and they may be engaged in *"(…) generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles to provide other energy services to its members or shareholders"* (EC 2019a). The Art. 16 goes further by allowing Member-States to grant citizens in energy communities the right to manage the distribution network in their area of operation and establish the relevant procedures, giving greater freedom to these arrangements to implement differentiated pricing mechanisms and targeted DR actions. Also, both definitions assume that community members must be involved in daily decision-making and operation control, and the potential revenues attained must be used to provide local services/benefits. However, the definitions diverge in what concerns (EC 2018b; EC 2019a):

- The geographical scope, since REC require participants to be in the vicinity of renewable projects, while CEC do not set physical boundaries;
- The activities performed, as CEC comprise generation, distribution, supply, consumption, aggregation, energy storage, EV charging, energy efficiency (EE) or other energy services, while REC promote the engagement into generation, trading, storage and supply of energy from renewable sources;
- The generation technologies, since REC only allow for renewable technologies whereas CEC are technology-neutral, meaning that both renewable and fossil-based technologies are acceptable; and
- The membership rules, as CEC consent large companies to participate as members or shareholders if their business is not energy-related, contrarily to REC. This distinction allows communities to be fully controlled by small end-users aiming to benefit from renewable energy or to be deployed in partnership with commercial stakeholders or social entrepreneurs (shared ownership models (Bolton and Hannon 2016; Steinberger et al., 2009)).

Currently, both CEC and REC definitions coexist under the same legislative package. However, whereas the CEC definition aims to set the role for energy communities in the energy market framework, REC focus on supporting the deployment of renewable energy resources.

Although establishing a first step towards harmonizing what is meant by energy community, the definitions presented by the directives are somewhat vague, regarding the concept and its implementation (Hicks and Ison 2018). If, on the one hand, this wide scope definitions may provide the adaptability required to adjust energy communities to different national contexts (Becker and Kunze 2014) and to boost innovation (van Veelen and Haggett 2017), on the other hand, the door is open for the concepts to be used inappropriately, at the risk of missing the sustainable community development and energy democracy goals (Bauwens et al. 2022). Thus, compromise solutions can be achieved by adjusting the broad definitions to specific contexts (by defining the actors, the legal structure, the voting rights, the scale, etc.) and motivations (by stating who benefits from the project and how) (Bauwens et al. 2022; Hicks and Ison 2018; Walker and Devine-Wright 2008). Therefore, in the scope of this work, energy communities must be understood as locally and collectively organized energy systems, encompassing the concepts of sustainable energy communities

(Romero-Rubio and Díaz 2015), community energy (Brummer 2018; Walker and Devine-Wright 2008), community microgrid (Gui et al., 2017), community- based virtual power plant (Mourik et al. 2020) and prosumer-community groups (Cao et al. 2019),often used in this context.

Within the scope of this work, energy communities are:

- Engaged in all the energy-related activities announced by RED-II and IEMD;
- Implemented mainly within, but not restricted to, a specific geographic area;
- Not attached to specific technology restrictions – although renewable generation must be privileged;
- Supported by fully integrated smart-grid infrastructures, as well as storage devices, as a way of allowing the development of differentiated energy services and the exploitation of demand flexibility;
- Open to the participation of residential and non-residential members (local-authorities and small businesses), who are willing to work collaboratively to reach common goals and must be at the center of the decision-making processes, even if the investment and infrastructure ownership belongs to other stakeholders;
- Run or not run for commercial purposes although the main aim is to fulfill the energy needs of local communities, allowing them to reach some degree of energy autonomy by optimally managing their resources, while delivering social and environmental benefits.

In this setting, this definition encompasses place- and interest-based models (depending if members join due to geographical proximity - communities of place - or common interests, goals or passions - communities of interest (Bauwens 2016)), driven by not-only-for-profit goals, with democratic and shared ownership and organization rules, narrowing the scope of the European definitions to a more specific context and motivation. The main differences and similarities between EU definitions and the one proposed in the scope of this work are summarized in Table 1.

Table 1 Comparison of CEC, REC and own definitions.

Dimensions		REC	CEC	Own definition
Activities	Energy generation:			
	• Renewable electricity.	✓	✓	✓
	• Non-renewable electricity.	X	✓	✓
	• Renewable heat.	✓	X	X
	Energy sharing.	✓	✓	✓
	Distribution.	X	✓	✓
	Supply.	X	✓	✓
	Consumption.	✓	✓	✓
	Aggregation.	X	✓	✓
	Energy storage.	✓	✓	✓
	Energy efficiency services.	X	✓	✓
	Electric mobility services.	X	✓	✓
Ownership and control	Citizens, local authorities, and SMEs since their primary economic activity is not energy related.	✓	✓	✓
Purpose	Creation of social and environmental benefits rather than focus on financial profits.	✓	✓	✓
Location	Close to energy projects.	✓	X	✓
Smart grid Infrastructures	Smart metering and ICT infrastructures.	-	-	✓

2.1.1. *ENERGY COMMUNITIES AND COLLECTIVE RENEWABLE SELF-CONSUMPTION: IS IT THE SAME?*[b]

Although often mentioned interchangeably in the literature, LEC and CRSC are different: while LEC, both REC and CEC, must be set as legal entities and can be involved in a wide set of activities ranging from energy (electricity and heat) generation, supply, aggregation, distribution, energy efficiency and electric mobility services, CRSC are informal arrangements, usually initiated by end- users living in space constrained settings (e.g., residents of multi-tenancy buildings), who aim to own energy generation and storage technologies to consume self-generated energy. Therefore, the range of energy management activities in CRSC projects is usually limited to generation, consumption and sharing (Frieden et al., 2019) and these projects are generally ruled by informal internal agreements established between the participants, defining the guidelines for members to access and exit, the energy sharing rules, the distribution of potential costs and profits, the management of the energy surpluses, etc.

In multi-tenancy settings, CRSC projects are typically based on single energy generation assets collectively operated. PV technologies are usually the preferred ones due to the decreasing costs over the last years and the technology readiness (Hahnel et al. 2019). Solar PV systems are installed on the buildings' rooftop (or nearby the consumption site) and can be either run to operate as self-consumption units, supplying the local demand with the self-generated energy, or as small production units, exporting all the generated energy to the grid (Brown et al, 2019; Pappalardo and Debizet 2019). CRSC in multi-tenancy settings have the potential to play a key role in the decarbonization of cities, since these buildings represent about 48.6% of the overall EU's residential building stock (Frieden et al. 2019; Jager-Waldau et al. 2019). In turn, CRSC initiatives can also be run at the neighborhood level. In such configurations, a set of shared distributed generation systems located in different sites is collectively managed and operated to supply the CRSC project participants (Arbeille and Al. 2020; Frieden et al. 2019). Also, the sharing of surpluses between CRSC projects is allowed and encouraged by the RED-II and IEMD (EC 2018b; EC 2019a). Similarly to what happens in individual self-consumption projects, also in CRSC projects the energy generated by the collective technologies must be self-consumed or exported to the low- voltage distribution grid. Thus, energy transactions must be supported by sophisticated smart metering and ICT infrastructures, required to keep track of energy and cash flows. Also, in multi- tenancy CRSC projects, the use of the buildings internal network infrastructures reduces the transmission and distribution network costs, as the public distribution grid is not used to transfer self-generated energy (Dóci and Vasileiadou 2015; Munkhammar et al., 2013; Roberts et al., 2019), while in neighborhood-scale CSC projects, the involvement of local network operators is required as public networks are used to transfer the energy generated to the consumption sites. According to the legislation currently in force in some countries as Portugal, the use of the public transmission and distribution networks to transfer energy between generation and consumption sites (when they are geographically separated) is allowed but the payment of network access tariffs is due (Portuguese Government 2022). To promote a fair grid payment, the energy transactions between generation and consumption sites using public networks are exempted of the payment of the tariff components corresponding to upstream network components, as well as the general economic interest costs associated with energy policies, which represent approximately 40% of the total cost usually charged to residential consumers (Portuguese Government 2020). Consequently, whenever the use of public networks for energy transfer within the project is foreseen, transaction costs must be included in the project cost structure (EC 2018b; EC 2019a).

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[b] Based on Research paper V.

The deployment of CRSC neighborhood-scale projects and energy exchanges between multi- tenancy CRSC are still not allowed in several European countries due to the lack of adequate regulatory frameworks (Arbeille and al. 2020; Frieden et al. 2019; Jager-Waldau et al. 2019), while other countries are more advanced in this matter. Countries as Denmark, Finland, or the United Kingdom, allow CRSC projects in private grids (Jager-Waldau et al. 2019), while countries as Austria, Germany, France and Switzerland are pioneers in CRSC regulation, having flexible and sophisticated frameworks allowing for energy sharing between buildings. For instance, the French legal framework on this topic (the *Autoconsommation collective etendue* (ADEME 2019)) allows for virtual self-consumption between buildings within a 2 km geographical range. In addition to regulatory issues, several other barriers have hindered the expansion of CRSC projects as (Luthander et al. 2015; Mühlenho 2017; Roberts et al. 2019; USDE 2016):

- The lack of know-how of building owners and consumers on the benefits and technical requirements;
- The scarcity of economic and technical support schemes aimed at promoting small-scale renewable projects;
- The building stock characteristics;
- The need for smart metering systems to allow for the accurate measurement of transactions and billing;
- The need for internal agreements regarding the use of the rooftop shared space and renting situations, etc.

2.1.2. *CONCLUDING REMARKS*

Power systems are evolving towards decentralized local generation and consumption models in which households, enterprises, public authorities, cities, and municipalities are expected to be active players as asset owners, investors, and decision-makers. This trend is boosted by the Clean Energy for all Europeans legislative package which endorses prosumers and prosumagers as new actors of power systems and defines the role of LEC, both CEC and REC, as well as CRSC. All these initiatives are expected to be key drivers in decarbonization and consumers' empowerment, paving the way for carbon-neutral territories. This ambition is being translated in the new European Commission initiatives as the 100 Climate-neutral Cities by 2030 Mission[4] whose drive is to promote and showcase 100 European cities in their systemic transformation towards climateneutrality by 2030.

Member-States are transposing the European directives into their national energy and environment plans, taking the first steps towards the introduction of CEI in their territories, whose successful implementation depends on policymakers to understand how technical, physical, social, and economic dimensions can be aligned, what kind of incentives are being/need to be promoted, and what barriers need to be overcome while considering the national realities. Therefore, assessing how policies designed to foster the implementation of such projects are perceived by the involved stakeholders may assist in the design of more effective programs and in the acceleration of real projects implementation.

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[4] https://ec.europa.eu/info/publications/100-climate-neutral-cities-2030-and-citizens_en

2.2. CHALLENGES AND ENABLERS OF A SUCCESSFUL IMPLEMENTATION

According to authors as Gjorgievski, Cundeva, and Georghiou (2021), CEI are implemented topursue the following goals:

- Economic savings - Energy communities are expected to offer economic benefits for theparticipants and shareholders, whether the projects are explicitly developed with a commercial purpose or not. For example, the Belgian *Ecopower* cooperative[5] allows shareholders to receive a maximum of 6% of its profits on an annual basis. CEI can also promote local job creation, support transformation processes and technological innovation which generates new revenue streams;

- Social innovation - These projects reinforce social cooperation, enhance energy literacy and allow for the citizens' participation in the energy system (Caramizaru and Uihlein 2020). Also, CEI can play a key role in alleviating energy vulnerability situations since they may create local jobs, provide renewable energy at lower prices and/or use profits to improve the living conditions of local populations (Hanke and Lowitzsch 2020);

- Decarbonization – Due to the reduction on greenhouse gas emissions related with energygeneration;

- Political targets – It is expected that CEI projects may contribute significantly for renewables penetration in countries' energy matrices, with benefits for national energy autonomy and economic competitiveness, the improvement on the quality of life of citizens and the achievement of national and international energy and environmental commitments;

- Innovation and modernization of power systems - Community projects will affect the daily operation and the business model of traditional power systems players in several ways. On the one hand, communities can offer energy and flexibility to the grid, increasing the efficiency of general operations and reducing the need for new network investments. Communities can also decrease network congestion issues at the same time as losses in distribution and transmission are reduced. The aggregation of community members' generation and demand can also help the system operators to balance supplyand demand more effectively, since DSM strategies can be designed for this purpose. Likewise, the balancing services offered by distributed community generation can be used to improve the system reliability and minimize the effects of power outages. Thesebenefits can be hindered due to several barriers and challenges. The first one is the access to funding. Financial and profitability challenges related to the required high initial investment, the lack of financial resources during the project lifetime and the long payback periods can curb investors' interest. These challenges can be overcome by designing effective financing schemes and facilitating access to credit sources for projects that prove to be technically and economically viable. In addition, inflexible market structures and uncertain feed-in-tariff levels can create hesitation in investors (Brummer 2018; Gjorgievski et al. 2021). Such challenges must be addressed at a regulatory standpoint.

The expected social innovation fostered by CEI may be hindered by the sociodemographic characteristics of citizens which must be considered as not every citizen will put the equal time and effort into these issues and only the ones with the knowledge and financial availability will have the willingness to be involved in LEC creation (Gjorgievski et al. 2021). End-users' barriers to acceptance may hinder the deployment of CEI since

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[5] https://www.ecopower.be/

people may not recognize the benefits offered by participating in renewable energy projects and, therefore, refuse them. The dependency on volunteers to initiate and develop community initiatives, the progressive lack of interest over the project lifetime, the skepticism about renewables reliability and the "not in my back yard" phenomenon (for instance, some cases of local communities contesting solar developments were reported (O'Neil 2020)) can compromise the success of these projects. Thus, information and awareness campaigns should be promoted so that end-users realize the advantages of investing and/or participating in collective energy schemes.

CEI are technically constrained by both technologies (generation, storage, metering, etc.) as well as the infrastructure itself. Not all community projects require an advanced technical infrastructure nor state of the art systems. For simpler configurations, besides metering, almost no enabling technologies are required. Still, as systems tend to become more sophisticated, the use of equipment and software is required in both the physical and virtual layers. The physical layer allows for energy generation and demand-side flexibility delivery (through batteries, smart appliances, EV, etc.). Energy sharing, both within the community and with external players, requires the existence of grid connections (one for each actor) as well as an advanced metering infrastructure (AMI) encompassing smart meters, networks, and communication systems (Gjorgievski et al. 2021). Decentralized generation technologies and demand-side flexible loads are at the heart of energy communities (São José, Faria, and Vale 2021). In turn, the virtual layer consists of an information system (which can be enabled by ledger systems (Silvestre et al. 2019)), allowing to establish a local market operation, pricing strategies and energy management systems controlling the components of the physical layer. Currently, both ICT and metering networks need to be further deployed and reinforced to allow for the full use of physical and virtual layers. Therefore, system operators must be prepared to modernize and optimize power system operation while CEI can work as testing laboratories for new demand-side management strategies and energy efficiency measures, motivating technological innovation and the emergence of new business models.

Also, the lack of flexible energy markets can also prevent the exploitation of new services and products and innovative business models fostered by CEI. Due to renewables intermittency, a greater focus is placed on the demand side, which needs to be more efficiently handled to adjust to local supply availability. Despite being influenced by many factors, residential PV-based prosumers are only able to take advantage, in average, of about 30% of their self-generated electricity (EC 2015). These numbers may be enhanced when DSM and storage strategies are exploited (up to 65-75% (EC 2015)). However, DSM programs are still little attractive, mainly due to the reduced tariff differentiation between on- and off-peak periods (Zayed et al. 2020), and batteries are still too expensive (Zame et al. 2018). Thus, wherever allowed, prosumers with self-generated surpluses choose to sell them to last resort traders and retailers, being remunerated through feed-in-tariffs (FiT) which, although drastically reduced in recent years due to national policies, are still an advantageous option for prosumers (Lang, Ammann, and Girod 2016). From the grid side, the large penetration of renewable sources in the electricity matrix and the decreased aggregated demand (due to the increased self-consumption rates) lead to a lower capacity to take in the surplus electricity generated by an increasing number of prosumers' installations. Moreover, the injection of uncoordinated surplus generation can undermine the stability of power networks due to the inversion of flows, affecting voltage and frequency (Bonetto et al. 2017). Anticipating these scenarios, RED-II and IEMD required that LEC must be "*financially responsible for the imbalances they cause in the electricity system*". On the other hand, in less flexible market structures, LEC may be responsible for revenue losses of key market players, giving rise to imbalances in tariff schemes (as regular non-community-members may have to support higher costs for network tariff components). Therefore, policymakers and regulators must be able to design fair policies and pricing mechanisms to ensure energy communities are effectively charged for the imbalances caused in the system while end-users not adhering to community projects are not burdened with the system extra costs. Effective incentive policies and flexible regulatory frameworks, allowing to pursuit different business models, can help to overcome some of the identified implementation barriers and attract private funding.

Thus, in a nutshell, the successful dissemination of LEC, both REC and CEC, is largely dependent on: the inspiring environment at European level that empowers energy consumers to become producers of their own energy (prosumers and prosumagers) and to participate more actively in energy systems and markets; an empowering regulatory framework which promotes all possible configurations of collective renewable-based energy generation; the existence of incentivizing financial mechanisms which mitigate the high upfront cost an initiative this type can represent; and the growing awareness of citizens, SMEs and municipalities regarding the benefits of renewable and local energy generation. In turn, technical, regulatory, and economic challenges must be considered by policymakers and market players to foster CEI dissemination.

2.3. ENERGY COMMUNITY BUSINESS MODELS[C]

Until recently, few studies have addressed community-centered business models (BM). For instance, Lowitzsch et al. (2020) defined "renewable energy clusters" and analyzed “regulatory sandboxes” for energy community creation, without exploiting the underlying BM. In Nolden et al., (2020), the evolution of energy communities in England was reviewed and three BM archetypes were identified based on grant funding, feed-in-tariffs and incentives, and long-term agreements to build large community projects. In turn, Hall and Roelich (2016) proposed local energy archetypes, although the more innovative BM[6] are hypothetical. Four energy communityBM (ECBM) were also proposed by Tounquet (2019), namely: 1) cooperative investment, based on citizens paying fixed membership fees or variable stakes to become members of communities acting as energy producers; 2) energy sharing, based on the allocation of surplus energy among community members; 3) aggregation, based on providing flexibility to different system operators; and 4) microgrids, based on communities capable of fully operating their distribution grid autonomous from the power grid. Though, these archetypes do not cover all the possible activities left open by the European directives, such as e-mobility or energy efficiency.

A review and systematization of ECBM archetypes[7], comprehensively covering all the legal forms and governance models announced in the European directives (EC 2018b; EC 2019a), was missing in the literature. Peer-reviewed literature on energy business models focusing on electricity as the main energy vector, since it is a common element in both directives, was examined. Drawingon Osterwalder and Pigneur's definition of BM (Osterwalder and Pigneur 2010), the Business Model Canvas (BMC) was used to fully describe and compare the main dimensions of ECBM derived from the literature. The Lean Canvas (LC) framework was also used to further identify the market challenges and proposed solutions offered by each BM archetype. The combination of both BM frameworks provides a comprehensive set of boxes and tasks that help to visualize andconceptualize the BM, shedding light on their main strengths and weaknesses, facilitating the analysis of

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[c] Chapter based on Research paper II.

[6] In the scope of this work, the concept of ‘innovative’ business models is used to refer to theoretical models which are still very scarcely exploited in real applications since they usually involve high levels of ICT, the enrolment of new market operators and the change of the roles played by traditional market operators.

[7] Following Hall and Roelich (2016), an ‘archetype’ refers to a generic form of a BM. The design of the archetypes is intended to better frame the discussion of BM and organizational structures in community settings.

policymakers and business managers regarding BM opportunities, and uncovering the main barriers they may face, helping to develop better regulatory and business backgrounds. BMC and LC blocks are presented in Fig.2.

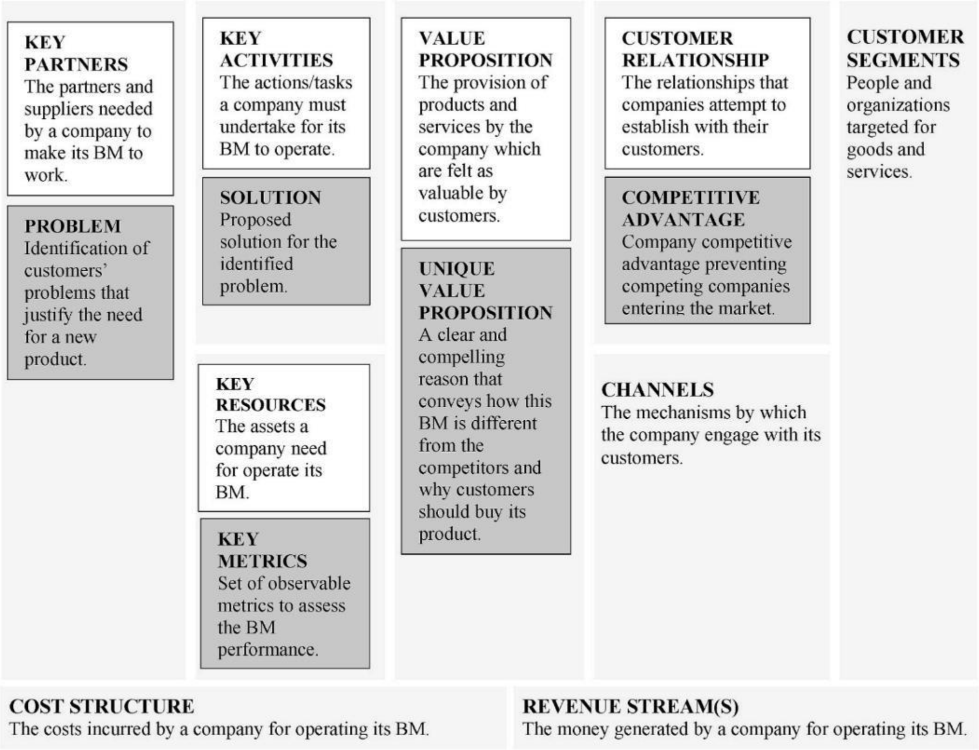
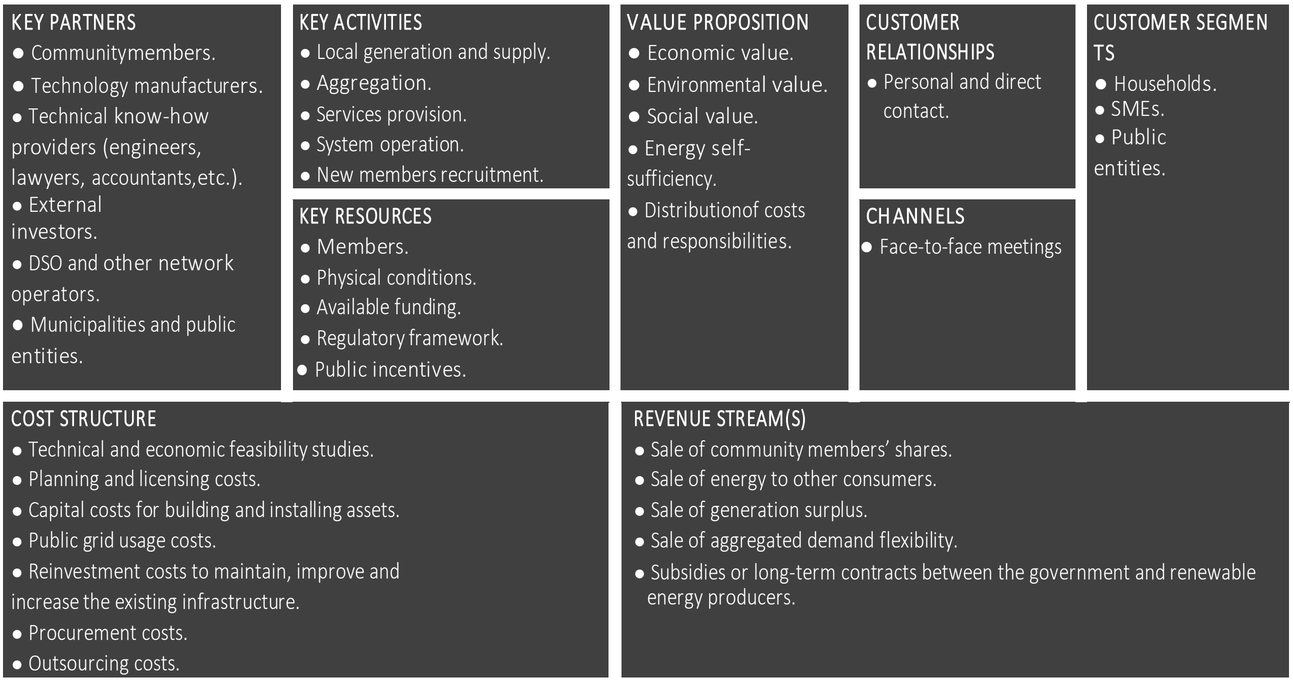


Fig. 2 BMC and LC models. Legend: white text boxes: BMC blocks; grey text boxes: LC blocks; no frame boxes: common blocks.

Community-shared BM (Horváth and Szabó 2018) or ECBM (Cai et al. 2017, 2019; Hamwi and Lizarralde 2017) have been created by proactive citizen groups striving to decide how their energy is generated. Backing to collective energy roots, reinforced by RED-II and IEMD, community members must be financially involved and the whole BM must be created by, for and with them (Mourik et al. 2020). Therefore, members should be considered in the overall arrangement design, implementation and operation, influencing how the ECBM value is generated and the risks and costs are shared (Mourik et al. 2020; Yildiz 2014). Given the investment required, external financial involvement is also possible through different types of partnerships. Thus, from the investment and assets ownership perspective, ECBM can be categorized under the label of the customer-side BM and/or the third party-side BM, since both, as well as hybrid forms, are possible.

Although energy communities are not primarily run for profit, ECBM must guarantee their shareholders the return of their investment by benefiting from cheaper energy supply, selling surplus generation or participation shares, or by self-consuming and thereby reducing their power grid dependency (Tounquet 2019). Some studies, as Bauwens (2019), revealed that the return on investment is one of the most important determinants for community shareholders to enroll in such initiatives. However, the value proposition of energy communities goes far beyondthe economic dimension (Hicks and Ison 2018; Mourik et al. 2020). The environmental contribution due to renewable energy generation, the ability to choose the technologies to generate energy, the social innovation created by shifting the role played by consumers, who become customers, asset owners and company shareholders, are also relevant value propositions of ECBM (Koirala et al. 2016). Also, by joining a community, all the costs and risks are shared, removing the high upfront cost barrier (Koirala et al. 2018).

As announced by the European directives, ECBM 'key activities' include local generation, supply, storage, consumption, trading, aggregation, e-mobility, and energy related services, as well as system administration. 'Key resources' include: the members, due to the social and financial value they bring to the projects; the available area for implementing generation and storage facilities; the financing resources to implement and manage the project (either from members and partners); and technical know-how, which can be outsourced (in this case, outsourcing costs must be considered in the 'cost structure'). The availability of incentives for renewable energy producers, as well as enabling regulatory frameworks, can also be understood as key resources for the operationalization of such initiatives. Households, SMEs, and public entities, which constitute the 'customers segment' are also 'key partners' alongside technology suppliers, external investors, DSO, energy suppliers and other power system entities (as aggregators). Since, in most communities, participants are both involved as customers and business developers (except for projects financed by third parties), the 'customers relationships', and the communication 'channels' are personal and direct. The 'costs structure' of these BM must comprise: the costs of performing technical and economic feasibility studies to examine the viability of the community project; the planning and licensing costs; the capital costs of building and installing generation, storage, management and distribution assets; the costs for using the public distribution network; the reinvestment costs to improve and expand the existing infrastructure during the projects life time beyond the costs incurred to operate and manage the infrastructure. Also, if the energy community project is not able to fulfill the energy needs of their members, energy procurement costs must be considered. The 'revenue streams' come from the sale of participation shares (shareholding mechanisms allow for communities to be flexible to the entry and exit of members, without compromising the participation of the remaining ones (Interreg Europe 2018)), energy contracts with suppliers or other external entities to whom the surplus generation or other energy services is sold, and subsidies or other long-term contracts between the government and renewable energy producers. The BMC of an ECBM is displayed in Fig. 3.



KEY PARTNERS
- Community members.
- Technology manufacturers.
- Technical know-how providers (engineers, lawyers, accountants, etc.).
- External investors.
- DSO and other network operators.
- Municipalities and public entities.

KEY ACTIVITIES
- Local generation and supply.
- Aggregation.
- Services provision.
- System operation.
- New members recruitment.

KEY RESOURCES
- Members.
- Physical conditions.
- Available funding.
- Regulatory framework.
- Public incentives.

VALUE PROPOSITION
- Economic value.
- Environmental value.
- Social value.
- Energy self-sufficiency.
- Distribution of costs and responsibilities.

CUSTOMER RELATIONSHIPS
- Personal and direct contact.

CHANNELS
- Face-to-face meetings

CUSTOMER SEGMENTS
- Households.
- SMEs.
- Public entities.

COST STRUCTURE
- Technical and economic feasibility studies.
- Planning and licensing costs.
- Capital costs for building and installing assets.
- Public grid usage costs.
- Reinvestment costs to maintain, improve and increase the existing infrastructure.
- Procurement costs.
- Outsourcing costs.

REVENUE STREAM(S)
- Sale of community members' shares.
- Sale of energy to other consumers.
- Sale of generation surplus.
- Sale of aggregated demand flexibility.
- Subsidies or long-term contracts between the government and renewable energy producers.

Fig. 3 Energy community business model canvas.

Most energy communities have been primarily involved in local generation and self-consumption due to the longstanding tradition of these initiatives in Northern Europe countries (Wierling et al. 2018). More recently, the evolution of ICT-based infrastructures and energy exchange platforms boosted selling and sharing activities in collective settings, allowing to optimize the utilization of local energy resources, to maximize the community members' economic benefits and underpin the deployment of local energy markets (LEM) (Eurelectric 2019; Mengelkamp et al. 2018; Verschae et al., 2016). In addition, the IEMD opens room for Member-States to grant communities the right to own, establish, purchase, or lease the distribution network in their area of operation (EC 2019a). Energy communities may, therefore, become local DSO, under the general or the 'closed distribution system operator' regime, meaning that the community becomes responsible for "*ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity, for operating, maintaining and developing under economic conditions a secure, reliable and efficient electricity distribution system in its area with due regard for the environment and energy efficiency*." (EC 2019a). By owning and operating their internal distribution network, energy communities gain power over the prices charged to customers and may implement targeted DSM actions, giving rise to BM aimed at demand flexibility management (CEER 2019). The deployment of customized DSM strategies allows for energy communities to aspire to be self-sufficient from the power grid by balancing local demandand supply, which may be easier in fossil-fueled CEC than in REC, since the dispatchable supply- side can be adjusted according to the community power demand. REC are expected to increase in next years, contributing to achieve the European decarbonization goals, raising greater challenges in terms of supply management due to the intermittency of renewable generation. Thus, a higher pressure is put on DSM-based BM, which are key to strengthen the system stability, optimize the integration of intermittent renewable resources and create new value streams since demand flexibility may be aggregated and traded in electricity markets (Niesten and Alkemade 2016). Finally, energy communities can also be created to provide energy efficiency and e-mobility integrated services, fulfilling the activity list announced by both directives.

Eight BM archetypes were identified from the literature and their core dimensions are comprehensively presented in the following sections. Although this list is not extensive due to the high number of possible hybrid models, it gives an overview of the main ECBM, considering the different objectives, ownership rules and actors currently considered.

2.3.1. *ENERGY COOPERATIVES*

Energy communities organized as energy cooperatives are by far the most common in Europe (Caramizaru and Uihlein 2020). Currently, about 1,500 renewable energy cooperatives are members of the European federation of citizen energy cooperatives (REScoop.eu) (more than 800 have been reported in Germany only (Braunholtz-Speight et al. 2018)), serving more than one million European citizens (Bauwens et al., 2016). However, the real number of such initiatives is uncertain, and an inventory carried out by REScoop.eu was able to identify more than 2,400 renewable energy cooperatives across Europe (Bauwens 2017; EC 2019b).

Energy cooperatives are a classical example of citizen-led initiatives in which end-users join to raise the funding for owning energy generation systems (Bauwens et al. 2016; Wierling et al. 2018). Various organizational forms and financing models may exist but all of them are based on voluntary and open membership rules, democratic control (typically based on the '*one participant one vote*' rule) and the economic participation of members (Wierling et al. 2018). Energy cooperatives are usually constituted as companies (for profit-making) (Fig.4). In this case, they can be created as retail cooperatives by shareholders involved in the shared-financing of medium and large-size PV or wind power plants (communities of interest), being able to compete with other market players (Tounquet 2019). They can also be local nonprofit cooperatives, created to supply specific local regions (communities of place) on the basis of self-consumption and sale of surpluses (financial outcomes are reinvested in the community) (Bauwens et al.

2016; Van Der Schoor et al. 2016). Energy cooperatives may be involved in the management and operation of regional low-voltage distribution networks, acting as local DSO, which allow them to define billing conditions, incentivize self-consumption through dynamic pricing schemes and exempt cooperative members of paying some use-of-system[8] tariffs (Brown et al. 2019). For instance, in countries as Portugal, energy cooperatives may play the role of retailers and low-voltage DSO, having grid concession contracts which allow them to buy energy from other suppliers and resell it to consumers (Eurelectric 2019). In turn, in countries as The Netherlands, energy cooperatives can only be involved in local generation and supply, without assuming any specific role in network management (Eurelectric 2019). Also, although some cooperatives are created to provide renewable energy to their members at cheaper or market equivalent prices (Herbes et al. 2017), others, acting as retail cooperatives, can charge tariffs above retail competitors, justifying the gap with the remuneration of suppliers (Bauwens 2019).

Energy cooperatives governance is usually in the hands of shareholders (households, SMEs, public entities, and other investors), being part of the revenues reinvested in the community (e.g., improvement of infrastructures) and the rest distributed among the shareholders according to the cooperative statutes (Caramizaru and Uihlein 2020; Tounquet 2019). Thus, cooperative shareholders may be supplied with renewable energy while being financially compensated by their investments through direct payments. Larger energy cooperatives can benefit from collaborating closely with municipalities, which can provide extra sources of technical knowledge and funding. In some cases, the management responsibility is put in the hands of public entities (municipal utility BM), which become responsible for managing the energy cooperative on behalf of customers, while benefiting from cheaper energy for public services (as street lighting) (Ceglia et al. 2020; Engelken et al. 2016; Hall and Roelich 2016). Municipal energy cooperatives have been developed in countries as Denmark, Germany, France and Spain, where municipalities play a role in either energy supply and distribution activities (e.g., *Eléctrica de Cádiz*) or in supply only (e.g., *Barcelona Energia*) (Eurelectric 2019).

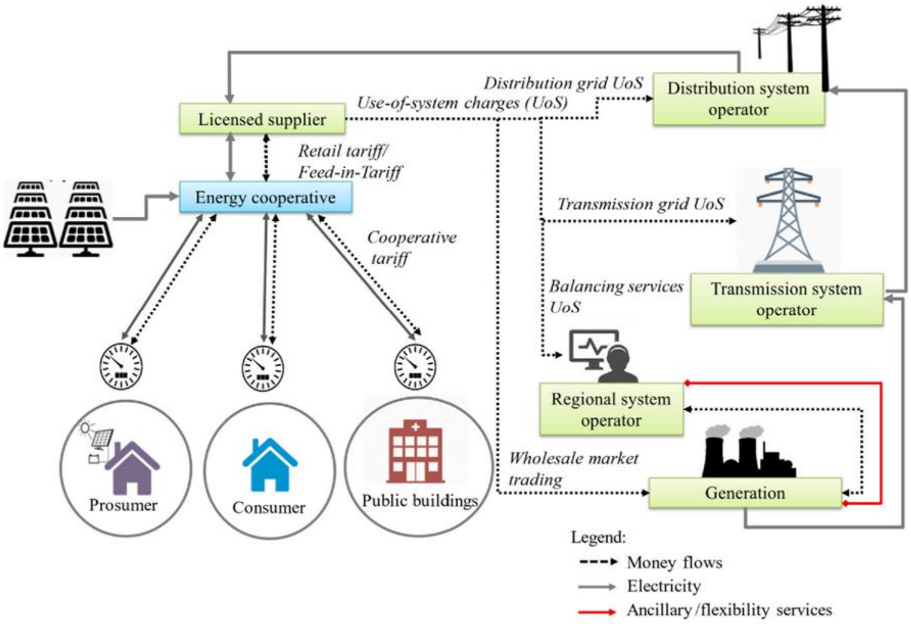


Fig. 4 Energy cooperative business model.

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[8] Use-of-system tariffs are intended to recover the costs incurred by DSO, transmission system operators and other system operators, which are responsible for installing, maintaining, and operating the distribution and transmission grids. These tariffs are charged to customers and distributed among the different system operators.

2.3.2. *COMMUNITY PROSUMERISM*

Energy communities dedicated to prosumerism are typically communities of place created by prosumers, playing the role of decision-makers, investors, and customers, who join to benefit from special financing conditions in the acquisition of assets (as bulk purchase), to gain dimension to participate in flexibility markets, to benefit from collective energy efficiency initiatives or to participate in LEM (Brown et al. 2019; Campos et al. 2020). For instance, the *Svalin community* in Denmark is a successful case of a community prosumerism BM which aims to maximize participants' savings within a peer-to-peer (P2P) energy trading.

Collective or individual generation and storage systems are acquired, and long-term power purchase agreements (PPA) are established between community members and energy suppliers, which become responsible for buying the surplus generation and supplying the remaining required power. Community members can also buy and sell all their electricity within the community boundaries (in LEM), exempting them from paying tariff components related with medium and high voltage distribution and transmission networks (Koch and Christ 2018; EC 2017). In turn, if transactions with non-community energy suppliers are established, *use-of- system* tariffs are due. In these arrangements, power and monetary transactions between community participants and external retailers can be intermediated by local grid controllers, which keep record of all the exchanges (Fig. 5). These devices can play a passive role by keeping the record of the transactions (as ledgers), or an active one helping participants to make decisions and interfacing with external players (as choosing better supply offers or facilitating the establishment of smart contracts (Panagiotis et al. 2019)). By joining in communities, prosumers may aggregate their demand and surpluses, gaining extra power to negotiate better conditions with retailers and last resort traders. This is one of the main benefits of these BM, although they require consensus from all parties, and physical and technological infrastructures capable of supporting and keeping track of energy, money, and information transactions for billing purposes.

Potential revenues obtained by selling excess energy can be distributed by prosumers to reimburse their investment or reinvested in the community, to improve social infrastructures and expand installed generation or storage capacities.

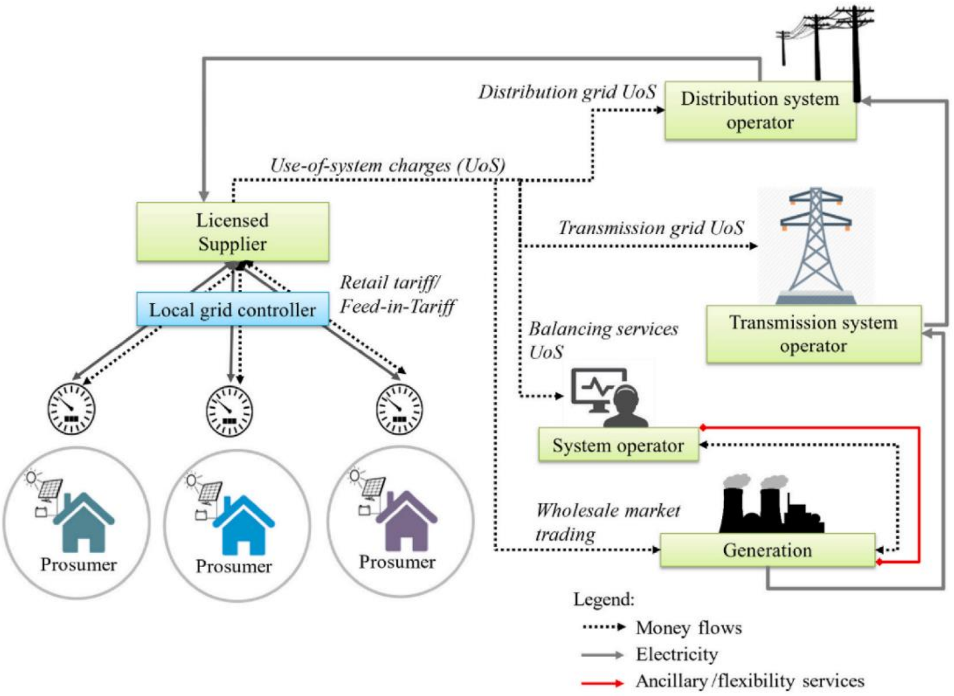

Fig. 5 Community prosumerism BM.

2.3.3. *LOCAL ENERGY MARKETS*

LEM are typically developed by prosumerism-driven communities, which aim to work collaboratively to maximize their self-sufficiency and reducing the amount of power traded with external entities (Brown et al. 2019; Mendes et al. 2018). In LEM, trading conditions, as pricing, can be directly negotiated between market participants (prosumers and consumers), allowing prosumers to select to whom they sell their energy and consumers to choose the market participant they buy their energy from, at the same time as they know how it is generated (Mendes et al. 2018; Viviers, Castadot, and Pascal 2018). In these BM, the revenues from energy sales are typically distributed among prosumers and consumers who benefit from savings due to differences between retail and market tariffs. Market participants consensually manage the trading platforms, while agreements are signed with energy retailers and the DSO to guarantee the supply and trading system reliability.

LEM members (consumers and prosumers playing the role of investors, decision-makers, and customers) can be closely located physically (e.g., within the same low-voltage distribution grid), giving rise to place-based LEM. Members can also share common interests but be physically apart, joining virtually to create community virtual power plants (Mourik et al. 2019) or prosumer- community groups (Cao et al. 2019)). Community virtual power plants are still rare in the EU setting mainly due to regulation limitations. For instance, in Belgium, a community virtual power plant project is facing major difficulties due to the regulatory barrier for P2P transactions (Mourik et al. 2019). Another project is being implemented in Germany, Austria, Switzerland, and Italy, connecting people who consume, generate, store, and share energy virtually (the *sonnenCommunity*), by taking advantage of smart storage assets. Both the IEMD and RED-II exempt energy transactions under the same distribution grid from paying the unused upstream distribution and transmission network fees. Therefore, communities of place may be more attractive to these BM as prosumers may sell their surplus generation within low-voltage energy community boundaries at more advantageous conditions (Sousa et al. 2019).

LEM are established to promote P2P energy exchanges either in a fully decentralized way, allowing community members to freely negotiate with each other (Sorin et al. 2018), or more centrally, through intermediate entities. These entities work as trading facilitators between the market participants, find the best matches and solve community imbalances by negotiating with retailers (Sousa et al. 2019; Verschae et al. 2016). A hybrid approach between the two previous BM is also possible, which is, for some authors, as Sousa et al. (2019) and Long et al. (2017), the most suitable solution for scalability. Despite the attention received in the literature, issues related with the negotiation processes among peers, as well as local energy balance control issues, have prevented the exploitation of full decentralized P2P markets in real settings (Zhang et al. 2019). In turn, centralized markets have been paid less attention, although they are expected to become more common in the next years (Moret and Pinson 2019). However, due to their configuration, centralized markets are limited to communities of place (Akter, Mahmud, and Oo 2017; Olivella-Rosell et al. 2016; Verschae et al. 2016).

Sophisticated ICT, net-metering infrastructures and software-based trading platforms are required to keep record of all energy, information, and money transactions (Fig. 6). The blockchain technology has been identified as a powerful ledger scheme to keep track of the transactions in LEM, although it requires a considerable computational power and energy consumption due to the need to solve security and cryptocurrencies related problems (Silvestre et al. 2019).

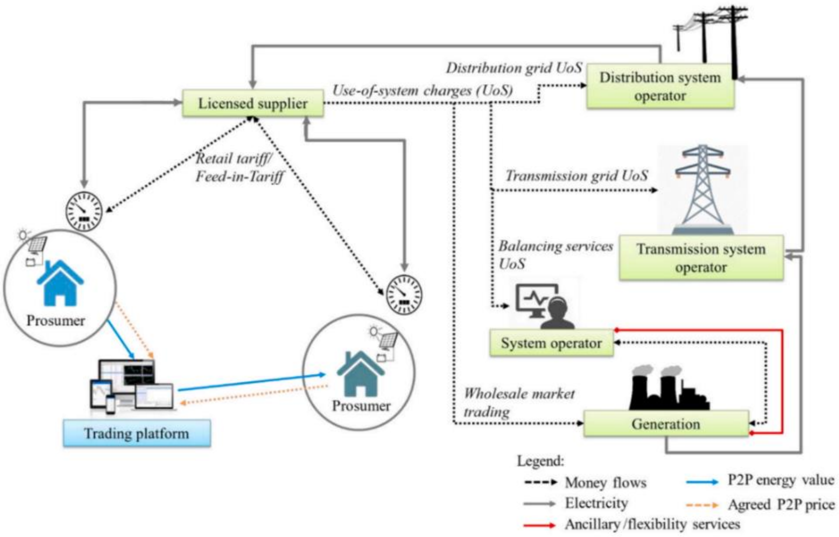

Fig. 6 Community local energy market based on peer-to-peer trading.

2.3.4. *COMMUNITY COLLECTIVE GENERATION*

Collective self-consumption BM are based on shared generation (usually solar PV) and storage systems, which are installed on the rooftop of multi-tenancy buildings or in the vicinity of consumption sites, being the power output shared among several customers (Fig.7). Due to their characteristics, these BM are constituted as communities of place. Typically, the investment is shared by the dwelling owners (consumers, decision-makers and investors) and sophisticated net-metering and ICT-based infrastructures are required (Pappalardo and Debizet 2019). Also, the distribution of the self-generated energy and potential revenues from the sale of surpluses depends on rules established voluntarily and collaboratively among all project participants (Chan et al. 2017). These BM are emerging across Europe. The *Windkraft Simonsfeld* and the *Za Zemiata* are examples of collective generation initiatives being implemented in Austria and Bulgaria. In some countries, these projects are implemented as microgrids, and surplus sales are not allowed (Frieden et al. 2019). Thus, the regulatory framework can limit innovation in these BM.

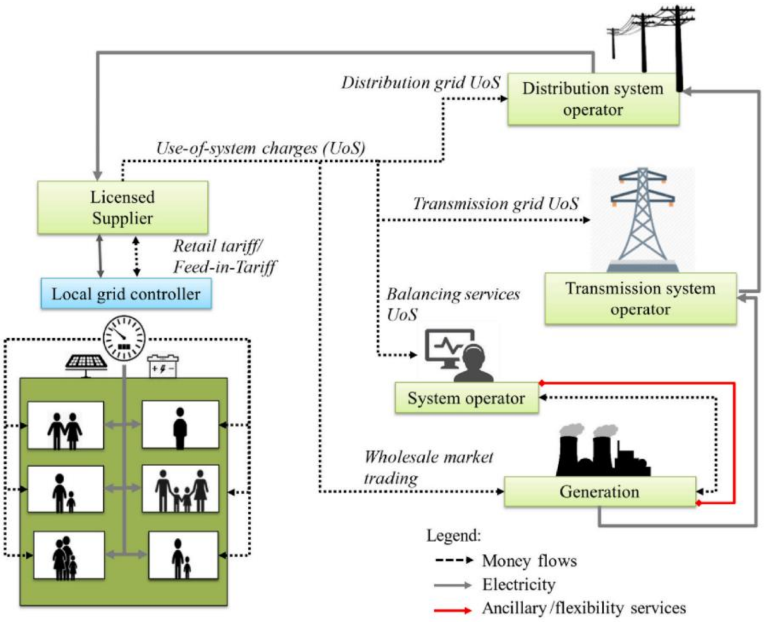

Fig. 7 Community self-consumption system in multi-tenancy buildings.

2.3.5. *THIRD-PARTY-SPONSORED COMMUNITIES*

The potential of ECBM has been recognized by several entities interested in supporting and investing in the sector (Seyfang et al. 2014). Looking for expanding their customers and services portfolios (Hamwi and Lizarralde 2019), utilities and technology companies may be willing to provide technical advice and financial support in the form of grant funding, dedicated investment funds, or fully financing energy community projects (Seyfang et al. 2014). When these entities finance such projects, they usually maintain the assets ownership, being responsible for the project governance and investment decisions. In these circumstances, the entities sponsoring the project are the main decision-makers but cooperate closely with local communities to build customized energy supply solutions and community representatives are usually involved in the decision-making processes (Hamwi and Lizarralde 2019). The whole financial effort and risks are put on the investors side, which are remunerated through long-term PPA signed with customers. Users benefit from renewable and typically cheaper energy while being engaged in local energy-related programs.

Community virtual power plants (Mourik et al. 2020) can be exploited by companies owning several energy projects. These management models are already in place in some pilot-projects across Germany and the Czech Republic (Eurelectric 2019). The so-called ‘local pool and sleeve’ BM are also starting to increase in communities sponsored by utilities, which pool distributed generated resources from a geographical area to supply a specific set of customers without using other wholesale market actors (sleeving) (Hall and Roelich 2016). Figure 8 displays the describedBM general architecture when it is run by a utility.

In turn, non-profit local authorities, and social entrepreneurs, aiming to create local economic development (Interreg Europe 2018), to ease specific social problems (as poverty and poor housing conditions) and boost social change, may also promote energy community projects in specific areas (usually socially disadvantaged) (Becker, Kunze, and Vancea 2017; Hiteva and Sovacool 2017). In these models, the social entrepreneurs raise the required funding and keep the infrastructure management close to local consumers, promoting engagement. The profits obtained from the sale of surplus energy are fully reinvested in the community.

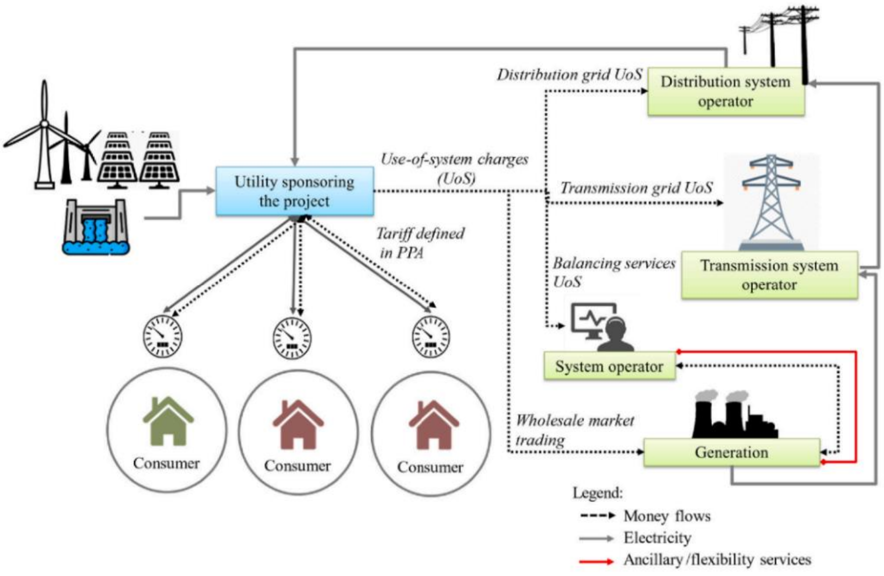

Fig. 8 Utilities-sponsored business model archetype.

2.3.6. *COMMUNITY FLEXIBILITY AGGREGATION*

More sophisticated and technology-dependent BM can also be deployed in communities aimingto engage in collective DSM strategies to provide demand flexibility to grid operators through aggregation (Rajabi et al.

2017). Flexibility markets are difficult to access by small consumers, who may face high costs and fail to meet the compulsory volume requirements. In Europe, aggregation BM are usually targeted to industrial and commercial customers as they can provide larger amounts of flexibility (Malizou 2018). However, energy communities are expected to make residential demand flexibility commercially attractive and European directives strongly encourage aggregation, recognizing the potential of these BM in generating new revenue streams (Rajabi et al. 2017). By pooling the available flexibility provided from multiple members, community aggregators can achieve the volumes required to make offers in balancing, reserve, and ancillary markets, thus enabling the participation of small end-users in such markets (Malizou 2018).

Community aggregators may be created to operate at a local level and the flexibility collected is grouped by a larger aggregator. Alternatively, community aggregators can also operate directly at the power system level, provided they are able to meet the required conditions (Fig. 9). Bilateral contracts are signed between community aggregators and customers through which customers commit to deliver fixed amounts of flexibility by changing energy consumption patterns and benefiting from reduced energy bills. Dispatchable and non-dispatchable DSM programs can be implemented to exploit customers' flexibility. In dispatchable programs, customers voluntarily accept that external operators control their appliances during peak periods through direct load control (Rajabi et al. 2017). In non-dispatchable or price-based programs, customers are exposed to dynamic pricing signals to influence their demand profile (Rajabi et al. 2017). Penalties can be charged if the promised amounts are not delivered, strengthening the commitment on the customer side (Malizou 2018). In these settings, community members have one contract with external energy suppliers to buy/sell the required energy and the surplus generation in a typical prosumerism contract, and a separate one with the aggregator (Malizou 2018). Sensors, smart meters, home energy management systems (HEMS), monitoring apps, etc. are provided by aggregators to help customers delivering the contracted flexibility (Hamwi and Lizarralde 2017).

Due to the characteristics and activities performed, these communities are generally made up of members who share the same interest in participating in flexibility markets (communities of interest) and can be started by aggregators, who aim to exploit these niches, or by end-users. Regulatory frameworks play a key role in the deployment of these BM as they can constrain the aggregators scope of action. Also, technological and ICT infrastructures are key for the success of aggregation activities.

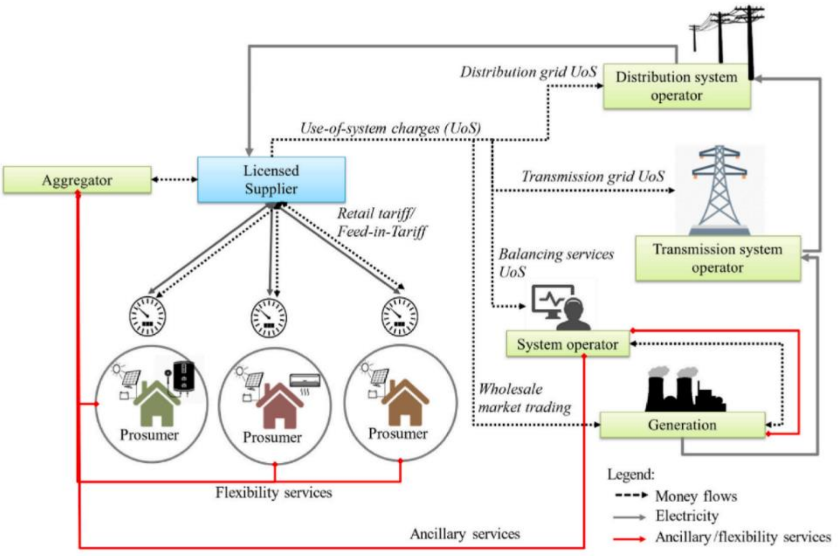

Fig. 9 Community aggregation business model.

2.3.7. *COMMUNITY ESCO*

External companies may establish partnerships with energy communities to jointly create and operate community ESCO aiming to provide EE services (e.g., energy audits, buildings insulation, etc.) and/or renewable energy supply (electricity, heat, or both). Energy communities driven towards energy demand reduction via energy efficiency strategies and procuring electricity and heat combined solutions are specially targeted by these BM (Fig. 10) (Tounquet 2019). Thus, ESCO BM can be simultaneously defined as communities of place and interest.

ESCO are different from traditional energy consultants or technology suppliers as they can also finance systems and their remuneration generally depends on the energy savings achieved by customers. Several BM variants can be exploited. For instance, the solar-as-a-service BM allows end-users to become prosumers, with community ESCO financing the PV panels and assuming the responsibility for the installation, maintenance, and upstream supply (Steinberger et al. 2009). Heat-as-a-service is also commonly exploited in district heating and combined heat and power projects, with ESCO owning the infrastructure and offering energy performance contracts for internal temperature comfort (Steinberger et al. 2009). In both cases, besides generation systems, community ESCO can also provide energy efficient systems (air conditioners, electric water heaters, etc.) and buildings retrofit solutions. By providing such services, ESCO ensure customers extra energy savings, which, in turn, safeguard ESCO remuneration as these companies are only compensated by the energy savings achieved. Two main ESCO remuneration schemes are possible: guaranteed savings, if ESCO promise to deliver certain levels of energy savings, or shared savings, if the savings attained are split during a given period in accordance with a pre- defined contract between customers and ESCO (Dressen 2003). Customer savings can be shared between ESCO and customers in different ways and used to reimburse ESCO of their investments or for local reinvestment. In these BM, investing companies hold the assets, structures, and the decision power. However, as the projects are customized and dependent on local conditions, members of the community are deeply involved in the decision-making processes. Depending on the extension of the investment needed to provide contracted services, economic barriers can halt these BM.

ESCO are more common in Member-States exploring combined power and heat solutions. Therefore, it is expected that community ESCO BM will also have greater relevance in communities exploiting combined solutions.

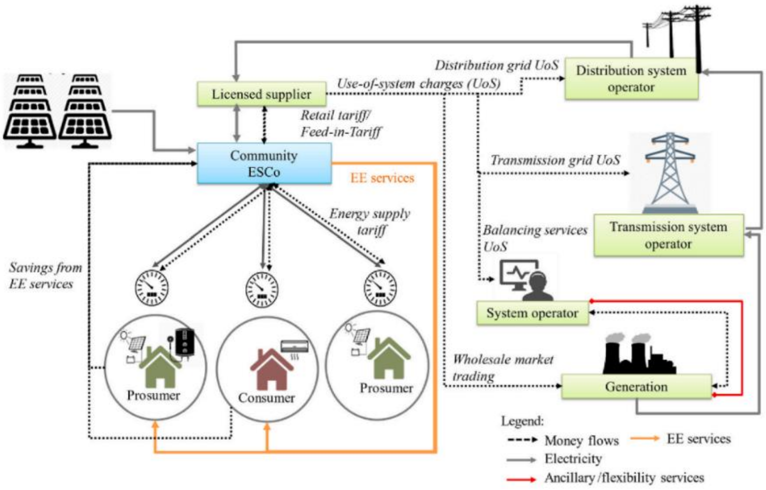

Fig. 10 Community ESCO business model.

2.3.8. *E-MOBILITY COOPERATIVES*

LEC encourage EV as mobility solutions, providing fossil-fueled free transportation services, and as extra sources of flexibility. Thus, e-mobility based BM may develop clean mobility solutions, while alternative value streams are exploited. E-mobility cooperatives are created by engaging shareholders (households, SMEs, public entities, social and technical entrepreneurs, etc.) to provide community public transportation, car-sharing or car-pooling services. These cooperatives can also exploit their assets (electric cars, buses, motorbikes, etc.) as flexibility resources (Brown et al. 2019; Niesten and Alkemade 2016). Batteries can be used as storage resources, exploiting vehicle-to-grid and grid-to-vehicle modes to reduce energy bills by procuring energy during off- peak periods and providing flexibility services, which can be pooled by aggregators to deliver ancillary services to the grid (Brown et al. 2019). Additionally, if these cooperatives are also involved in power generation, battery storage helps to maximize local self-consumption and self-sufficiency. In these BM, community participants may be involved (through partnerships or not) as shareholders, decision-makers, and mobility customers.

In energy communities with high shares of EV (communities of place), smart charging schemes can be designed to schedule load operation to off-peak periods or when local energy generation is available, thus optimizing the utilization of local resources and flattening demand peaks (Brown et al. 2019). Hybrid BM, exploiting combined mobility and flexibility solutions are also possible (Brown et al. 2019). One example is presented in Fig. 11, which illustrates how community mobility service providers can be created to offer e-mobility services with energy generated by community members (Brown et al. 2019). These mobility providers own EV and/or electric buses to deliver car-sharing or public passenger transportation services, for profit-making, being powered by energy resources delivered by community prosumers. In these settings, instead of selling their surplus generation to an energy supplier, prosumers would make it available, upon payment or reduced service prices, to e-mobility services providers. As these BM are developed for profit-making, fees are charged for the services delivered (Brown et al. 2019). Usually, partnerships between energy communities, DSO, energy suppliers and EV technology providers may be required.

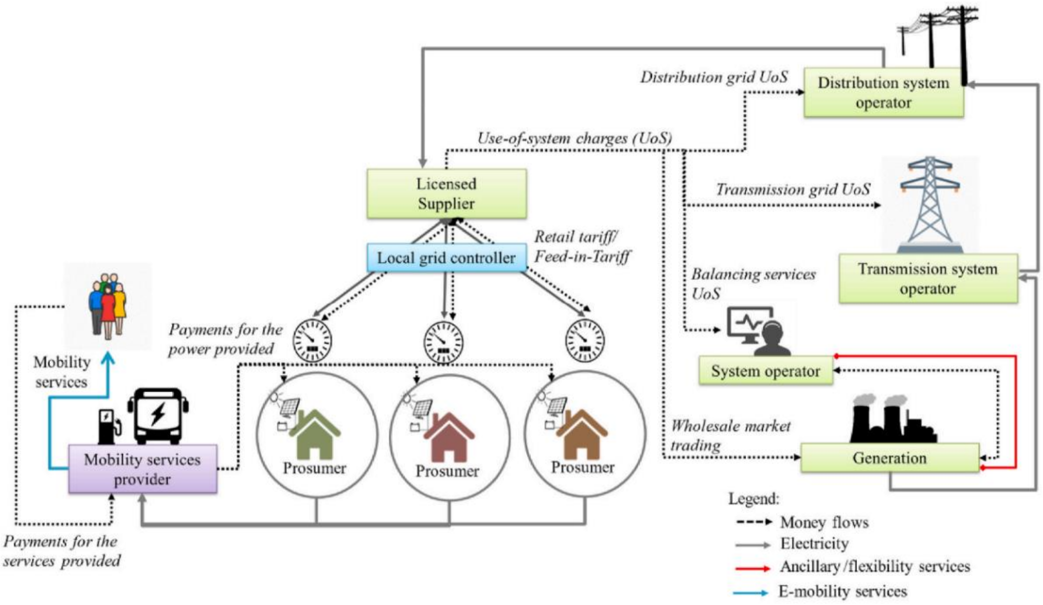

Fig. 11 E-mobility cooperative business model.

These models are highly technological and require reinforced physical structures to handle the power demanding charging processes of e-mobility assets. In addition, regulatory barriers, due to vehicle-to-grid and grid-to-vehicle transaction, and economic barriers triggered by the large volume of investment may hinder the development of these BM.

2.3.9. *COMPARISON OG BMC AND LC PERSPECTIVES*

In the next section, the proposed BM archetypes are analyzed according to the BMC and LC core dimensions.

Customers segment

In general, the 'customers segment', as defined by the IEMD and RED-II, may include households, SMEs, and public institutions. Some ECBM require the 'customers segment' to have the financial capacity and the available space conditions to become prosumers (community prosumerism and LEM), while others promote the participation of public institutions (energy cooperatives) or the inclusion of low-income consumers (third party sponsored ECBM). Multi-tenancy buildings, where space is constrained, are the focus of collective generation BM, whereas end-users living in smart homes or owning appliances deemed for demand management and willing to accept DSM actions are targeted by community aggregation BM. Communities developing energy efficiency or e-mobility services are targeted for customers aiming energy-efficient integrated solutions.

Market challenges and proposed solutions

The need to solve energy supply issues and the willingness of consumers to participate in local generation, self-consumption, and trading activities, underpins the creation of most energy communities. Several BM may be settled to provide cheaper and reliable local energy supply (energy cooperatives, community prosumerism, collective community generation, LEM and third party-sponsored initiatives), allowing to minimize the dependence on external supply parties by deploying energy chains involving generation, supply, and trading. In these settings, the high initial investment, the lack of space for implementing generation and/or storage assets and the reliance on external entities to ensure the distribution of the locally generated energy may hinder their deployment. The high up-front investment barrier is overcome through shared investments, partnerships with public entities and utilities which become responsible for financing community projects, while long-term PPA are signed with customers to warrant investors payments. The lack of space for generation facilities is solved by sharing collective generation and storage assets or building offsite power plants. The reliance on distribution entities facilitates the emergence of communities responsible for managing both generation and distribution facilities, playing the role of energy suppliers and local DSO.

The lack of integrated solutions to provide energy efficiency and e-mobility services fosters the emergence of ECBM committed to delivering such services. Finally, the need to grasp the necessary volumes for participation in flexibility markets boosts the emergence of community aggregation models. The aggregation of community members' flexibility (or aggregation of multiple communities' flexibility) solves the problem identified in communities aiming to participate in energy markets, whereas the creation of local ESCO and e-mobility service providers allow communities striving for implementing integrated energy-efficient solutions. Most of these BM require sophisticated ICT infrastructures to guarantee information exchange in real time.

Value proposition

Overall, the 'unique value proposition' of ECBM is the opportunity to be involved in the energy generation process and the sharing of the up-front costs, as the economic barrier may hinder the participation of end-users in these settings. Communities mostly engaged in prosumerism activities publicize energy self-sufficiency and the access to renewable energy to end-users aiming to reduce their energy bills by self-consuming and selling their surplus generation as their main ‘value propositions’. Also, providing the access to renewable energy and collective behavioral change in communities without the required physical and economic conditions, which would never have the means to benefit from such services (through third party-sponsored or collective generation BM), are the ‘unique value propositions’ offered by such models. In turn, the possibility to participate in energy markets through aggregation and the creation of customized energy efficiency and e-mobility services, while exploiting alternative value streams (as the extra flexibility provided by EV storage) are the ‘unique value propositions’ offered by BM deployed in communities aiming to exploit DSM strategies and provide energy services. The economic driver may be understood as a relevant ‘value proposition’ of some ECBM as energy cooperatives.

Key activities, partners, and resources

Most of these BM ‘key activities’ include energy generation (onsite and offsite), consumption, trading, management, distribution, and supply, as announced in the European directives. Additionally, all the backstage activities (as daily operation, repair and maintenance, marketing, recruitment of new members, etc.) must be considered since they are key in supporting the projects over time. Specific BM may request customized activities. For instance, the community aggregation BM ‘key activities’ are based on the monitoring, controlling, and pooling of the demand flexibility provided by customers, interfacing with system operators to trade the aggregated resources and establishing penalties for non-compliance.

To perform such activities, ‘key resources’ are required, namely: 1) the members willing to participate and the investors willing to finance these projects; 2) the physical space to install generation and storage assets (onsite or offsite) as well as all the required technical infrastructures (ICT, net metering, distribution networks, etc.); 3) the regulatory framework, shaping the role of local DSO, aggregators, and all the potential entities involved in ECBM; 4) the long-term financial means to support project implementation over their lifetime (e.g. government incentives spread over time to encourage and maintain the interest of shareholders and participants); and 5) demand flexible loads to exploit demand sensitive BM. ‘Key partnerships’ are established between energy communities and: network operators, since distribution networks are used; retailers and last resort traders, which ensure communities power deficit selling and surplus generation buying; technology providers, which may offer relevant technical assistance; social entrepreneurs, local entities, utilities or other partners financing projects; and system operators, if demand flexibility is exploited for commercial purposes.

Channels and customer relationships

Overall, in energy communities, direct and close relationships are established between the different entities through direct (face-to-face) and indirect (e.g., digital, written) communication channels, including meetings, client support platforms, websites, etc. In more technology-based BM, as community aggregation and community virtual power plants, the relationship with customers is mostly indirect and supported by automated devices. Also, these relationships are commonly established over a long period of time consistent with the lifetime of the project to ensure its stability and financial continuity as well as the interest of the stakeholders. For this purpose, physical infrastructures (generation and storage assets, distribution networks, smart meters, AHEMS, etc.), automated devices and key partnerships (DSO, energy suppliers, etc.) are required.

Cost structure and revenue streams

The ‘cost structure’ and ‘revenue streams’ of the ECBM archetypes discussed are quite similar. All the BM involve fixed costs, incurred over the project lifetime (as energy procurement costs, if the project cannot guarantee the total supply of energy to its members and acquires energy from third parties, technology and land acquisition costs, rents, interest expenses, assets depreciation, etc.), and variable costs (as wages and other monthly operating costs). Communities using public distribution or transportation structures must also include the payment of use-of-system tariffs.

These payments must be considered whenever the community does not control its local distribution network. In turn, the costs of building new community distribution networks must be included if they are required to ensure the contracted services (e.g., heat distribution networks for community ESCO BM). Also, costs related with technical-economic feasibility studies must be considered in projects 'cost structures' as they raise investors' attention. The continuous payments from members or external customers are key to financially support these projects andkeep investors and shareholders' interest. The revenue streams include transaction-based revenues due to the selling of energy, energy efficiency and e-mobility services and recurring revenues due to long-term contracts. Incentives and subsidies provided by governments to boost renewable-based projects may also be comprised. The selling of ownership shares, surplus energy to other community members, to external retailers or last resort traders, and balancing, reserve and ancillary services to system operators must also be acknowledged as revenue sources.

Key metrics

'Key metrics' to assess BM performance may include a wide range of indicators as the community member savings and the number of community members served by the services (EE, e-mobility, energy supply, etc.) provided by ECBM. In communities driven towards local generation, self- consumption and trading, key indicators can help to understand how systems are performing regarding self-consumption and dependence from external supplying entities, allowing to understand how improvement strategies can be designed to optimize the use of local resources. Therefore, indicators such as the share of community demand supplied by local resources can help to assess the success of these BM. In communities owning and managing distribution networks, key indicators should provide a clear view of possible network issues (as congestion points), whereas communities aiming to manage their demand flexibility should adopt key indicators that inform about the potential of demand flexibility, facilitating the work of aggregators. Consequently, indicators as the community demand flexibility traded in energy markets could reveal how such BM are performing.

Competitive advantage

These BM are flexible and allow members to join or leave at any time, transferring or selling their assets and obligations to others. This feature is not possible or easily implementable in classical BM. Additionally, the social value created in any of these BM is not reproducible in other contexts. The energy autonomy, the increasing resiliency of communities capable of providing differentiated energy services and creating commercial value for residential demand flexibility are the most relevant competitive advantages of ECBM.

Figure 12 synthesizes and compares the different dimensions of LC and BMC mentioned above, grouping BM according to their main objectives.

Fig. 12 Comparative analysis of ECBM combining the BMC and LC frames. Color meaning: white text boxes: communities involved in energy generation, self-consumption and supply (energy cooperatives, community prosumerism, collective generation and third-party-sponsored BM); dark gray: communities aiming to manage demand (community flexibility aggregation); light gray: communities providing energy efficiency and e-mobility services (community ESCO and e-mobility cooperatives); black: all archetypes.

2.3.10. *CONCLUDING REMARKS*

Although not extensive, the proposed set of archetypes covers a wide range of possible BM in energy community settings, addressing the current and prospective regulatory and technological frameworks.

Several trends emerged from the previous analysis. First, the majority of the ECBM identified are involved in self-consumption and surplus generation trading, which is explained by the long- lasting tradition of energy cooperatives in Northern Europe countries. These BM aim to engage citizens in local energy generation to achieve some autonomy from the power grid and profit from the sale of surplus energy. Second, the initial shared investment and the provision of the complete value chain including generation, distribution and supply seem to be the main reasons explaining why energy cooperatives are, by far, the most widely exploited collective initiatives. Third, as most community projects are focused on renewable generation, REC are the most prevalent type of energy communities implemented across Europe. Finally, most of the existing projects are financially supported by small local investors (customer-side BM), who are simultaneously involved as asset owners, investors, and consumers, whereas third-party investment is mostly used to create value in low-income settings. Additionally, differentiated BM are starting to emerge to allow communities to control their distribution network, optimally manage the resources generated locally, develop local energy markets, and provide integrated EE and e-mobility services, lining up towards the CEC definition introduced by the IEMD. Indeed, by not restricting the type of technologies, opening the scope for more activities to be carried out, and allowing communities to own and control their internal distribution network, the IEMD establishes an especially attractive environment for novel BM to emerge. However, due to the IEMD recency, the higher dependence on ICT, as well as the need for new market players operating as intermediaries between customers, network operators and the market, these BM are still in their early development stages from the business perspective.

2.4. TO WHAT EXTENT ARE COLLECTIVE ENERGY PROJECTS ABLE TO ALLEVIATE ENERGY POVERTY? [d]

At a social level, CEI are presented as enablers of energy democratization (Palm 2021), raising energy use awareness, and increasing public acceptance of renewables (Azarova et al. 2019; Koirala et al. 2019), while fostering social cohesion. CEI have also the potential to pave the way to more inclusive energy systems by redistributing financial and social benefits of local energy generation within the community (Burke and Stephens 2018; Hanke, Guyet, and Feenstra 2021; Hanke and Lowitzsch 2020).

The legal frameworks to achieve these goals are being created, both at European and national levels. Still, there is a risk that, with poorly designed incentive mechanisms and policies, these projects may end up creating additional forms of exclusion, which should be considered in policy design since everyone's contribution is needed in the energy transition targeting carbon neutrality. With the aim of not leaving anyone behind while ensuring that the energy transition costs and benefits are fairly distributed, the EC fostered consumer protection both in the second (Directive 2003/54/EC and Directive 2003/55/EC) and the third energy packages (Directive 2009/72/EC and Directive 2009/73/EC), drawing attention to the need of protecting poor citizens against electricity and gas disconnection due to the inability of bill payment. This attention paid to energy poverty, which is perceived at the EU level as the "*inability to keep homes adequately warm*" given the lack of an official definition, brought this issue up for discussion thus giving rise, among other tools, to the Energy Poverty Observatory (EPOV), intended to offer an open-access tool to support energy poverty decision making at local, national and EU levels (EU Energy Poverty Observatory 2019).

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[d] Chapter based on Research paper VI.

The energy poverty focus was reinforced in the Clean Energy package, being acknowledged in key EU documents, namely: the Energy Performance of Buildings Directive (EPBD), which requires effective actions to be outlined in national building renewal strategies; the Energy Efficiency Directive (EED), which entails energy efficiency measures to be especially designed to support poor energy consumers; the RED-II, which focuses on the potential of renewables and CEI in alleviating energy poverty, since "e*mpowering jointly acting renewables self-consumers also provides opportunities for renewable energy communities to advance energy efficiency at household level and helps fight energy poverty through reduced consumption and lower supply tariffs*" (EC 2018b); and the recast of the IEMD, which underpins the need of each Member-State to adopt appropriate definitions, adapted to national realities, for 'vulnerable customers' and 'energy poverty', acknowledging the effect of "*income levels, the share of energy expenditure of disposable income, the energy efficiency of homes, critical dependence on electrical equipment for health reasons, age or other criteria*" (EC 2019a).

Both the EED and the EPBD aimed at making a relevant contribution to the mitigation of energy poverty by addressing an important driver - the energy and thermal performance of buildings. However, due to the extension of the building stock and the amount of investment required, the refurbishment benefits only take effect in the medium and long term. In turn, both the RED-II and the IEMD reinforce the need for Member-States to ensure that all citizens are able to participate in CEI as these initiatives should be "*open to all potential local members based on nondiscriminatory criteria*" (EC 2018b; EC 2019a). These documents draw attention to vulnerable consumers who, due to their social characteristics and threatened by conditions of energy poverty, may be excluded from the energy transition (Hanke et al. 2021). Despite these safeguards, no guidelines are further given on how Member-States should proceed to ensure the inclusion of vulnerable consumers on a level-playing field (Lowitzsch and Hanke 2019).

Considering the previous overview, several questions may be raised. The first and perhaps most relevant one is: *how are CEI able to effectively benefit both regular participants and vulnerable consumers?* The existing literature provides some answers. Due to the geographic proximity between energy consumption and generation installations, participants (regular and vulnerable ones) may self-consume the renewable energy generated, reducing the energy bought from the grid and, consequently, reducing costs. Whenever the consumption and generation sites are not the same and the distribution network is used to convey the energy produced to the consumption points, the public network use must be paid but the unused network access tariff components are exempted, effectively reducing the total price charged. Thus, CEI are expected to be able to provide cheaper energy supply conditions. Also, the initial high up-front investment barrier, which prevents many citizens of participating in renewable-based projects, is flattened due to the sharing among the multiple participants (Caramizaru and Uihlein 2020), third-party investors and partnerships (Burger and Luke 2017). Lastly, as CEI are not designed for profit making, the potential revenues achieved (from the sale of surplus energy, services, etc.) can be locally reinvested to fund energy efficiency actions, improve collective facilities, etc. (Vandevyvere et al. 2021). In addition to the economic benefits, CEI also create social value by promoting social cohesion, bringing people together and getting them to discuss energy-related issues, and improving their energy and environmental literacy.

Since CEI are expected to be mostly initiated by citizens who gathered the required conditions to create and actively manage in a daily basis these projects, a second research question would be: *how can the inclusion of vulnerable consumers be promoted and how is it ensured from a regulatory standpoint?* To answer this question, it is necessary to analyze the long-term national strategies included in 2021-2030 national energy and climate plans (NECPs) where, among other matters, Member-States define measures for CEI implementation and for energy poverty alleviation. An analysis of the NECPs of the 27 EU Member-States revealed that only four of them - Portugal, Spain, Italy, and Greece - proposed tangible measures linking CEI and energy poverty alleviation, as highlighted by Hanke et al. (2021). Energy poverty alleviation requires scientific knowledge, synergies among policies and action. Still, these steps are only being taken in a restricted number of EU Member-States, which are trying to fight energy poverty by including vulnerable consumers in collective energy models.

Portugal is one of the countries at the forefront of inclusive CEI. In addition to belonging to this limited group of countries proposing combined strategies to promote energy communities while fight energy poverty, Portugal is a case study of excellence as:

- It is a country with one of the highest levels of energy poverty in the EU (EU Energy Poverty Observatory 2019). Despite the mild climate, a considerable share of the residential energy demand is due to space heating, reflecting the poor thermal quality of the building stock. Nearly a quarter of the Portuguese population (24.4%) lives in dwellings with leaky roofs, walls, window frames, floors or foundations. It also performs badly regarding the number of households failing to keep housing adequately warm. In 2020, 17.5% of the Portuguese households were unable to keep home adequately warm, being the fourth worst EU country in this matter (EuroStat 2020);
- It is one of the EU countries with weaken economic outputs, low income and high economic disparities (GINI coefficient of equivalized disposable income: 31.9). The median equivalized income of Portuguese households is well below the European average (in 2020, the EU average annual median income was around 17 K€ while the Portuguese one was just over 10 K€ (Eurostat 2018)), which greatly influences the living conditions of the population (Fuinhas and Marques 2012) and exacerbates the situations of energy poverty;
- It is taking the first steps towards CEI having a high potential for decentralized solar-based energy generation, due to its availability of solar energy (IRENA 2020), which makes it a country of excellence for the development of both individual and collective energy self- consumption projects.

In this setting, *what specific measures are being fostered and what pilot-projects are emerging linking CEI and energy poverty alleviation in Portugal?* To answer this question, an overview of the policies and measures targeting energy poverty alleviation and CEI, taking as starting point the Portuguese NECP and the long-term strategies for collective self-consumption diffusion and energy poverty alleviation was carried out.

2.4.1. *AN OVERVIEW OF ENERGY VULNERABILITY*

According to estimations of the International Energy Agency, between 1.3 and 2.6 billion people currently experience energy poverty worldwide, thus suffering from several social and economic consequences (IEA et al. 2021). In the EU, the situation is also quite worrying as between 50 and 125 million Europeans are energy poor (EU Energy Poverty Observatory 2019), a situation that may have been further aggravated by the COVID-19 pandemic. The size of the numbers and the implications at social, economic, political, environmental, health and climate levels, makes energy poverty a key issue of the current European policy agenda (Boeri et al. 2020). Energy poverty is so challenging that is acknowledged in the United Nations' Agenda 2030 as one of the key actions included in Sustainable Development Objective 7 "Ensuring access to affordable, reliable, sustainable, and modern energy systems for all".

Despite the political and social relevance and extensive research on the topic, there is still no consensual definition for energy (or fuel) poverty: while in developing countries the concept is used to describe the lack of access to energy sources, in developed countries it is understood as the failure of households to keep acceptable energy services at an affordable cost (Moore 2012; Zalostiba and Kiselovs 2021). In the scope of this work, the term is used to describe the inability of a household to access the energy it needs to ensure a dignified standard of living at a tolerable price. This definition, praised by authors as Thomson, Snell, and Liddell (2016) as a key step to increase the political acknowledgement and visibility of the problem, requires a consensual understanding of what is a "decent standard of living" and what are acceptable costs, which should be dealt differently by each country. Considering the definition adopted, energy poverty is mainly caused by low incomes, high energy needs, mostly due to low energy efficient housing (i.e., poorly insulated, damp and with old appliances), and high energy prices (Rademaekers et al. 2016; Thomson and Snell 2013). In addition to these factors, there are also social, physical, economic, and structural factors such as weather conditions, fuels availability, the housing conditions (ownership, renting, etc.), etc., contributing to energy poverty (Dobbins et al. 2019; Pye and Dobbins 2015). This is, therefore, a multi-dimensional problem, not exclusive to households in economic poverty.

Since there is no consensual definition for the problem, there is not also a common definition to refer to whoever suffers from the consequences. In line with the energy poverty definition adopted in this work, energy poor (or vulnerable) consumers are perceived as consumers who, due to their socio-demographic characteristics (income levels, energy efficiency of the homes they live in, age, etc.), find themselves in a situation of energy poverty (i.e. struggle to afford a sufficient energy service level), are susceptible to disconnection of energy services and have limited ability to take informed energy decisions (Pye and Dobbins 2015). Thus, energy vulnerability is used to refer to a context created by the interplay between consumers' individual characteristics, political choices and economic disparities leading to some citizens being at risk of falling into energy poverty (Bouzarovski 2014, 2018; Dobbins et al. 2019; Okushima 2017). The lack of a transversal definition of energy poverty is not *per se* the biggest impediment to fighting this problem. Still, it contributes to the lack of a methodology to quantify and monitor this dimension in different countries (Bouzarovski, Petrova, and Sarlamanov 2012; Kyprianou et al. 2019). Consequently, there is a range of methodologies used to quantify this phenomenon, among which we may find (Rademaekers et al. 2016; Thomson and Snell 2013; Zalostiba and Kiselovs 2021):

- Expenditure-based methods, based on determining the relation between households' energy expenditure and income;
- Consensual-based methods, based on the investigation of the self-evaluation of poverty, the "perceived deprivation", by collecting self-evaluation data on the ability to adequately heating a home; the aptitude to pay utility bills; the presence of heating devices; dampness in walls and/or floors; the quality of window frames, etc.[9];
- Direct measurement methods, based on the evaluation of whether a sufficient level of energy services (heating, lighting, cooling etc.) is guaranteed by conducting direct measurements and comparing results with a certain standard.

The only data available to produce a comparative study among countries, collected from the consensual-based approach, are provided by the EPOV. The four main indicators include: 1) the arrears on utility bills, which describes the share of population having debts on utility bills; 2) the low absolute energy expenditure

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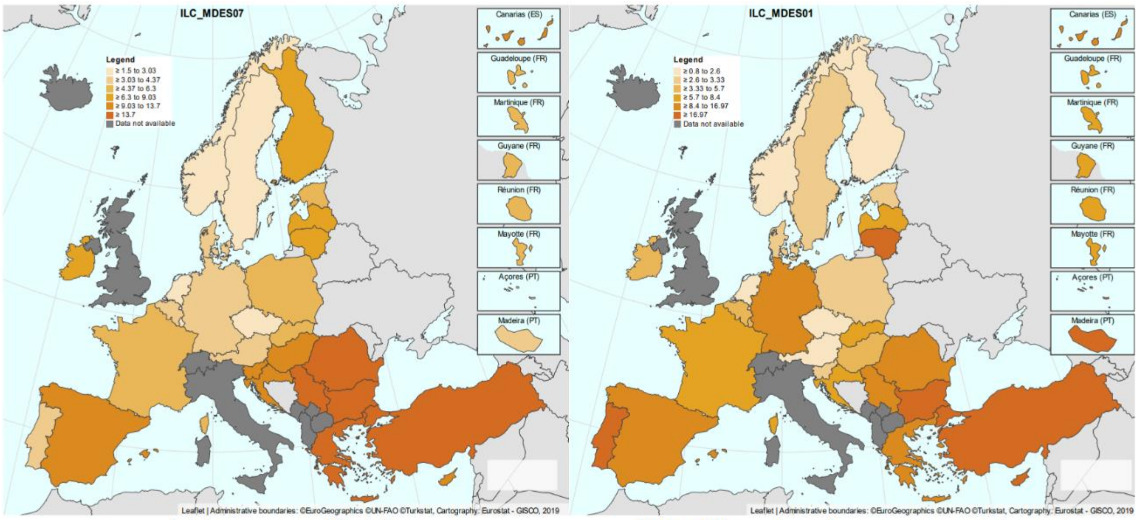
[9] This approach is commonly used at the EU level due to its ability to capture a wide range of factors influencing energy poverty. A large set of information is collected from the pan-European Survey on Income and Living Conditions (EU-SILC) available at: https://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-living-conditions.

(M/2)[10] showing the share of population whose absolute energy expenditure is below half the national median; 3) the high share of energy expenditure in income (2M), which translates the amount of population whose share of energy expenditure is more than twice the national median level; and 4) the inability to keep home warm, presenting the share of population not able to keep their home suitably warm. The EPOV indicators, especially 1) and 4), alongside several studies, as Bouzarovski (2014) and Bouzarovski and Herrero (2017), have revealed a higher prevalence of energy poverty in Southern and Eastern EU countries (Fig.13). Authors as Bouzarovski and Simcock (2017) discuss that spatial differences in energy poverty prevalence across the EU largely is a result of the structural inequalities of Member-States, their social and economic policies, and the status of energy systems.



(a) Arrears on utility bills (b) Inability to keep home adequately heated

Fig. 13 Energy poverty indicators across EU countries (source: https://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-living-conditions).

2.4.2. ARE COLLECTIVE ENERGY INITIATIVES WITHIN THE REACH OF ALL CONSUMERS? KEY SOCIO-TECHNICAL FACTORS REQUIRED FOR CEI PARTICIPATION

A key question being discussed is whether CEI are able to bring the anticipated social and structural changes in the energy landscape in a fair, affordable and inclusive way (Caramizaru and Uihlein 2020; Pye et al. 2019). These initiatives have the potential to offer consumers more choices to participate in the energy transition, including for those on vulnerable conditions who cannot otherwise afford to join. In addition to offer cuts in energy bills (by means of self- consumption and local surplus sharing, as well as by the exploitation of feed-in-tariffs from renewable installations) (Saunders, Gross, and Wade 2012) and create enabling conditions for local development, participants may benefit from dividends and energy efficiency services (Caramizaru and Uihlein 2020; Hanke and Lowitzsch 2020). Still, the success of such initiatives relies on meeting certain socio-technical conditions.

The first one has to do with context and existing conditions. CEI are expected to be initiated in rural environments due to the availability of space for the installation of wind or PV technologies or in urban neighborhoods with detached houses (Palm 2021). Multi-tenant buildings can also create CEI but are limited by the onsite available space. Still, offsite generation is possible in these situations. The situation regarding housing is also an important aspect to consider as tenants typically have a limited power of action over the

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[10] *M* refers to the national median energy expenditure.

adoption of energy efficiency measures. For these reasons, consumers who live in multi-family buildings and in rental conditions, find themselves in a situation prone to renewable energy exclusion.

A second condition is consumers' literacy and their ability to make sound energy decisions. One of the tools for consumers energy empowerment is choice, whether of suppliers and tariff schemes, supply options, technologies, etc. The consumption/prosumption options are, in theory, available to all, and consumers are assumed to have access to information and the cognitive skills necessary to understand them regarding the pros and cons (Ioannidou 2018). Still, authors as Hanke and Lowitzsch (2020) and Ruggiero et al. (2021) argue that consumers' knowledge regarding energy is limited and only those with the time and knowhow to understandthe complexity of the conditions and offers will be able to enjoy the energy transition benefits. Itis, therefore, unlikely that citizens with low energy knowledge will be able, by themselves, to realize the benefits and operation principles of self-consumption projects. Indeed, Mirzania et al. (2019) discussed that the lack of consumers' understanding of the CEI operating principles and technologies has been perceived as the main cognitive barrier impeding consumers to engage insuch projects. This issue can be further aggravated by the incorporation of storage systems and electric mobility into CEI, the development of more sophisticated business models involving aggregation and demand-side management, and an emerging trend towards collective energy "professionalization" which discourages newcomers (Nolden et al. 2020).

The successful implementation of CEI thus requires that consumers are aware of the advantagesof CEI, fully realize what they involve and how they operate. Still, the necessary physical, regulatory, and economic conditions must exist. A key factor boosting CEI implementation is the existence of an enabling regulatory framework favoring these projects and allowing different configurations and business models to emerge (Hanke and Lowitzsch 2020). While some projects are driven towards energy justice and self-sufficiency (as showed by Reis et al. (2020), the inclusion of vulnerable consumers in self-sufficiency driven CEI may be advantageous to absorb local generation surpluses and reduce grid interactions), larger initiatives may have a commercial purpose, not being suitable for certain types of consumers, especially the most disadvantaged ones (Jenkins 2019). Therefore, not all CEI should be perceived as equity-enhancing as different projects are emerging and must be allowed by the regulatory framework. Also, these projects require access to funding. CEI may help participants to achieve energy and money savings and the shared initial investment lowers the risk and the total individual investment amount (Koirala et al. 2016). Still, the financial barrier persists as one of the main bottlenecks of CEI implementation as the up-front cost of renewable technologies hampers consumers to invest, especially the most vulnerable ones. Despite the sharing investment, the average initial investment to become a CEI participant may range from 100 – 500 € (Caramizaru and Uihlein 2020; SCORE H2020 2020). Thus, there is a risk that CEI might create social disparities as these projects are more likely to be initiated by moderated to higher income households (Devine- Wright et al. 2017). In turn, the consumers who may not have the financial resources to invest in, may be overloaded with a higher burden of energy policy costs and public grid fees due to the loss of revenues from grid operators (Caramizaru and Uihlein 2020). As the financial stability of national power systems depends on the adequate contribution of all consumers, when part of them produce their energy, overall grid demand decreases. At the same time, grid access tariff exemption is being proposed to promote CEI implementation. Combined, these factors contribute to the decrease of the basis from which the total costs of the electricity system are generally recovered. As a result, the grid tariffs charged to the consumers remaining in traditional power supply systems, including the vulnerable ones, may increase (Lowitzsch and Hanke 2019; Palm 2021). Lastly, whenever technical conditions for participation are required (e.g., smart metering), situations of inequality between consumers tend to worsen (Hanke and Lowitzsch 2020). Thus, enabling incentive programs aimed at the acquisition of the required setups must be promoted.

The relationship income-education-context is, therefore, crucial in the energy transition: while the ones fulfilling the required conditions (regular prosumers) or even surpassing them (“professional” prosumers) are able to fully benefit from the enabling framework created and take advantage of all the value delivered by CEI, the ones who do not want to participate (regular consumers) or do not meet the requisites (the vulnerable consumers) can be pushed aside.

2.4.3. THE PORTUGUESE CONTEXT

Portugal, in its 2021-2030 NECP[11] proposed an integrated vision to guide its climate and energy ambitions. This document highlights the combined strategy for energy efficiency, dissemination of renewables and alleviation of energy poverty, with interrelated lines of action and measures. Fig. 14 displays the lines of action promoting a fair energy transition in the Portuguese NECP.

Line of action 3.2 - Dissemination of distributed energy, energy self-consumption and energy communities

- Measure 3.2.2 – To promote the creation and development of energy communities
- Measure 3.2.3 - To support the establishment of energy communities in partnership with municipalities

Line of action 8.1 - To ensure a just energy transition

- Measure 8.1.1 - To design a Strategy for a Just Transition

Line of action 8.2 - To fight energy poverty by improving the vulnerable consumers protection instruments

- Measure 8.2.1 - To promote a long-term energy poverty alleviation strategy
- Measure 8.2.2 - To create a national energy poverty assessment and monitoring system
- Measure 8.2.3 - To further develop tools to protect vulnerable consumers
- Measure 8.2.4 - To develop energy efficiency and renewable energy support programs to mitigate energy poverty
- Measure 8.2.5 -To promote local strategies driven towards energy poverty mitigation

Measure 8.2.6 - To disseminate information to mitigate energy poverty

Fig. 14 Measures announced in the Portuguese 2021-2030 NECP to promote a fair energy transition.

Line of action 3.2 addresses local renewable energy generation and CEI. The current national policy on this topic is based on the transposition of REDII, which created a legal framework for collective self-consumption and REC in Portugal (Decree-Law 15/2022). This framework was recently reinforced by the transposition of IEMD which created a new regulatory framework establishing the organization and functioning of the Portuguese power system (Portuguese Government 2022). To create an integrated dissemination policy (measure 3.2.2), CEI are referred to in several Portuguese strategic documents for the buildings sector, including the Long-Term Strategy for the Renovation of Buildings[12] where CEI are expected to “*strengthen the installation of equipment for self-consumption from renewable energy sources*". CEI are also mentioned in the proposal of a 2021-2050 Long-Term National Strategy for Energy Poverty Alleviation[13] as "*ways to support the participation of vulnerable consumers in energy and collective self-consumption*”.

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[11] https://ec.europa.eu/energy/sites/ener/files/documents/pt_final_necp_main_pt.pdf

[12] https://dre.pt/dre/detalhe/resolucao-conselho-ministros/8-a-2021-156295372

[13] https://www.dgeg.gov.pt/pt/areas-transversais/relacoes-internacionais/politica-energetica/proposta-de-estrategia-nacional-de- longo-prazo-para-o-combate-a-pobreza-energetica/

Additionally, in the Recovery and Resilience Plan[14] a share of 35 million €, out of the 610 million € allocated to energy efficiency in buildings, is intended to support CEI to achieve 93 MW of total installed capacity in 2025.

Similarly to what is announced in RED-II, the Portuguese REC regulatory framework allows citizens, small and medium sized companies, private and municipal entities, to produce, consume, share, store and sell locally generated renewable energy, as long as they are equipped with smart metering systems and located at the same voltage level (Portuguese Government 2022). To accelerate REC implementation, the Government also approved supporting schemes to create a level playing field. Network tariffs for self-consumption using the public distribution grid are already in place (Regulation 266/2020 and Directive 1/2021) and individual and collective self- consumption projects are exempted from paying General Economic Interest Costs (CIEG), a component of network tariffs associated with energy policies (Portuguese Government 2022).

In line with measure 3.2.2 (Fig. 14), measure 3.2.3 highlights the role of municipalities in the process of setting up CEI, both in the context of municipally owned social housing as promoters and enablers of other local energy projects, due to their proximity position in the territory and awareness regarding energy poverty prevalence. For these reasons, municipalities must be encouraged to promote CEI driven towards energy poverty alleviation, with positive local impacts on the energy performance and welfare of households.

Line of action 8.1 has a broader scope and aims to ensure an equitable and just energy transition. Measure 8.1.1 seeks to safeguard the opportunities and risks associated with the energy transition towards carbon neutrality in 2050 through a Strategy for a Just Transition. This document, which will be drawn up jointly by representatives of the Central and Local Administration, energy, environment, industry, economy, and academia sectors, should consider the interests of companies, workers and society for a fair and inclusive transition that promotes national competitiveness. In this document, special attention should be paid to citizens in a context of energy vulnerability, especially regarding the access to information. Collective energy projects driven towards energy poverty mitigation can be promoted by empowering citizens through knowledge and the provision of information, not only about benefits, requirements, funding and incentives, and technologies, but also about efficiency in the use of energy and behavioral change required to maximize the benefits of these projects (Hanke and Lowitzsch 2020). Therefore, a special attention should be paid to the information provided to consumers on how CEI can help them to improve their welfare. Lastly, the measures included in the scope of the line of action 8.2 focus directly on what needs to be done to assess, quantify and fight energy poverty at the national level, both through the design of a long-term strategy for energy poverty mitigation - considered in measure 8.2.1 – and the creation of a national system to diagnose and characterize the size of the phenomenon and identify monitoring indicators and strategies – measure 8.2.2. The national commitment against energy poverty embodied in the Long-Term National Strategy for Energy Poverty Alleviation must be highlighted due to the high expectations it places on CEI. The Strategy is anchored on four guiding principles: increasing the energy performance of homes, strengthening conditions for access to energy services, reducing energy consumption costs, and strengthening knowledge and access to information on energy through improving the energy literacy of the citizens. Based on these principles, the Strategy promotes an inclusive energy transition, by supporting CEI that: 1) include and involve vulnerable consumers "*aiming at reducing the burden on the energy bill, promoting increased self-consumption and energy sharing*"; 2) promote the involvement of vulnerable households in "*new forms of energy production, storage and sharing and their integration in Renewable Energy Communities*"; alongside municipalities and local energy agencies which help to define "*local strategies to fight energy poverty, aiming*

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[14] https://recuperarportugal.gov.pt/climate-transition/?lang=en

at a more local and direct approach".

Measure 8.2.3 focuses on the mechanisms allowing to reduce energy charges for domestic consumers so that energy prices are not an exclusion factor in accessing these commodities (electricity and natural gas). Among these mechanisms, the Social Tariff on electricity and natural gas stands out as a key economic-based measure with a strong impact on energy accessibility. Other measures are in place to protect vulnerable consumers, e.g., by not allowing disconnection by suppliers due to utility bill arrears. The promotion of more structural actions to fight energy poverty, such as incentives to change consumption patterns, interventions aimed at making investments in energy efficiency, buildings refurbishment and programs aimed at the integration of renewable energies, are contemplated in measure 8.2.4. Measure 8.2.5 focuses on the need for incentives to local energy strategies that aim fighting energy poverty through local actions, among which CEI. Lastly, measure 8.2.6 is oriented towards awareness and access to relevant information to support decision-making, since the dissemination of relevant information allows for consumers to increase energy literacy and make more informed decisions.

Despite the regulatory efforts and stakeholders' expectation regarding this issue, fully functioning REC in Portugal are still scarce although different promoters have tried to develop them. The *Bairro Solar*[15] project initiated by EDP aimed to promote and facilitate prosumerism: consumers with rooftop space for the installation of PV technologies can become prosumers while neighbors with no available space can benefit from surplus energy generated in a nearby installation. Thus, both prosumers and neighbors benefit from locally generated renewable energy. In August 2021, Cleanwatts[16] a Portuguese cleantech company, in partnership with a private social institution from Miranda do Douro, Portugal, announced the creation of one of the first REC in the country. This project is based on the installation of PV panels on the institution roof area, allowing to reduce energy costs by around 10%. A similar project is being created in São Pedro Velho, in the municipality of Mirandela, where a second 27 kWp REC is being implemented with an estimated reduction of energy costs of over 20%. These two latter initiatives are part of the social innovation project *Cem Aldeias*[17] which aims to impact the lives of 20,000 people in 100 small Portuguese villages by combining energy efficiency and renewable energy generation to mitigate energy poverty.

The fight against energy poverty through CEI is indeed an important motivation for different promoters, mainly local government entities. Examples of this trend are the *Smart Pole by Nova SBE* project[18] in Cascais, which studies the implementation of a financial, legal and technical model capable of supporting the country's first municipally-participated energy community; the European project *POCITYF*[19] led by EDP, which aims to install building integrated photovoltaic(BIPV) solutions in eight municipal buildings in Évora to generate 800 MWh/year, the surplus of which will be shared with buildings from the historic center; and the *Asprela+Sustentável*[20] project, described in Table 2.

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[15] https://www.edp.pt/bairro-solar/

[16] https://www.cleanwatts.energy/

[17] https://jeune-europe.org/2020/08/jeune-with-cem-aldeias-against-energy-poverty/

[18] https://www.eeagrants.gov.pt/en/programmes/environment/projects/projects/cascais-smart-pole-by-nova-sbe/

[19] https://pocityf.eu/

[20] https://asprelamaissustentavel.pt/

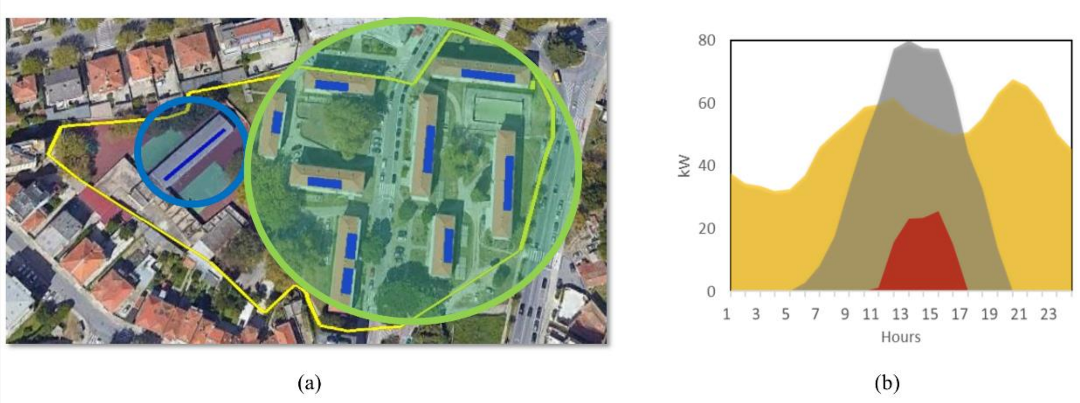
Table 2 Agra do Amial case study in the framework of the Asprela+Sustentável project.

The Agra do Amial renewable energy community

Agra do Amial's REC was the first project to receive the classification of pilot-project by the Portuguese Energy Regulator. This REC is part of a broader project, the "Asprela + Sustentável" project, funded by the EEA Grants, which aims to create a living lab to test innovative services and technologies, helping the Porto city to achieve carbon neutrality. Developed in cooperation with different Portuguese entities, the project seeks to encourage the consumption of renewable energy, sustainable electric mobility, and storage. In addition, the project also has a strong social component as the energy community is being implemented in the social housing neighborhood of Agra do Amial, one of the several ones in the city of Porto under the municipality's responsibility. Social neighborhoods shelter households in a situation of economic deprivation and represent a high cost for the municipalities. However, these buildings represent a high potential for REC implementation since they generally have large available rooftop areas, making them an asset of interest for photovoltaic-based energy generation.

Agra do Amial REC involves 181 households (355 people) in the Agra do Amial neighborhood, built in 1960 and refurbished in 2002. On average, these households pay a symbolic rent of €29 to the municipality; however, they have monthly energy costs almost three times higher (around €80), translating the poor energy and thermal conditions these households live in. Agra's elementary school also integrates the REC and host one of the two photovoltaic systems (13 kWp installed in the school and 101 kWp in the rooftop of the neighborhood). The locally generated energy is intended to preferably supply buildings where they are installed and surpluses will be stored in regular and second-life batteries being implemented as a way of contributing to an increasingly circular economy, which is a key goal of the Asprela+Sustentável project. At the school, 21 kWh of second-life batteries are being installed, while in the neighborhood a battery bank with a capacity of 133 kWh is to be implemented.

Also, three charging stations for electric vehicles (22 kW each) will be made available receiving surpluses from the REC. Considering the socio-demographic characteristics of the inhabitants of the Agra do Amial community, it is unlikely that the electric vehicle charging service will be for the service of the residents. Therefore, charging systems are being designed for public use and the charging payment will be reinvested in the community. Alongside this solution to promote electric mobility in the Asprela area (in which the Agra do Amial is included), mobile apps will be developed to alert users to periods of reduced charging prices due to the existence of generation surpluses or locally stored energy.



(a) (b)

Fig. 15 (a) Surrounding area of the Agra do Amial community, including the school (blue circle) and housing (green circle) and (b) Expected community functioning in a typical summer day, Yellow: demand; grey: generation: red: stored surplus.

Currently, the neighborhood and the school consume annually around 602 MWh. The REC is expected to be able to supply around 26% of the annual electricity needs, avoiding the emission of about 57ton CO_2 annually. It is also estimated that participants' electricity bills will be reduced by approximately 10% due to self-consumption. Exemption from the payment of CIEG as well as tariff components related to unused distribution and transport networks will be applied to supply electricity at a price around 40% lower than the retail price, which will greatly contribute to reduce the participants energy bills and minimize energy poverty.

Despite the contribution of the reduced energy costs, savings provided by the REC by themselves are not enough to improve the living conditions of these households. For this purpose, in addition to the creation of the REC, further actions must be specifically developed aimed at alleviating energy poverty. An exhaustive survey of the living conditions and energy poverty related indicators will be carried out to understand the real extent of the problem and how it can be effectively mitigated. Then, tailored energy efficiency measures will be proposed, and engagement mechanisms combined with awareness campaigns will be promoted so that participants understand the real benefits of REC and take advantage of all of them. To reinforce awareness and involve the students at Agra's school, gamification schemes will be developed to involve them in the management and monitoring of the performance of the PV plant. In addition, from a circular economy perspective, measures related to the water cycle, through the monitoring and control of the water in the streams of the Asprela central park, currently under construction, as well as initiatives such as "Good Food Hubs", which bring the community closer to sustainable agriculture practices, will be promoted.

As for initiatives that simultaneously support collective energy generation and energy poverty, two Portuguese projects are mentioned in the Long-term strategy for energy poverty mitigation as examples to follow in this topic. The first is the Horizon 2020 Porto Energy ElevatoR[21] led by the Porto Energy Agency[22] which aims to mitigate energy poverty by promoting energy efficiency in 3000 dwellings, encouraging individual and collective self-consumption with the installation of 12 MW of renewable PV energy. The second is the POWERPOOR[23] project, which has the involvement of Coopérnico[24], a renewable energy cooperative, which also aims to encourage the use of alternative financing models to promote energy efficiency and renewable energy to fight energy poverty.

2.4.4. *CONCLUDING REMARKS*

CEI are expected to actively contribute to energy justice by engaging with vulnerable and underrepresented groups of citizens and provide them access to cheaper renewable energy, energy efficiency and other valuable energy-related services, helping to alleviate situations of energy poverty. Still, as shown by the low number of countries proposing effective measures to fight energy poverty through collective energy generation in national NECP, CEI actively promoting energy poverty mitigation remain an exception. The analysis of innovative projects emerging in Portugal show how collective renewable energy projects can be designed to include vulnerable groups of citizens in the energy transition. A set of challenges that CEI face may limit their ability to effectively mitigate energy poverty. The first is a restricted understanding of the dimensions underlying energy poverty and the lack of a consensual definition. As a result, the recognition of energy poverty situations, the development of tailored and adequate procedures to engage vulnerable citizens, and the delivery of adequate energy services, is hampered. Due to their presence in the territory and proximity to citizens, municipalities, supported by energy agencies, can play a key role in such settings by supporting justice driven CEI both by helping to identify local energy poverty situations (e.g., in social

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[21] https://portoenergyhub.pt/

[22] https://www.adeporto.eu/

[23] https://powerpoor.eu/

[24] https://www.coopernico.org/

housing neighborhoods owned and managed by the municipality) and becoming promoters or project partners themselves to provide funding and technical know-how to initiate CEI. The second is the access to funding: vulnerable consumers do not have the required funding to initiate by themselves renewable energy projects which, especially at the beginning, often depend on members/investors to provide the required financing capability. Such usually high upfront contributions are a barrier for the participation of vulnerable consumers with limited financial means. This raises an additional question: should vulnerable consumers be supported to have the access to the required financing or should CEI receive additional incentives to facilitate the inclusion of vulnerable groups? On the one hand, direct subsidies would immediately increase vulnerable households' income while providing a strong incentive for participation; on the other hand, it could lead to situations of rebound effects and inefficient use of energy. The solution can be a combination of both: financial support, combined with technical support and training, must be provided to these citizens to improve their living conditions in an energy efficient way, while CEI are supported in the form of fee and tax exemptions or direct incentives, if they include vulnerable groups as members. In addition to funding, the degree of involvement necessary to participate in a CEI depends also on citizens' energy literacy and time availability. As previously discussed, the vulnerability context is often associated with low energy literacy levels; thus, the lower the threshold in terms of the required knowledge and commitment the more likely the participation. This does not necessarily mean that vulnerable consumers lack the cognitive capacity to participate but rather that they need todeal with more pressing daily challenges. Also, regardless of the level of financial participation in the project, vulnerable consumers must be included in the governance and membership of CEI to reinforce the sense of belonging and commitment necessary for an active participation. These seem to be the ingredients for successful equity enhancing CEI which must be safeguarded from the regulatory framework viewpoint.

2.5. MODELING

This section reviews energy modeling starting by framing the need for different modeling methods to deal with LEC technical, social, and organizational dimensions, addressing specific CEI modeling strands and detailing the mathematical modeling approaches in the literature.

2.5.1. THE CHANGE IN POWER SYSTEMS AND THE INFLUENCE ON MODELING [E]

The so-called energy transition raises several technical, social, economic, and environmental challenges which must be addressed at the technical and policy making level. As the current decentralization of power systems is fostering the emergence of new operation rules and business models, different modeling strategies are required to support decision-makers in the design of more effective energy policy. The complexity created by the role of new actors in the operation of power systems requires a greater coordination among all the involved entities and leads to the need of more flexible and adaptive methods to provide adequate decision support to market players and policy makers. From a modeling point of view, distributed energy systemsas energy communities bring additional challenges due to the number of entities involved and the dynamics created by the interactions established between them (Ma and Nakamori 2009). By promoting greater consumer participation, opening room for different entities to participate in energy systems and relying on end-users decision-making processes, CEI assume a noticeable socio-technical dimension. Therefore, conventional techniques (such as optimization and forecast techniques, discrete-event simulations, etc.) usually applied to power systems modeling may miss to fully tackle the behavioral,

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[e] Based on Research papers I, III and IV.

social, and organizational dynamics embedded in CEI (Maand Nakamori 2009). Also, the pervasiveness of ICT, real-time monitoring and control devices, advanced metering infrastructures, etc., supporting CEI, is expected to generate massive amounts of data which require sophisticated data handling techniques (Antonopoulos et al. 2020).

Although all the recognized theoretical benefits, CEI are still challenging to model, create and operate in a way which complies with all stakeholders' interests. First, CEI are expected to accelerate the integration of distributed renewable energy into power networks, contributing significantly to the EU carbon neutrality goal. However, as the challenges of implementing CEI inthe field lead to many modeling exercises remaining in the theoretical field and real-world CEI exploiting the overall range of possibilities made possible by the current EU regulatory framework is scarce. Thus, it is not possible to know for sure (in a quantitative manner) the real benefits that CEI can bring to their members, to power systems and what impact these initiatives will have on EU carbon neutrality targets. In turn, the uncontrolled injection of massive amounts of renewable generation into power systems can create grid disturbances. Although several authors have studied the effects of the massive integration of distributed generation into power networks (Islam et al. 2015; Khabachev et al. 2017; McDonald et al. 2012; Sor, Fauzi, and Hidenori 2015), to the authors' best knowledge, these approaches have not addressed how this incoordination can be penalized.

Second, as multiple stakeholders operating in different actuation spheres (political, economic, technological, etc.) and holding different expectations and concerns are involved, multiple interests and expectations are at stake. The novelty of the regulatory frameworks on CEI, as wellas the little experience in implementing such projects, raises many uncertainties regarding the process and the alternative courses of action still exist hindering implementation. Thus, it is challenging to design a LEI without previously listing all the involved entities and knowing their expectations on the project. Relevant questions that may emerge in countries in which CEI are starting to be a reality are the following:

- *How can the regulatory framework include collective energy initiatives in a fair and coordinated way?*
- *To what extent the existing power system, and its participants, can/must adapt to the socio-technical transition created by the emergence of collective energy initiatives?*
- *What new roles can the stakeholders involved in conventional power systems play and what new entities will enter in these processes and under what circumstances?*

Aiming at presenting a comprehensive view of the complexity associated with decision-making in such settings, a Problem Structuring Methods (PSM) approach was developed to describe the decision context, presenting the main stakeholders, their roles, and motivations in CEI settings. This approach is further detailed in Chapters 3 and 4 and allow for a greater understanding of the operation of the national electricity system and the role played by different stakeholders.

Also, as the interests of the multiple entities involved may be conflicting, multi-objective optimization approaches are often adopted. In optimization approaches, decision criteria concerning economic, environmental, and social goals can be transformed into objective functions to be minimized or maximized subject to a set of constraints which implicitly defines the feasible solutions. As previously discussed, the purpose of CEI is to provide environmental, economic, and social community benefits. Thus, benefits (as emission reductions, influence on local economies, jobs created, inclusion of vulnerable consumers, costs, and savings, etc.) must be quantifiable (Alaton et al. 2020). From the community planners' perspective, those benefits can be conflicting, thus requiring the explicit consideration of multiple objective functions in optimization models thus enabling to unveil the trade-offs between the competing objectives (Fleischhacker et al. 2019). Such problems can be exploited using multi-objective optimization models.

Defining the objectives to be considered is not an easy task since individual decisions influence the community performance and modeling must be flexible enough to accommodate different stakeholders' views and priorities (Bakhtavar et al. 2020). For instance, Gao et al. (2021) recognized that choosing the optimal energy use strategy among different decision makers in a CEI is a complex task and proposed an energy multi-objective scheduling model based on a smart community energy management framework by considering the different utility assessment of decision makers. Different decision makers' utility assessments regarding energy management means different reactions to signs of price and availability of renewable energy and/or storage, which conflicts with the optimal management of collective resources. Fan et al. (2022) proposed a multi-objective collaborative optimization method to minimize the annual carbon emissions, annual total cost, and total grid interaction of a net-zero energy community energy system that combines hydrogen storage, electricity storage, and heat storage. Once again, minimizing operational costs, managing technologies dependent on renewables, and trying to maintain some self-resiliency from power grid is also a challenging task as grid price signals and renewable availability are often conflicting. An extensive literature set on energy multi-objective problems could be presented (as Salinas et al. (2013), Cao et al. (2019), Soares et al. (2017), and Bakhtavar et al. (2020)), still the conflicting objectives considered are often the same: users' utility and renewable availability and storage maximization, minimization of costs, GHG emissions, and network interaction. As it may be difficult to formulate multiple objective functions representing the concerns at stake in a community setting, the use of multi-criteria decision analysis (MCDA) techniques has been increasingly used (Mckenna et al. 2018). In MCDA approaches, the alternatives to be evaluated by the multiple criteria are explicitly known at the outset, whose performances in each criterion can be displayed in an impact matrix. Mckenna et al. (2018) proposed a MCDA approach aiming to help smaller German municipalities to develop decision support methods to assist the design of local energy strategies. This work used the results of a participatory approach to feed a linear optimization model assessing feasible LEC strategies in the 2030 horizon. The approach was tailored to a context characterized by a long tradition in collective energy initiatives. Therefore, the decision context was already clear to stakeholders, who have defined and clearly knew their roles and perspectives, contrary to what happens in other European countries taking the first steps which are struggling to implement projects in the field. Lode et al., (2021) used a participatory multi-actor MCDA model in a transition management approach context to assess the impact of LEC on power relations, political sphere, sustainability, and guidance, in the Netherlands. Also in this case, the approach is devoted to a specific context with a long-lasting tradition of CEI. Therefore, the perspectives elicited from the stakeholders are far more advanced than in countries starting to define regulatory frameworks for collective energy. Also, the exploitation of the transition management approach, despite providing an integrated view of LEC and CRSC, requires the existence of well-defined, comparable and assessable 'transition arenas'. The lack of implemented projects and the novelty of the concepts involved in collective energy projects make it impossible for many European countries to have a clear vision of what a 'transition arena' would look like.

Third, usually CEI do not know which composition of users is more suitable for their interests. For instance, in CEI driven towards energy trading – a common modeling strand in community energy projects – users must be equipped with the decision tools necessary to participate in LEM. LEC boost local electricity procurement and trading activities, fostering the development of LEM in which members are allowed to trade electricity within community boundaries (Mendes et al. 2018a; Moret, Pinson, and Papakonstantinou 2020). By participating in LEM, consumers, prosumers and prosumagers may act as traders to sell and buy self-generated electricity at more competitive prices and without the conditions applied by retailers (Viviers et al. 2018). Usually based on collaborative principles to facilitate electricity exchanges among participants, LEM can be shaped to drive participants to achieve common goals (such as self-consumption maximization

(Mendes et al. 2018)). Additionally, LEM can play a key role in lowering electricity prices. In many countries, electricity tariffs obey the additivity principle, meaning that generation, transmission, and distribution contributions to the overall cost are summed up and charged to customers by retailers, which are then responsible for reallocating the corresponding amounts to the different actors (generators, TSO, DSO, etc.). In community LEM, market participants assume the role of generators and suppliers, and electricity usually flows within the same voltage distribution network, which may exempt electricity exchange activities of the payment of tariff components related with unused transmission and higher voltage distribution networks, effectively lowering the price charged at local trading (EC 2018b; EC 2019a; Klein et al. 2019). Although the research on LEM is still in an early stage, different market structures have been proposed in the literature, highlighting two in particular (Guerrero, Chapman, and Verbič 2019; Moret and Pinson 2019; Shrestha et al. 2019; Sorin et al. 2018; Sousa et al. 2019; Verschae et al. 2016): 1) the P2P markets, in which electricity exchanges are made in a decentralized manner, allowing for peers (grid- connected parties) to freely negotiate with each other; and 2) the community-based markets, relying on intermediary entities to manage the market trading activities and facilitate the relationships between the LEC and external systems operators (as retailers and DSO). The community-based exchange scheme designation is used in the scope of this work to refer to a collective model of electricity exchange, constrained by the physical boundaries of the LEC (limited by the low-voltage local distribution network), operating according to rules agreed by all stakeholders and controlled by a coordinating entity that manages transactions while interfacing with external retailers. The booming research in P2P electricity exchanging often leads to disregarding other models, which can have a great potential in the context of LEC. Indeed, authors as Moret and Pinson (2019) stressed that community-based markets are much less common in the literature but are expected to become more usual in the near future due to their adequacy to LEC electricity trading activities.

Local electricity trading is generally associated with purely decentralized P2P models, disregarding more centralized markets. Extensive theoretical and practical research has been dedicated to P2P electricity trading, which allows for electricity trading among prosumers without the need of external supervision (Guerrero et al. 2019). In such arrangements, generation surpluses are transferred and sold to other users through platforms that register all transactions, allowing for them to decide from whom they purchase electricity and to whom they sell it. Despite the attention paid in the academic literature, P2P electricity trading is not yet at the stage of mass integration. Scalability issues related to the negotiation processes among peers, as well as local electricity balance control issues, are compromising the dissemination of fully decentralized P2P models (Zhang et al. 2019). Additionally, although emerging tools, as the blockchain technology, aim to provide the needed digital infrastructure to support these markets, the large amounts of computing power and electricity consumption required to solve security and cryptocurrencies instability issues have been hindering the implementation of such technologies to support real- time transactive electricity markets (Hertz-Shargel and Livingston 2019; Silvestre et al. 2019). In turn, more centralized approaches also offer a significant potential for local electricity exchanging. One of these approaches concerns community-based markets, which are described as more reliable, since a central node helps matching buyers and sellers while also playing other roles, such as market clearance (Zhang et al. 2019). Due to their characteristics, these markets can only be implemented if participants are geographically close to each other, as in microgrids and neighborhoods (Akter et al. 2017; Olivella-Rosell et al. 2016). Also, due to their cooperative nature, these markets are more suitable for settings in which participants have similar interests, such as energy self-sufficiency (Sousa et al. 2019). However, as highlighted by Shrestha et al. (2019), community-based markets may face some challenges since participants' preferences on electricity usage may not be met at all time, and a high computational burden is put on the central entity, which must record all participants' data while ensuring fair electricity exchanges. So far, few studies have exploited the potentialities of such market structures. Emphasis is given to the works of Moret and Pinson (2019) and Zhang et al. (2019) that addressed community-based markets in different ways. The first one examined how a collaborative prosumers' community- based market could promote local electricity exchanges, while the second proposed a MAS environment to simulate a community-based market in which a coordinator agent interfaced a supplier agent, implementing a demand response program, while prosumer agents reacted (their consumption behavior was modeled through non-cooperative games) (Zhang et al. 2019). So far, few real-world projects have adopted this centralized model; however, it is expected that this type of markets will become more frequent as the number of LEC involved in these activities increases. This assumption is illustrated by the transposition of the RED-II to the Portuguese regulatory framework (Portuguese Government 2022), where the creation of a centralized entity, designated as collective self-consumption management entity, is expected to exist in the LEC. The role of this entity is three-fold: 1) to ensure the commercial relationship with the DSO (ensuring the payment of tariffs due to the use of networks) and with the TSO, if the sale of electricity surplus is carried out in an organized market or through bilateral contracts; 2) to establish contracts with market participants or facilitators for the sale of surpluses and for ensuring the existence of supply contracts for providing the electricity deficit; and 3) to exchange the collective self-produced electricity, revenues and costs, according to the LEC statutes (ERSE 2020a).

From a modeling point of view, local energy exchange completely changes the way in which energy flows, data, cash, and relationships between parts were modelled, creating an increased dynamics that modeling must be able to follow and solve. As a result, new modeling and simulation approaches must be developed to allow to support real-world LEM applications (Sotoet al. 2021).

Fourth, regulatory frameworks are constantly evolving, requiring a constant assessment of how CEI can be technically viable, economically bankable, and socially accessible and attractive. Also, although permitted and encouraged by the regulatory framework, the literature on CEI including other sectors than residential is scarce. The significant electricity demand of the tertiary sector, mostly dominated by small and medium-sized enterprises (SMEs), justifies the research interest in this sector as it can unfold a relevant untapped DSM potential (Wohlfarth et al.2020). The demand profiles of such a wide range of companies are quite diverse depending on the activity performed, the occupancy patterns and the use of different types of loads. Due to this heterogeneity and the lack of publicly available electricity consumption data on commercial activities, this sector is often excluded from modeling experiments (Voulis et al. 2017). However, CEI modeling must focus on exploiting the demand complementarity of residential and commercial sectors are mixed areas are common in most EU urban areas and the benefits this complementarity can bring to users and local power systems has been neglected from a modeling perspective.

2.5.2. *MATHEMATICAL MODELING OF COLLECTIVE ENERGY SYSTEMS*

CEI modeling challenges start during the planning stage as many configuration and decision variables must be listed and considered depending on the number and type of community participants and the systems and technologies involved. During this stage, CEI members and involved stakeholders, the resources available and the regulatory, social and economic framework must be clearly identified and characterized; the rules defining how core collective activities (i.e., consumption, storage, trading, the connection with the energy infrastructure) will be performed must be established; the relationships among involved parties must be known and the exploitation of how overall (project) and individual objectives can co-exist in the project must be performed (Fig. 16).CEI modeling challenges start during the planning stage as many configuration and decision variables must be listed and considered depending on the number and type of community participants and the systems and technologies involved. During this stage, CEI members and involved stakeholders, the resources available and the regulatory, social and economic framework must be clearly identified and characterized; the rules defining how core collective activities (i.e., consumption, storage,

trading, the connection with the energy infrastructure) will be performed must be established; the relationships among involved parties must be known and the exploitation of how overall (project) and individual objectives can co-exist in the project must be performed (Fig. 16).

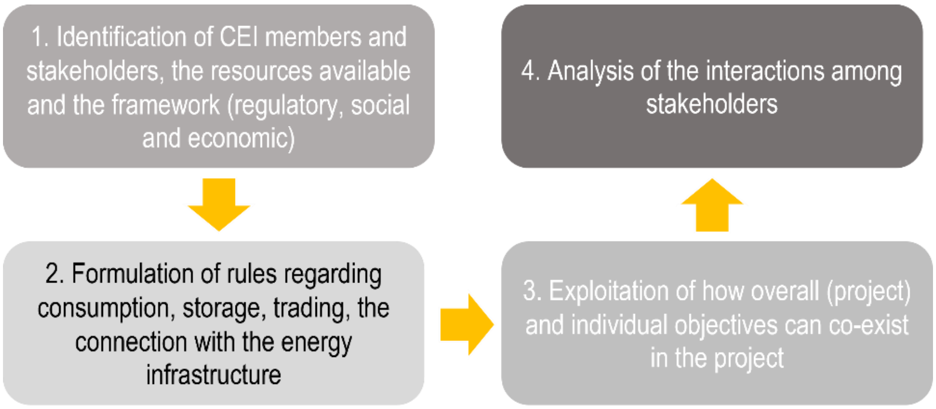

Fig. 16 Community planning steps.

Current energy planning tools applied to CEI use several modeling methods (Bakhtavar et al. 2020). Among those, scenario-based planning is widely used to tackle planning problems as alternative scenarios can be designed and compared (Hiremath, Shikha, and Ravindranath 2007). Still, these models often neglect in-between scenarios, which may limit the comprehensiveness of the analysis. This limitation can be overcome by mathematical optimization encompassing multiple scenarios instead of a scenario-based planning approach (Alsayed et al. 2014; Bakhtavar et al. 2020). But what objective functions should be optimized in CEI and what methodologies are usually used to do so?

Several objective functions to be maximized or minimized can be pursued in optimization models. Energy bill, energy required from the grid, investment, operation and maintenance costs, discomfort, losses, and voltage deviation, GHG emissions are common objective functions to be minimized in community-scale problems. Revenues, self-sufficiency, comfort, quality of service/reliability, social impacts are objective functions usually maximized (Antunes 2022). At the collective level, the maximization of collective self-sufficiency is the main objective function to pursue. It implies to minimize the buying interactions with power system operators and optimally manage demand and supply at the local level by matching consumption and generation as much as possible. Also, similarly to what happens at the individual level, it seems reasonable to exploit the collective cost minimization objective, considering how the energy generated and stored in shared systems is managed and how the interactions with the grid are made. This objective was exploited in works as Ye et al. (2017) and Luz and Silva (2021). Minimizing costs implies to actively exploit tariff schemes and steer demand towards periods of lower prices of time-of-use tariff schemes. It may also involve selling self-generated energy to maximize profits (instead of self-consuming or store it) and procure energy (to consume or store) when prices are lower. The cost minimization objective is not fully coincident with the energy autonomy maximization objective often associated with projects of this nature. The self-consumption maximization objective requires further exploiting the generation-demand-storage relationship and taking advantage of demand-side management strategies and storage devices to enhance the utilization of self-generated energy, as proposed in Luz et al. (2021).

Regarding the mathematical approach, mathematical programming methods are used to obtain the exact optimal solutions to different types of optimization models as linear, nonlinear, mixed- integer linear/nonlinear programming models. However, for some complex models (due to their nonlinear and/or combinatorial nature) it may not be possible to obtain the optimal solution within an acceptable computation time. Therefore, meta-heuristics as Simulated Annealing, Taboo Search, Particle Swarm Optimization, Genetic Algorithms or Differential Evolution can be used to obtain approximate (hopefully good quality) solutions with a moderate computation effort (Frangopoulos 2017; Zafar et al. 2018). Cosic et al. (2021) proposed a mixed-integer linear programming (MILP) model to the optimal planning of a renewable energy community based on a real case study in Austria. Nine energy community members are considered and distributed PV and storage systems, different electricity tariff scenarios and market signals are considered. Results reveal that participants can benefit both economically (costs reductions of around 15%) and environmentally (collective carbon dioxide emissions reduction of around 34%). Stephant et al. (2021) proposed a community model with a set of various actors (PV generators, electric vehicles, storage system and commercial buildings) and uses game theory to model the preferences of each user. This framework is also used to design a mathematical model where each actor optimizes individually its power profile. An Alternating Direction of Method of Multipliers algorithm is used to obtain solutions. Results revealed that the proposed approach leads to a maximization of local energy exchanges with benefits for all parties. Chis and Koivunen (2019) developed a coalitional game theory-based optimization method to minimize electricity costs of households in a smart community. In the proposed model, some households own renewable energy sources alongside energy storage systems, while the remaining ones are simple energy consumers. The proposed model includes exchange of locally generated energy and show that by participating in the community these households may considerably reduce their costs in comparison to performing individual cost optimization. Simulation results show that the proposed method may reduce the electricity costs for prosumer/prosumager households by around 18%, while consumer households may reduce their costs by 3%. Several other works that employ optimization tools could be presented. However, in general, these works do not address the different perspectives and objectives at stake, do not model loads and technologies in a detailed way, or do not consider individual consumption dynamics (e.g., different sizes of households, equipment ownership rates, etc.).

Furthermore, optimization models need to consider uncertainties and variability, especially regarding resources availability and energy demand (Yue et al. 2018). Stochastic, fuzzy, interval and robust programming methods are often exploited to deal with uncertainty of load variation, energy pricing, solar radiation, energy usage behavior, etc., and find robust solutions (Antunes 2022).

2.5.3. *DISTRIBUTED ARTIFICIAL INTELLIGENCE*

Artificial Intelligence (AI) has been identified as key to deal with modeling and decision support (Ali and Choi 2020; Antonopoulos et al. 2020). Distributed Artificial Intelligence (DAI) is a subfield of AI that is based on the interactions of intelligent agents capable of making decisions to achieve goals while co-habiting in an environment populated by other agents (Chaib-Draa et al. 1992). Based on a programming paradigm for software engineering called Agent-Oriented Programming (AOP), agent-based modeling (ABM) including multiagent systems (MAS) are a sub-field of DAI (Merabet et al. 2014). ABM has emerged as one possibility to introduce intelligence in modeling processes by designing agents unveiling perception, reasoning, learning, decision-making, problem solving, interaction and communication skills (Rizk, Awad, and Tunstel 2018). Agents enable to deal with smaller components resulting from the decomposition of complex and large systems. This breakdown allows each element of the model to be comprehensively represented and the most adequate methods for each element are used to solve specific issues (Dijkema, Lukszo, and Weijnen 2012).

Basic principles

According to authors as Kremers (2012) and Coelho et al. (2017), ABM is an adequate tool to model dynamic systems as it is based on simple, but heterogeneous entities and allow detailed representation. Although the motivations for choosing ABM are different depending on the problem to be tackled, the main advantages of this technique include: (i) the possibility of modeling and investigating local interactions between agents; (ii) agents reacting in real time to environmental phenomena that stem from the specific nature of the application and; (iii) modeling is organized into sublayers and/or components, which reduces the effort in solving a more complex problem (Xie and Liu 2017). The modeling flexibility allows adding or removing agents and changing the structure of the system without the need to completely change the model. On the other hand, a considerable amount of data is required to parameterize the models (many of them based on assumptions) (Xie and Liu 2017). Therefore, large datasets are availableas model outputs and calibration and validation can be challenging as some rules are heuristically defined by modelers.

One of the first steps of the agent-based modeling process is the construction of the set of assumptions about the agents (Kovák and Pastircák 2014). Agents need reasoning skills to decide on when and what to do under certain circumstances. These skills are embedded in the agent’s architecture and can be more or less sophisticated depending on what kind of decisions and actions agents need to perform to reach their goals. Agents take sensory input from the surrounding environment and from other agents while performing actions upon the environment(through actuators), to reach their goals. Thus, they must be able to reason and decide how to act in specific circumstances (Lez-Briones et al. 2018). The rules driving their behavior are implemented in the architecture and consist of a set of modules used to define actions agents must perform (Maes et al. 1991). Different architectures must be created defining the complexity of the action rules implemented. The most well-known agent architectures are described as follows (Lez-Briones et al. 2018):

- **Purely reactive** - agents decide uniquely based on the current situation, ignoring everything they have learned in the past. If-then-else or condition-action rules are usually adequate to define the actions performed by these agents;
- **Model-based** - agents can make decisions based on past inputs even if they cannot observe part of the environment at a given instant. Inference mechanisms using decision states and heuristics to construct decision trees are commonly used by these agents to decide which actions they will take next;
- **Goal-based** - agents have an explicitly represented model of the environment and deliberately choose to perform actions that they know to lead, with some probability, to the accomplishment of their goals;
- **Utility-based** - agents may perform actions expected to maximize their utility (function defined to measure the performance of a given choice). Multicriteria decision-making techniques can be exploited in this setting to allow agents to express preferences or define subjective probabilities, assigning coefficients of importance to the multiple criteria, etc.;
- **Learning** - agents can improve their performance by anchoring their decisions on the knowledge gained through iterative attempts or previous experiments. Evolutionary computing or neural networks can be used if an optimal solution in a complex or large solution space is required or if an agent must decide based on patterns;
- **Belief-desire-intention** - the agents’ reasoning is supported on concepts which can be used to predict human behavior: they observe the world, get and update information (beliefs), reason about their aims (desires), and, based on preferences, decide how to act to reach the objectives they are committed to (intentions).

Agents can also be designed to establish different types of interactions based on their goals, resources, and skills. These interactions can be positive, if the agents have common goals and help each other to reach them, or negative, if the agents have conflicting goals thus leading them to compete for scarce resources. Positive interactions can be further classified into:

- Collective, if agents are unaware of other agents' existence but share a common goal and each agent contributes to its accomplishment;
- Cooperative, is similar to collective interaction except that agents are aware of other agents' existence;
- Collaborative, if agents do not have common goals but help each other achieve their individual goals;
- Coordinative, if agents within an environment work together to minimize interference and achieve their individual goals (Rizk et al. 2018).

In a community setting, cooperative strategies are particularly relevant as all the members' individual decisions affect the overall community performance. Therefore, a special focus is given to these interactions.

MAS application in energy systems

MAS have been widely used to model different dimensions and issues related to energy systems. Due to its characteristics, this approach is suitable to represent energy demand dynamics in residential and non-residential scenarios (Rai and Henry 2016). While Lin et al., (2017) describe an ABM formulation to exploit the energy saving potential in an office building under different pricing mechanisms, the work of Evora et al. (2011), for instance, applies an ABM approach to simulate disaggregated residential electricity demand profiles considering different appliances and usage profiles. MAS can also be used to model larger scales. For instance, the work of Kahrobaee et al. (2014) describe an ABM approach to target a neighborhood in which end-users are modeled as autonomous agents with their own demand profiles and generation/storage systems. In this model, residential agents may choose to use locally generated energy, charge/discharge their batteries, manage their loads, and even trade electricity within their neighborhood to minimize their electricity costs. Also, microgrids and decentralized smart grid scenarios have been widely addressed by MAS techniques. In Pipattanasomporn et al. (2009), the authors describe a MAS to control a distributed smart grid and incorporate intelligence through communication strategies compatible with an internet protocol-based network. This work confirms that MAS can be used for managing a microgrid operation in a simulated environment and, when endowed by appropriate communication protocols, MAS can be applied in real settings. A similar approach is used in Logenthiran et al. (2011), which proposes a multi-agent approach to schedule the use of distributed energy resources in an island system. The model results showed that the approach is efficient in monitoring, controlling, and operating a simulated system. Specific energy areas addressed by MAS approaches are further discussed in the next sections.

ELECTRICITY MARKETS

Electricity markets have been widely exploited by MAS. In Praça et al. (2001), a multi-agent approach models an electricity competitive market, including auctions based on the rules of the Iberian Electricity Market operator, and agents represent sellers, buyers and the market operator that receives bids from traders and sets market prices. The same authors present the first version of a MAS-based approach simulator including auction-based markets and negotiations made through bilateral contracts (Praça et al., 2003). An upgrade to this simulator was developed in 2011, using machine learning techniques to support the decisions made by the negotiating agents. Agents representing aggregators were also incorporated into this version (Vale et al., 2011).

DEMAND FLEXIBILITY IN SMART GRID SETTINGS

MAS has also been used to model different strategies of automated energy demand management (Guo et al.2010) and to represent energy demand dynamics in residential and non-residential scenarios, as in Rai and Henry (2016) and Lin et al. (2017). Davarzani et al. (2019) proposed a MAS framework to exploit flexible price-based demand response strategies in a low voltage network. In this work, a multi-objective genetic algorithm was used to determine the optimal scheduling of residential loads and the amount of required demand reduction to keep the grid stability. In Ramchurn et al. (2011) a control mechanism based on the use of autonomous agents embedded in smart meters to exploit energy management actions is described. Optimization algorithms are run by the agents to minimize the users' electricity bill and to satisfy their consumption preferences (Ramchurn et al. 2011). Still, although models combining agent modeling and optimization techniques emerge in the literature, they are still mostly applied to individual (household-level) settings and do not consider the dynamics created by demand/flexibility aggregation that may exist in community settings and how such aggregation can be used as an added-value service in energy/flexibility markets.

ENERGY COMMUNITY SETTINGS

Mittal et al. (2019) developed an ABM approach to model a zero LEC which applies the ABM methodology in an urban neighborhood to predict to what extent households are willing to adopt renewable energy when facing multiple options (rooftop PV and green pricing programs). In Kahrobaee et al. (2014), autonomous agents with their own demand profiles and generation and storage systems must decide how to use locally generated energy, when to charge/discharge batteries, how to manage loads, and even when to trade electricity within the neighborhood to minimize electricity costs.

Exact optimization methods, as in Morsali et al. (2020), and nature-inspired metaheuristics (as genetic algorithms (GA) (Zhao et al. 2013) and evolutionary algorithms (Logenthiran, Srinivasan, and Shun 2012; Salinas, Li, and Li 2013)) were embedded in MAS to optimize energy resources management (Frangopoulos 2017; Zafar et al. 2018). Vinyals et al. (2018) proposed a MAS to optimize the energy flows between a LEC of prosumers, revealing a good performance in enhancing community self-consumption and reducing the members' costs. Decision-making was based on the Alternative Direction Method of Multipliers algorithm. The work of Xiong et al. (2020) presented a MAS framework to coordinate and control the generation and demand in a microgrid with diversified consumers. The Tabu Search algorithm was used to minimize consumer agents' electricity bills and the power withdrawn from the grid and to maximize power quality.

Although approaches combining agent modeling and optimization techniques are emerging in the literature, they still fall short of considering heterogeneity in agents' preferences and goals, poorly reproducing the diversity of agents. Thus, models in which agents play different roles (i.e., prosumers, consumers and prosumagers), have distinct preferences and conflicting individual goals, while cohabiting in the same system, are still scarce in the literature.

LOCAL ENERGY TRADING

Regarding energy exchange, the MAS framework has also been used to exploit LEM. The work ofDomínguez-Navarro et al. (2017) presented a MAS-based local market in which a manager agentminimizes the electricity cost in an intra-market, while an inter-market is created when this agent offers the electricity surplus or requests the supply of the electricity deficit to other smart grids. Community-based market structures were also modelled using MAS in Liu et al. (2017) and Cai et al. (2017). In these works, intermediary agents were responsible for coordinating the interactions between prosumer agents and guide their actions towards the desired output. The work of Liu et al. (2017) employs ABM to simulate the energy sharing among prosumers in a microgrid setting. In this model, the aim is to maximize self-consumption and self-sufficiency and the energy trading is controlled by a manager agent. A manager agent is also used in the work of Cai et al. (2017) toassist the interaction between a set of prosumers in a community-based configuration. In this formulation, a price-based incentive scheme is used to reward prosumers' actions to manage energy demand and the bidirectional interaction between prosumers and the manager agent is modeled. In this model, the manager guides the prosumers actions towards the desired output, and the prosumers react by adjusting their actions. Once again, despite their relevance, these approaches often exploit agents with very similar features (low diversity) and miss to address individual preferences. Additionally, to the author best knowledge, besides a preliminary work from the author on this issue (Research paper IX), no other works have yet modeled the inclusion of this type of consumers in local electricity exchange schemes.

2.5.4. CONCLUDING REMARKS

MAS are a comprehensive way of simulating structuring complex, large-scale, dynamic, heterogeneous, and distributed systems containing multiple agents which cooperate with each other to achieve their individual objectives (Zhou, Wu, and Long 2018). MAS are an effective solution to solve complex tasks in decentralized environments, as is the case of energy communities, due to their efficiency, stemming from the division of a complex task into several smaller tasks assigned to distinct agents (Dorri et al. 2018; Huhns and Stepenhs 2000). Consequently, the associated processing and energy consumption costs are split over the multiple agents, which produce an overall low-cost solution when compared with a centralized setting in which a single entity must solve an overall complex problem. The distributed tasks assigned to multiple agents can be solved by applying customized methods, which introduce further flexibility in the modeling environment. The distributed nature of problem solving in MAS offers high reliability, since if one agent fails the coherence of the model is kept, and the task can be easily redistributed to other agents (Dorri et al. 2018; Huhns and Stepenhs 2000). Therefore, MAS are a suitable tool for simulating the interaction of multiple community members that behave autonomously to reach their individual goals while co-existing in the same collective environment and maximizing the overall community self-sufficiency.

2.6. LITERATURE GAPS AND THESIS CONTRIBUTION

Based on the previous literature overview, the main research gaps motivating this work are as follows:

- The research on CEI have mostly focused on the residential sector and the complementarity of demand profiles of other activities such as SMEs and cross-sectoral activities with specific organizational, technical and behavioral constraints have not been properly exploited as flexibility resources;
- It is not yet clear (in a quantitative manner) the real benefits that CEI can bring to their members and to the power system as a whole;
- Although important steps are being taken at the regulatory level, CEI innovative business models are still scarce, hindering the exploitation of value-added products and services;
- From a methodological point of view, the combination of simulation and optimization techniques is scarce in this field, especially when behavioral, social and organizational dimensions should be included;
- In countries with little tradition of collective energy models, the expectations of stakeholders trying to initiate CEI and the barriers to implementation they face are poorly addressed.

This work focuses on the deployment of a comprehensive modeling approach to exploit different dimensions underlying a collective energy project. The main problem addressed in this work concerns the maximization of collective self-sufficiency. For this purpose, the energy generated locally through renewable sources must be optimally managed to match consumption and generation as much as possible. Complementary issues need to be considered in modeling, namely the regulatory framework evolution, the most adequate CEI configurations and the emerging business models. In this context, this PhD project aimed to develop a multidisciplinary approach combining simulation and optimization tools to exploit the complementarity of the demand-side flexibility pertaining to different users (e.g., households, SMEs, and cross-sectoral activities). The aim is to assess how CEI may contribute to the decarbonization of the power system and offer guidelines for their development and implementation. Also, as CEI may originate an increasing number of prosumer installations injecting energy into power networks, scenarios in which the injection of surpluses is unpaid, penalized or even prohibited should be considered to design more resilient and self-sufficient LEC.

In line of the problem described, a bottom-up MAS modeling approach is developed to exploit the behavioral dimension associated with the decision processes in residential settings, the organizational dimension related with SMEs and the technical and social dimensions related with managing multiple entities interacting in a collective setting. MAS modeling and optimization techniques (mostly based on single and multi-objective methods) were combined to simulate and optimize energy use and the available local energy generation, considering end-users' goals, preferences, behavioral practices, and organizational constraints. In addition, this thesis exploitsthe following specific objectives:

- To determine to what extent different demand-side flexibility profiles can be exploited to maximize the self-sufficiency of energy communities. Members with different demand flexibility profiles, preferences and objectives will be studied and modeled;
- To assess how different configurations (distributed, decentralized, and centralized) influence the community autonomy. The exploitation of different configurations will also allow addressing, from the modeling and optimization points of view, different cooperation frameworks between agents and distributed consensus algorithms, in addition to mathematical programming models and metaheuristics implemented to optimize the use of available energy resources;
- To evaluate the economic, environmental and social benefits that these communities bring to society and the power system, namely for members and stakeholders;
- To fully exploit the existing (and evolving) regulatory framework, pointing out solutions that potentially help to take greater advantage of community systems involved in the local generation, consumption, and energy sharing, as well as emerging business models.

Considering these objectives and the proposed approach, the main innovation of this work relies on:

- The integration of different sectors exploiting the complementary nature of electricity demand. The rationale for including non-residential members is twofold: first, these members have distinctive flexibility profiles which can be beneficial in community contexts aiming to achieve some degree of self-sufficiency; second, energy communities have been described in literature as purely residential arrangements, although European directives include SMEs as potential members. Therefore, the modeling of non-residential members in a community setup aims to be a step forward in the existing literature;
- The consideration of different dimensions that strongly influence energy demand flexibility;
- The combination of MAS modeling and optimization techniques, i.e., the agents are endowed with optimization rationality simulating the deployment of energy management systems based on low-

cost microprocessor hardware;

- The comprehensive assessment of the most realistic community business models as well as the new value streams they may create and the barriers they still face;
- The gathering and analysis of stakeholders' expectations on energy communities and their objectives in the process.

The results obtained are expected to support policy and decision-makers in the design of new energy policies and regulations focused on energy communities, collective self-consumption arrangements and other decentralized structures with the aim to shape a more reliable and sustainable energy system. This work is also aimed to be a basis for market stakeholders to define new business models adapted to new configurations of energy systems that may emerge in the future.

3. METHODOLOGY

This section includes two sub-sections: the Problem Structuring Methods approach used to assess the perspectives of Portuguese entities regarding the emergence of CEI in Portugal (section 3.1) and the multiagent approach developed to model different configurations of collective energy initiatives (section 3.2).

3.1. A PSM APPROACH TO ASSESS THE PERSPECTIVES OF PORTUGUESE STAKEHOLDERS REGARDING CEI

As explained in Section 2.5.1, in countries with little experience in CEI operation as Portugal, many uncertainties regarding the process and the alternative courses of action still exist hindering implementation. In this setting, Problem Structuring Methods (PSM), presented as a set of problem management procedures within the Soft Operational Research field whose purpose is to assist in the structuring of problems rather than to derive a direct solution (Rosenhead 1996; Smith and Shaw 2019), can be used to shed light on the collective energy framework in Portugal.

PSM, which are commonly used in group facilitation and participatory modeling approaches, arealso valuable when intangible or uncertain aspects must be evaluated (Lami and Tavella 2019; Rosenhead 1996). PSM are both structuring and facilitating methods as they offer a systematization process enabling the enhancement of the decision process at the same time as they create a participative environment in which stakeholders can debate and clarify the decision context, their roles and concerns (Bell and Morse 2007). Among PSM, the action-oriented Soft Systems Methodology (SSM) is one of the most recognized, which is ordinarily used to tackle uncertain situations in which the participants learn about the problem through an organized process designed to structure discussion and take actions to improve it (Checkland and Scholes 1990).

The approach is typically described as a seven-stage process (Fig. 17). It starts by taking the situation considered problematic (1) and expressing it (2) through a schematic representation (Checkland 2000). Then, the root definition of the system of purposeful behavior is formulated (3); the conceptual models of human activity are built; (4) and the models created are compared with the real-world ones (5). Lastly, both desirable and feasible changes are defined and proposed (6) and action is taken to improve the problematic situation (7). Steps 1, 2, 5, 6 and 7 are related with the so-called “real world”, i.e., the real environment where the problem occurs and where actions can be taken to change it, whereas the remaining two steps are performed in a conceptual world, the so-called “systems thinking world”, i.e., in a conceptual world. The SSM has evolved over the years resulting in an updated version with only four main activities (Checkland 2000): 1) finding out about a problem situation, including cultural and political issues; 2) formulation of relevant purposeful activity models; 3) debate the situation using the models, seeking for a) changes that would advance the situation and are perceived as both desirable and feasible, and commitments between conflicting interests; 4) taking action to foster the improvement of the current situation.

To elicit the stakeholders’ perspectives and ensure that no relevant dimensions were left out, several entities were invited for individual online meetings during June 2021 and others were invited to answer an online survey (carried out through the Lime Survey platform). All entities were contacted by email informing about the study and inviting them to participate. For those who showed interest in the interview, individual meetings were scheduled, while the rest were invited to complete the online survey.

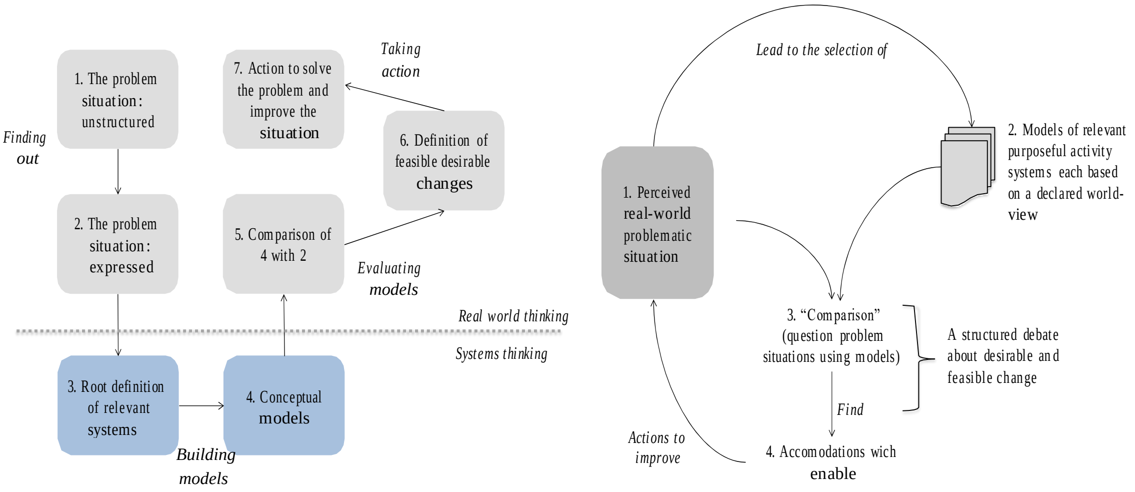

Fig. 17 The SSM processes. Left: the seven-stage approach (Checkland and Scholes 1990); right: the four-stage approach (Checkland 2000).

The stakeholders' engagement was intended to reveal meaningful inputs since these entities have relevant knowledge on the topic at the same time as their engagement helps to avoid alienation, especially of those ones with smaller dimension and, therefore, less power on political intervention (Gregory et al. 2020). In both approaches, the following questions were asked: *What are the entity's main interests in energy communities? What motivates the entity to get involved in his topic? What critical factors/barriers are delaying or hindering their diffusion? What benefits (for the energy system and societal) CEI can bring to the country?* The answers to these questions are intended to explain why the entities are interested in the topic, what are their expectations and motivations, what constraints to the implementation are being experienced, and what would be the benefits of a successful implementation. From the answers, motivations and critical factors hindering the dissemination of LEC in Portugal were retrieved. Appendix 1 presents the interview/online survey script.

Table 3 presents the list of participating entities: Coopérnico - Sustainable Development Cooperative C.R.L. is a consumer cooperative and market retailer; Vale d'Este Electric Cooperative is a cooperative playing the role of local distribution network operator and last resort retailer; Electricity of Azores (EDA) ensures the production, transmission and distribution of electricity in the Azores archipelago; E-Redes is the Portuguese distribution system operator (DSO); ERSE is the Portuguese energy regulator; Portuguese Secretary of State for Energy; Portuguese Directorate of Energy and Geology; DST Solar is a company which provides specialized services in the solar energy sector; PBBR is a law company which was involved in the transposition of the RED-II directive into national law; CleanWatts is a technology-based company that develops integrated energy management solutions for CEI; AreanaTejo and Porto Energy Agency are two regional energy agencies working with local authorities in the implementation of collective energy projects; INECTEC, INESC Coimbra and CE3C are three research centers from Porto, Coimbra and Lisbon, respectively, which are investigating on this topic; SmartWatt is a company developing artificial intelligence solutions and monitoring systems to optimize energy resources; Coimbra intermunicipal community, in representation of municipalities; DeLab and be.ERGOS are two energy consulting companies also interested and working on the topic.

Table 3 Participating Portuguese stakeholders.

	Roles										
Entity	Energy cooperative	Market retailer	DSO	Last resort retailer	TSO	Energy Producer	Policy-making	Regulator	Energy Service Companies	Energy Agencies/ Municipalities	R&D
Coopérnico – Sustainable Development Cooperative C.R.L.[i]	X	X									
Vale d'Este Electric Cooperative[ii]	X		X	X							
Electricity of Azores (EDA)[iii]		X	X	X	X	X					
E-Redes[iv]			X								
Energy regulator (ERSE)[v]								X			
Secretary of State for Energy[vi]							X				
Directorate of Energy and Geology[vii]							X				
DST Solar[viii]									X		
PBBR Law Company[ix]							X				
CleanWatts[x]									X		
AreanaTejo[xi]										X	
Porto Energy Agency[xii]										X	
INESCTEC[xiii]											X
INESC Coimbra[xiv]											X
CE3C[xv]											X
SmartWatt[xvi]									X		
Coimbra intermunicipal community[xvii]										X	
DeLab[xviii]									X		
be.ERGOS[xix]									X		

[i] https://www.coopernico.org/
[ii] https://www.ceve.pt/
[iii] https://www.eda.pt/
[iv] https://www.e-redes.pt/pt-pt
[v] https://www.erse.pt/inicio/
[vi] https://www.portugal.gov.pt/pt/gc21/area-de-governo/ambiente/secretarios-de-estado
[vii] https://www.dgeg.gov.pt/
[viii] https://dstsolar.com/
[ix] https://www.pbbr.pt/pt/
[x] https://www.cleanwatts.energy/
[xi] https://www.areanatejo.pt/
[xii] https://www.adeporto.eu/
[xiii] https://www.inesctec.pt/pt
[xiv] https://www.uc.pt/en/org/inescc/
[xv] https://ce3c.ciencias.ulisboa.pt/
[xvi] https://smartwatt.pt/
[xvii] https://www.cim-regiaodecoimbra.pt/
[xviii] https://delab.pt/
[xix] http://www.be-ergos.pt/

The SSM process starts with the 'finding out' stage (encompassing step 1 and 2 of the seven-stageSSM) aimed at describing the problem context. The current Portuguese electricity system encompasses several institutions and agents with roles at the generation, transmission, distribution, and consumption levels. With the emergence of CEI, the responsibilities and roles of such entities are altered, and different actors join the decision-making environment, making it even more complex. Thus, it is key to analyze the role of each of these entities and the relationships they establish with each other. This analysis is performed through a rich picture approach as it allows to start understanding the problem, the entities involved and the relationships between them through its graphical representation, turning an unstructured problematic situation into a graphically expressed problem.

After having an overview of the decision environment, the problem purpose(s), embodied in the so-called "root definition", must be formulated. Root definitions describe, in a set of sentences, the system's purpose, defining what the system is expected to accomplish (Checkland and Tsouvalis 1997). The writing of the root definition was shaped by the CATWOE framework, whose elements are presented in Table 4.

Table 4 CATWOE elements (Bergvall-k et al., 2004).

Mnemonic	Terms	Definition
C	Customers/Clients	The immediate beneficiaries or victims of the system results.
A	Actors	The participants in the transformation and the ones carrying out the activities.
T	Transformation	The core of the system's activity in which inputs are converted into outputs.
W	*Weltanschauung* or world view	The standpoint at which makes sense to develop the root definition.
O	Owner(s)	The individual(s) responsible for the system and for modifying or stopping it.
E	Environmental constraints	Constraints imposed by the external environment (e.g., legal, physical constraints).

The result of the CATWOE analysis informed by the answers retrieved from the semi-structured interviews with stakeholders and their answers in the online survey, result into a cloud of unstructured objectives. The Value-Focused Thinking (VFT) (Keeney 1992) methodology seemed suitable to refine and structure those objectives into a criterion tree as it allows to create hierarchies of "fundamental objectives" – which should be comprehensive, non-redundant, brief, and understandable - and networks of "means-ends" objectives – used to highlight the means required for achieving the fundamental (or "ends") objectives (Keeney 1992). This criterion tree allows to draw conclusions on what objectives are more important for which stakeholders and which ones should be prioritized to fasten the dissemination of CEI.

3.2. ENERGY COMMUNITIES' REPRESENTATION THROUGH MAS[f]

Increasing attention has been paid to MAS modeling, which are presented as suitable tools for simulating decentralized socio-technical systems as is the case of energy communities (Dijkema et al. 2012). As discussed in the previous chapters, MAS approaches are based on the decomposition of complex systems into smaller components represented by agents, whose behavior is formalized through algorithms and decision rules that execute actions performed to meet individual goals. These software-based agents are able to collaborate, compete and exchange information with other agents, which gives them a social capacity (Coelho et al. 2017). Still, agents have limited knowledge about future actions; thus, by endowing them with an adaptive behavior, they can adjust their actions according to the available resources and their objectives (Ma and Nakamori 2009). These characteristics, alongside with its flexibility in describing in detail the behavioral and structural aspects (policies, prices, technologies) of the system, make MAS an attractive tool to study the evolution of socio-technical systems (Coelho et al. 2017) despite the criticism pointed to this modeling approach due to the lack of verification and validation protocols required to ensure the operational validity of the obtained results (Akhatova et al. 2022).

Different community configurations were analyzed to assess to what extent agents with different characteristics and roles in the systems would influence the system. Also, different technologies, ownership schemes, and activities were evaluated (Section 4.2). At an initial stage, a simple configuration with only two agents, a consumer, and a prosumer, was examined to assess the adequacy of the Anylogic simulation tool. The agents were configured to manage the loads according to the renewable generation availability and price signals from the grid, and exchange surplus energy with each other. This work was published as the Research paper VII and is presented as Case study 1. This initial model was enlarged and enriched with more agents, creating a community setup and optimization rationality was introduced into the agents' architecture capturing the bi-objective cost and dissatisfaction problem.

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[f] Based on Research papers I, III, VII and VIII.

Additionally, a coordinating entity, also endowed with optimization rationality, was introduced in the modeling to assist the interactions within the community and external players. This formulation was exploited in Research paper III, VIII and X with variations which are fully described as Case study 2. Building on the previous modeling, the effect of price signals encouraging self-consumption and penalizing surplus injection into the grid was exploited in Research paper IX and the results presented as Case study 3.

In addition to residential agents, the inclusion of non-residential agents and cross-sectoral activities was considered. Three types of commercial buildings have been included in the modeling: a primary school, an office building, and a restaurant. Also, to bring the model closer to a real scenario, cross-sectoral activities such as the street lighting service and a public EV charging station were modeled. These loads represent services provided to, and by, the community and are considered by the coordinator agent as loads to be managed. This configuration was fully described in Research paper I, Publications 6, 7 and 9 and is presented as Case study 4.

To address the issue of renewable generation in space-constrained urban environments and conceptually differentiate energy communities and collective self-consumption, the modeling combining MAS and optimization was adjusted to a collective self-consumption model in a multitenancy building. Adjustments were made to the model to ensure its reasonableness and coherence, and the collective objective functions were changed at the level of the coordinating agent as these projects can be either initiated to minimize the overall energy costs or to maximize self-consumption which, as already discussed, may not be exactly coincident objectives. This case study was published as Research paper V and is presented as Case study 5.

Lastly, Case study 6 presents a community-based LEM designed to allow for and encourage the participation of vulnerable consumers. This work was published in Research papers IV and IX, which describe in detail how the inclusion of these consumers can be done within energy communities that aim to establish intra-community surplus selling markets, with added value for both local producers and consumers.

Although different dimensions and parameterizations were tested, a common basis was followed in all the experimentations: the MAS approach is used to model the community configuration and its agents and optimization algorithms are embedded into agents' architectures to exploit demand-side flexibility considering individual and collective objectives.

In the configurations analyzed (example in Fig. 18), residential and non-residential users, represented as agents, are geographically located nearby, and share the collective goal of generating, consuming, managing, and selling renewable energy resources to maximize the community self-sufficiency. Residential members can be either prosumers, if they own onsite energy generation and storage assets and consume from their own systems, or consumers, if they are dependent on external electricity suppliers. In some simulations, non-residential users as SMEs and cross-sectoral activities, such as public EV charging stations and street lighting services were also comprised to provide a realistic character to the simulated communities. Also, a coordinating entity was considered in most simulations to facilitate the management and distribution of the community energy resources, while keeping record of the financial and electricity transactions and interface with the power grid. All the community members are assumed to be physically linked to the power grid and virtually linked to the coordinating entity.

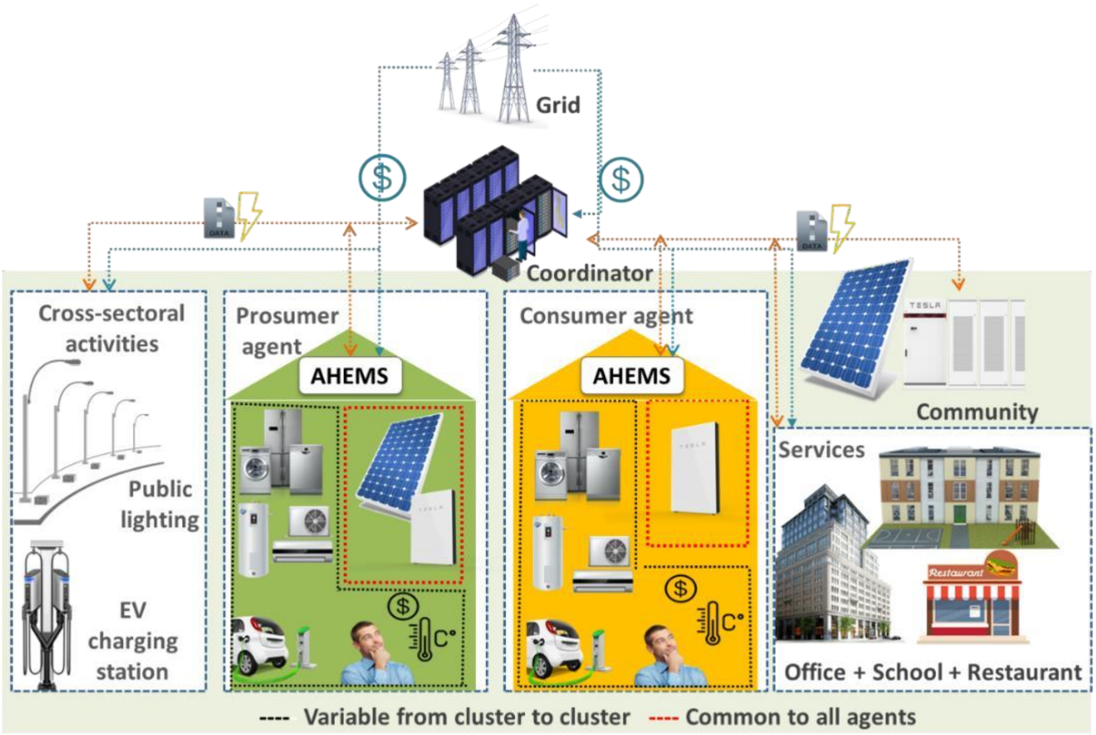

Fig. 18 Example of a LEC representation trough MAS.

3.2.1. *AGENTS ARCHITECTURE*

In MAS, the entities endowed with decision-making ability are considered agents. In this setting, the models herein exploited have two types of agents: residential agents, both consumers and prosumers, and a community coordinator agent. Non-residential and cross-sectoral activities do not make active decisions as their activities are less flexible. Therefore, they cannot be defined as agents. These components are included in the model as they may contribute to the system self-sufficiency, and they make modeling closer to a real scenario. Finally, electricity retailers are also considered as passive agents in the modeling since their intervention is low but required to give coherence to the model. The retailer agent function is to sell and buy electricity to the community coordinator agent at a known retail price. In the scope of this work, agents' architectures were assumed to include three main modules:

- A **technical module**, in which the physical characteristics of loads, generation and storage assets are exploited depending on the agent type (consumer/prosumer/prosumager/ community coordinator);

- A **decision-making module** (or reasoning module), representing the agents reasoning center and in which optimization algorithms are implemented. The adequate coordination of residential demand requires the consideration of several aspects (e.g., demand needs, operational constraints, integration of intermittent renewable generation sources and increasingly dynamic retail pricing) which increases complexity for users. Thus, automated home energy management systems (AHEMS) endowed with optimization algorithms are required to decide the load control actions to implement, reducing end-user's intervention while considering their preferences regarding energy services. In this setting, AHEMS aim to schedule demand management actions, deciding on when and how to operate loads, informing users about their expected electricity demand and/or supply deficit and generation surpluses. These decisions aim to individually minimize costs while accounting for the dissatisfaction such actions may cause to users (e.g., associated with changing the normal periods of appliances operation to profit from time-of-use tariffs). Preferences concerning how loads are operated should also be considered as they influence decisions on load scheduling and resources management. Agents were, therefore, assumed as rational entities aiming to maximize/minimize a given objective function;

- A **communication module**, which allows sensing input data (e.g., retail prices, outdoor temperatures, and solar radiation) and sending information to other agents. In smart prosumership settings, sensors may collect data on physical conditions as temperature, solar radiation, etc. and send them to the AHEMS.

These modules are key to exploit the behavioral, organizational, and social dimensions which are the basis of this work. The **technical module** was the one that allowed to model the agents' profile as realistically as possible, meaning that it allowed for the modeling of consumption and generation profiles, which represent typical electricity consumption technologies in households, commercial entities, and cross-sectoral activities, thus establishing the **operational rules and constraints of the energy system**. In turn, the **decision-making module** permitted the modeling of the agents' **behavioral dimension** through the incorporation of preferences in the decision process. As explained, the agents' decision processes in this work were framed in an optimization setting, in which the exploitation of preferences is usually little common. Still, the behavioral dimension was addressed in these processes through the exploitation of sensitivity to cost and comfort, as well as in the modeling of different types of households and equipment ownership rates. Additionally, the behavioral dimension was also further addressed in community configurations designed to exploit the inclusion of energy vulnerable consumers and their possible participation in local energy markets. The behavioral dimension was, in this setting, reflected both at the level of the decision-making and technical modules. Lastly, the agents' **communication module** was essential to define the organizational structure of the community energy model, since it was through it that agents **communicated and exchanged information**. Thus, this module was responsible for the setting up of the organizational relationships (of cooperation, sharing, etc.) between the different community agents.

3.2.2. *RESIDENTIAL AGENTS*

Technical module – Loads, generation, and storage[g]

The agents' energy demand includes manageable loads (DSM actions may be implemented by the AHEMS that can control the equipment) and non-manageable baseloads, which include the appliances whose utilization is less flexible as is the case of kitchen equipment, lighting and entertainment (including desktops, laptops, television, etc.). In turn, within the range of manageable loads, the following appliances are comprised:

- Time shiftable loads, including laundry machines (LM), tumble dryers (TD) anddishwashers (DW);

- Thermostatic controlled loads (TCL), as air conditioners (AC), electric water heaters(EWH) and fridges; and

- Interruptible loads, as electric vehicles (EV) and static batteries.

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[g] Based on Research paper III and IV.

To shiftable loads modeling, data collected through energy audits were used to reproduce their power profiles and the algorithmic approach must ensure that the operation cycles of the LM, DW and TD can be completed within the planning period. The behavior of TCL is reproduced by physically-based models (PBM), which are used to compute indoor temperatures and the power necessary in each interval of the planning period. For the AC, the PBM presented in Gomes, Antunes, and Martinho (2013) is used to compute, at each interval, the total heat loads in the buildings, considering heat transfer through the walls and windows, the internal heat gains and the heat losses due to indoor air renewal, according to the following expression:

$$T_{room}(t+\Delta t) = T_{room}(t) - \frac{y(t)\cdot P_{AC}\cdot COP - H_T(t)}{m\cdot c_p}\cdot \Delta t \tag{1}$$

where $T_{room}(t)$: indoor room temperature at time t [°C]; $H_t(t)$: total heat load at time t [W]; Δt: length of the time interval the planning period is discretized into [s]; P_{AC}: power of the AC [W]; COP: AC average coefficient of performance; m: air mass [kg]; cp: specific heat of the air [J/kg·°C] and $y(t)$: binary variable representing whether TCL is operating at time t. $H_T(t)$ is computed by adding the latent heat component $H_L(t)$ [W], including the heat transfer through the envelope (H_e) and the indoor air renewal (H_r), and the sensible heat component $H_S(t)$ [W], representing the internal heat gains (H_i) and heat gains through walls and windows (H_w). Typical building constructive solutions, dwelling sizes and occupation profiles were considered in dynamic building simulations performed to compute heat transfer (gains and losses). When the AC is operating in the cooling mode, $y(t)$ is calculated as:

$$y(t) = \begin{cases} 1, if\ T_{room}(t) \geq T_L(t) \wedge T_{room}(t) < T_{room}(t-1)) \vee T_{room}(t) \geq T_H(t) \\ 0, otherwise \end{cases} \tag{2}$$

where $T_H(t)$: maximum reference temperature of the thermostat at time t [°C] and $T_L(t)$; minimum reference temperature of the thermostat at time t [°C]. Similarly, the PBM presented in Soares, Antunes, and Oliveira (2017) and Gonçalves, Gomes, and Antunes (2019) is used to reproduce the EWH operation, considering the heat losses in the water container and the energy available to heat the water during a given time interval. The heat losses in the reservoir are computed as:

$$P_{losses}(t) = A\cdot U\cdot \Delta T' \tag{3}$$

where $P_{losses}(t)$: heat losses at time t [W]; A: enveloping area of the water reservoir [m^2]; U: heat transfer coefficient of the water reservoir [W/m^2·°C] and $\Delta T'$: difference between the water temperature inside the EWH and the outdoor temperature [°C]. In turn, the thermal energy transferred by the EWH to the water is given by:

$$Q(t) = (P_R - P_{losses}(t))\cdot \Delta t\cdot 3600 \tag{4}$$

where $Q(t)$: existing energy to heat the water at time t [Wh]; P_R: power of the heating resistance of the EWH [W], Δt: elemental time interval [s] and 3600 is the required conversion factor to maintain the unit coherence (seconds to hour). The water temperature in the reservoir is calculated as:

$$T_{water}(t+\Delta t) = T_{water}(t) + \frac{v_t\cdot P_R - P_{losses\,(t)}}{M\cdot c_p} \tag{5}$$

$$T_{water}(t) = \frac{M - m_t}{M}\cdot T_{hot}(t) + \frac{m_t}{M}\cdot T_{network}(t) \tag{6}$$

where $v(t)$ is the binary variable representing whether the EWH is operating at time t, being defined as:

$$v(t) = \begin{cases} 1, if\ (T_{water}(t) \leq T_L(t)) \vee (T_{water}(t) \leq T_H(t) \wedge T_{water}(t) > T_{water}(t-1)) \\ 0,\ otherwise \end{cases} \tag{7}$$

where $T_{water}(t)$: temperature of the water in the EWH at time t [°C]; $T_{network}(t)$: temperature of thewater in the supply network at time t [°C]; $T_H(t)$: maximum reference temperature of the hot water at time t [°C]; $T_L(t)$: minimum reference temperature of the hot water at time t [°C]; $T_{hot}(t)$:desired temperature of the hot water at time t [°C]; M: total mass of water to be heated [kg]; c_p: specific heat of the water [J/kg·°C] and $m(t)$: amount of hot water consumed at time t [kg]. The hot water demand is related to the household size. Hence, hot water consumption profiles, reservoir capacities and EWH powers were adjusted according to the household size.

The operation of cold appliances, as fridges, was modeled by a simplified PBM based on the works of Laguerre and Flick (2010) and Hovgaard et al. (2012). The temperature inside the fridge is computed as:

$$T_{fridge}(t+\Delta t) = T_{fridge}(t) + \frac{w(t) \cdot P_{fridge} \cdot COP - A \cdot U \cdot (T_{room}(t) - T_{fridge}(t))}{M \cdot c_p} \cdot \Delta t \tag{8}$$

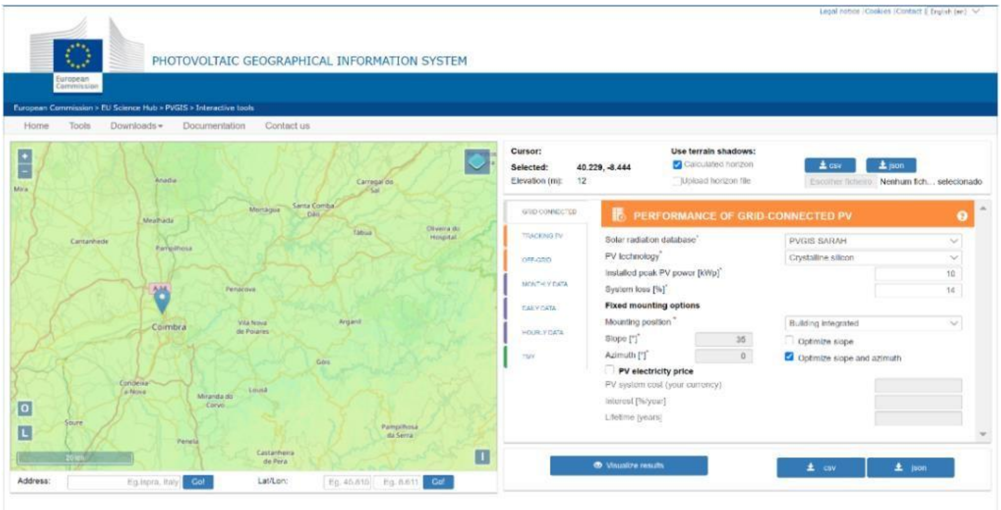
where $T_{fridge}(t)$: temperature inside the fridge at time t [°C]; $T_{room}(t)$: room temperature at time t [°C]; A: fridge envelope area [m^2]; U: heat transfer coefficient [$W/(m^2 \cdot °C)$]; M: mass of air insidethe fridge [kg]; cp: specific heat of the air [J/kg °C]; P_{fridge}: fridge compressor power [W]; COP: average fridge coefficient of performance and $w(t)$: binary variable representing whether the fridge is operating at time t, which is calculated as:

$$w(t) = \begin{cases} 1, if\ (T_{fridge}(t) \geq T_L(t) \wedge T_{fridge}(t) < T_{fridge}(t-1)) \vee (T_{fridge}(t) \geq T_H(t)) \\ 0,\ otherwise \end{cases} \tag{9}$$

where $T_L(t)$ and $T_H(t)$ are the minimum and maximum reference temperatures of the fridge at time t [°C].

Lastly, all the agents are assumed to own static batteries and EV. These systems are used for different purposes depending on the agents: prosumagers use them to store self-produced Energy, whereas consumers store energy they buy from the grid when the price is lower to operate loads or to sell and obtain benefits when the price is higher. At each interval of the planning period, static and EV batteries are associated with a particular state-of-charge (SoC) and each user defines a minimum SoC value that should be satisfied. The initial SoC, charging power,minimum final and ideal final SoC should be defined. Also, the EV is assumed to work in grid-to- vehicle (G2V) and home-to-vehicle (H2V) modes, receiving electricity from the grid or the self- generation system and storing it, and in vehicle-to-grid (V2G) and vehicle-to-home (V2H) modes,providing the stored electricity to be self-consumed or sold (to the grid) whenever it is advantageous for the agent.

Regarding energy generation, PV technologies were considered as they are expected to be preferred in Portuguese CEI. Temperature and solar radiation profiles for the location of Coimbra, in the central region of Portugal, were used and retrieved from the Photovoltaic Geographical Information System (Fig. 19). In all configurations analyzed, onsite individual PV systems were assumed to be smaller than 10 kW_{peak}, as according to a definition of the International Energy Agency (IEA) this should be the maximum installed capacity for residential prosumers (IEA 2014).



Cursor:
Selected: 40.229, -8.444
Elevation (m): 12
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☐ Upload horizon file
Escolher ficheiro Nenhum fich... selecionado

PERFORMANCE OF GRID-CONNECTED PV
Solar radiation database* PVGIS SARAH
PV technology* Crystalline silicon
Installed peak PV power [kWp]* 10
System loss [%]* 14
Fixed mounting options
Mounting position* Building integrated
Slope [°]* 35 ☐ Optimize slope
Azimuth [°]* 0 ☑ Optimize slope and azimuth
☐ PV electricity price
PV system cost (your currency)
Interest [%/year]
Lifetime [years]

Fig. 19 Screenshot of the PVGIS tool (available in: https://re.jrc.ec.europa.eu/pvg_tools/en/#PVP).

Decision making module

In the proposed modeling, all residential agents are assumed as being optimization-oriented, meaning that their decisions on electricity use and resource allocation are optimized by the AHEMS. These agents, whether prosumers, consumers or prosumagers, aim to minimize their electricity costs, which is the first objective function of the problem to be solved in the AHEMS (OF1). To this end, the optimization algorithm must decide on when to consume, store, sell or buy electricity and how to use the electricity stored. By interfering with daily energy use practices, the scheduled demand-side actions may cause disturbances in daily routines and affect comfort standards. Thus, a second objective function (OF2) is included aiming to minimize the potential dissatisfaction caused by the AHEMS decisions. In this bi-objective problem, the trade-offs between the cost and comfort dimensions are captured in a Pareto front, since better cost solutions are achieved at the expense of worst discomfort results and vice-versa.

$$OF1 = \min \sum_{t=1}^{T} (BP_t \cdot \Delta t \cdot ((\sum_{j=1}^{n} P_{jt} + \sum_{b=1}^{m} P_{bt} + \sum_{s=1}^{k} P_{st} + \sum_{e=1}^{v} P_{et} + BL_t) - SC_t)) - (PS_t \cdot SP_t \cdot \Delta t)) \; [EUR] \quad (10)$$

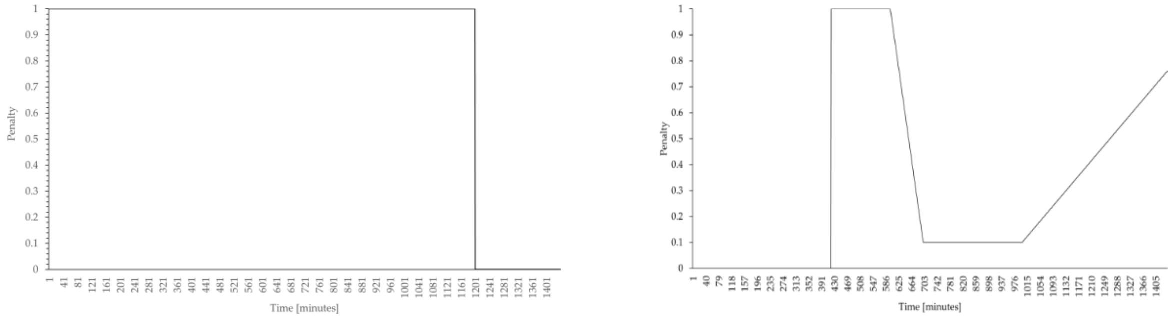
$$OF2 = min \sum_{t=1}^{T} (\sum_{j=1}^{n} \frac{TSP_{jt} \cdot y_{jt}}{100} + \sum_{b=1}^{m} \frac{TVP_{bt}}{1000}) + \sum_{e=1}^{v} \frac{\max{(0, IFC_e - SOC_{et}}}{10} \quad (11)$$

In these equations, the following parameters were considered: T: number of time intervals of the planning period (t=1,…,T); n: number of shiftable loads (j=1,…,n); m: number of TCL (b=1,…,m); k: number of static batteries (s=1,…,k); v: number of EV (e=1,…,v); Δt: length of the time interval [min]; BL_t: power requested by the baseload at t [kW]; BP_t: energy retail tariff at t [€/kWh]; SP_t: energy selling tariff at t [€/kWh]; TSP_{jt}: time slot penalty for shiftable load j operating at t; TVP_{bt}: temperature variation penalty for TCL b not imposing the temperature in the desired range at t; and IFC_e: ideal final SoC for EV e [%].

The following decision-variables were considered: P_{jt}: power requested by the shiftable load j at t [kW]; P_{bt}: power requested by the TCL b at t [kW] (as defined by the PBM); P_{st}: power requested by the static battery s at t [kW]; P_{et}: power requested by the EV e at t [kW]; SC_t: total power used for self-consumption at t [kW]; PS_t: total power sold (to the retailer or other LEC members) at t [kW]; Y_{jt}: binary variable representing whether shiftable load j is operating at t; SOC_{et}: SoC of EV e at t [%].

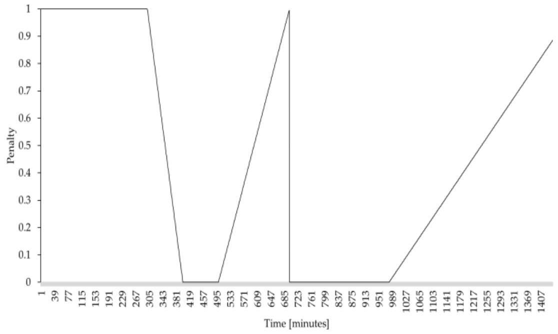
The OF1 (Eq. 10) considers the cost of the electricity consumed by each load and the potential revenues obtained from selling surpluses (to the retailer agent or other LEC members). The OF2 (Eq. 11) comprises three components (normalized through different scaling factors to be aggregated in a single dimension), namely: 1) time slot penalties for shiftable loads; 2) temperature variation penalties for TCL and 3) penalties for the gap between ideal and actual EVSoC.

For shiftable loads, users may define preferred time slots for their operation based on the convenience to do related tasks (such as clothes hanging). The time shift between the most convenient time slots defined by users and the periods determined by the AHEMS to operate such loads are penalized according to the time slot penalties (TSP_{jt}) displayed in Figure 20. Data collected through surveys and interviews was used to define realistic users' preferences (Lopes et al. 2018).



(a) Tumble dryer

(b) Dishwasher



(c) Laundry machine

Fig. 20 Time slot penalties.

For each TCL, temperature ranges are defined to express the users' thermal comfort levels. Variations between these bounds and the effective temperature computed by PBM are also accounted as discomfort. For the AC and cold appliances, the temperature variation penalty (TVP_{bt}) is computed as:

$$TVP_{bt} = \begin{cases} e^{\frac{T_{bt} - HRT_b}{HRT_b - LRT_b} - 1}, if\ T_{bt} > HRT_b \\ e^{\frac{LRT_b - T_{bt}}{HRT_b - LRT_b} - 1}, if\ T_{bt} < LRT_b \\ 0,\ otherwise \end{cases} \tag{12}$$

For the EWH, the TVP_{bt} is computed as:

$$TVP_{bt} = \begin{cases} e^{\frac{LRT_b - T_{bt}}{HRT_b - LRT_b} - 1}, if\ T_{bt} < LRT_b \\ 0,\ otherwise \end{cases} \tag{13}$$

where TVP_{bt}: temperature variation penalty for the TCL b at time interval t; T_{bt}: temperature provided by TCL b at time interval t determined by the PBM (°C); HRT_b: maximum reference temperature for TCL b (°C) and LRT_b: minimum reference temperature for TCL b (°C). For these loads, temperature deviations have different impacts on the users' discomfort. While in the case of the AC and the fridge, going beyond the reference bounds means thermal discomfort and disturbance of the food refrigeration service, for the water heating, the user comfort is only disturbed when the water temperature does reach the lowest temperature specified. Thus, no penalty is considered whenever the water is heated above the minimum reference temperature. The time slot and temperature variation penalties have been established according to the previous experience of the authors in energy audits and energy efficiency studies. Lastly, the differences between the SoC of EV and static batteries at the end of the optimization and the ideal SoC defined by users are also considered in the dissatisfaction measurement.

The problem constraints are formulated in Eq. 14-28. These expressions shape how generation, static and EV storage resources are used (Eq. 14-19) and how self-consumption (Eq. 20) is computed, considering the physical characteristics of the problem. Particular attention should be paid to the calculation of self-consumption. Contrary to what is usual in other studies that only consider the electricity locally generated, this model assumes that, whenever it results in lower costs for agents, electricity can be purchased from the retailer and stored in batteries (static andEV). Therefore, self-consumption can be provided by the electricity locally generated, or electricity stored in the batteries (bought to the retailers or from self-generation).

$$PL_t = \sum_{j=1}^{n} P_{jt} + \sum_{b=1}^{m} P_{bt} + BL_t \qquad t = 1,\ldots,T \qquad (14)$$

$$PL_t = PGrL_t + PGeL_t + PEL_t + PSL_t \qquad t = 1,\ldots,T \qquad (15)$$

$$PG_t = PGeGr_t + PGeL_t + PGeE_t + PGeS_t \qquad t = 1,\ldots,T \qquad (16)$$

$$PGeE_{et} + PGrE_{et} = PEGr_{et} + PEL_{et} + P_{et} \qquad t = 1,\ldots,T;\, e = 1,\ldots,v \qquad (17)^{h}$$

$$PGeS_{st} + PGrS_{st} = PSGr_{st} + PSL_{st} + P_{st} \qquad t = 1,\ldots,T;\, s = 1,\ldots,k \qquad (18)$$

$$PS_t = PGeGr_t + \sum_{s=1}^{k} PSGr_{st} + \sum_{e=1}^{v} PEGr_{et} \qquad t = 1,\ldots,T \qquad (19)$$

$$SC_t = PGeL_t + PEL_{et} + PSL_t \qquad t = 1,\ldots,T \qquad (20)$$

$$y_{jt} = \begin{cases} 1, \text{if } T_j^{start} \le t \le T_j^{start} + \mathrm{D}_j \\ 0, otherwise \end{cases} \qquad \begin{matrix} j = 1,\ldots,n \\ t = 1,\ldots,T \end{matrix} \qquad (21)$$

$$1 \le T_j^{start} \le T - D_j + 1 \qquad j = 1,\ldots,n \qquad (22)$$

$$P_{jt} = f_j\left(r - T_j^{start} + 1\right) \cdot y_{jt} \qquad j = 1,\ldots,n;\, t = 1,\ldots,T \qquad (23)$$

$$\theta_{bt}^{min} \le \theta_{bt} \le \theta_{bt}^{max} \qquad t = 1,\ldots,T;\, b = 1,\ldots,m \qquad (24)$$

$$SOC_s^{min} \le SOC_{st} \le SOC_s^{max} \qquad t = 1,\ldots,T;\, s = 1;\ldots,k \qquad (25)$$

$$SOC_e^{min} \le SOC_{et} \le SOC_e^{max} \qquad t = 1,\ldots,T;\, e = 1;\ldots,v \qquad (26)$$

$$SOC_{et} = SOC_{e(t-1)} + \left(\frac{\eta_{ech} \cdot P_{et} \cdot \Delta t}{Cap_e}\right) - \left(\frac{\eta_{edch} \cdot (PEGr_{et} + PEL_{et}) \cdot \Delta t}{Cap_e}\right) \qquad t = 1,\ldots,T;\, e = 1,\ldots,v \qquad (27)$$

$$SOC_{st} = SOC_{s(t-1)} + \left(\frac{\eta_{sch} \cdot P_{st} \cdot \Delta t}{Cap_s}\right) - \left(\frac{\eta_{sdch} \cdot (PEGr_{st} + PEL_{st}) \cdot \Delta t}{Cap_s}\right) \qquad t = 1,\ldots,T;\, s = 1,\ldots,k \qquad (28)$$

The following parameters were considered: D_j: duration of the operation cycle of shiftable load *j* [minutes]; θ_{bt}^{min} and θ_{bt}^{max}: lower and uppers temperature bounds of TCL *b* at *t*, respectively [°C]; θ_{bt}: temperature of

---

[h] At each *t*, the EV and static batteries are only in a single state (self-consuming; injecting surplus; idle; charging). Therefore, therespective constraints and auxiliary binary variables required to guarantee this condition were considered.

the space being conditioned by the TCL b according to the PBM at t [°C]; SOC_s^{min} and SOC_s^{max}: minimum and maximum SoC of static battery s, respectively [%]; SOC_e^{min} and SOC_e^{max}: minimum and maximum SoC of EV e, respectively [%]; $f_j(r)$: power requested by shiftable load j at stage r of its working cycle (r =1,…,Dj) [kW]; PG_t: expected PV generation at t [kW]; η_{ech}/η_{edch}: charging/discharging efficiency of the EV battery e [-]; η_{sch}/η_{sdch}: charging/discharging efficiency of the static battery s [-]; Cap_e: capacity of EV battery e [kW]; and Cap_s: capacity of static battery s [kW].

The following decision-variables were considered: PL_t: sum of power requested by shiftable, TCL and baseloads at t [kW]; $PGrL_t$: power supplied by the retailer for feeding loads at t [kW]; $PGrE_{et}$: power supplied by the retailer for charging the EV battery e at t [kW]; $PGrS_{st}$: power supplied by the retailer for charging the static battery s at t [kW]; $PGeL_t$: power from PV generation for feeding loads at t [kW]; $PGeGr_t$: PV power injected (into the grid or in the LEC) at t [kW]; $PGeE_{et}$: PV power for feeding the EV battery e at t [kW]; $PGeS_{st}$: PV power for feeding the static battery s at t [kW]; PEL_{et}: power from the EV battery e to feed the loads at t [kW]; $PEGr_{et}$: power injected (into the grid or LEC) by the EV battery e at t [kW]; PSL_t: power from the static battery s to feed the loads at t [kW]; $PSGr_{st}$: power injected (into the grid or LEC) by the static battery s at t [kW]; T_j^{start}: starting interval of the operation cycle of shiftable load j; SOC_{st}: SoC of static battery s at t [%].

Pricing is a keystone of this model as it guides both the optimization processes, and the energy exchange processes within the LEC. The outputs of agents' individual optimization trigger the buying and selling bids in the LEC exchanging scheme. However, at the time residential agents perform their individual optimizations, they are not aware whether or how much they will benefit (sell and buy) from LEC participation, as only after knowing the outcomes of residential agents the community coordinator agent decides how to share the collective energy resources. Thus, the optimization processes of residential agents are run based on a worst-case premise, that is, all procurement and sale transactions are carried out with the retailer. To simulate a retail tariff, an eight-tiered time-of-use (ToU) tariff was designed considering the wholesale market price dynamics. This tariff is considered as the buying price (BP_t) whenever buying transactions with the retailer agent are carried out. In turn, when surplus generation is sold to the retailer, agents are remunerated through a feed-in-tariff (FiT) (SP_t), established as 80% of the BP_t. The ToU tariff is assumed to be announced by the retailer 24h in advance.

To explore trade-off solutions in a bi-objective optimization setting, differences in comfort and cost sensitivity were considered by creating three cost/comfort sensitivity profiles, namely: 1) the cost-oriented profile, 2) the balanced profile and 3) the comfort-oriented profile. For cost- oriented agents, better cost solutions are selected in the Pareto front at the expense of worst dissatisfaction results. Comfort-oriented agents are mostly concerned about comfort standards, meaning that better dissatisfaction solutions are chosen in the Pareto front at the expense of worst cost results. In turn, balanced agents look for compromise solutions trading-off cost and comfort in a more balanced manner. This feature is randomly assigned to each agent.

The strong combinatorial nature of the mathematical models used to reproduce the operation of some loads (especially the TCL) imposes a high computational burden for the solvers; therefore, other approaches have been used to compute near-optimal solutions in an acceptable timeframe (Rasouli et al. 2019). Customized metaheuristics, namely GA, in which solutions expectedly converge towards a non-dominated (Pareto optimal) front where solutions of interest are located have produced sound results (Soares et al. 2017). GA are probabilistic search and optimization methods based on the progress of a population of solutions through selection, crossover, and mutation operators, which gradually converge to regions of the search space where high qualitysolutions for the problem are found (Cunha, Takahashi, and Antunes 2012). To deal with the bi- objective problem, a Non-Dominated Sorting Genetic Algorithm (NSGA-II), based on Soares et al. (2017) and Gonçalves et al. (2019), which was tailored to the physical features of the problem isproposed. The NSGA-II is an elitist multi-objective optimization algorithm in which offspring populations are generated using crossover and mutation operators, and the evolving generations are selected according to non-dominated sorting and crowding distance (Deb et al. 2002).

The proposed NSGA-II flowchart is displayed in Fig. 21 and its operation is summarized as follows.

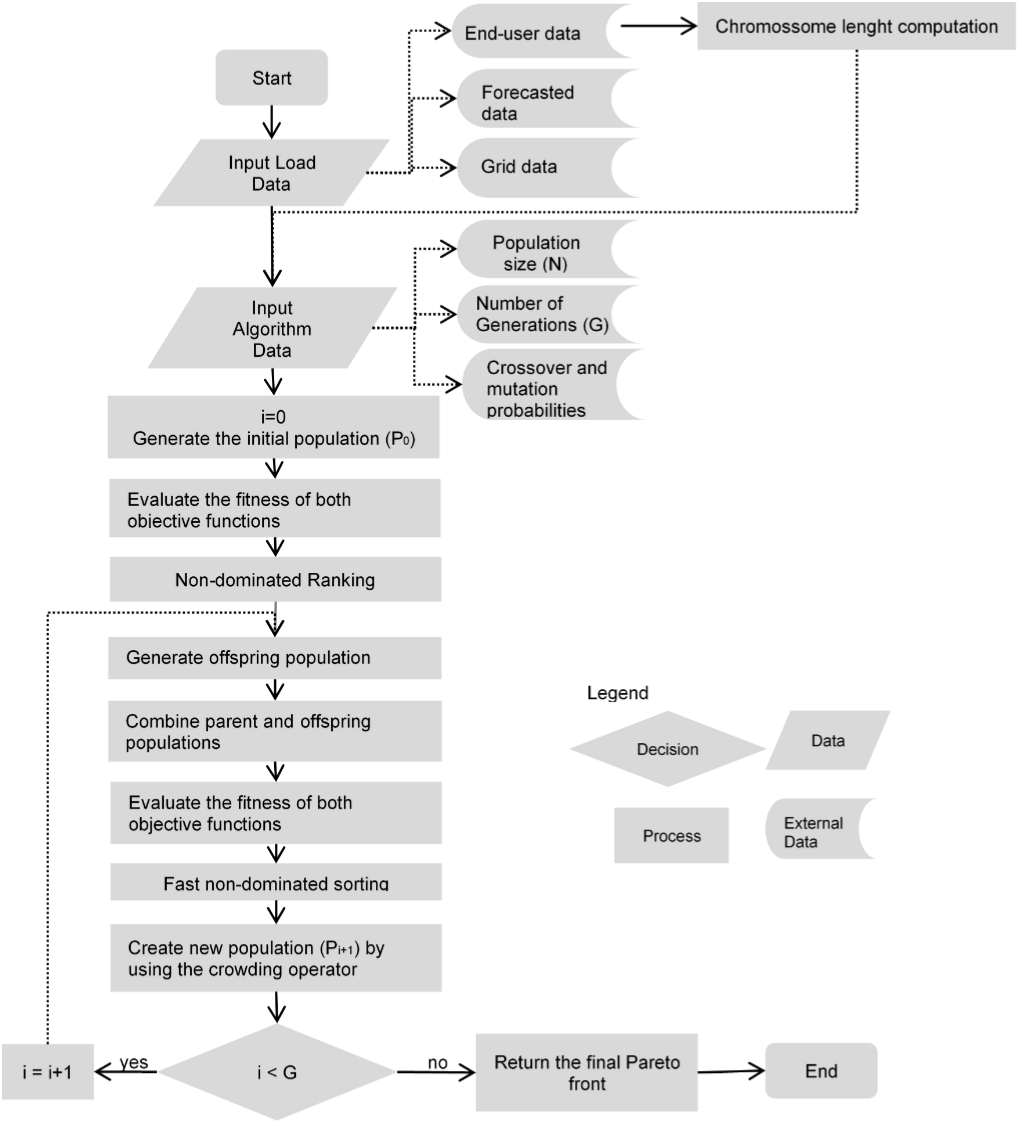


Fig. 21 NSGA-II flowchart.

In a pre-processing stage, external data are used to shape each agent's load profile. Simulations are run for the day-ahead and the input information includes energy prices, weather conditions, expected baseload demand, preferred time slots for the allocation of shiftable loads, comfort temperature ranges for TCL and the desired SoC for static and EV batteries. The population size (*N*), the number of generations (*G*) and the probabilities of the crossover and mutation operators are also specified at this stage to run the optimization process. The process starts by randomly generating the initial parent population (P_0) according to the features of the loads being managed. The selection operator selects the parents of the next generation based on a binary tournament. At this stage, the PBM are used to compute the temperatures and the power profileof TCL; the time allocation of shiftable loads is defined according to the solution encoding and a generic model is used to compute the power profile and the SoC of storage systems.

The solution encoding represents the AHEMS feasible management actions considering the optimization objectives: shiftable loads are initialized by randomly selecting a starting interval for their operation while ensuring that their operation can be fully completed within the planning period (Eq. 21-23); TCL are initialized by defining target temperatures for each interval of the planning period, while upper and lower temperature bounds are considered to respect users' admissible comfort temperature ranges (Eq. 24); the state of static and EV batteries must also be defined for each interval of the planning period among four possible ones: self-consumption and surplus injection; electricity injection; idle; charging from the grid. These states are influenced by battery capacity and by the minimum SoC defined by users (Eq. 25-28). Thus, while in the case of shiftable loads what is relevant is the starting minute within the scheduling period, for TCL the requested power at each time interval depends on the effective and the target temperatures. Therefore, these loads are represented by the maximum admissible temperature in each interval. To better model the usual consumer practices, a precedence rule of the LM over the TD utilization has been imposed, implying that the LM is randomly initialized if the TD can still fully operate within the remaining time until the end of the planning period. In turn, the DW is initialized randomly without concern for the allocation of the remaining loads. For the EV and the static battery, at each interval, states are coded representing the different possible operation states (self-consumption and selling the surplus; selling electricity; idle; charging). For the EV and the static battery, the operators ensure that the minimum SoCs are not violated and EVs are only used within their availability period. The final EV minimum SoC is not guaranteed by design and, therefore, should be explicitly verified.

A fitness function is assessed by computing power and temperatures profiles based on the: demand defined by the PBM, the time allocation of shiftable loads, the power required and the SoC of storage systems. The fitness of each solution (individual) in the initial population is evaluated regarding both objective functions and a ranking is assigned to each solution based on Pareto dominance (Deb et al., 2002, Goldberg, 2013). After the selection operator (binary tournament) to choose the parents, the offspring population is generated through the customized crossover and mutation operators, which are aimed at balancing intensification vs. diversification in the search space. For the shiftable loads, the mutation operator changes the starting minute of the operation cycle according to a predefined deviation bound, while the crossover operator swaps the load starting minute between two individuals. For the TCL, the mutation operator changes the maximum temperature within a given deviation bound and the crossover operator exchanges the maximum temperatures of both parent solutions. The crossover operator on static batteries and EV exchanges the parent solutions operation states (self-consumption and selling the surplus; selling electricity; idle; charging).

The mutation operator applied to static batteries and EV randomly selects an operation state among the 4 possible ones. Then, parent and offspring populations are combined in a pool, creating a population with twice the size of the initial one. The scheduling of shiftable loads, the storage charging/discharging processes resulting from the application of the operators and the appliance consumption patterns resulting from PBM are used to evaluate the fitness of offspring solutions. A non-dominated sorting scheme is used to identify the non-dominated front and a population size of *N* individuals is maintained. The crowding operator is used to set a crowding distance to each solution within the same front. If two individuals present the same rank during the non- dominated sorting, the one with a larger crowding distance is selected thus promoting population diversity to enhance the search (Deb et al. 2002). This procedure is repeated until the predefined number of generations is reached. Then, the Pareto front is identified, and the final solution can be chosen according to the consumer's profile.

Communication module

At the beginning of the simulation, information on the expected weather conditions (PV generation and outdoor temperatures) and retail pricing for the day-ahead are introduced as inputs. Further information on agents' preferences, baseload profiles, manageable loads specifications are also uploaded. Users' preferences, the baseload profile and load features are expected to be directly collected by the AHEMS and internally communicated to the decision- making module. The individual optimization performed by each residential agent gives the outcomes for its objective functions: the expected cost and dissatisfaction associated with the integrated management of all energy resources for the day ahead. They also know how much power they need to request (to the community or to the grid) and the available surplus generation they must sell (to the grid or to the community). This information is sent to the community coordinator agent.

3.2.3. *COMMUNITY COORDINATOR AGENT*

As residential agents, the coordinator is a goal-based agent aiming to manage and distribute the energy resources generated and stored in the energy assets owned by the community, while interfacing with the grid to buy and sell the remaining energy. These decisions are taken in an optimization environment aiming to minimize the overall community costs, which implies to minimize the overall power withdrawn from the grid (therefore, maximizing the community's self-sufficiency) and to maximize surplus selling. To reach this goal, a GA implemented in the coordinator agent architecture solves a single-objective cost minimization problem, similar to the residential agents' one (Fig. 22).

```
Input: input data, population size ($N$), number of generations ($G$), genetic operators probabilities;
Generate initial population $P_0$;
Evaluate the fitness of $P_0$;
for $i$=1 to $G$ do
    Select parents from current population $P_{i-1}$;
    Perform crossover and mutation operations to generate offspring population $P_i$ of size $N$;
    Evaluate the fitness of the new population $P_i$;
end for
Output: Return the Pareto front;
```

Fig. 22 Pseudocode of the coordinator agent algorithm.

This algorithm receives LEC members demand and surplus/deficit profiles as input data and decides on how to manage collective assets (generation and storage) if existing, while it interfaces with the retailer agent to supply/buy the remaining electricity necessary. At the end of the coordinator agent optimization, information on the amount of electricity bought and injected into the grid is transmitted to LEC members who need to recompute their individual cost results. The objective to be achieved by the coordinator agent is typically the minimization of LEC members total costs. For this purpose, the cost minimization objective function of residential agents and some of their constraints need to be adjusted. The following considerations are assumed:

- CEI agents demand is perceived as a non-manageable load by the coordinator agent algorithm to ensure that individual objectives are respected;
- If existing, the power demanded to charge collective batteries (which can receive electricity from the grid and from the self-generated electricity of prosumers) must also be considered in the LEC cost minimization objective function;

- The total power used for self-consumption at the coordinator agent level also includes the electricity generated and stored in the collective assets (if existing) and used to minimize the overall power requested from the grid;
- The electricity generated by collective PV systems or from the collective battery can also be injected into the grid whenever advantageous or required.

3.2.4. *DATA AND PROBLEM INSTANTIATION*

The following sections describe the data used in the different simulations carried out and presented in Chapter 4.

Representation of different household sizes

To create a model close to a realistic setup, agents representing different household sizes were included in the models. According to INE (2013)[25] 37.5% of the total Portuguese households have one or two members; 41.1% are households composed by a couple with one child and the remaining ones are couples with two or more children. Thus, three residential agent types were created representing households having one to two persons, three persons, and four or more persons. Also, the share of each residential agent type in the modeling is maintained to adjust modeling to a realistic setting. To maintain modeling coherence, different assumptions were considered regarding load utilization, renewable generation, and storage, as these dimensions are a function of the household size.

To determine heating and cooling needs influencing the TCL operation, the thermal performance of residential homes with different sizes was simulated for both seasons. Three different dwelling sizes were considered: a smallest, a medium and a largest one (Fig.23). The housing layout was inspired in Reis (2016) and Reis, Figueiredo, and Samagaio (2021). Two different constructive solutions were modeled representing the standard values enforced by the Portuguese Law 40/90 (solution 1) and Law 379-A/2013 (solution 2) as these are the type of constructive solution with more representativity in the current Portuguese building stock. Considering the Portuguese buildings statistics, 15% of the dwellings in the community were assigned the constructive solution 1 and 85% the constructive solution 2. The buildings layout and constructive solutions were used to carry out dynamic buildings simulation to compute the heat losses and gains through the building envelope, the losses from the air renewal due to indoor ventilation, and the internal and solar gains for the different housing typologies to be included in the AC system modeling.

To create flexibility in the model while maintaining some coherence, the assignment of the dwelling sizes to the different household sizes was made according to a probabilistic scheme displayed in Table 5.

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[25] A new census on the Portuguese population was carried out in 2021. Still, by the time most of the simulations were carried out, the results of this new survey were not available. Thus, data from the older population census were used.

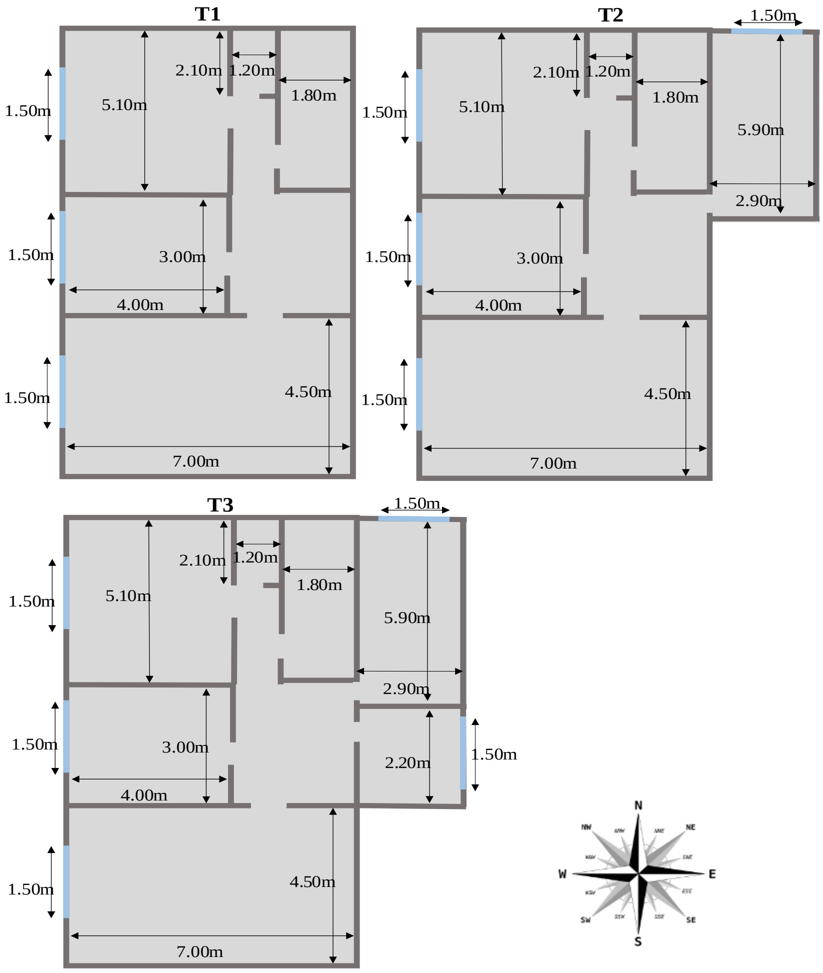

Fig. 23 Considered buildings layout.

Table 5 Assignment of household sizes and dwellings.

Household size	Probability of each household size being assign to a housing typology [%]		
	T1	T2	T3
1–2 persons	75	20	5
3 persons	5	75	20
4 or more persons	0	25	75

Loads

SHIFTABLE LOADS

Data retrieved from energy audits carried out by members of the Institute for Systems Engineering and Computers at Coimbra (INESC Coimbra)[26] research team were used to reproduce the operation of shiftable loads. The power profiles of the different shiftable loads are displayed in Fig.24 as well as the different use profiles (standard and ECO) included to create variability in the data. These profiles are assigned randomly among agents.

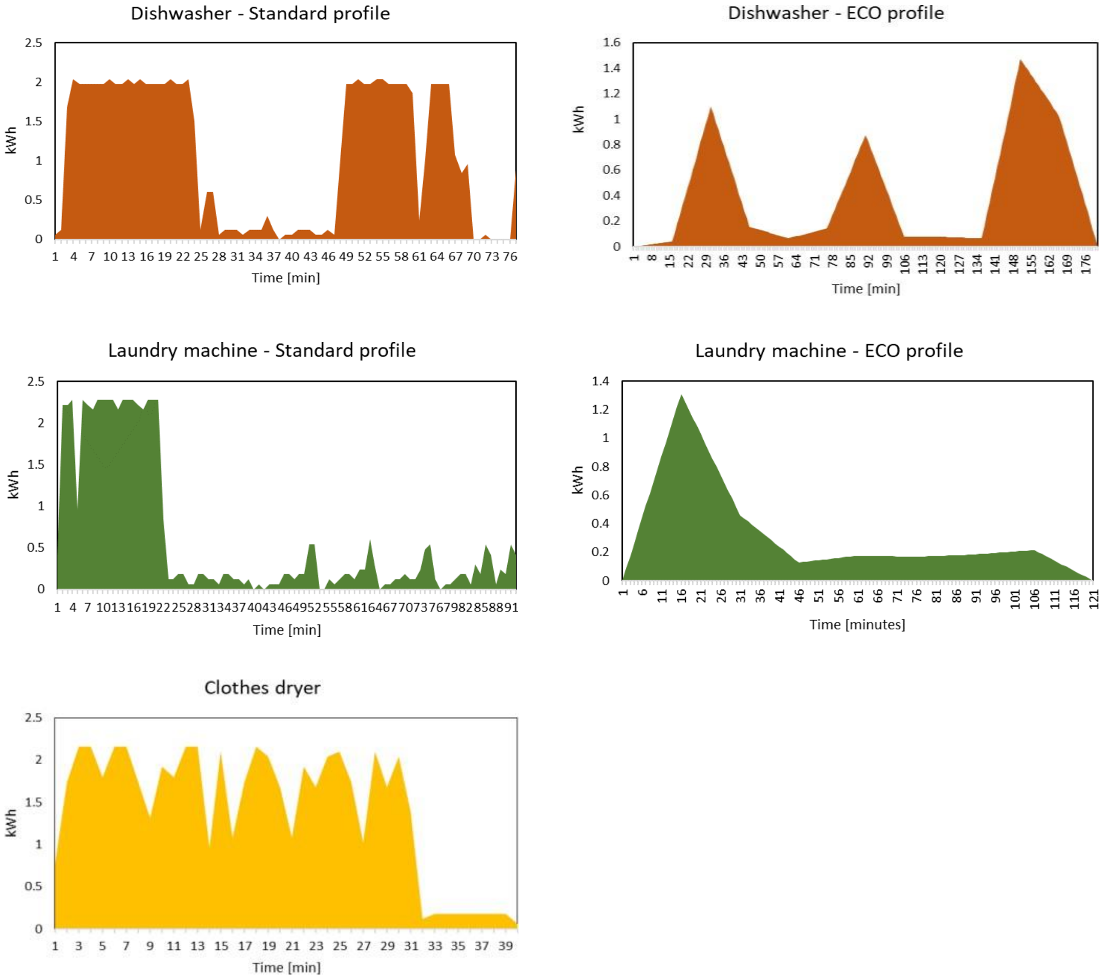

Fig. 24 Shiftable loads profiles.

THERMOSTATICALLY CONTROLLED LOADS

Regarding equipment, in preliminary simulations, the same fixed speed compressor (nominal power of 800 W) non-inverter AC system was considered for all residential agents, independently of the household size. In more recent simulations, differentiated nominal powers were considered as a function of the dwelling size as displayed in Table 5. The same type of fridge (90 W) was considered for all type of agents. The hot water consumption was also adjusted depending on the household dimension, and different water reservoir capacities and EWH nominal powers were assumed (Table 6). For the smaller (1–2 persons) and medium (3 persons)household sizes, a water tank capacity of 100 liters and an EWH power of 1500 W were considered, while for the larger (4 or more people) a 150-L water tank and a 1550 W EWH were assumed. Table 6 also displays the number of weekly cycles of each shiftable load depending on the household size. In turn, Table 7 displays the users' temperature conditions for all the TCL used to model their thermal comfort as well as to assess their dissatisfaction regarding the operation of TCL controlled by the optimizations run in AHEMS.

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[26] https://www.uc.pt/en/org/inescc

Table 6 Assumptions regarding household sizes.

		Smaller household	Medium household	Larger household
Probability of living in each dwelling typology [%]	T1	75	20	5
	T2	5	75	20
	T3	0	25	75
Weekly cycles of shiftable loads*	LM	2	3	4
	DW	2	3	4
	TD	2	3	4
Hot water consumption	Reservoir capacity [l]	100	100	150
	EWH power [W]	1500	1500	1550
AC power [W]		800	1000	1500

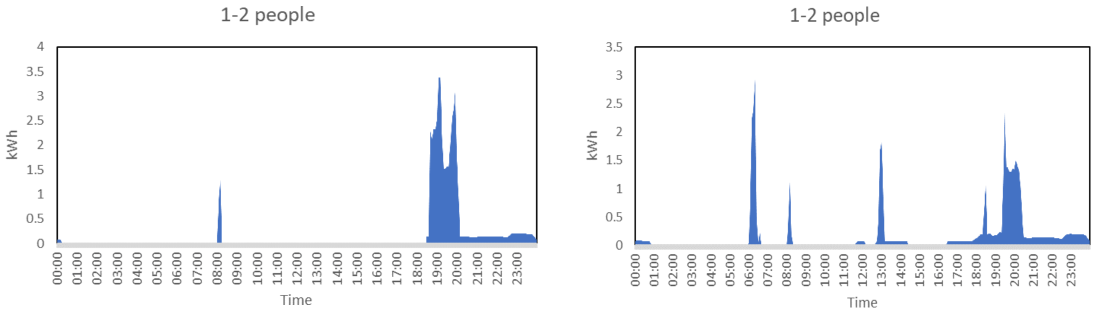
*Retrieved from Pakula and Stamminger (2010).

Table 7 Temperature ranges defined by users for each TCL.

TCL		Upper bound [°C]	Lower bound [°C]	Maximum Ref. [°C]	Minimum Ref. [°C]
AC	Heating mode	24	20	22	21
	Cooling mode	28	24	26	25
EWH		85	45	55	50
Fridge		9	5	8	6

BASELOADS

The baseload profiles (Fig. 25) were also created based on data collected from energy audits and adjusted according to the household size and the occupation profile. Two occupation profiles were considered: the working profile, including households whose members are engaged in professional/school activities outside the dwelling during weekdays; and the retired/ unemployed/homework profile, comprising households whose members stay mainly at home during the day.



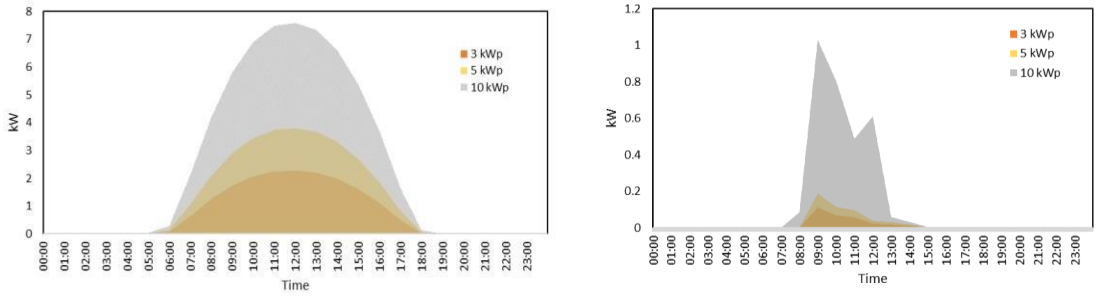
a) Working outside households

b) Mostly staying home households

Fig. 25 Example of baseload profiles.

PV generation

Regarding PV generation, several installed capacities were considered, and generation data was generated accordingly. Fig. 26 illustrates a PV generation profile of a 10 kW_p system, the maximum PV capacity considered for an individual presumption system, and Table 8 presents the assignment of different installed PV capacities as function of the household size. These assumptions were made taking into consideration possible roofing areas available to install these capacities.



a) Summer day

b) Winter day

Fig. 26 PV generation profile of a 10 kWp PV system.

Table 8 Assignment of PV capacities and household sizes.

PV capacity*		Smaller household	Medium household	Larger household
Probability of having the installed PVcapacity [%]	3kW	70	0	0
	5kW	30	70	0
	10kW	0	30	100

*Due to space constraints, residential PV systems are expected to be smaller. According to the E-REDES Opendata platform (https://www.e-redes.pt/pt-pt/e-redes.opendatasoft.com/pages/homepage) most of the existing PV installations are smaller than 4 kWp.

Storage: Static batteries and electric vehicles

To model both individual static and EV storage systems, the models proposed by Tremblay and Dessaint (2009) were used as starting point and complemented by the MatLab's SimPowerSystems battery model developed in Soares (2016). According to these models, charging and discharging processes are dependent on the type of battery (e.g., lead-acid, lithium- ion, etc.). As in Soares (2016), for static storage systems the lead-acid battery was assumed, and the lithium-ion model was used for EV storage systems.

For static storage systems, two battery capacities were assumed. Batteries with a capacity of 6.4kWh were assigned for smaller households/smaller PV generation systems, while for bigger generation systems, 13.5kWh storage systems were considered[27]. According to manufacturer's specifications, the charging power for the 6.4kWh battery is 2.0kW while for the 13.5kWh system is 7.0kW. The minimum SoC value is set as 20% for static batteries as well as an initial SoC of 25% while the minimum final (75%) and ideal final SoC (100%) was assumed the same for both static batteries and EV.

Different EV models were included and randomly distributed among agents and manufacturers specifications were used in the simulation of charging/discharging processes. The EV battery capacities considered in this model instantiation range from 22 to 100kWh and the charging powers from 6.6 to 22kW, according to the technical models' characteristics (Table 9). The minimum SoC defined by users for EV was set as 26%, based on Franke et al. (2015), an initial SoC was set as 30% and the ideal SoC is 100%. As the use of EV is linked to users' daily routines, EV charging operations were restricted to an availability period, representing the time interval between arriving home at the end of the day and leaving the next day. EV charging may start after 8 p.m. and be completed before 9 a.m.

Based on the charging and discharging models proposed by Brady and O'Mahony (2016) which consider the daily travelled distances, to further bring modeling closer to a real situation, average daily travelled distances

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[27] The two models of Tesla Powerwall were considered.

for weekdays and weekends were assumed. Considering these distances and specific consumption data, the EV SoC is updated before the optimization to simulate a realistic charging/discharging process.

Table 9 EV characteristics considered in the modeling.

Parameters	Model 1	Model 2	Model 3	Model 4	Model 5
Charging/Discharging power (kW)	7.4	7.4	7.4	6.6	22
Capacity (kWh)	22	33	42.2	40	100
Initial SOC			0.3		
SOC lower bound			0.26		
SOC lower bound after unplugging			0.75		
Ideal SOC after unplugging			1		
Energy consumption (kWh/km)	0.167	0.186	0.186	0.172	0.172
Distance traveled during weekdays (km)*			15.6		
Distance traveled during weekends (km)			5		

* Average value retrieved from mobility surveys.

Algorithm parameterization

Optimizations are done for the day ahead with 1-min discretization[28]. Therefore, for a planning period of 1 day, T = 1440 intervals and Δt is given by 1/60 h. Simulations are run for seven days (one week) to better represent residential dynamics, covering weekdays (day 1 to 5) and weekends (last two simulation days) for summer (August) and winter (January) seasons.

From a modeling point of view, running the simulations for several days requires initializing the optimization processes several times and, to keep modeling consistency, information between simulation days must be adjusted, namely regarding:

- The SoC of batteries, since in the first simulation day, the initial SoC is an input but in the first interval of the second simulation day, the SoC must be coherent with the value in the last interval of the previous day and so on; and
- The indoor temperatures of the AC and in the EWH water reservoir must also be attuned following the same reasoning.

The parameters displayed in Table 10 were considered for the algorithms implemented in both residential agents and coordinator agent architectures.

Table 10 Algorithm parametrization.

Population Size	Number of Generations (*G*)	Probabilities of Operators [%]		
		Loads	Mutation	Crossover
50	200	Shiftable loads	20	50
		TCL	60	50
		EV	20	30
		Static battery	30	30

---

[28] Although most energy data is only available with a 15-min time discretization, this finer temporal resolution was assumed to understand if the model would be able (as a matter of computational effort) to support a real-time implementation.

Implementation tools

The object-oriented Anylogic modeling software was used, in some settings, to create the MAS model and display the results dynamically (Figs. 27 and 28). The Anylogic tool introduces multimethod simulation modeling, combining discrete event, agent based and system dynamic simulation models. By doing so, agents can be modeled though customized properties such as consumer behavior, individual skills, schedules, performance data, or energy-related profiles.

Anylogic[29] also allows for running optimization models. Still, some experiments revealed that, due to the complexity of the optimization methods implemented in the scope of this work, namely the implementation of non-exact optimization algorithms made the model very difficult to implement in this software as it is not designed to deal with this kind of approach. Thus, a combined approach was adopted: the model was implemented in the Eclipse Java Integrated Development Environment (IDE) as it allows for both agents' creation and optimization running, and whenever results need to be displayed dynamically they are exported and adapted to run in the Anylogic platform. When there is no need for the dynamic display of the optimization outcomes, results are printed in an Excel/CSV format.

● Rainy Day
○ Cloudy Day
○ Sunny Day

Fig. 27 Screenshot of the Anylogic visualization console.

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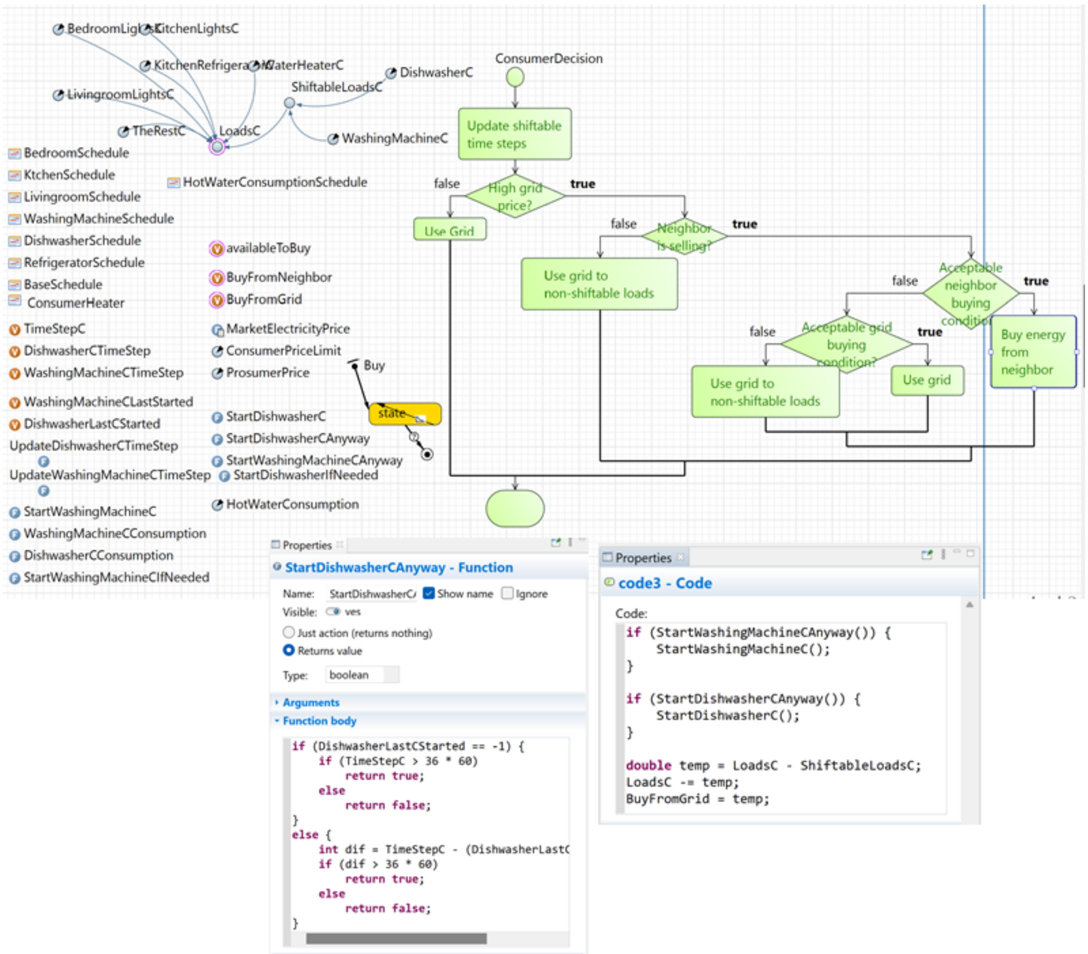
[29] https://www.anylogic.com/



StartDishwasherCAnyway - Function

Name: StartDishwasherC/ ☑ Show name ☐ Ignore
Visible: yes
○ Just action (returns nothing)
● Returns value
Type: boolean

```
if (DishwasherLastCStarted == -1) {
    if (TimeStepC > 36 * 60)
        return true;
    else
        return false;
}
else {
    int dif = TimeStepC - (DishwasherLastC
    if (dif > 36 * 60)
        return true;
    else
        return false;
}
```

code3 - Code

Code:

```
if (StartWashingMachineCAnyway()) {
    StartWashingMachineC();
}

if (StartDishwasherCAnyway()) {
    StartDishwasherC();
}

double temp = LoadsC - ShiftableLoadsC;
LoadsC -= temp;
BuyFromGrid = temp;
```

Fig. 28 Screenshot of the Anylogic agent creation console.

3.2.5. *CONCLUDING REMARKS*

The agent-based approach is a computer simulation of an artificial “world” occupied by discrete decision-making entities (agents) whose behaviors rule the interactions between them. It is suitable for addressing “what-if” settings and incorporate actors’ perspectives in the system. Thus, this approach reveals adequate to be used in the modeling of renewable-based energy communities in which agents have different goals and perspectives and in which a wide-range of configurations and assumptions can be made. One of the main reasons for choosing ABM over traditional equation-based modelling approaches in energy modeling is its ability to integrate heterogeneity and adaptivity. However, this option for a closer representation of a real context dependent on the uncertainty of the agents' behavior has an associated cost: the lack of verification and validation protocols, which is one of the main criticisms of ABM (Akhatova et al. 2022).

Verification and validation guarantee the operational validity of a model. One of the main reasons pointed for missing out models’ validation is the difficulty to obtain real data and thus performing empirical validation (Akhatova et al. 2022). In such circumstances, the performance of the computational model cannot be operationally authenticated and consequently, the results can be considerable as ‘questionable’. The simulations which will be further presented and discussed in the next sections are based on conceptual LEC models, supported by a set of assumptions informed by the existing literature on energy communities and the authors experience on smart grids as well as behavioral and technical demand response research and practice. As the LEC modeled have not been materialized, there is no real basis for comparison that allows to discuss how far the model outcomes are to represent the behavior of the target system (correctness) or to what extent the conceptual framework of the model and the target system match (consistency) (Bitonto et al. 2012). Therefore, results must be understood as experimental and exploratory.

However, to create models as close to reality as possible, physically based models were used to model the functioning of electrical loads, data from energy audits were loaded to reproduce operating cycles and climate information was used to create renewable generation profiles and reproduce the thermal behavior of buildings, influencing the operation of thermal loads. Additionally, human behavior was modeled (i.e., preferences in the use of loads) by considering information gathered in existing social studies and giving degrees of freedom regarding sensitivity to cost and comfort parameters.

4. RESULTS AND DISCUSSION

This chapter is divided into two main sub-sections: the first one presents the results of the Problem Structuring Methods approach developed to clarify the implementation framework of CEI in Portugal, raising clues for modeling whereas the second one includes the results of six case studies exploiting different configurations and dimensions.

4.1. PROBLEM STRUCTURING RESULTS

4.1.1. THE FINDING OUT STAGE

Fig. 29 presents a rich picture representing the current framework of collective energy initiatives in Portugal, highlighting the main stakeholders and their relationships, which are described as follows. This analysis was mostly supported by literature on the topic (scientific literature, European and national legislation, pilot-project descriptions, etc.) and by the perspectives elicited from the conversations (semi-structured interviews) with stakeholders identified in Table 3. The Portuguese context was used as reference.

The Portuguese power sector, as most European power sectors, was gradually liberalized and since 2006 all consumers in mainland can choose their electricity supplier (ERSE 2021a). The sector is steered by international (European Commission) and national (government) guidelines that set energy and carbon emission objectives to be achieved for the 2030 and 2050 horizon. As referred before, regarding CEI, the European directives 2018/2001/EU (RED-II) and 2019/944/EU (IEMD) are being transposed into Member-States national energy plans. In Portugal, Law 15/2022 (Portuguese Government 2022) transpose both RED-II and IEMD. This law is complemented by Regulation 8/2021 (ERSE 2021b) which regulates the electricity self-consumption, and by Ordinance 6453/2020 (Portuguese Government 2020) which exempts self-consumption projects using the public distribution grid of paying economic interest costs (CIEG) on access network tariffs.

The political guiding principles drive the actions of different stakeholders, including government through governmental agencies, such as the Directorate General of Energy and Geology (DGEG) and ERSE, the Portuguese regulator. DGEG is responsible, among other functions, for the approval of individual and collective renewable electricity generation projects (for self- consumption and grid injection until a maximum installed capacity of 1 MW) and LEC (DGEG 2021). In turn, the ERSE's role is to protect the interests of consumers and promote competition between agents intervening in markets, developing regulation, supervision, and inspection activities (ERSE 2020a; ERSE 2021a). The regulator is responsible for defining the rules to be applied to consumers (both in CEI and in the traditional supply schemes), producers, transmission and distribution networks operators, retailers, as well as all entities operating in the power system. It is also responsible for designing tariffs (the Portuguese electricity system operates under the principle of tariff uniformity throughout the national territory) and for the fair allocation of costs along the electricity value chain (ERSE 2020a; ERSE 2021a). This function is especially relevant in collective energy configurations as several issues are raised: regulators must ensure that CEI do not pay for components of the system they do not effectively use (e.g., high voltage distribution networks) at the same time they must warrant these initiatives pay for disturbances they may cause in the system and consumers who stay in traditional supply models are not burdened with extra costs caused by collective initiatives.

The value chain of the Portuguese power sector encompasses electricity generation, transmission, distribution, retail, and consumption. The generation activity, both under the ordinary rule (based on fossil sources and large hydroelectric power plants) and the special rule (including cogeneration and generation from renewable sources), operates under a free competition regime (ERSE 2020a; ERSE 2021a). The Portuguese power system operates under a regulated market of a single buyer, which means that producers invest in generation capacity and are remunerated by selling energy to a market operator which manages the daily and intraday Iberian markets (OMIE 2021). The power generated in power plants is transported to the consumption points by the nationwide transmission network operator. This entity has responsibilities in the overall technical management of the system, so its role in balancing demand and supply in a context where distributed and decentralized generation is promoted is key to ensuring security and quality of supply (ERSE 2020a; REN 2021). The transmission network feeds the distribution network from which most end-users are supplied. High, medium, and low voltage distribution networks are managed by more than a dozen of distribution network operators (ERSE 2020a; Portugal Energia 2021). In a context of collective energy projects where the sharing of locally generated energy is promoted and the sale of surpluses to retailers is allowed, the DSO play a key role as they must ensure the infrastructure conditions for these transactions to take place, being remunerated through the payment of tariff components related with the use of distribution networks.

Electricity retailers are responsible for managing the relationships with end-users, including billing, and are subject to obligations regarding quality, continuous power supply and the delivery of suitable information to consumers (ERSE 2020a; Portugal Energia 2021). These entities can freely buy and sell electricity and have the right to access the transmission and distribution networks upon the payment of access tariffs established by the regulator. Retailers may be classified as market retailers, if they buy and sell electricity to end-users through the establishment of contractual relationships, and as last resort retailers, if their main purpose is to guarantee the supply/purchase of electricity to consumers in exceptional situations (e.g., termination of contracts with supplier, supplier change, etc.) (ERSE 2020a; Portugal Energia 2021). Retailers have a crucial role in collective energy systems as they are responsible for supplying the energy deficit which local generation assets are not able to provide at the same time as they may buy energy surpluses, allowing collective consumers to make some profit from the sale of self-generated energy (Niesten and Alkemade 2016). The commercial relationships between CEI members, retailers and DSO are intermediated by a collective self-consumption management entity (*Entidade Gestora do Autoconsumo – EGAC* in Portuguese), announced in the Portuguese regulatory framework under the Law 15/2022 (Portuguese Government 2022). This entity is responsible for informing the DSO about the energy sharing rules, establishing relationships with retailers for selling/buying surpluses/deficits and ensuring the corresponding payments. In increasingly decentralized energy systems, aggregators (also defined in Law 15/2022) may also emerge as relevant power system players. The role of these entities in power systems is heavily dependent on the degree to which demand-side flexibility is treated in markets as a resource, which varies considerably across Europe. In fact, until recently, in most European countries, as Portugal, the access of aggregators to markets is neither not expected nor possible(Malizou 2018). However, with the foreseen emergence of innovative collective energy business models exploiting demand-side flexibility aggregation allowing for the participation in energy and flexibility markets, aggregators are expected to gain a more prominent role.

The last segment in the power systems' value chain is consumption, which includes both the consumers who will be involved in collective energy projects (which the analysis is focused on) and those who will remain in typical energy supply models. Companies, municipalities, and public entities can be initiators of collective energy projects; however, special attention has been paid to residential consumers as they are very numerous, they can leverage the energy transition by gathering the required private funding, and because the social, environmental, and economic benefits created by small-scale projects can be significant for the local improvement of communities' living conditions (Caramizaru and Uihlein 2020).

Due to the novelty of the LEC concept in Portugal and the scarcity of projects working as example, it is expected that residential consumers wanting to start these projects will face difficulties and have to resort to external entities in search for technical, bureaucratic and financial support. Municipalities and energy agencies can provide such support (for instance, by means of establishing dedicated one-stop-shops to support citizens and local entities in this issue). Due to its proximity to communities, municipalities can promote the development of local energy projects in two ways. First, by initiating themselves the projects, taking advantage of their facilities and becoming energy producers, reducing their demand, sharing surpluses at reduced costs and setting an example for citizens (Vandevyvere et al. 2021). Second, by supporting projects initiated by citizens, facilitating administrative processes, providing technical support, informing on funding schemes, as well as by publicizing such initiatives, fostering participation and engagement (Vandevyvere et al. 2021). Regardless of their participation as promoters or creators of collective energy models, municipalities are deeply interested in such initiatives since the originated local benefits (social, economic, and environmental) are reflected in investments in local infrastructures benefiting all citizens.

Collective energy project promoters can resort to municipal and regional energy agencies, which can provide technical support and facilitate projects structuring, the contact with other entities (e.g., retailers and DSO), access to funding schemes, etc. (Portugal Energia 2021). These entities can, in turn, resort to the national scientific and technological system, which include universities and research centers, to resolve more technical issues, and to the financial system, which facilitate the access to funding. In fact, both the scientific and the financial system establish relationships with all the different actors to provide qualified human resources and knowledge and to provide funding solutions, respectively. Due to the activities in which CEI may be involved, requiring automation and control, and generating large volumes of data, a wide array of technologies (smart metering and monitoring devices, software platforms, etc.) and customized services are required. Thus, the role of technology providers (manufacturers and retailers) as well as energy service companies (ESCO) and e-mobility companies must also be highlighted. Technology providers are responsible for manufacturing and/or retailing the required technologies and services required to develop CEI. These products and services have a great added value and their development in national territory is highly promoted since, in addition to creating jobs and economic value, it fosters the country's technological innovation. In addition to manufacturing and selling products, many technology providers also offer services such as system sizing, operation, and maintenance, etc. The products and services provided by these companies are sold to both consumers (residential, commercial, industrial) and network operators (for the sake of clarity of Fig. 29 these relationships were not evidenced), who demand quality, efficiency, and low cost. ESCO invest and develop energy efficiency projects according to performance contracts signed with consumers who want to reduce their energy bills without the involvement in the process and the initial investment barrier (Dressen 2003). These companies can assist the creation of CEI by providing the required infrastructure and funding, selling turnkey services. The role of e-mobility companies, including e-mobility network managers (responsible for the management of energy, information, and financial flows), charging operators (responsible for installing, operating and maintaining charging sites) and e-mobility retailers (responsible for the retail of electricity for charging EV batteries) (Portugal Energia 2021), should also be highlighted as electric mobility is an increasing trend.

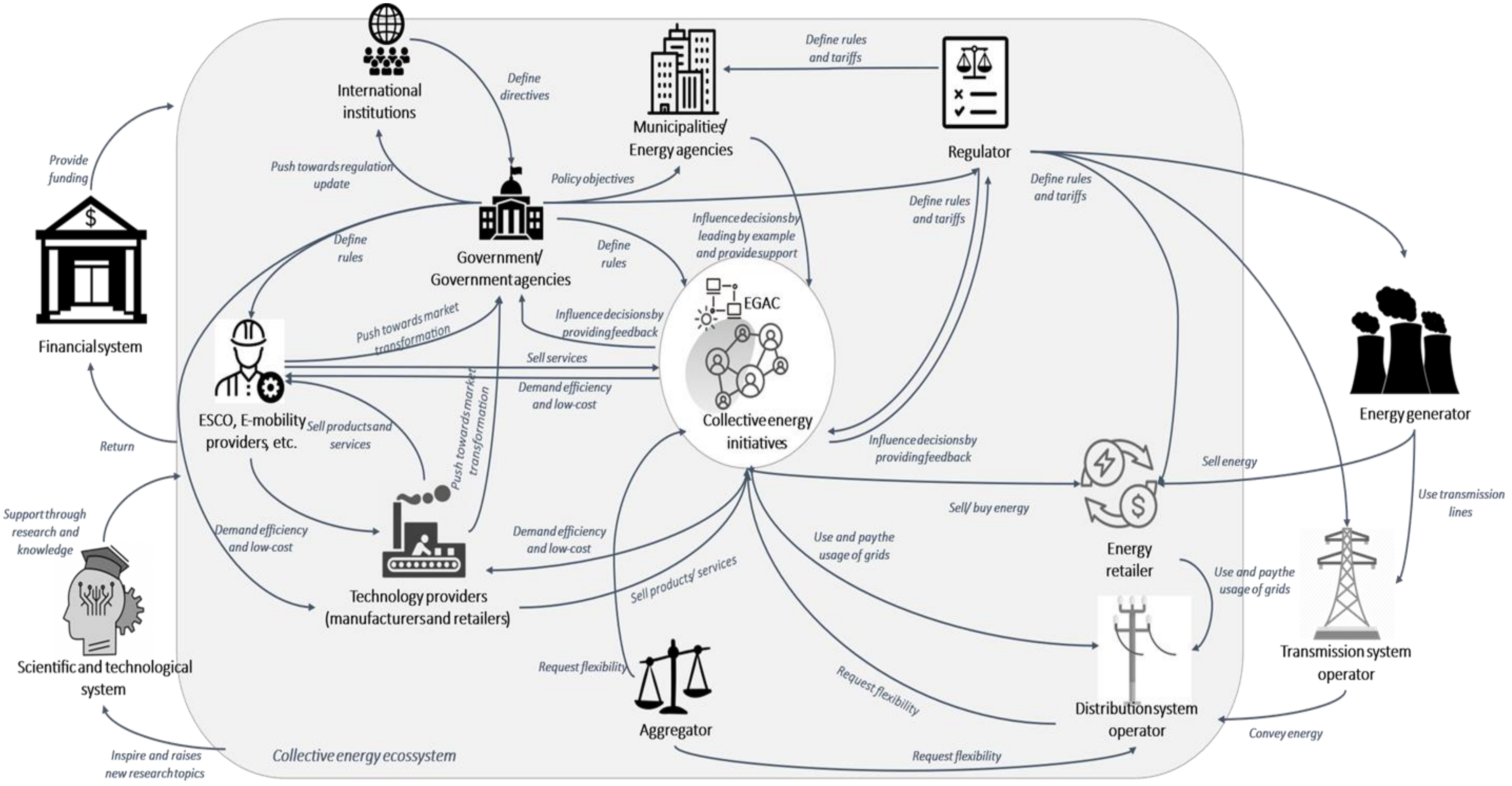


Fig. 29 Rich picture of the Portuguese collective energy initiatives environment.

4.1.2. STAKEHOLDERS EXPECTATIONS

Given the heterogeneity of perspectives gathered from stakeholders, a comprehensive root definition was built and presented as follows:

A system to boost penetration of decentralized renewable energy, contributing to the achievement of energy and carbon emission goals, to promote the efficient usage of local energy resources, to empower citizens and communities to participate in collective energy initiatives and foster innovative business models. These aims are achieved by fostering private investment while providing customers with extended consumption options and local benefits, encouraging the optimal usage of self-generated energy and energy efficiency measures and behaviors, and by exploiting new value streams and value-added products and services.

This root definition encompasses different perspectives that reflect the expectations of different players:

- Policymaking perspective (PMP): Stakeholders involved in policymaking envision the benefits of collective energy initiatives at a country level. It is expected that CEI projects will be mostly supported by renewables. Thus, these energy initiatives can contribute significantly for renewables penetration in countries' energy matrices, with benefits for the country energy autonomy and economic competitiveness, the quality of life of citizens and the achievement of national and international energy and environmental commitments.

- Techno-economic perspective (TEP): Technology companies and network operators also focus their expectations on the technological innovation and the emergence of new business models associated with collective energy projects. Due to renewables intermittency, a greater focus is placed on the demand side, which needs to be more efficient and flexible to adjust to local supply availability. Therefore, CEI can work as testing laboratories for new demand-side management strategies and energy efficiency measures. This expectation is shared by policymakers, technology companies and network operators. In addition, the enabling framework fostered by European directives encourage the emergence of innovative business models to maximize the value created by some of the announced activities (e.g., local energy sharing, aggregation, etc.). These activities are expected to create value-added services and products (e.g., local demand flexibility, e-mobility, etc.) over which revenue streams can be exploited. In this setting, entrepreneurs and technology-based companies are expected to become stakeholders, bringing new perspectives and innovation to power systems operation.

- Social perspective (SP): The expectations regarding the benefits for citizens and communities are also relevant. CEI are expected to be mainly created by and for citizens who commit to finance and own an energy generation system so that they can control how their energy is generated and supplied. These projects reinforce social cooperation, enhance energy literacy, and allow citizens' participation in the energy system (Caramizaru and Uihlein 2020). Also, CEI can play a key role in alleviating energy vulnerability situations since they may create local jobs, provide renewable energy at lower prices and/or use profits to improve the living conditions of local populations (Hanke and Lowitzsch 2020).

The different perspectives are discretized in the CATWOE analysis presented in Tables 11 – 13.

Table 11 CATWOE analysis of the root definition for the policy-making perspective (PMP).

Terms		Unveiled objectives
Customers/Clients	Country and society in general, power system operators and companies.	Greenhouse gas emissions reduction; energy self-sufficiency; impacts on climate change and human health; lower use of fossil fuels.
Actors	International institutions; national governments; regulators; retailers; DSO; individual and collective prosumers; technology providers; financial system; scientific and technologic system.	Higher penetration of renewables; achievement of energy and environment targets; energy independence; maximize profits and return of investments; power systems competitiveness; energy supply resiliency and reliability.
Transformation	Increase the share of renewable energy in national matrices, reducing external energy dependence and contributing to the achievement of energy and environmental goals.	Higher penetration of renewables; achievement of energy and environment targets; energy independence.
World view	International agreements shape the national energy and environment goals whose achievement depends on the acceptance and private investment of citizens in renewable energy, taking advantage of existing energy resources.	Higher penetration of renewables; achievement of energy and environment targets; energy independence.
Owner(s)	International institutions; national governments and regulators; financial system; society.	Higher penetration of renewables; achievement of energy and environment targets.
Environmental constraints	International commitments; local conditions; technologies readiness levels and costs; financial resources/investors; society.	Efficient utilization of the existing potential; leveraging of private investment.

Table 12 CATWOE analysis of the root definition for the techno-economic perspective (TEP).

Terms		Unveiled objectives
Customers/Clients	CEI members and local communities; energy producers; DSO; TSO; retailers; aggregators; technology providers; ESCO and e-mobility companies.	Deployment of enabling technologies and human skills; self-sufficiency; economic benefits; profit from flexibility commercialization (maximize the value of flexibility in markets); balance of supply and demand/ avoid grid congestion; delay network investments; maximization of revenues/ minimization of losses; increasing efficiency and competitiveness; exploitation and selling of new products and services; new partnerships and long-term contracts; participation in new markets; involvement in advanced R&D projects; profitability of projects.
Actors	International institutions; national governments; regulators; retailers; DSO; individual and collective prosumers; technology providers; financial system; scientific and technologic system.	Higher penetration of renewables; achievement of energy and environment targets; energy independence; maximize profits and return of investments; power systems competitiveness; energy supply resiliency and reliability; demand for differentiated products/services; creation of qualified jobs; exploitation of new value streams.

Terms		Unveiled objectives
Transformation	Creation of new value streams and value-added products/services (energy supply, energy efficiency, flexibility, e- mobility), with benefits for everyone involved in the value chain, leading to amore resilient and self-sufficient power system.	Projects profitability; power systems competitiveness; energy supply resiliency and reliability; demand for differentiated products/services; creation of qualified jobs; exploitation of new value streams.
World view	New activities (energy sharing, local aggregation, e-mobility, etc.) foster theemergence of novel business models toexploit valuable products and services, encouraging innovation and competitiveness, at the same time as new actors enter, as stakeholders, in the value chain. In addition, CEI can help to reduce power systems inefficiencies by promoting optimal demand and supply matching strategies, energy efficiency measures and behaviors.	Exploitation of endogenous energy resources; losses/inefficiencies minimization; maximization of thecost-effectiveness of local generation investments.
Owner(s)	International institutions; national governments and regulators; financialsystem; society.	Higher penetration of renewables; achievement of energyand environment targets.
Environmental constraints	Regulatory framework; inflexibility of the electrical system; competition; (un)attractive return on investments; readiness of technologies; size of investments; human resources qualification; bureaucracy in CEI licensing processes; lack of clarity regarding medium- and long-term incentives; know-how; social acceptance and engagement; physical restrictions (of grids and buildings); shortage of R&D projects on the ground.	Modernization of power and communication grids; enhancement of human resources; technology diffusion; increase of R&D projects and cooperation between research institutions and entities in the field; mitigation ofregulatory barriers; promote attractive investment opportunities; foster countries' technological maturity; development of highly qualified human resources.

Table 13 CATWOE analysis of the root definition for the social perspective (SP).

Terms		Unveiled objectives
Customers/Clients	Country and society in general, power system operators and companies.	Energy bill minimization; energy self-sufficiency; social benefits; access to renewable and cheaper energy; benefit from collective profits distribution.
Actors	International institutions; national governments; regulators; retailers; DSO; individual and collective prosumers; technology providers; financial system; scientific and technologic system.	Gathering of private investment for energy transition; better quality of services; benefits for all stakeholders; increased energy-related knowledge and information among consumers; mitigation of energy markets access barriers; mitigation of energy poverty/vulnerability issues.
Transformation	Active participation of citizens and communities in energy related decisions as they are able to recognize the benefits of their engagement and are willing to invest and contribute for hastening the energy transition.	Energy literacy promotion; energy fairness; social acceptance; collaboration and participation; developmentof community social values.

Terms		Unveiled objectives
World view	CEI empower consumers by including them in decision-making, allowing them to play an active role in the energy transition and providing them with better access to information and extended consumption options (becoming prosumers or prosumagers).	Inclusion of energy vulnerable consumers; mitigation of energy poverty; enhancement of local infrastructures.
Owner(s)	International institutions; national governments and regulators; financial system; society.	Higher penetration of renewables; achievement of energy and environment targets.
Environmental constraints	Citizens' literacy and economic circumstances; regulatory framework; national historical context (e.g., social policies, incentive schemes, position in relation to renewables, etc.).	Increasing the population's energy literacy (and increasing engagement in collective energy settings); mitigation of energy vulnerability situations and inclusion of low-income consumers.

4.1.3. *FUNDAMENTAL OBJECTIVES*

The SSM supported by the stakeholders' collaboration enabled to unveil a "cloud" of objectives concerning the implementation of CEI. As it is aimed to exploit the key goals behind collective energy settings, the "cloud" of objectives was dissected to differentiate fundamental and means-ends objectives and structured them as a tree (Table 14). The tree of fundamental objectives is not customized to a specific stakeholder or consider an explicit perspective; thus, it does not specify which objectives are the most relevant ones (the order in which they appear in the tree is arbitrary). Though, Table 14 details to which stakeholders' set each means-objective would be more relevant. For this purpose and for the sake of the figure's simplicity, the stakeholders identified in Fig. 29 were grouped into four categories, namely: *policymakers*, including the international institutions, national governments and regulators; *promoters and beneficiaries*, including the citizens engaged or not in collective energy systems and municipalities; *power system operators*, encompassing all the entities playing roles at the power systems (energy producers, TSO, DSO, retailers and aggregators); and *providers*, which includes all other entities that provide products and services necessary for the pursuit of collective energy initiatives.

Table 14 Tree of fundamental objectives identifying the involved stakeholders grouped as follows: policymakers; promoters and beneficiaries; power system operators; providers. Each objective is also associated with the identified perspective (PMP, TEP and SP).

Fundamental objective	Perspective	Means-ends objective	Stakeholders raising the objective as relevant
To ensure energy equity, openness, and fairness	PMP and SP	Access to better information fostering better decision-making	Policymakers; promoters and beneficiaries
		Parity among players	Policymakers; promoters and beneficiaries
		Access to new energy services and supply conditions	Promoters and beneficiaries
		Fair tariff schemes	Policymakers; promoters and beneficiaries
To ensure local security of supply	TEP	Efficient utilization of energy resources	Policymakers; promoters and beneficiaries; power system operators; providers
		Self-sufficiency and control	Policymakers; promoters and beneficiaries; power system operators
		Reliability and quality of energy services	Promoters and beneficiaries; power system operators

Fundamental objective	Perspective	Means-ends objective	Stakeholders raising the objective as relevant
To benefit participants, local communities, and the country	PMP and SP	Energy bill reduction / access to cheaper energy	Policymakers; promoters and beneficiaries
		Energy awareness/social acceptance	Policymakers; promoters and beneficiaries; power system operators
		Energy vulnerability mitigation	Policymakers; promoters and beneficiaries
		Contribution to local development	Policymakers; promoters and beneficiaries
		Impact on the country energy dependence (and trade balance)	Policymakers
		Impact on the local and national economic activity and employment rate	Policymakers
		Indirect impact on national budget	Policymakers
		Impact on the literacy and qualification of human resources	Policymakers; promoters and beneficiaries
To benefit the environment	PMP and SP	Energy and climate targets	Policymakers
		Impact on human health and ecosystems	Policymakers; promoters and beneficiaries
		Aesthetics impacts	Promoters and beneficiaries
To ensure the economic feasibility of CEI	PMP and TEP	Return on investment/ profitability	Promoters and beneficiaries
		Investment requirements	Promoters and beneficiaries
		Stakeholders' readiness	Policymakers; promoters and beneficiaries; power system operators
		Technology friendliness	Policymakers; promoters and beneficiaries; power system operators
		Legal and administrative framework	Policymakers; promoters and beneficiaries; power system operators; providers
To modernize and endow power systems' infrastructures with 'smartness'	TEP	Online management of data	Power system operators; providers
		Integration of distributed renewable generation	Policymakers
		Ability to manage and monitored assets remotely	Promoters and beneficiaries; power system operators; providers
		Reduction of congestion issues and technical losses	Power system operators
		Exploitation of new value streams (including storage)	Power system operators; providers
		Reinforcement of ICT and metering networks	Power system operators; providers

The first one, *to benefit the environment,* encompasses the means-objectives related with the consequences of energy generation for the environment, namely for the health of people and ecosystems. To reduce the dependence on fossil-fueled energy generation and foster renewables has been one of the main targets of energy and environmental policies to solve a pressing problem: the harmful effects of fossil fuels combustion for the environment. The diffusion of decentralized renewable-based generation, e-mobility services, the increase in energy efficiencyand the rational energy usage promoted by CEI can contribute to reduce overall power systems' carbon intensity, with positive effects for human health (reduction of respiratory problems caused by air pollution) and ecosystems (emissions reduction, contamination of soil, air, and water).

The Portuguese 2030 Energy and Climate Plan (PNEC 2019) establishes a target for the incorporation of renewables for the 2030 horizon of 47% (31% in 2020), which implies 80% of the electricity production coming from renewable sources in that year, with a special focus on wind and solar photovoltaic energy (with expected installed capacities of 9.3 GW and 9 GW, respectively, in 2030) in distributed generation models. According to these targets, a great pressure is put on CEI projects, which are perceived as key to achieve national energy and climate commitments. Additionally, the environmental impacts of energy generation and supply activities (e.g., the visual aspect of power plants, renewables integration into building façades and roofs, the noise and vibration provoked, etc.) cannot be disregarded as it may trigger the so-called "not in my backyard" effect.

The second one, *to benefit participants, local communities, and the country,* aims to address the benefits created by CEI for participants, promoters, local communities, and the country and is mainly desired by policymakers and promoters/beneficiaries. This objective encompasses eight lower-level objectives. Three of these are more social in nature and concern: a) the creation of *energy and environment awareness and social acceptance*, with repercussions on the development of efficient energy use behaviors, the acceptance of renewables and the engagement into energy related activities; b) the *mitigation of situations of energy poverty and social exclusion*, through the promotion of collective actions and social involvement and the supply of renewable energy as well as energy efficiency services at cheaper prices, and; c) the *contribution to local development*, through the reinvestment of collective profits in communal facilities. The remaining means-objectives concern the economic and technological influence of CEI on the: d) participants' *access to renewable and cheaper energy* as well as *energy bill reduction* due to self-consumption and surpluses sharing; e) countries' *energy dependence and trade balances*, namely in minimizing imports and maximizing exports of energy and equipment; f) *local and national economic activity*, as the creation of new companies (and jobs) is expected, although a large portion of the activities to develop have a great automation component, which may translate into changes in employment/ unemployment rates; g) *national budgets*, which can be enhanced by, for example, minimizing the share of national subsidies allocated to reduce situations of energy vulnerability or to improve local infrastructures; and h) *qualification of human resources*, through the creation of highly qualified technical staff as well as new value streams (technologies and know-how), which can be used to leverage the countries technological potential.

The third fundamental objective raised by these two perspectives, *to ensure equity, openness, and fairness in collective energy systems,* translates the ambition of creating participative and fairer energy systems, in which consumers are empowered to partake in energy markets on an equal footing with other market participants. This objective encompasses four lower-level ones, namely: a) *access to better information fostering better decision-making* – the access to better and more disaggregated data is expected to trigger the adoption of more efficient energy usage behaviors in energy consumers (CEI participants or not); b) *access to new energy services and supply conditions* – CEI are expected to promote the exploitation of differentiated energy offers and services ranging from the supply of renewable energy generated locally to the aggregation of demand flexibility to be traded in energy and capacity markets, including energy efficiency and e-mobility services. In addition, new energy supply conditions are expected to emerge due to the emergence of community virtual power plants and community energy markets; c) *parity among players* – CEI promote parity between entities by, for example, empowering participants (usually small consumers) to access energy and flexibility markets, through aggregation, on an equal footing with larger entities; d) *fair tariff schemes* – as discussed previously, CEI are expected to impact power systems in different ways (increased distributed renewable injection, local demand and supply balancing, trading of local energy surpluses, etc.). These changes entail costs which cannot be disregarded: for example, the uncoordinated injection of surpluses into power grids can cause imbalances and damage grid assets, resulting in costs for power systems operators. In addition, many CEI projects are expected to operate as grid-connected, which means that public networks will be used for local energy exchanges. In both situations, new remuneration schemesmust be designed so that CEI are fairly charged for the infrastructures used and potential problems caused at the same time as the other stakeholders are not penalized.

When the policymaking and the techno-economic perspectives are analyzed together, a fourth fundamental objective emerged: *to guarantee the economic sustainability and the feasibility of collective energy systems*. This objective, raised by promoters and investors, is key as projects' economic feasibility stimulates the continuous involvement of stakeholders and economic entities. This objective encompasses five lower-level ones, namely: a) *return on investment/profitability* – it concerns the maximization of revenues reached from selling surpluses, energy supply, energy efficiency, e-mobility or demand flexibility services and the minimization of costs, e.g., electricity bills, operational costs, etc.; b) *investment requirements* - it concerns the minimization of investment and the debt burden. At the community level, the initial up-front investment is shared among the involved members, removing the investment barrier. Partnerships, bulk purchases (of technology or energy), incentives for small and micro energy generation units and tax reduction policies can also be options to smooth the economic requirements associated with these projects; c) *readiness of the involved entities* – it concerns the gap between the real performance of entities (especially consumers) and what is expected from them. CEI require participants and power system operators to play roles for which they are currently not fully prepared and, therefore, discrepancies between achieved and expected results may occur; d) *technologies easiness to use* - many of the decisions to be made in this context (e.g., self-consume, trade surpluses, store self-generated energy in batteries) require the usage of enabling devices (e.g. smart meters, energy management systems) that must be easy to use by LEC members; e) *legal and administrative barriers* – governments must ensure that "*unjustified regulatory and administrative barriers to renewable energy communities are removed*" (EC 2019a), meaning that the institutions that grant the required permissions, licenses and economic resources for the pursuit of these projects must ensure that these processes take off easily and quickly as possible.

The techno-economic perspective raises a fifth fundamental objective: *to modernize and endow power systems' infrastructures with new capabilities.* This objective covers the infrastructural changes which are necessary for the full exploitation of the activities to be performed in collective energy settings and is mostly desired by power system operators and technology providers, who want to increase the efficiency and "smartness" of operations. It comprises several lower-level objectives, namely: a) *online management of data* – it refers to the access of real-time generation and demand data, which is required to balance local demand and supply as efficiently as possible. The amount of data generated requires the automation of decision-making processes and raises data privacy concerns; b) *integration of higher shares of distributed renewable generation* and *exploitation of storage assets* – CEI are expected to be mainly supported by distributed renewable technologies whose energy is used to enhance self-consumption and promote local self-sufficiency. Storage devices (e.g. home and electric vehicles batteries) are also beginning to raise the interest of CEI members who aim to maximize the use of self-generated energy and increase self-consumption rates; c) *managing and monitoring network assets remotely* – the modernization of power systems through the addition of ICT enables operators, among other things, to manage power systems assets (e.g. lines, generators, transformers) and act preventively, avoiding problems and failures, and reducing overall costs; d) *reduction of local grid congestion and technical losses* – it translates the efficiency with which energy flows are transmitted from generation to consumption points. The local management of the self-generated energy and the sharing of surpluses within CEI boundaries is expected to reduce congestion in local distribution lines, decreasing technical losses; e) *exploitation of novel value streams and storage assets* – the diffusion of decentralized energy generation and consumption settings encourages the emergence of new entities and the exploitation of added-value energy services and offers as well as the further exploitation of demand-side management strategies and storage assets, which are able to provide extra sources of demand flexibility; and f) *reinforcement of ICT and metering networks* – it is a key condition to allow the activities announced by the European directives for CEI to be fully implemented and exploited. So far, in Portugal, the rollout of smart meters is still falling behind. It was expected that by the end of 2020, 80% of Portuguese households would have smart meters, and by 2022 the smart metering rollout would be completed. However, according to estimates from the distribution network operator E-Redes (https://www.e-redes.pt), the entity responsible for the rollout of the smart metering network, by the end of 2022, only 4 million of households are equipped with a smart metering equipment and the rollout should by fully completed by 2024. Therefore, there is still a long way to go in creating the essential technical conditions for the implementation of collective energy systems in the country.

By investigating the techno-economic and the self-sufficiency perspectives, a last fundamental objective was retrieved: *to ensure local security of supply*. This objective is a key concern in collective energy models, especially in those running in off-grid modes, for promoters/ beneficiaries and power system operators. One of the basic premises of CEI is that the local generation capacity (installed in participants' facilities or nearby) must be able to supply, fully orpartially, the local energy needs, reducing the dependence of external energy suppliers and reaching the so-desired energy self-sufficiency. This objective involves three lower-level ones: a)the *efficient utilization of energy resources* – it refers to the maximization of the usage of the self- generated energy through the exploitation of demand-side management strategies, including storage devices, as well as by sharing energy surpluses within the collective project; b) *self- sufficiency and control* – these objectives are related with the systems' capability of being able to run without resorting to external energy suppliers (which depends on the optimal management of the self-generated energy); c) *reliability and quality of the service* – it refers to the quality of supply and the risk of supply due to renewable intermittency or poor management of local self- generated energy resources. Storage devices, dispatchable fossil-fueled generation technologies (permitted by the IEMD (EC 2019a)) or contracts with external energy providers to supply deficits can be used to ensure the security of local energy supply.

4.1.4. *CONCLUDING REMARKS*

A problem structuring methodological approach enriched by the participation of representatives of the main stakeholders, allowed to identify and structure a set of fundamental objectives translating the expectations these entities hold on regarding these new energy initiatives. The dialogue with these entities proved to be essential to clarify roles, expectation, and perspectives, to validate assumptions and to raise the debate on the need for different entities to be heard and considered in the design of policies on this topic. Indeed, the inclusion of the stakeholders' insights on the development of a socio-technical transition, as is the case of the diffusion of collective energy systems, should be at the center of policymaking, since these actors are the ones that most contribute to its success in the short and medium term.

The Portuguese stakeholders revealed high expectations regarding the benefits that CEI can have for the country, for consumers and for the modernization of the electricity system. They recognize CEI as a political and social commitment to allow for the achievement of national decarbonization and energy poverty targets. The sharing of the investment, the development of energy efficiency strategies including urban rehabilitation, the existence of large rooftop areas with sun exposure and the privileged situation of the country in terms of exposure to sunlight, the awareness of more participative consumers involved in the fight against climate change and energy poverty, are acknowledged opportunities for CEI in the Portuguese context. However, some barriers are identified by these entities as hinderers of the diffusion of CEI. The existence of "grey areas" and the lack of specificity of the current regulatory framework, the bureaucracy and complexity of licensing processes and the access to financing mechanisms, the difficulty in predicting the economic viability of community energy projects and the associated costs, the lack of definition regarding the sharing rules, the resistance to change of market agents and a market that is not very open to new business models are the main factors acknowledged by stakeholdersas barriers to the implementation of CEI projects in Portugal.

The vision of these entities can be optimistically biased due to the interest such stakeholders have on collective energy projects. As projects start to be implemented, these expectations may change. Also, although due to the scarcity of actual projects in the field at the time of this work, the perspectives of energy cooperatives and local entities (representing municipalities and energy agencies) were considered as a proxy for consumers' perspectives. However, citizens promoting such projects are expected to face several other barriers as they are not assumed to be energy experts and, therefore, the creation of a collective energy project from scratch is foreseen to raise additional difficulties. Thus, this analysis should be repeated periodically to assess how stakeholders' expectations change over time and understand the perspectives of citizens initiating these projects.

4.2. MODELING RESULTS

4.2.1. ENERGY TRANSACTIONS BETWEEN TWO COMMUNITY MEMBERS[i]

Overview

In energy communities, prosumers are one of the most important agents since they may share energy surplus generated by renewable energy sources with the grid and/or other end-users in the community (Zafar et al. 2018). To facilitate the consumption of locally generated energy, theprice at which prosumers sell electricity to the grid is generally lower than the price at which they buy electricity from the grid, which encourages prosumers to share energy surplus instead of selling it to the grid (Zhou et al. 2017). Thus, the exchange of energy between neighbors, who may be consumers or prosumers, is promoted and an income can be obtained from these peer- to-peer transactions. In this context, the neighborhood scale is relevant, and the flexibility of different community members must be considered to reduce the energy required from the grid and to minimize end-users' electricity costs.

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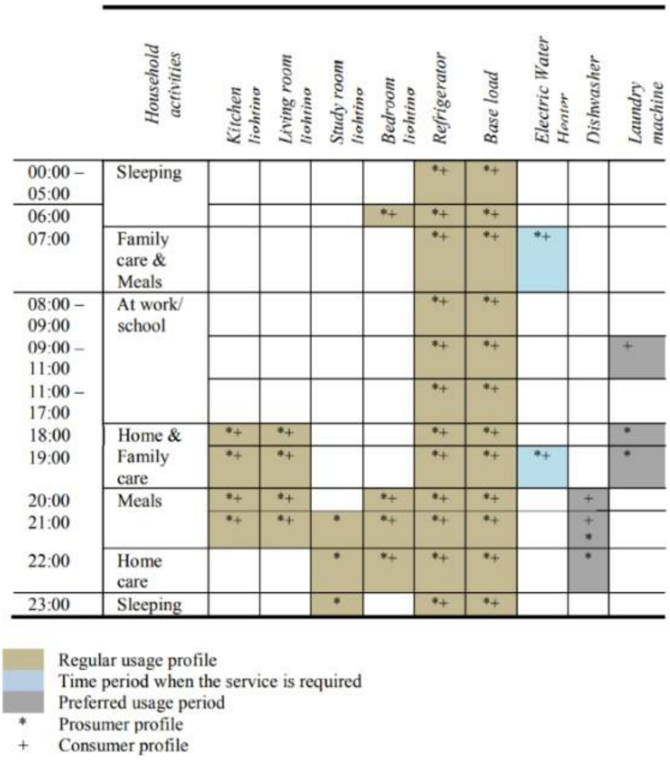
[i] Based on Research paper VII. Publication 4 builds on this work and proposes an ABM model to examine the effects of increased consumer participation within a local energy system by modeling a diverse set of agents and assess the effects of P2P trading on thefinancial outcomes as well as the share of renewable energy utilized within the local energy system.

This work presents the preliminary stages of a systemic approach aimed at to assess load management flexibility within an energy community with only two residential agents (a prosumer and a consumer). The prosumer agent has the capability to generate renewable energy through PV panels with maximum nominal power of 5kW peak. It is assumed that the PV generation curve depends essentially on the weather conditions. To model this component, three different weather states were considered: a sunny day, where maximum PV generation can be achieved; a partly cloudy day, where it is admitted that half the production available on a sunny day can be obtained, and a rainy day, where no generation is available. The prosumer micro-storage system consists of a 3kWh battery which charges when PV generation exists and discharges when loads should be supplied. Also, the storage system is assumed to be available to discharge when the grid price is higher than a price threshold established by the prosumer. If the stored energy is not sufficient to supply load operation, the prosumer must decide whether to accept the grid energy price (represented ad a five-tiered ToU tariff) or he can manage the loads in a favorable way, by shifting load operation (of the LM and the DW) to lower price periods. It is also assumed that these services will have to be satisfied within 36 hours regardless the electricity price (condition added to ensure that the household comfort is not affected and based on a typical weekly load usage). Regarding the EWH, the periods when hot water is needed are known and the equipment operation was optimized to run in periods of lower ToU prices that immediately precede the instant when hot water is required or when there is sufficient storage to supply it.

When there is a surplus of energy generated, the prosumer has the possibility to sell it, thus obtaining a financial income. It is assumed that the prosumer prefers to sell energy surplus to other community members instead of selling it to the grid, opting for the sale to the grid only if no neighbor shows interest in the purchase. Thus, in this situation, the prosumer agent sends a message to the neighbors informing them of the amount of energy he can provide and the price. If any of the neighbors accepts the deal, the P2P transaction takes place.

On the consumer agent side, the modeling is easier since only the loads and the decisions made regarding the electricity provider are considered. These decisions depend on the ToU tariff and the price that the prosumer offers (a fixed price of 0.10 €/kWh was considered). The consumer's flexibility regarding the prices that he/she is willing to accept is addressed through a parameter defining the price threshold. If the options are not fully satisfactory, the consumer is still able to time shift the operation of the clothes washing machine and/or the dishwasher usage. Agents' consumption profiles were created based on Lopes et al. (2016) and are presented in Table 15. In future approaches, given the increasing rate of adoption, the EV (as a load) should be integrated into the model, and the flexibility associated with it should be considered. These profiles are merely illustrative, and the model is flexible to accommodate other ones.

Table 15 Agents' loads profile.



	Household activities	Kitchen lighting	Living room lighting	Study room lighting	Bedroom lighting	Refrigerator	Base load	Electric Water Heater	Dishwasher	Laundry machine
00:00 – 05:00	Sleeping					🟫 *+	🟫 *+			
06:00					🟫 *+	🟫 *+	🟫 *+			
07:00	Family care & Meals					🟫 *+	🟫 *+	🟦 *+		
08:00 – 09:00	At work/ school					🟫 *+	🟫 *+			
09:00 – 11:00						🟫 *+	🟫 *+			▨ +
11:00 – 17:00						🟫 *+	🟫 *+			
18:00	Home & Family care	🟫 *+	🟫 *+			🟫 *+	🟫 *+			▨ *
19:00		🟫 *+	🟫 *+			🟫 *+	🟫 *+	🟦 *+		▨ *
20:00	Meals	🟫 *+	🟫 *+		🟫 *+	🟫 *+	🟫 *+		▨ +	
21:00		🟫 *+	🟫 *+	🟫 *	🟫 *+	🟫 *+	🟫 *+		▨ + *	
22:00	Home care			🟫 *	🟫 *+	🟫 *+	🟫 *+		▨ *	
23:00	Sleeping			🟫 *		🟫 *+	🟫 *+			

🟫 Regular usage profile
🟦 Time period when the service is required
▨ Preferred usage period
* Prosumer profile
\+ Consumer profile

Results and discussion

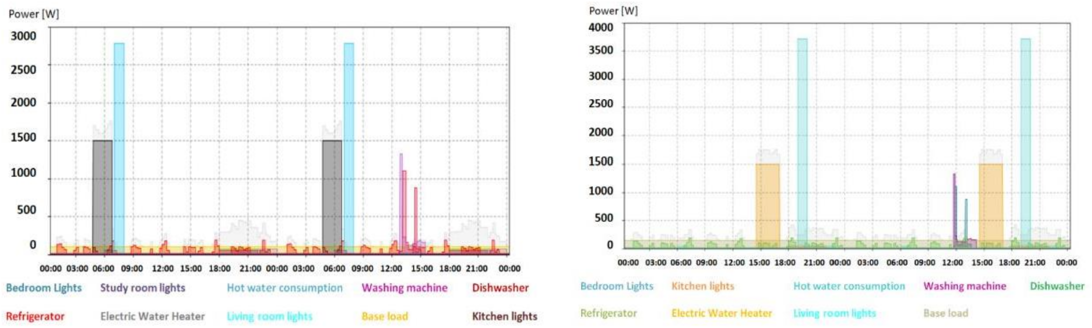
Considering the variations of the two parameters that directly influence the agents' behavior (price and PV/stored energy availability), three scenarios were created (summarized in Table 16). In Scenario A, where an initial situation without any energy stored and without PV generation (rainy weather) were considered, agents can be more sensitive to changes in grid electricity price as they are dependent on it to supply their loads. To assess the effect of grid price sensitiveness,distinct price responsiveness degrees (responsive, i.e., is not willing to accept high grid prices, and unresponsive, i.e., is willing to accept high grid prices) were simulated for both agents. Scenario B refers to a situation of cloudy weather (half of the peak PV generation available) in which different initial states were considered regarding the amount of energy stored (no stored energy and half of the storage capacity). In this scenario, it is assumed that the prosumer agent is unresponsive to the grid energy price fluctuation while the consumer agent is responsive to grid prices and aims to maximize the purchase of energy from the prosumer agent. Finally, in Scenario C, no energy stored is available at the beginning of the simulation, but the sunny weather conditions (full PV generation) allow for exploiting energy sharing between agents.

Table 16 Summary of tested scenarios.

	Weather conditions			Prosumer agent price sensitivity		Consumer agent price sensitivity		Initial stored energy	
Scenario	Rainy	Cloudy	Sunny	Responsive	Non-responsive	Responsive	Non-responsive	Yes	No
A	X			X	X	X	X		X
B		X			X	X		X	X
C			X		X	X			X

RESULTS OF SCENARIO A

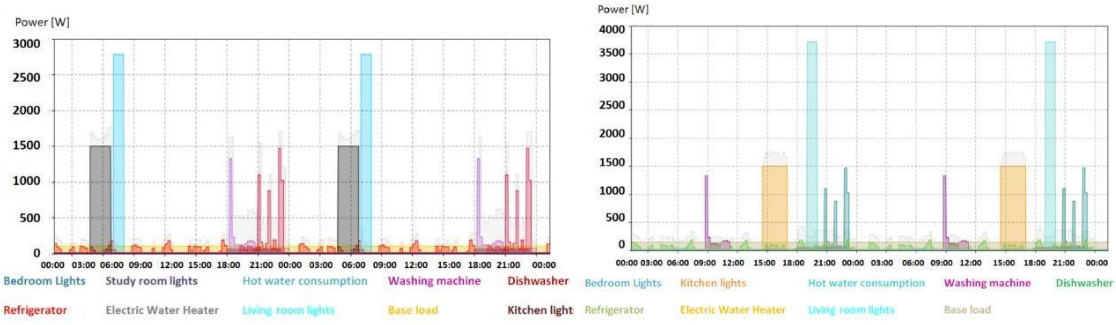
Regarding Scenario A, when faced with no PV generation and no energy stored, being grid price responsive, the prosumer agent must use the grid to supply the non-shiftable loads (lighting, refrigerator, base load and water heating) so that comfort requirements are not compromised but the loads whose operation can be time shifted (DW and LM) are delayed until the price threshold is satisfied. If this condition is not fulfilled during a maximum period of 36 hours, the loads are operated independently of the price, which is the case displayed in Fig.30. Regarding water heating, the period in which this service is required, and the energy needed (shown in light blue bars) are known. However, the EWH can operate in earlier periods with lower prices, ensuring that the service is satisfied when required. In the case of the prosumer, it takes 8-time steps of 15-minutes to heat the amount of water required (shown in grey bars). Similar conditions have been specified for the consumer, so the results are similar. In this case, higher hot water consumption is considered; therefore, 10-time steps were necessary to provide the amount of hot water required. In turn, under the same weather conditions, if agents are unresponsive to grid price, shiftable loads are started according to the initial schedule reflecting the prosumer's time slots and the consumer's preferences for load operation (Fig.31).



a) Consumption profile for a price responsive prosumer agent.

b) Consumption profile for a price responsive consumer agent.

Fig. 30 Results of scenario A for price responsive agents.



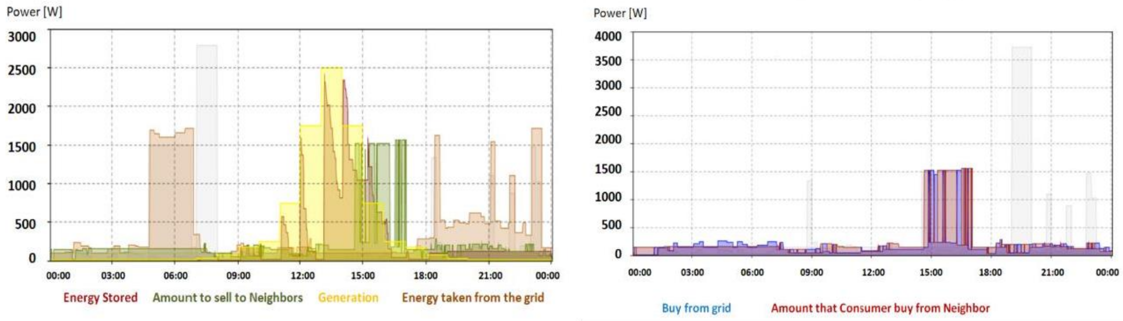
a) Consumption profile for a price unresponsive prosumer agent.

b) Consumption profile for a price unresponsive consumer agent.

Fig. 31 Results of scenario A for price unresponsive agents.

RESULTS OF SCENARIO B

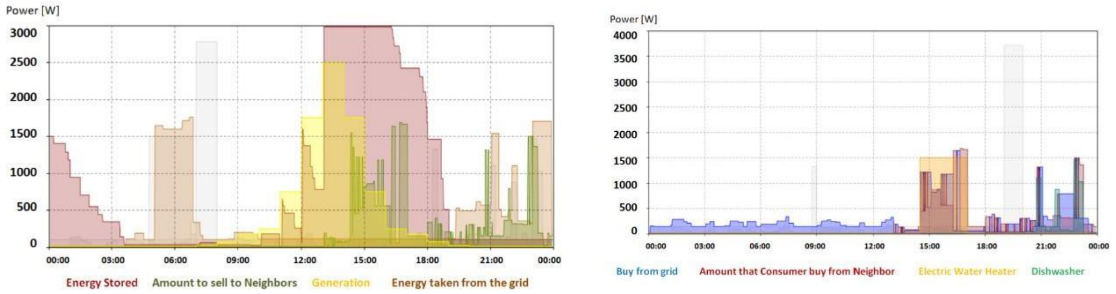
In cloudy weather conditions, only half of the potential PV generation is reached. However, since in the period of highest generation the prosumer agent consumption is low, it allows part of the energy to be stored and the remaining part to be provided to the neighbor. By being grid price unresponsive (accepting the grid price), prosumer's shiftable loads are supplied at the preferred time slots since in that period the energy stored is not sufficient to supply these loads (Fig.32). In turn, by being responsive to grid price, the consumer agent is not able to start shiftable loads at its preferred time slots. However, by accepting the price offered by the neighbor (prosumer), the consumer agent can buy enough energy for the EWH operation. Starting from an initial condition with half of the storage capacity, the energy available for the prosumer agent to sell is higher than in the previous simulation (no stored energy was available at the beginning of the simulation period) (Fig.33a), which allows the consumer agent to purchase enough energy to connect the DW in the preferred time slot (Fig.33b).



a) Energy that the prosumer takes from the grid, store, produce and is available to sell to the consumer.

b) Energy that the consumer buys from the prosumer and from the grid.

Fig. 32 Results of scenario B for both agents when no storage is available at the initial stage.



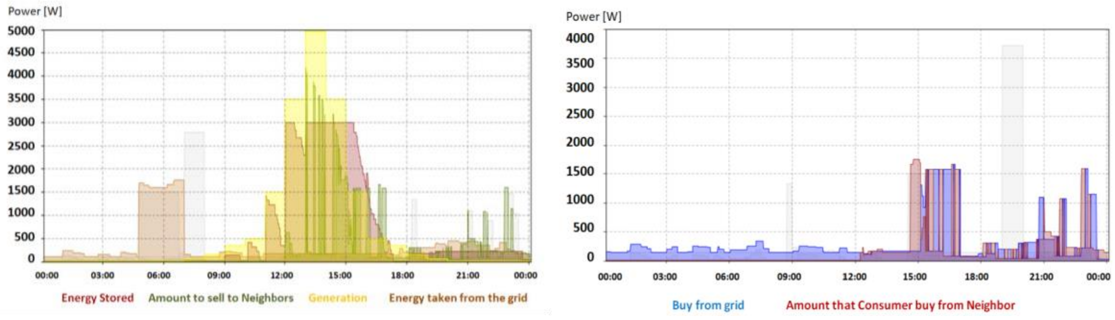
a) Energy that the prosumer takes from the grid, store, produce and is available to sell to the neighbor, starting with half of the storage capacity.

b) Energy that the consumer buys from the prosumer and from the grid when the prosumer has stored energy to sell.

Fig. 33 Results of scenario B for both agents starting with half of the available storage capacity.

RESULTS OF SCENARIO C

In a sunny day, starting from an initial situation with no stored energy, to supply the EWH the prosumer agent must accept the price conditions and buy energy from the grid (Fig. 34). However, once the PV generation begins to be available, the prosumer system starts to store energy and sends information to the consumer on the available amount of energy to trade. Attention is drawn to the fact that since the maximum storage capacity is below the PV generation peak, this surplus is also made available for sale; even in these conditions there is not sufficient stored energy to supply the prosumer's shiftable loads in the preferred time slots. The same happens with the consumer who cannot use the LM in the period specified. When checking whether the price offered by the grid is higher than the price offered by the prosumer, the consumer buys the energy it needs from its neighbor. Thus, most of the energy the consumer needs after this period are satisfied by the energy purchased from the prosumer.



a) Energy that the prosumer takes from the grid, store, generate and is available to sell to neighbors.

b) Energy that the consumer buys from prosumer and from the grid.

Fig. 34 Results of scenario C for both agents.

Concluding remarks

This work is a preliminary step in the exploration of P2P energy transactions between community members with distinct characteristics. Some simplifications and assumptions have been made to make models manageable, but this work revealed that the ABM approach is appropriate for addressing of the behavioral dimension associated with demand-side flexibility, presented in thismodel through the sensitivity to cost and loads usage preferences. This work also highlights the complexity of daily decisions in a context of dynamic prices which require automated support, and which should be considered in future developments.

4.2.2. *EXPLOITING RESIDENTIAL DEMAND-SIDE FLEXIBILITY IN ENERGY COMMUNITIES BY COMBINING OPTIMIZATION AND AGENT MODELING* [j]

Overview

Building on the conclusions of Case Study 1 regarding the complexity of managing daily decision making in a community environment in face of dynamic pricing signals, this work presents a morecomplex configuration in which a MAS approach is combined with GA to evaluate to what extent the demand-side flexibility of a set of prosumagers in a LEC can be exploited by considering individual cost and dissatisfaction minimization objectives to achieve collective self-sufficiency. A NSGA-II algorithm is implemented at community coordinator level to optimize the communal resources (minimize the energy costs of the overall community) and at the prosumager agents level to minimize cost and dissatisfaction objective functions.

As in the previous model, each agent is treated as an individual entity in the model since it has a specific consumption profile and individual goals to achieve. The loads of all prosumager agents comprise a base load and manageable loads (shiftable loads; TCL, and interruptible loads), modeled as explained in Chapter 3. Prosumager agents are differentiated by considering different household sizes implying different hot water

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[j] Based on Research paper VII. Publication 4 builds on this work and proposes an ABM model to examine the effects of increased consumer participation within a local energy system by modeling a diverse set of agents and assess the effects of P2P trading on the financial outcomes as well as the share of renewable energy utilized within the local energy system.

consumption profiles, number of operation cycles per week of shiftable loads and different heating and cooling needs (as explained in Chapter 3). Therefore, although these agents have the same type of appliances, their consumption profiles are distinct. Also, when prosumager agents are created, each one is assigned a greater or lesser sensitivity to cost and comfort which allows to classify agents as: 1) cost driven; 2) balanced and 3) comfort driven. These profiles are randomly distributed in equal proportions among the prosumer agents independently of the household size represented.

To simulate the operation of an automated decision support system, each prosumager agent wasassumed to be equipped with an AHEMS endowed with optimization algorithms aiming to schedule loads operation according to PV and storage availability and price signals. AHEMS (which in real settings can be implemented in a low-cost microprocessor) are responsible for deciding when to consume from self-generation or storage and how to schedule loads to obtain the best solutions for these agents. AHEMS are also assumed to be integrated into a system with communication properties as although they do not communicate directly with each other (among prosumagers), these systems are able to communicate with a coordinator agent that interfaces with the power grid and manages the community resources. The AHEMS of each prosumager sends to the coordinator agent information on the power it needs and cannot satisfy by means of its own resources and on surplus generation it cannot store in individual storage systems. When power is requested by prosumagers, the coordinator assigns community resources (generation or storage) if existing or, if there are not enough resources, buys the necessary power from the grid (represented through a passive agent[30] in the system). In turn, if there is surplus generation from prosumagers, this information is also passed on to the coordinator, which checks whether there is sufficient capacity in the communal storage system or sells it to the grid making profits from that sale. The costs of buying and selling energy to the grid are calculated by considering an eight-tiered ToU tariff inspired on the Iberian day-ahead wholesale market (to which the remaining tariff components were added). This tariff is presented to agents as the grid buying price (BP_t), whereas the remuneration paid for the injection into the grid (SP_t) was defined in this case study as 80% of the BP_t.

The optimizations are done for the day ahead (next 24 hours) with 1-minute discretization. The modeling was run for a period of one week (7 days - day 1 to 5 are working days and the last two days are the weekends) to exploit different social residential dynamics in summer and winter generation scenarios, covering working days and weekends.

Variation between simulations

This framework was exploited in two complementary works. In the first one (Research paper VIII), 100 prosumager agents co-inhabit the same community, and all have similar generation and storage characteristics. In addition to the individual resources, the community was assumed to own an extra PV system (175kW$_{peak}$) coupled to a static storage system of 210kWh (the capacity of a Tesla Powerpack system) and all prosumagers have installed a PV generation capacity of 10kW$_{peak}$ coupled with a static storage system with 6.4kWh of capacity. The modeled communityis assumed to be located at Coimbra, in the central region of Portugal, which affects the installed PV generation. The modeled community arrangement is displayed in Fig. 35a. In a second work (Research paper III), 100 residential agents including consumers

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[30] A passive agent is an entity which does not make any active decision in the model. Its role is considered as it is requested to keepmodeling coherence.

and prosumagers are assumed to co-exist in the same collective environment (Fig. 35b). The main difference between these agents is the existence of local generation, owned by prosumagers and not by consumers. However, it was assumed that all agents own storage systems independently of having generation systems or not. As in Research paper VIII, all prosumagers were assumed to own a 10 kWp PV system and all the agents own a 6.4 kWh capacity static battery. Also, a shared PV power plant coupled to a static battery with similar characteristics of the ones used in Research paper VIII were considered to provide additional energy resources to community members. Also, in this case, the collective resources are managed and distributed by a coordinator agent, which is also responsible for interfacing the grid. To assess how different shares of prosumagers/consumers would influence the community self-sufficiency, five scenarios were exploited (Table 17).

Table 17 Summary of tested scenarios.

Scenario	Weather conditions		Type and share of agents	
	Summer	Winter	Consumer	Prosumager
A	X	X	100%	-
B	X	X	75%	25%
C	X	X	50%	50%
D	X	X	25%	75%
E	X	X	-	100%

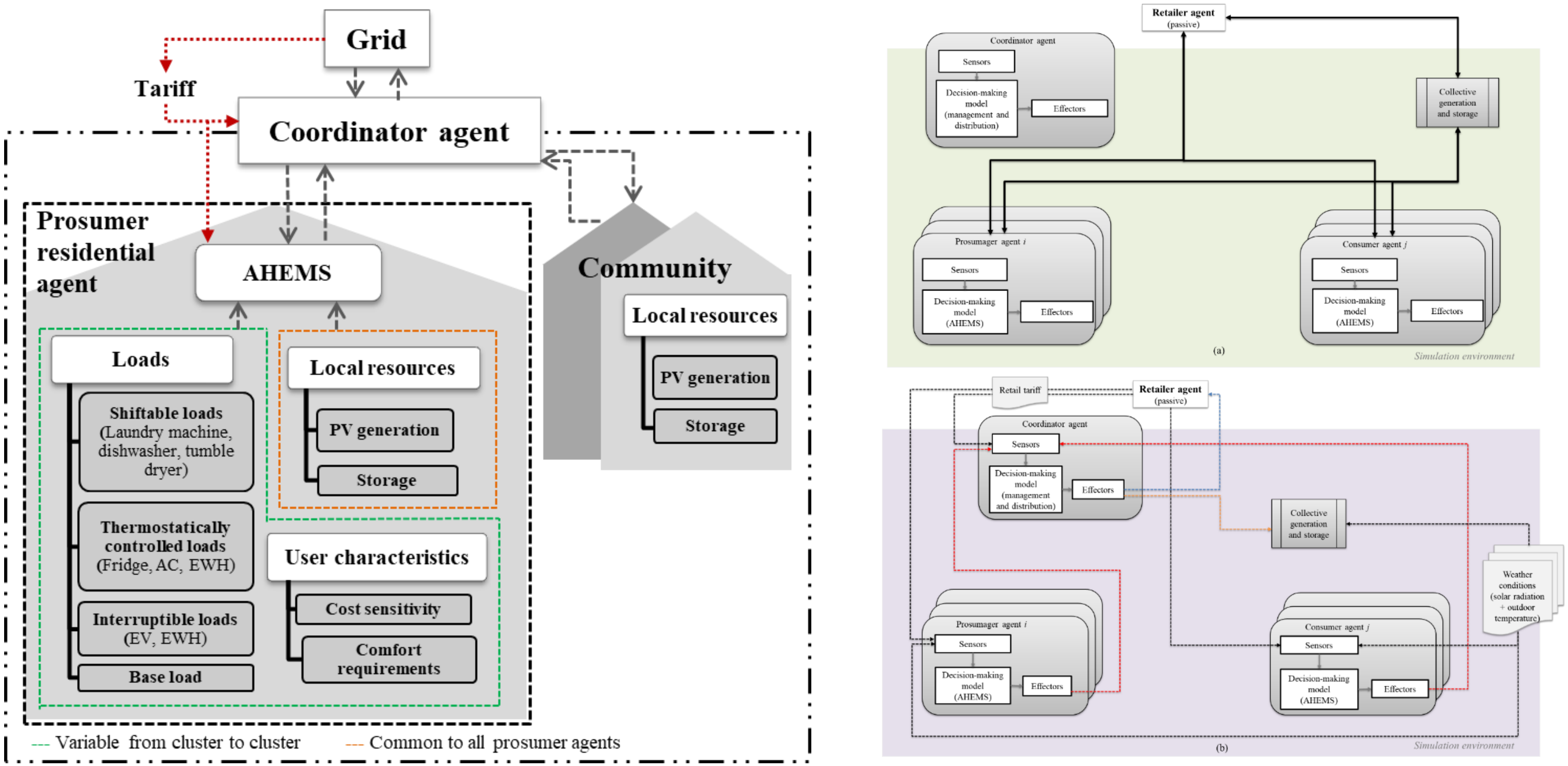
As the results of Research paper VIII and Scenario E of Research paper III are similar, only the results of Research paper III are fully presented and discussed in the next sections.

Results and discussion

RESIDENTIAL AGENTS' OPTIMIZATION RESULTS

The aggregated power profiles of all residential agents, in each sub-scenario and season, are shown in Fig. 36. These profiles are sent to the coordinator agent and highlight the periods of demand and availability for sale. Similar patterns of demand are found across scenarios:

- Demand peaks are concentrated in the lower ToU price periods, corresponding to night/dawn time, since the AHEMS, aiming to minimize costs, allocate the operation of shiftable loads, the charging of EV batteries, and part of the EWH operation to these periods.
- Energy can be bought in these periods for charging the static battery as well, since it can be economically beneficial to buy energy at a low price to store and consume it later to avoid high price periods.
- The greater or lesser presence of consumers vs. prosumagers does not change the demand patterns considerably. This occurs due to the nature of the loads considered and particularly to the agents' objective functions.
- Minimizing costs may not necessarily mean to maximize self-consumption. It may be advantageous to sell self-produced energy in periods of higher prices and to procure energy from the grid during lower price periods, even at the expense of some discomfort. Indeed, the periods of solar availability coincide with the higher tariff price periods. Thus, in these intervals, the AHEMS avoid buying energy from the retailer to satisfy the baseload and use the existing local resources for self-consumption (local generation andstorage). As these loads do not demand much energy, the AHEMS makes a share of these resources available for sale to increase the agents' income, which positively affects their objective of minimizing costs.

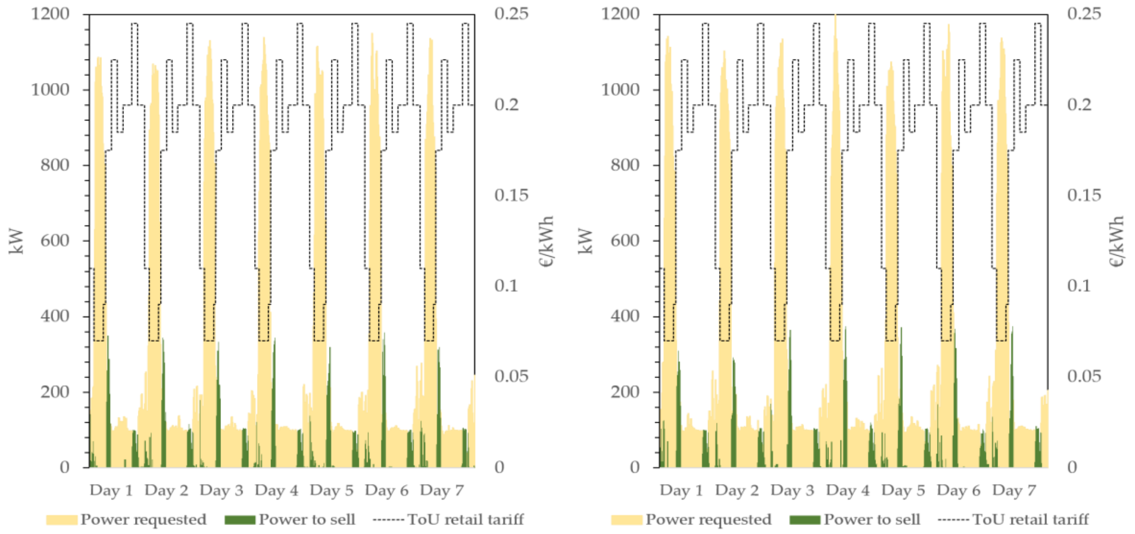


a) Research paper VIII

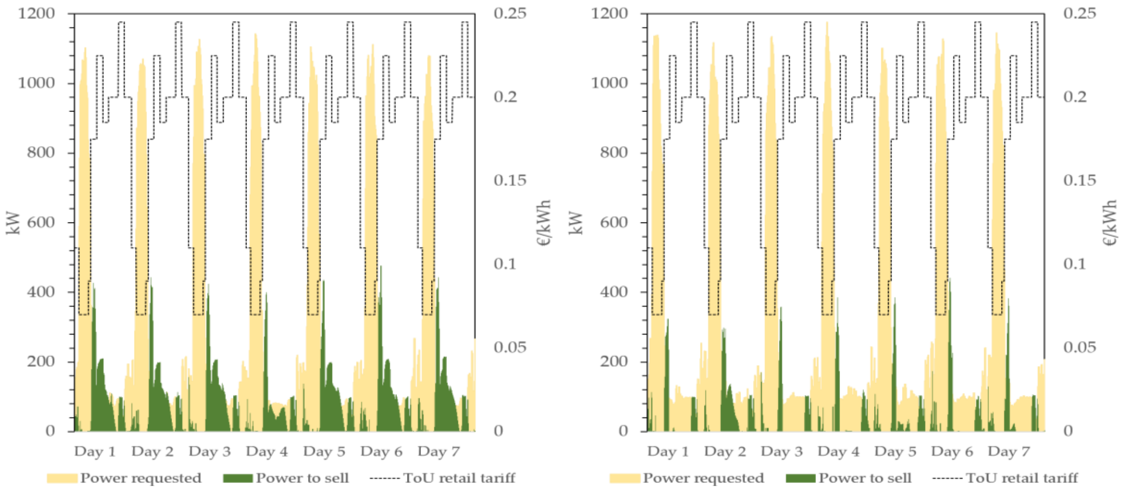
b) Research paper III

Fig. 35 Community arrangement in Research papers III and VIII. In the case of Research paper III representation, energy flows (a) and information flows (b) are highlighted. Black solid lines: energy flows; black dashed lines: input data from the environment; red dashed lines: individual optimization outputs; blue dashed line information on the remaining power requested and generation surplus; orange dashed line: information on how collective resources are used.

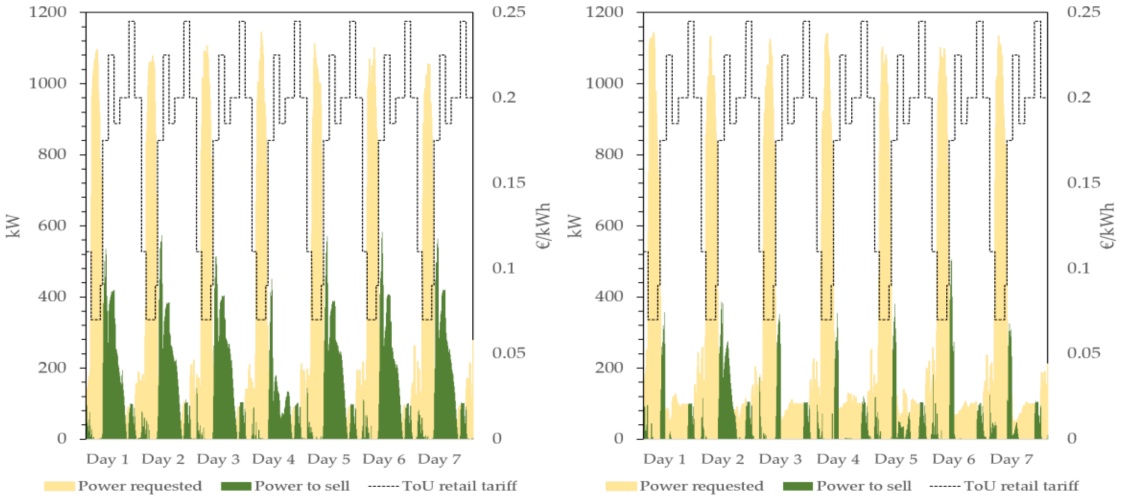
Between seasons, slight demand variations are seen amid scenarios, with a small demand reduction in the summer due to the increased availability of local resources allowing to enhance self-consumption. Additionally, in summer, the variation in outdoor temperatures leads to less energy being spent in space heating/cooling or water heating processes, which also slightly reduces energy demand. This amount of surplus generation in summer that is available for sale is higher than the corresponding one in winter. As expected, as more prosumagers are added tothe community, more energy is made available for sale. In scenario A, these resources include only the energy stored in consumers' static batteries, procured during lower ToU price periods, and offered for sale to maximize benefits, while in the remaining scenarios the surplus from local generation is also included.



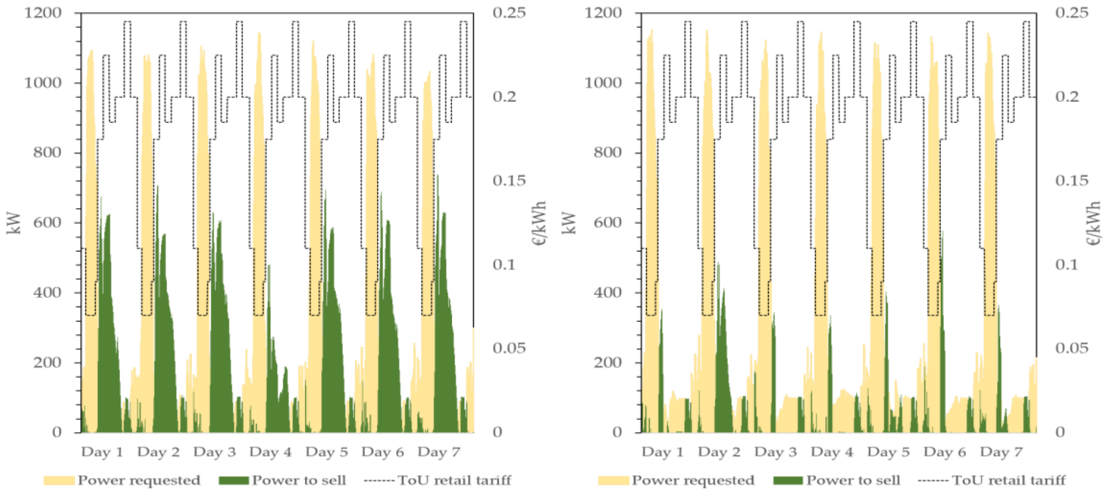
a) Scenario A



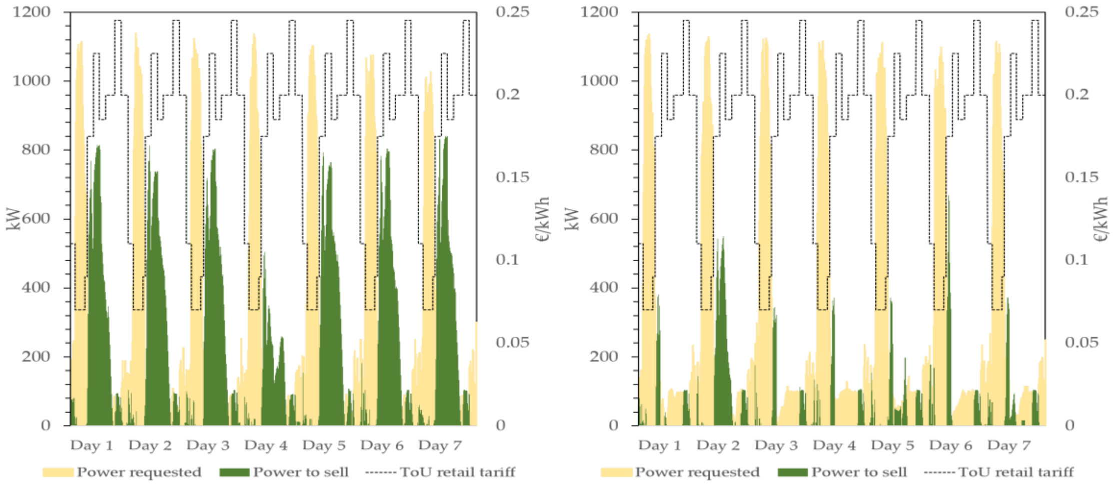
b) Scenario B



c) Scenario C



d) Scenario D



e) Scenario E

Fig. 36 Power requested and injected by residential agents in summer (left) and winter (right).

When the above results are broken down by agent, they unveil that the demand peaks, which derive from the sum of the individual demand profiles, depend mainly on the characteristics of the agents, the size of the household and their loads. Figure 37 displays the results for a balanced agent in the most extreme scenarios (A and E) in the first simulation day of the winter season. The trends regarding self-consumption and power available to sell are clearly presented and as expected, in scenario A only the stored energy is used for self-consumption and sale, while in scenario E more resources are available for those purposes. Therefore, scenario E is expected tobe the setting that brings the best economic results to community members.

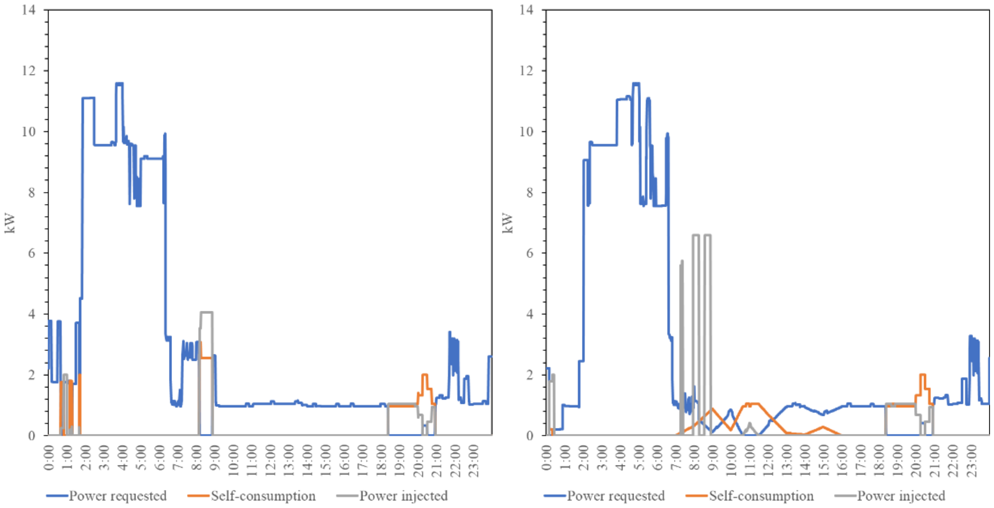


Fig. 37 Power requested, self-consumption and power available to sell by a balanced agent in Scenarios A (left) and E (right) during a winter simulation day.

COMMUNITY OPERATION AND SELF-SUFFICIENCY ACROSS SCENARIOS

The overall community performance derives from the decisions made by the coordinator agent optimization processes. Results are very similar to those shown in Figure 36. The community demand is concentrated in periods of the lower tariff price, to where the individual optimization processes allocate most of the load operation. These demand peaks correspond to periods with no renewable generation; thus, the coordinator agent allocates part of the energy stored in the collective storage system to smooth these peaks. Although these reductions are graphically undetectable, the examination of the results reveals that the distribution of community resources reduces the average demand for residential agents by about 15.5% in summer, while in winter the reduction is around 12.2%. These results may seem little impressive since much of the community's energy is sold while it could be allocated to residential agents. However, considering the way the cost minimization objective function is defined, it is more advantageous to let community members to buy energy from the retailer during the low-price periods (night/dawn) and distribute the collective energy resources during the higher price periods (during the day). This resource allocation is reflected in the predominance of self-consumed energy during these high price periods. As the cost minimization objective function also includes sales, the coordinator's algorithm decides on the sale of energy (from collective assets and surplus from residential agents) during periods of high prices (daytime).

Also, in communities characterized by a large incorporation of renewables, self-sufficiency can be assessed. There are several ways of determining self-sufficiency according to the goals initially defined for the community. In the scope of this work, as self-consumption also involves energy withdrawn from the grid to be kept in storage systems, the overall system energy self-sufficiency cannot be calculated directly. Instead, a generation/demand ratio is used and understood as a proxy for self-sufficiency, examining the relationship between local generation (including the energy sold to the grid and the one used for self-consumption) and demand (net power requested plus self-consumption), as displayed in

Eq. 29.

$$Self - sufficiency(\%) = \frac{Energy\ generated(kWh)}{Energy\ consumed\ (kWh)} \times 100 \tag{29}$$

The average results for each simulation week in each sub-scenario and season are shown in Fig. 38. As expected, the greater participation of prosumagers in the community model leads to more energy available for sale and self-consumption. Thus, there is an improvement in self-sufficiencyfrom scenarios with only consumers (A) to scenarios with more prosumagers (E). At the same time, the energy consumed is kept approximately constant, since the demand (the power requested) of consumers and prosumagers is similar. The only source of fluctuation in the utilization of generated energy is due to self-consumption, which gradually increases with the incorporation of prosumagers in the community.

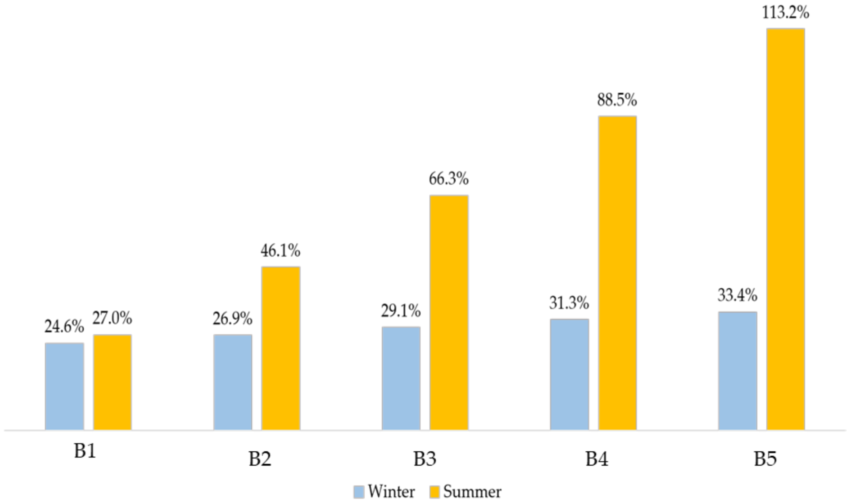


Fig. 38 Theoretical energy self-sufficiency across scenarios.

These results must be interpreted at the light of the definition of energy self-sufficiency presented above: a self-sufficiency above 100% does not necessarily mean that the LEC could be completely autonomous from the power grid since only the total amounts of locally generated and consumed energy are evaluated and not how the energy is being effectively used (sold, exchanged, wasted, etc.). An energy balance analysis that considers the relationship between the energy generated and consumed over the simulation time, considering losses and inefficiencies, would be essential to accurately determine the energy autonomy of this community.

As mentioned previously, the objective functions of both residential agents and the coordinator were defined based on one of the main motivations pointed out in the literature for end-users to participate in LEC projects - minimizing the energy bill. Since participants are supposed to finance generation and storage assets (individual and/or collective), it seems reasonable that they want to be economically compensated for their investment. As it can be seen from the results, these objectives are not directly aligned with the maximization of community self-sufficiency. On the one hand, reducing costs requires minimizing the power purchased from external entities, which actually happens, although with little expression. On the other hand, by including the selling component in the cost minimization objective function and with prices varying over time, the economic benefit from selling easily exceeds the demand reduction component. Thus, future work may favor the maximization of self-consumption at the level of the coordinator agent without the sale of surpluses.

COMFORT ASSESSMENT AND ECONOMIC BENEFITS

Regarding costs and dissatisfaction, depending on the agents' sensitivity, the individual optimization processes compute diversified solutions in the non-dominated front, i.e., with lower cost, lower dissatisfaction, or balanced solutions. The average costs obtained for each agent profile, in each scenario and season, are presented in Table 18 and the dissatisfaction results are displayed in Table 19. Average weekly costs and standard deviations of cost and dissatisfaction are also provided to facilitate the comparison of results. Results are displayed as heatmaps to facilitate the understanding and focus on the most relevant trends.

Table 18 Individual average costs [€]. Green: best cost; yellow/orange: average cost; red: worst cost; W: winter; S: summer.

		Scenario A		Scenario B		Scenario C		Scenario D		Scenario E	
	Day	W	S	W	S	W	S	W	S	W	S
Cost-driven	1	−4.8	−4.8	−4.2	2.7	−4.1	5.1	−4.1	5.1	−4.1 5.1	
	2	−4.9	−4.8	−1.2	2.6	0.1	5.2	0.3	5.0	0.6	5.0
	3	−4.8	−4.8	−4.4	2.7	−4.2	5.1	−4.2	5.1	−4.2	5.1
	4	−4.7	−4.8	−4.6	−0.8	−4.6	0.4	−4.6	0.4	−4.6	0.4
	5	−4.9	−4.9	−4.0	2.6	−3.7	5.1	−3.7	5.3	−3.7	5.0
	6	−4.9	−4.8	−3.9	2.6	−3.6	5.3	−3.6	5.3	−3.6	5.0
	7	−4.9	−4.4	−4.1	3.0	−3.6	5.4	−3.6	5.4	−3.6	5.4
Week average/		−4.8	−4.6	−3.8	2.4	−3.4	4.5	−3.4	4.5	−3.3	4.4
Std. dev.		0.1	0.2	1.2	0.7	1.6	1.8	1.6	1.8	1.8	1.8
Balanced	1	−5.6	−5.2	−5.5	−5.1	−5.2	−0.5	−4.7	4.3	−4.7	4.3
	2	−5.6	−5.0	−5.5	−5.1	−3.1	−0.6	−0.7	4.2	−0.7	4.2
	3	−5.5	−5.1	−5.5	−5.4	−5.2	−0.5	−4.9	4.3	−4.9	4.3
	4	−5.6	−5.6	−5.6	−5.3	−5.5	−2.9	−5.3	−0.3	−5.3	−0.3
	5	−5.7	−5.3	−5.6	−5.7	−5.2	−0.7	−4.3	4.2	−4.3	4.2
	6	−5.6	−5.5	−5.6	−5.5	−4.9	−0.5	−4.2	4.1	−4.2	4.1
	7	−5.6	−5.3	−5.6	−5.3	−5.1	−0.2	−4.4	4.6	−4.4	4.6
Week average/		−5.6	−5.3	−5.6	−5.3	−4.9	−0.8	−4.7	3.6	−4.1	3.6
Std. dev.		0.1	0.2	0.1	0.2	0.8	0.9	1.5	1.7	1.5	1.7
Comfort-driven	1	−6.8	−6.8	−6.8	−6.5	−6.3	−6.2	−6.6	−4.1	−5.9	3.1
	2	−6.6	−6.6	−6.6	−6.5	−6.6	−6.3	−5.3	−4.1	−1.7	3.0
	3	−6.5	−6.6	−6.5	−6.6	−6.5	−6.6	−6.4	−4.0	−5.9	3.3
	4	−6.8	−6.6	−6.7	−6.3	−6.8	−6.6	−6.7	−5.3	−6.6	−1.5
	5	−6.7	−6.8	−6.7	−6.5	−6.7	−6.5	−6.4	−4.1	−5.4	3.2
	6	−6.6	−6.6	−6.6	−6.6	−6.1	−6.6	−6.2	−4.0	−5.2	3.2
	7	−6.6	−6.5	−6.6	−6.5	−6.4	−6.5	−6.3	−3.9	−5.3	−3.4
Week average/		−6.7	−6.6	−6.6	−6.5	−6.5	−6.5	−6.3	−4.2	−5.1	1.6
Std. dev.		0.1	0.1	0.1	0.1	0.2	0.2	0.5	0.5	1.6	2.8

Table 19 Individual dissatisfaction results [-]. Green: best dissatisfaction; yellow/orange: average dissatisfaction; red: worst dissatisfaction; W: winter; S: summer.

		Scenario A		Scenario B		Scenario C		Scenario D		Scenario E	
	Day	W	S	W	S	W	S	W	S	W	S
Cost-driven	1	5.1	3.5	3.8	3.6	3.8	3.5	3.8	3.5	3.8	3.5
	2	9.9	6.1	7.1	5.1	3.2	4.0	3.2	4.0	3.2	4.0
	3	3.9	3.9	3.7	3.9	3.6	4.0	3.6	4.0	3.6	4.0
	4	5.0	5.6	3.9	4.9	3.8	3.8	3.8	3.8	3.8	3.8
	5	4.3	3.3	3.5	4.7	3.7	6.0	3.7	6.0	3.7	6.0
	6	3.8	14.7	4.0	9.6	4.1	10.4	4.1	12.4	4.1	10.4
	7	3.7	15.5	3.5	9.3	3.4	9.2	3.4	9.2	3.4	9.2
Week average/		5.1	7.5	4.2	5.9	3.7	5.8	3.7	6.1	3.7	5.8
Std. dev.		2.2	5.3	1.3	2.5	0.3	2.8	0.3	3.4	0.3	2.8

		Scenario A		Scenario B		Scenario C		Scenario D		Scenario E	
	Day	W	S	W	S	W	S	W	S	W	S
Balanced	1	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5
	2	1.4	1.5	1.4	1.5	1.4	1.5	1.4	1.5	1.4	1.5
	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	4	1.4	1.5	1.4	1.5	1.4	1.5	1.5	1.5	1.5	1.5
	5	1.4	1.3	1.4	1.3	1.5	1.4	1.5	1.4	1.5	1.4
	6	1.5	1.7	1.5	1.7	1.6	1.7	1.6	1.6	1.6	1.6
	7	1.5	2.0	1.5	2.0	1.5	2.1	1.4	2.2	1.4	2.2
Week average/		1.4	1.6	1.4	1.6	1.5	1.6	1.5	1.6	1.5	1.6
Std. dev.		0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.3	0.1	0.3
Comfort-driven	1	0.2	0.7	0.0	0.6	0.3	1.1	0.3	0.8	0.0	0.8
	2	0.1	0.7	0.2	0.6	0.3	1.0	0.3	0.8	0.1	0.8
	3	0.3	0.8	0.2	0.9	0.1	1.5	0.6	0.9	0.1	0.8
	4	0.3	0.7	0.1	0.8	0.7	0.7	0.6	0.9	0.1	0.7
	5	0.2	0.7	0.1	1.2	0.4	0.7	0.6	0.9	0.3	0.7
	6	0.1	0.9	0.4	1.0	0.4	0.1	0.4	0.1	0.3	1.1
	7	0.5	0.9	0.4	0.6	0.6	0.6	0.4	0.6	0.0	0.6
Week average/		0.2	0.7	0.7	0.8	0.4	0.8	0.5	0.7	0.1	0.8
Std. dev.		0.1	0.1	0.2	0.2	0.2	0.4	0.1	0.3	0.1	0.2

As expected, lower cost solutions are assigned to cost-driven agents, lower dissatisfaction solutions are associated with comfort-driven agents, and intermediate solutions are allocated to balanced agents. When residential agents perform their individual optimizations, they are not aware whether they will receive collective energy or not. Therefore, in addition to their own energy resources, they can only use energy purchased from and sold to the retailer. In scenario A, all solutions are translated into costs (shown with a negative sign) since as all the agents are consumers, the whole power needed to supply loads is procured from the grid, representing costs for the agents. For this reason, A is the scenario where the worst cost solutions for the residential agents are verified. Due to the lower availability of renewable generation in winter, also in scenarios B, C, D and E, solutions lead to costs that agents must bear. In summer, the situation is different. In B and C, cost-driven agents can reach benefits, whereas balanced and comfort-driven agents still have high costs, because of their lower comfort flexibility. In these scenarios, the amount of self-generated surplus made available for sale is still not enough for comfort-sensitive agents to enjoy benefits. In scenario D, all the agents can achieve benefits due to a greater share of energy made available for sale. Though, scenario E is the one displaying the best cost results as most agents have benefits from the sale of self-generated energy.

Regarding the comfort assessment, a closer look reveals very high values of dissatisfaction (quantified through a constructed indicator) in summer in the two last simulation days for cost- driven agents in all scenarios. These values are originated from the higher outdoor temperatures considered in the simulation of the AC operation (average temperatures of 26.4°C, compared to a mean value of 21.5°C in the remaining days). As the same AC equipment was considered to cope with the temperature variation and different dwelling areas were assumed, the system may not be able to keep the cooling needs within the desired limits, which gives rise to high levels of discomfort.

After the coordinator agent optimization, the average economic benefits for residential agents are revealed. The differences between the average costs calculated initially by the agents and after the distribution of collective resources by the coordinator agent show that, in all scenarios and seasons, there are benefits in belonging to a community with these characteristics. In addition to the demand reduction due to the distribution of collective energy, residential agents also profit from the distribution of the benefits obtained from the sale of collective surpluses to the retailer.

These benefits are equally shared among the residential agents and are included in the final cost estimates, which allows to reduce the agents' average costs or increase their expected benefits as shown in Table 20. The comfort-driven agents are the ones who benefit the most from being in the community, as they are also the ones that consume more energy and are charged with higher costs to maintain their comfort standards.

Table 20 Agents' cost variation after coordinator optimization [%]. Blue: average costs reduction; yellow: average benefits increase; W: winter; S: summer.

	Cost-Driven		Balanced		Comfort-Driven	
Season / Scenario	W	S	W	S	W	S
A	16.7	22.9	28.6	33.9	40.3	43.9
B	2.6	6.3	33.9	45.0	44.8	58.8
C	2.9	8.1	31.3	50.2	50.7	63.5
D	11.7	11.8	26.8	16.6	52.4	47.8
E	23.5	15.9	36.6	41.6	49.0	47.0

Concluding remarks

The previously discussed approach presented a MAS framework developed to reproduce the operation of a LEC formed by residential agents (consumers and prosumagers) willing to engage into DR actions to minimize energy costs while considering comfort requirements. By including optimization processes at two levels (residential agents and coordinator), the results show the optimal management of collective resources, according to the objectives defined for the LEC.

Each residential agent is analyzed individually as it represents an individual household with its own goals regarding cost and discomfort minimization and preferences regarding energy utilization. Depending on agents' goals, the benefits of belonging to the community can vary considerably. Comfort-driven agents proved to be the most benefited economically, especially in scenarios with the highest energy surplus available since the sharing of collective resources allows for them to maintain their comfort standards at a lower cost. As this result emerged as relevant in the scope of this work, future approaches should exploit different ways of sharing costs and revenues. This work considered that local collective resources are managed by a centralized agent which distribute them between agents, not considering their individual contribution in terms of demand and local injection. To ensure greater equity in the allocation of collective resources, prioritization rules can be further defined to penalize agents who consume more and provide fewer surplus resources.

Different settings were studied to assess to what extent agents playing the role of consumers and prosumagers influence the overall system self-sufficiency. As expected, the greater presence of prosumagers enhances the community self-sufficiency, as more energy resources are available. However, a detailed analysis of the energy balance over time is necessary to assess the real energy self-sufficiency of the community. In addition, future research should further exploit how different goals can be encompassed in LEC, since the participants' individual goals may not be directly aligned with the general goal of energy self-sufficiency. As demonstrated in this work, although cost minimization goals are usually the most relevant for residential users, they may conflict with self-sufficiency ambitions since, depending on the price schemes, selling self- generated energy may be economically more advantageous than self-consuming. Therefore, the regulatory framework of LEC and the energy markets must be able to prevent situations that promote injections into the grid for profit purposes at the expense of self-consumption, according to the non-profit nature of CEC and REC. In fact, this issue is quite relevant in the current context, *since the number of small on-site distributed energy generation initiatives is increasing with possible negative consequences for power systems stability. Hence, it is important assessing how far apart the individual objectives of community members are from the collective self-sufficiency goals, how LEC can be penalized for not managing efficiently their energy resources, and the extent to which these inefficiencies can disturb the operation of power systems.*

4.2.3. *THE EFFECT OF GRID PRICE SIGNALS IN ENERGY COMMUNITIES' OPTIMAL OPERATION* [K]

Overview

As price signals showed to be a key factor influencing the optimization processes being implemented, this case study aims to exploit to what extent a LEC operation is influenced by price signals encouraging and penalizing the injection of self-generated electricity according to the overall power system needs.

The general architecture of the MAS-based LEC model is depicted in Fig. 39. This LEC is composed by 30 prosumager agents (acting in their own interest), physically connected to the same medium/low-voltage transformer where a coordinator agent (acting in the collective interest) is located.

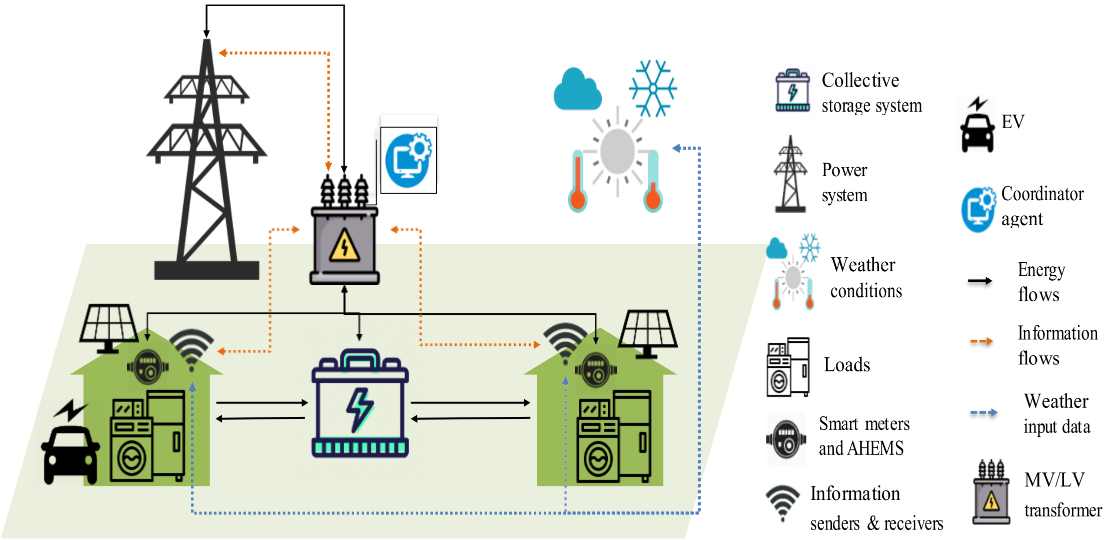


Fig. 39 Proposed LEC model.

As in the previous case study, each prosumager agent is assumed to be equipped with an AHEMS, which can control the residential loads and communicate with the coordinator agent, and optimization algorithms are embedded into these devices to help agents to manage their electricity resources (loads, generation, and storage). Prosumagers' surpluses may either be injected into the grid or stored in a collectively owned static battery with a capacity of 210 kWh. This asset is managed by the coordinator agent who, after receiving the profiles of all residentialagents and the price signals from the retailer agent (passive agent), decides whether the surplus electricity provided by the prosumager agents is stored or injected into the grid. The outputs of prosumagers' optimization are used as inputs by the coordinator agent, thus ensuring their preferences are not neglected during the coordinator decision processes. The decisions made by the coordinator consider that the injection of surpluses into the grid can be either:

- Incentivized - Scenario A;
- Not remunerated - Scenario B or
- Penalized - Scenario C.

[K] This section is based on Research paper X.

Prosumager agents' loads were modeled according to the methodology described in Chapter 3and the NSGA-II algorithm presented before was also used in this work. Price signals, whose objective is to trigger and align LEC members' behavior with the proper functioning of the electrical system (Yanine et al. 2019), are used to simulate the different scenarios. Thus, the eight-tiered ToU tariff, inspired on the Iberian day-ahead wholesale market is assumed as the grid buying price (BP_t), whereas the remuneration paid for the injection into the grid (SP_t) changes in each scenario. In scenario A, the injection of surpluses into the grid is encouraged and remunerated at a constant price of 0.035€/kWh (value defined in accordance with Article 27-D of the Portuguese Decree-Law 76/2019, which defines the tariff for selling electricity by small producers). In scenario B, it is assumed that surpluses can be either dissipated or injected into the grid but not remunerated (SP_t= 0€/kWh), meaning the surplus electricity is wasted and LEC members are not fully taking advantage of their investment. Finally, in scenario C, the injection of surpluses is penalized (SP_t = - 0,035€/kWh), meaning that LEC members must pay by the injection of poorly managed electricity surpluses. This scenario, which could be avoided by generation curtailment, is included to study some recent policies aimed at to penalize uncoordinated injection in low-voltage distribution networks.

Results and discussion

IMPACT ON LEC PERFORMANCE

Figure 40 depicts the overall LEC performance in the second simulation day of the different scenarios and in both seasons. Several conclusions can be drawn from it:

1. As discussed previously, the ToU tariff considered as the grid buying price biases the way residential loads are scheduled and trigger demand peaks in night/dawn periods;
2. Seasonality considerably influences the LEC performance as the predominance of self-generated electricity in the summer is noticeable (translated by the high rates of self-consumption and power available to inject into the grid) because of PV generation;
3. Despite being unpaid or penalized, part of the self-generated electricity continues to be made available for injection into the grid. As, due to the ToU tariff design, the residential optimization processes avoid PV generation periods (which correspond to more expensive periods) for the scheduling of loads, only a fraction of locally generated electricity is used to supply demand. Additionally, to simulate a realistic scenario in which people go out during the day to work/school, EV are only available at the end of the day/night. Thus, EV batteries are not available to directly store the self-produced electricity, limiting storage to the collective battery. The collective battery, in turn, may not have enough capacity to store all the electricity made available by LEC members, thus forcing waste or grid injection. If no generation curtailment options are considered and LEC members are not able to balance demand and generation effectively, they must bear the inefficiency costs.

Table 21 summarizes the overall electricity self-consumed, requested, and injected into the grid for the different scenarios and seasons.

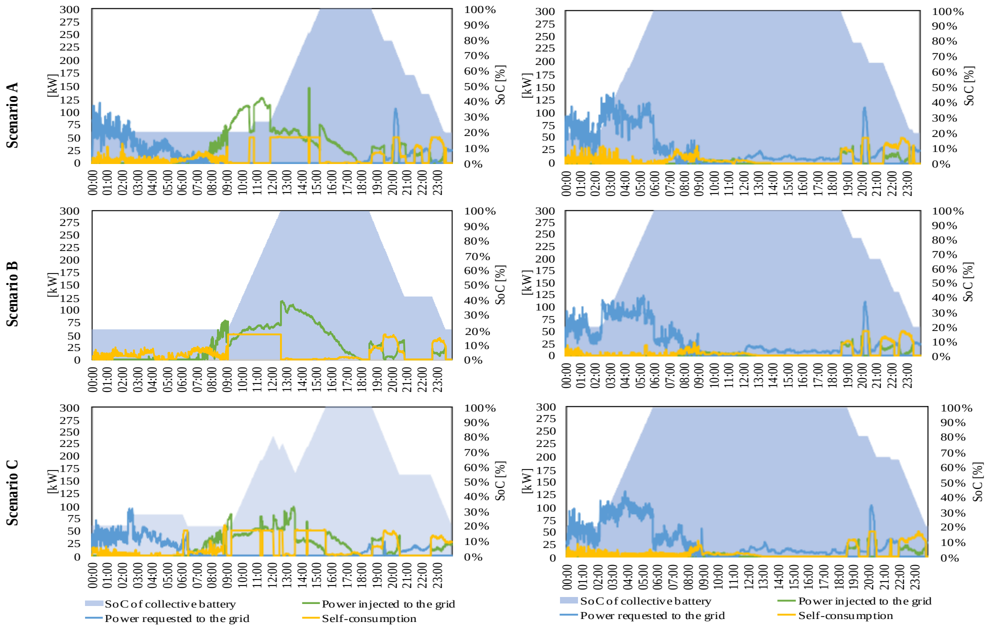


Fig. 40 Overall LEC performance across scenarios in the summer (left side) and winter (right side) seasons.

Table 21 Impact of scenarios on the LEC indicators. Legend: Sum: summer; Win: winter.

Scenario and season		Self-consumption (kWh/week)	Grid requests (kWh/week)	Injections into the grid (kWh/week)
A	Sum	2613.28	2740.32	3795.67
	Win	1825.38	5186.53	622.92
B	Sum	2706.76	2693.42	3440.54
	Win	1900.59	5112.14	487.59
C	Sum	3115.00	2632.27	2917.04
	Win	1986.64	5106.03	427.59

The non-remuneration (Scenario B) and penalization of surpluses injection (Scenario C) lead to lower amounts of power injected into the grid. Since it is disadvantageous in terms of costs to inject self-generated electricity into the grid, these resources are used to reduce the amounts of energy requested to the grid, increasing the self-consumption rates. The values are more expressive when the injection of surpluses is penalized (Scenario C), resulting in a weekly increase in self-consumption of 19.20% and 8.83% in the summer and winter, respectively. In this scenario, the weekly injection of electricity into the grid is also reduced by approximately 17.88% in summer and 31.40% in winter. These results reveal that there is still room for exploring strategies encouraging self-consumption, providing insights on how optimal penalization schemes can be developed by network operators by revealing how LEC behave vis-a-vis these signals. Also, these results provide valuable hints for LEC managers, helping them to anticipate possible scenarios and encouraging them to make better decisions (e.g., the self-generated electricity surplus injected into the grid can be curtailed by adding extra storage capacity).

IMPACT ON PARTICIPANTS’ OUTCOMES

Regarding the average daily costs and dissatisfaction, Tables 22 and 23 present the results achieved discretized by agent type. Comfort-oriented agents are charged with higher costs in all scenarios (average of 3.72 €/day in summer and 5.22 €/day in winter per agent) but achieve better (lower) dissatisfaction results. In turn, cost-oriented agents are benefited with lower cost solutions (average of

2.11 €/day in summer and 3.10 €/day in winter) at the expense of higher dissatisfaction results. The influence of restrictions on the injection of generation surpluses is noticeable in the worsening of the costs results across scenarios.

Table 22 Average daily costs (€/day) by agent. Legend: M: Mean; SD: Standard deviation; Sum: summer; Win: winter.

		Cost-oriented		Balanced		Comfort-oriented	
Scenario and season		M	SD*	M	SD	M	SD
A	Sum	1.46	0.97	1.81	1.06	2.65	1.39
	Win	2.91	0.92	3.55	1.04	4.95	1.93
B	Sum	2.10	0.70	2.50	0.78	3.45	1.17
	Win	3.18	0.76	3.67	1.05	4.97	1.87
C	Sum	2.78	0.68	3.25	0.84	5.02	1.86
	Win	3.21	0.65	3.80	0.90	5.73	2.06

*The standard deviation translates the household size variability within the set of agents with the same sensitivity to cost and comfort.

Table 23 Average dissatisfaction (-) by agent**. Legend: M: Mean; SD: Standard deviation; Sum: summer; Win:winter.

		Cost-oriented		Balanced		Comfort-oriented	
Scenario and season		M	SD	M	SD	M	SD
A	Sum	2.71	0.97	0.86	1.06	0.14	1.39
	Win	2.87	0.92	1.58	1.03	0.12	1.92
B	Sum	2.90	0.69	0.80	0.78	0.14	1.17
	Win	2.61	0.75	1.86	1.05	0.11	1.87
C	Sum	2.85	0.68	0.69	0.84	0.13	1.88
	Win	2.91	0.65	1.28	0.90	0.12	2.06

** Note: Dissatisfaction is an artificial measure that translates the deviations between the preferences expressed by agents and the results computed by the optimization process.

Between the extreme scenarios (A and C), agents costs get worse, especially in summer. This happens since the available storage and the reduced demand during generation availability periods are not enough to absorb the existing PV generation, forcing the injection of surpluses into the grid and the payment of penalties.

Concluding remarks

The results showed that the LEC adjust its operation in face of the grid changing conditions, which have been modeled through price signals, by reducing the total amounts of power injected and increasing the total amount of power self-consumed. These outcomes unveil relevant clues both for the design of future grid-connected LEC and network operators. In scenarios of non- remuneration or penalty of the electricity injected into the grid, LEC must be able to curtail surplus generation, either by changing consumption patterns (changing individual cost minimization goals to self-consumption maximization goals and including non-generating members) and increasing the local installed storage capacity. In turn, network operators should be able to send dynamic pricing signals, encouraging or penalizing generation injection into the network, according to the system needs. Additionally, hints can be drawn for the design of customized tariff schemes and incentive programs for LEC, which must consider both the state of the network and the characteristics of demand. In this model, perfect forecast assumptions are made regarding loads, generation, and electricity prices. In future work, robust optimization approaches will be developed to model the uncertainty in parameters, ensuring that community members achieve satisfactory results for a range of plausible scenarios.

4.2.4. *INCLUDING NON-RESIDENTIAL ENTITIES IN LEC MODELING*[l]

Overview

To further expand the model and bring it closer to a realistic setting in which commercial and cross-sectoral activities may also be included in LEC at the same time as different and complementary demand-side flexibility profiles are exploited, the modeling process was adapted to accommodate residential and non-residential agents assumed to be geographically located nearby and sharing the collective goal of generating, consuming, and selling renewable energy resources to maximize the community self-sufficiency.

In this work, the proposed community includes 100 residential agents, three SMEs (represented by a primary school, an office building, and a restaurant), two cross-sectoral activities (street lighting and public EV charging services), a coordinator agent, and a (passive) retailer agent. The SMEs were selected due to their common integration in residential environments. Also, to provide a realistic character to the simulated community, the chosen cross-sectoral activities can offer energy services to the community whereas the coordinator entity is considered to facilitate the management and distribution of the community energy resources, while keeping record of the financial and electricity transactions and interface with the power grid.

A 175kW$_p$ community PV system coupled to a 210kWh capacity battery is considered. Residential prosumager agents have also individual 10kW$_p$ PV systems coupled to 6.4kWh storage devices. The agents' architecture (technical, decision-making – including optimization – and communication modules) is similar to the ones already presented and described in Chapter 3.

The overall community MAS operation is described as follows. Residential agents receive inputs on electricity retail prices and weather conditions. Based on this information and specific characteristics pertaining to end-users' behavior modeling (such as sensitivity to electricity prices), residential agents decide on how they operate their loads. Thus, information on the remaining power needed to supply their loads and/or their generation surplus is transmitted to the coordinator agent alongside with the expected power requested by SMEs and-cross-sectoral activities. The coordinator agent also receives information on prices and weather conditions. Considering the information received from all community members, the retail prices, and the existing community resources (from the PV generation and storage), the coordinator agent decides how much collective energy is distributed among members and how much is sold to or required from the retailer. Figure 41 displays the proposed community MAS framework.

For the coordinator agent, the collective PV system and static storage system, owned by all community members, are assets to be directly managed and the energy generated and stored in those assets needs to be fairly distributed by all members. External data on weather conditions is transmitted to the coordinator agent, which uses this information to predict how much collective energy resources are available. PV generation data is communicated to the coordinator agent alongside data on retail pricing, the requested power from non-residential end-users and cross-sectoral activities, as well as the remaining power needed from residential agents and their available surplus generation. Optimization processes were embedded on the coordinator decision center to decide on how community resources should be

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[l] This section is based on Research paper I.

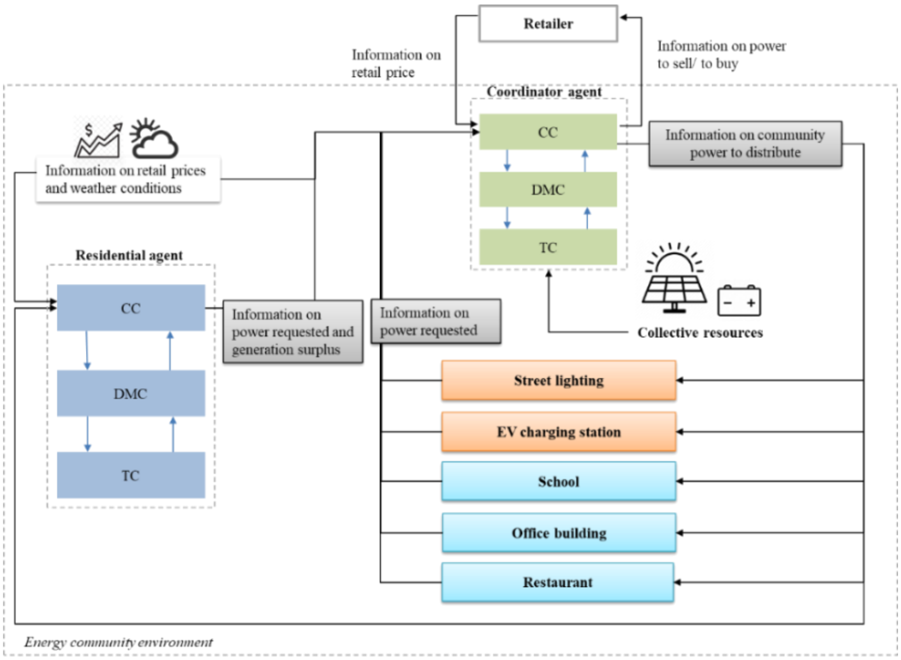

Fig. 41 Overview of the proposed community MAS framework.

distributed to minimize the overall power requested to the grid (and therefore, maximize community's self-sufficiency). At this level, the problem to be solved is a cost minimization problem representing the minimization of the power demanded to the grid, which requires using first the locally generated resources and only then buying the remaining power needed from the power grid. Thus, the algorithm determines when to store, sell to or buy electricity from the grid and how to use the energy stored depending on external energy price signals received from the retailer agent. For SMEs, demand data retrieved from the U.S.A. Department of Energy (DoE) public database[31] were used.

Consumption profiles for typified commercial buildings were obtained by processing data collected from national surveys and through building dynamic simulations. Based on this information, lighting, ventilation, space heating and cooling as well as appliance hourly consumption profiles were derived. The most similar profiles to the Portuguese context regarding building size and weather conditions were selected.

As stated previously, designing adequate demand management strategies to exploit the potential flexibility of SMEs is a challenging task since it implies a comprehensive knowledge about buildings and equipment characteristics, occupation profiles, etc., only achievable with detailed energy audits. As comprehensive information on SMEs was not available, a more conservative approach was adopted based on load reduction levels. As in the proposed community model, SMEs do not generate energy resources, they were assumed to be willing to adopt load reduction measures (e.g., by resetting temperatures of TCL, shedding non-critical loads as lighting and standby appliances, etc.) to contribute to reduce the overall community demand. The reduction levels are based on flexibility levels advised by Ofgem (2012), which considers the organizational, technical, and behavioral constraints regarding each

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[31] Available on https://openei.org/datasets/files/961/pub/

type of energy use and activity performed. The rationale behind the considered load reduction levels is as follows:

- Lighting and appliances are especially sensitive to control actions. Without the detailed characterization of a specific building lighting needs, any interference can compromise the activities performed. SMEs loads also comprise appliances used in food refrigeration/freezing, which are also considered sensitive due to food quality and safety reasons. Hence, no reduction to these loads has been considered;
- Space heating and cooling directly influence the users' thermal comfort and the activities performed. However, conditioned spaces offer some thermal inertia and, thus, a load reduction of 10% was admitted;
- Ventilation is a more flexible load in the sense that none of the activities performed in buildings are directly compromised if load control is performed. Therefore, a reduction of 20% was considered.

The power demand profiles that the coordinator agent receives from SMEs are already adapted according to the load reduction levels considered above.

For the public lighting service, the electricity demand needed to lighten a residential area with the size of this community was estimated considering the best lighting techniques available and requirements defined by RNAE et al., (2018). Some flexibility can also be assumed for the street lighting service by implementing light-on-demand techniques. To reduce the overall demand, controllable dimmers are assumed to exist on street lighting stations to limit consumption by applying a dimming profile. Therefore, the coordinator agent only receives the street lighting demand profile after the dimming profile limitation is already implemented.

The charging station simulation has a different nature since the EV arrival is random during the planning period. An average daily number of 25 EVs charging was defined and the most likely timeframe for arrivals was settled between 9 a.m. and 8 p.m. Different charging powers are madeavailable (a fast power charging of 22 kW and a rapid charging mode of 50 kW) and different initial EV battery SoC are generated randomly, being assumed that vehicles with lower SoCs would choose faster charging modes to minimize the time spent in the charging process. EV charging is included in the model as a service provided by the community and, as such, is paid by users. The charging tariff has two price ranges, based on the tariff applied by one of the electric mobility retailers currently operating in Portugal, to which a fixed cost is added. These costs are computed depending on the random number of charging operations completed per simulation day and the corresponding costs/profits are merged with the overall costs and profits calculatedby the coordinator agent. Due to its random nature, no action is performed by the coordinator agent on these loads, which are understood only as demand to be satisfied.

Results and discussion

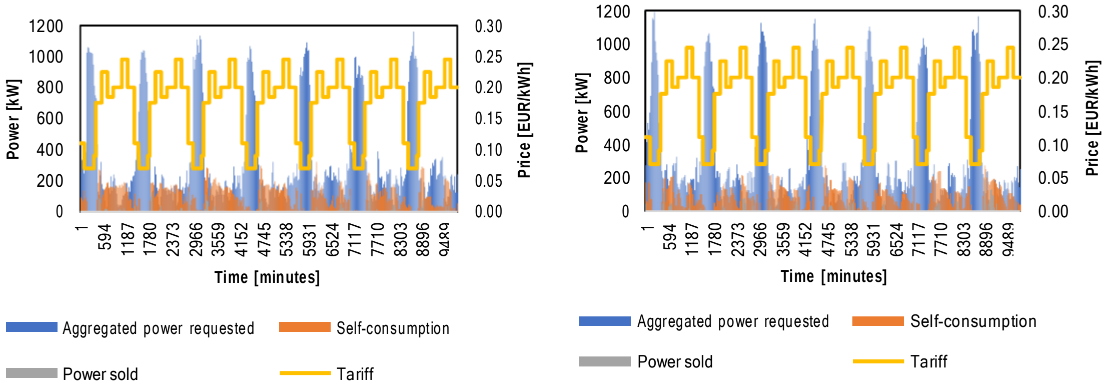
OVERALL COMMUNITY PERFORMANCE

To assess how the presence of prosumagers influence the community performance, three scenarios were created (Table 24). The overall community performance in each one of these scenarios is displayed in Figure 42.

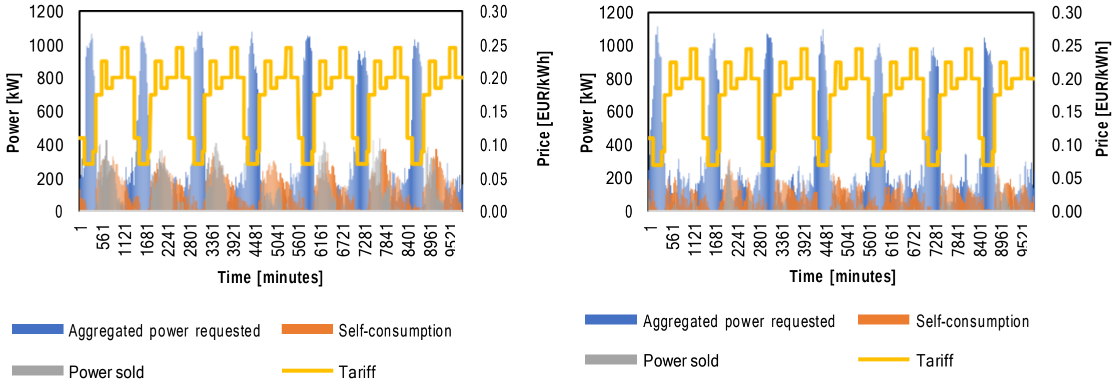
Table 24 Summary of tested scenarios.

Scenario	Weather conditions		Type and share of agents	
	Summer	Winter	Consumer*	Prosumager
A	X	X	100%	-
B	X	X	50%	50%
C	X	X	-	100%

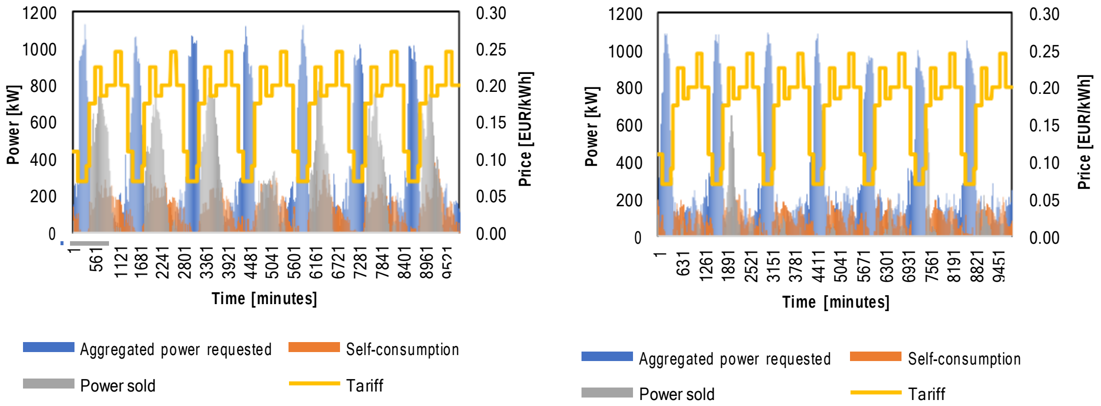
*In this model, consumers are also assumed to own storage systems (static and EV batteries).



a) Summer (left side) and Winter (right side) community performance in Scenario A



b) Summer (left side) and Winter (right side) community performance in Scenario B



c) Summer (left side) and Winter (right side) community performance in Scenario C

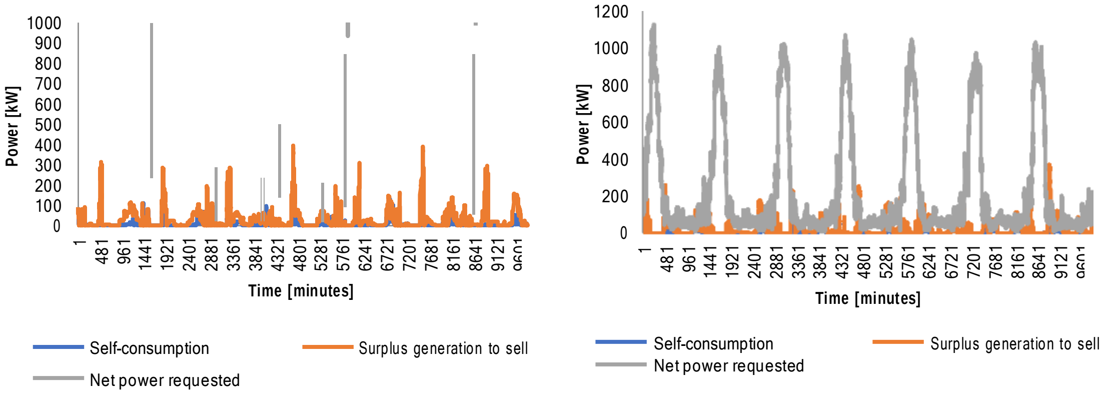
Fig. 42 Community performance.

The results clearly show the influence of residential prosumagers in the community. The high presence of these agents in scenarios B and C originates an increased surplus generation sold to the grid and allows much of the demand in periods of PV availability to be met through self- consumption. In scenario A, there is a slight increase in the power sold in winter compared to summer when the power used for self-consumption is higher. In this scenario, as the energy resources result from the community system and the energy stored in residential agents' batteries, self-consumption is prioritized in summer, when the overall community demand is higher, whereas in winter more resources are made available for sale. The differences in the results regarding the available power to sell and self-consumption between simulation days and seasons reveal the changes in available solar radiation, reflecting the uncertainty associated with renewable generation. Additionally, the largest amount of surplus generation sold to the grid allows anticipating profits for the community.

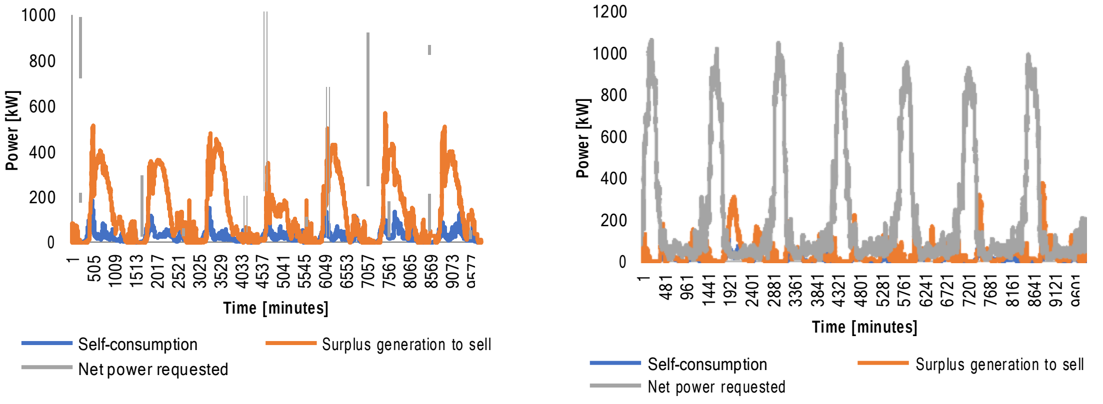
The results also reveal the advantage of having a community with diversified agents, capable of absorbing the energy generated locally. In the case study, PV generation is available during the daytime period, which corresponds simultaneously to the periods of higher prices and functioning periods of SMEs. As one of the objective functions of residential agents is cost minimization, the algorithm implemented in their decision-making module avoids scheduling the operation of manageable loads for periods of high retail prices (mostly daytime), concentrating it in night/dawn periods. During daytime, the residential demand is low as it is only used to supply baseloads. In turn, the functioning periods of SMEs is mostly during daytime, which allows to take advantage and absorb the locally generated energy, either by prosumers or the collective system. These results are noticeably verified in the self-consumption levels, displayed in Figure 42.

A closer analysis of the community consumption profile allows identifying the members who contribute the most to the total aggregated demand. Figure 43 highlights the major influence ofresidential agents in the community system operation. This dominance is explained by the loads considered, especially the EV charging, which is very power demanding. The results also highlight the greater availability of surplus generation for sale as well as the greater use of self- consumption in Scenarios B and C, due to the larger number of prosumagers in the community which is translated in more available local generated power. In Scenario A, the existence of power to sell by residential agents is due to the purchasing of power in low-priced periods and stored by consumer agents, which is then sold at higher price periods for profit making.

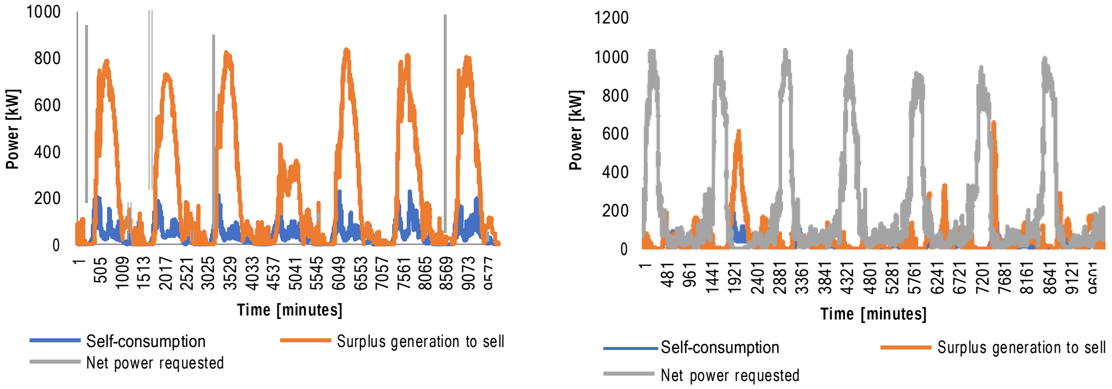
The concentrated demand peaks in night/dawn periods shown in Figures 42 and 43 are due to how the residential AHEMS optimization algorithm was parameterized and indicate the influence of the time-differentiated tariff scheme chosen.



a) Summer season (left side) and in winter season (right side) in Scenario A



b) Summer season (left side) and in winter season (right side) in Scenario B

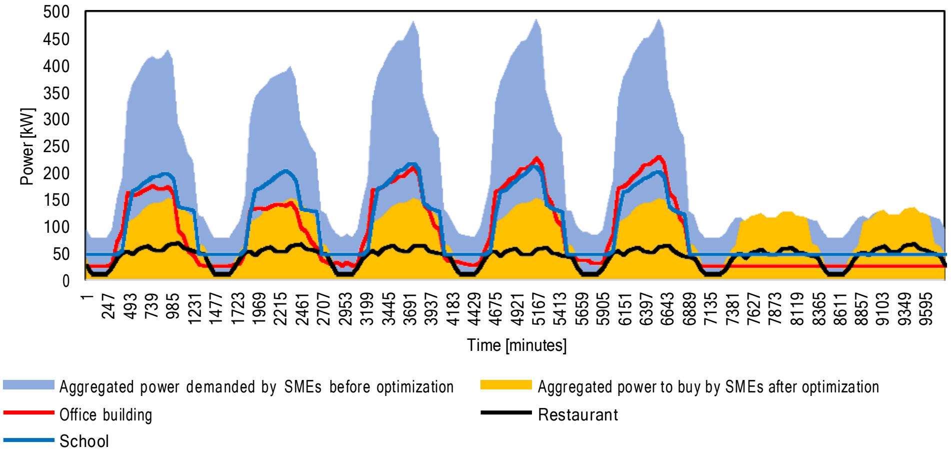


c) Summer season (left side) and in winter season (right side) in Scenario C

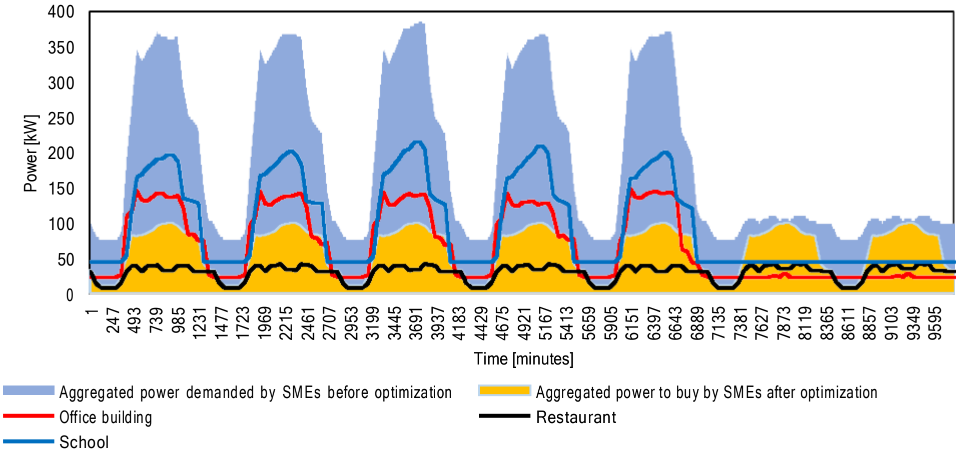
Fig. 43 Residential agents' performance under different scenarios.

Figure 44 displays the initial aggregated power requested by SMEs on the different seasons and the remaining power they need to buy after the community resources allocation performed by the coordinator agent.

The demand profiles of commercial buildings are variable from day to day and between weekdays and weekends as a function of their typical operation periods, which overlap almost perfectly with the PV availability periods. Thus, by overlying Figures 42 and 43, it is expected that a share of the generation surplus from residential agents and part of the energy generated by the collective system is used by these members. The power requested by the restaurant is higher during weekends (two last days of simulation) reflecting a higher demand of customers in these days. In turn, a big drop in energy demand is verified in the two last simulation days for the office building and the school, which illustrates their regular operating profile, typically during weekdays. In both seasons, large part of the SMEs demand is supplied by community resources. Still, part of their demand needs to be fulfilled by external suppliers.



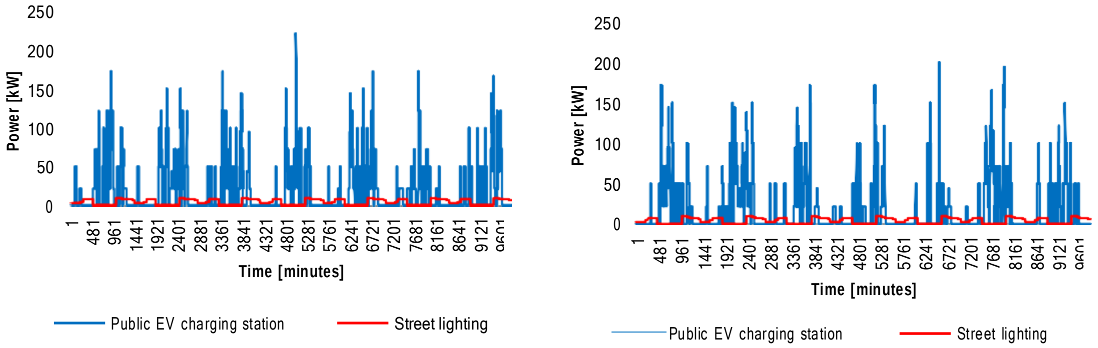
a) Summer season



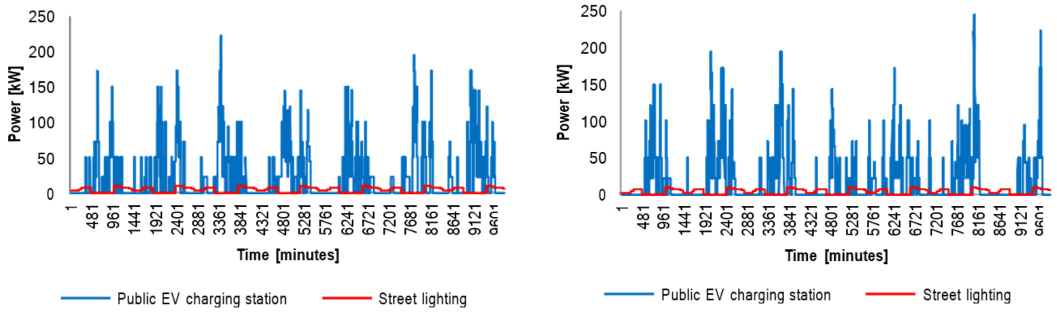
b) Winter season

Fig. 44 SMEs performance.

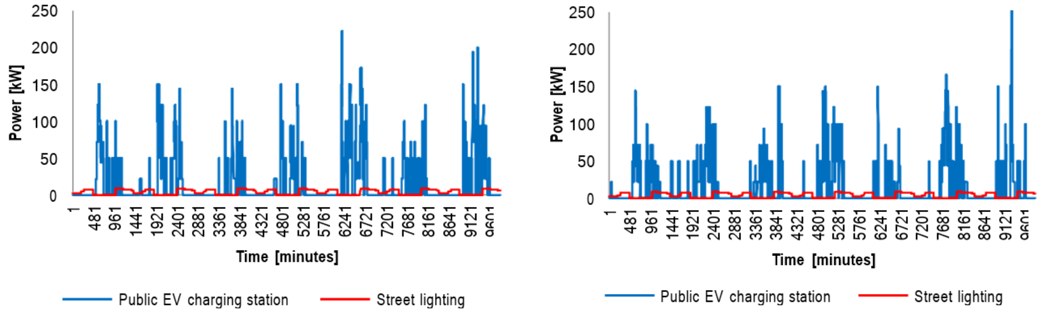
Figure 45 displays the cross-sectoral activities' power demand under the different scenarios. The street lighting service contribution to the overall community demand is almost residual. Nevertheless, the impact of the public charging station in some periods is considerable as several EVs can be charged at the same time. The demand of the public EV charging station is variable between scenarios and seasons due to its random nature. Therefore, as the number of EVs charging during a simulation day is generated randomly and more than one EV is allowed to charge at the same time, some demand peaks appear during the simulations. As the public EV charging is paid by users, some profit can be generated from this service.



a) Summer season (left side) and winter season (right side) in Scenario A



b) Summer season (left side) and winter season (right side) in Scenario B



c) Summer season (left side) and winter season (right side) in Scenario C

Fig. 45 Cross-sectoral activities performance.

Considering the self-sufficiency calculation assumptions presented in Eq. 29, in winter, a self- sufficiency of 20.4% can be reached when there are no residential prosumers in the community. That value increases to 23.9% when half of residential agents generate energy and to over 28% when all residential agents are prosumagers. In summer, the numbers are significantly different. Even without any residential prosumager, the community can achieve a self-sufficiency of 22.6% only resorting to the energy generated by the collective system and the energy that residential consumer agents sell for profit. This value rises to 53.4% when half of the residential agents are prosumagers, reaching 89% when all agents are prosumagers, clearly demonstrating the importance of these agents in autonomous systems.

COMMUNITY COSTS AND PROFITS

Regarding cost and profit allocation, as described above, the optimization performed at the coordinator agent level aims to guarantee that the energy needs of all community members are met at the lowest cost for the overall community. This means that energy is purchased from the grid whenever locally generated energy is not enough and generation surplus is sold when local storage is not available, obtaining profits for the community. Therefore, the community's aggregate costs and profits attained by selling locally surplus generated energy, are calculated according to Eq.30:

$$Community\ costs = \sum_{t=1}^{T}(NPRCom_t \times BP_t - PSCom_t \times SP_t) \times \Delta t\ [€] \tag{30}$$

In each interval t, $NPRCom_t$ is the aggregate net power requested by the community [kW]; BP_t is the grid buying price [€/kWh]; $PSCom_{tcom}$ is the aggregate power sold by the community [kW]and SP_t is the grid selling price [€/kWh]. The net power requested refers to the sum of all the power requested after self-consumption from residential agents.

Based on Eq. 30, the community's costs (negative values) and profits (positive values) for each simulation day in each season and in each scenario are displayed in Table 25. As expected, the costs are more significant in the winter season and when there are fewer residential prosumagers, as a lower PV availability means less renewable energy being used for self- consumption and, therefore, more power being requested from the grid. Scenarios A and B have the higher aggregate costs for these reasons. On the other hand, in Scenario C in the summer, the community has profits because of the sale of surplus generation from residential prosumagers.

Table 25 Community costs and profits under different scenarios [€].

	Scenario A		Scenario B		Scenario C	
Day	Summer	Winter	Summer	Winter	Summer	Winter
1	-655.33	-749.70	-141.25	-677.18	340.67	-642.99
2	-676.80	-723.47	-181.31	-482.03	306.30	-172.90
3	-674.74	-617.21	-173.88	-623.24	351.21	-547.02
4	-700.91	-627.25	-430.13	-612.85	-145.11	-687.70
5	-814.52	-735.71	-253.22	-721.21	184.35	-584.10
6	-768.97	-677.85	-276.77	-625.04	233.36	-516.53
7	-829.81	-586.49	-314.46	-519.52	162.76	-474.55

The daily costs of cross-sectoral activities must be distinguished from the rest, since these services are provided to and by the community and, therefore, have a different nature. The public lighting service has an approximate daily cost of €15.9, which is constant over the different simulation days and seasons, and the profit of the public EV charging station is variable, depending on the (random) daily number of EVs charged. The profits of the charging station, which are originated from the application of the tariff, are displayed in Table 26.

Although the results in Table 26 indicate that, in average, more EVs are charged in summer, this occurs solely due to the random setting of the number of EVs to be charged daily. Therefore, this should be understood as merely illustrative of the set of simulations presented.

Table 26 Public EV charging station profit

	Scenario A				Scenario B				Scenario C			
	Summer		Winter		Summer		Winter		Summer		Winter	
Day	Profit [€]	EVs loaded	Profit [€]	EVs loaded	Profit [€]	EVs loaded	Profit [€]	EVs loaded	Profit [€]	EVs loaded	Profit [€]	EVs loaded
1	14.68	21	13.64	15	10.54	11	10.11	11	8.55	9	10.04	11
2	14.64	21	16.27	28	16.59	28	16.59	27	11.16	12	12.70	13
3	16.09	28	13.13	14	15.73	26	13.75	14	8.05	8	9.04	10
4	12.18	14	10.65	11	16.64	28	8.99	9	10.06	11	15.67	26
5	16.07	28	8.02	9	11.12	12	13.27	14	15.67	27	7.07	8
6	10.79	11	15.26	26	12.71	12	16.72	28	9.09	10	14.25	21
7	14.06	21	10.64	11	15.85	26	8.02	8	15.18	26	10.59	11

The potential costs and profits of the community are required to be properly distributed. Depending on the community's objectives and how it is operated, the costs and profits can be distributed among investors, who may be community members, external investors, municipalities, etc. The proposed community model is based on the premise that all the investments were made by the members, who expect to obtain a financial return on their investment. In this context, a fair cost and profits distribution scheme must be formulated, reflecting each member's contribution to the overall power requested and injected.

In communities composed by members with distinct consumption profiles, contributing differently to the overall self-sufficiency, and as different investment scales are involved, it is necessary to ensure a fair mechanism to distribute community costs and profits. Different approaches can be adopted to distribute costs and profits fairly. In the scope of this work, a cost and profit distribution scheme is proposed based on the proportional contribution share of each member to the community overall net consumption and power injected, computed according to Eq. 31.

Since cross-sectoral activities are services directly provided to and by the community, their costs are not incorporated into the community's cost and profit-sharing scheme. Thus, only the contribution of residential agents and the office building, the school and the restaurant are considered.

$$Contribution\ share = \frac{\sum_{t=1}^{T}(NPRhsor_t - PShor_t)}{\sum_{t=1}^{T}(NPRh_t - PSh_t) + \sum_{t=1}^{T}(NPRo_t - PSo_t) + \sum_{t=1}^{T}(NPRr_t - PSr_t) + \sum_{t=1}^{T}(NPRs_t - PSs_t)}\ [\%] \tag{31}$$

In each interval *t*, $NPRhsor_t$ and $PShsor_t$ is the aggregate net power requested and the power sold by residential agents, the office building, the restaurant and the school, respectively [kW]; $NPRh_t$ and PSh_t is the aggregate net power requested and power sold by all residential agents, respectively [kW]; $NPRo_t$ and PSo_t is the net power requested and the power sold by the office building, respectively [kW]; $NPRr_t$ and PSr_t is the net power requested and the power sold by the restaurant, respectively [kW] and $NPRs_t$ and PSs_t is the net power requested and the power sold by the school, respectively [kW].

The proposed distribution scheme (Eq. 32) depends on the overall community costs or profits, calculated according to Eq. 30. Its rationale is as follows: if, at the end of the simulation day, the community has recorded costs as an outcome of buying more energy from the grid than the energy sold, those costs are distributed according to each member's contribution to the aggregate community net consumption. Likewise, profits are distributed according to the surplus generation injected by each member. In this way, costs are allocated proportionally to those who consume more, and profits are distributed to benefit those who inject more.

$$Costs/profits\ distribution = \begin{cases} Community\ costs\ \times Contribution_{hsor} & if\ Community\ costs\ > 0 \\ Community\ costs\ \times (1 - Contribution_{hsor}) & if\ Community\ costs\ < 0 \end{cases} \tag{32}$$

Table 27 displays the contribution shares of each type of community member to the overall demand, translated into power requested from and injected into the community, in each scenario and for each season. Residential agents are the ones who contribute the most to the power requested in Scenario A, since in this scenario residential agents have no generation and all the power needed must be purchased either from the community or the grid. In scenario B, the weight of residential agents on the aggregate power requested is lower due to the greater presence of prosumagers, representing a higher use of own resources for self-consumption and a reduction of the power requested from the grid. The negative values presented for Scenario C in the summer season illustrate the amount of surplus generation made available for injection and sale to the grid. In fact, the results revealed the significant amount of energy sold, which originates the collective profits for this scenario and season. Also, in this scenario, the fourth day of simulation costs exceed profits, although by a low margin due to an atypical low availability ofPV generation. After residential agents, the primary school is the one which contributes the most to the community power demand, followed by the office building and the restaurant. Due to their typical working profiles on weekdays, the school and office contribution shares on the weekend decrease, since only base (uncontrollable) loads remain in operation. Due to this lower consumption on weekends, the contribution of the restaurant and residential agents increases.

Table 27 Contribution shares of each type of community member to the overall demand.

		Summer				Winter			
	Day	Homes [%]	School [%]	Restaurant [%]	Office [%]	Homes [%]	School [%]	Restaurant [%]	Office [%]
Scenario A	1	68.82	15.82	4.41	10.95	77.82	11.22	3.12	7.84
	2	67.23	15.63	6.17	10.98	77.02	11.00	4.25	7.73
	3	67.36	14.05	5.31	13.28	76.42	10.19	3.78	9.62
	4	67.44	13.66	4.89	14.01	76.50	9.90	3.47	10.12
	5	67.18	13.38	5.03	14.40	77.16	9.35	3.45	10.05
	6	67.76	12.67	12.78	6.78	77.28	8.98	8.94	4.80
	7	67.21	12.38	13.79	6.62	76.37	8.97	9.86	4.80
Scenario E	1	39.38	30.76	8.57	21.29	77.54	11.36	3.16	7.94
	2	42.56	27.40	10.80	19.24	70.75	14.00	5.41	9.84
	3	40.62	25.56	9.66	24.16	75.87	10.43	3.86	9.84
	4	57.61	17.79	6.36	18.24	76.43	9.93	3.48	10.15
	5	41.07	24.04	9.04	25.86	75.83	9.89	3.65	10.63
	6	43.68	22.14	22.33	11.84	75.52	9.68	9.63	5.18
	7	40.44	22.49	25.05	12.03	74.76	9.58	10.52	5.13
Scenario C	1	-38.09	59.62	31.04	47.42	76.62	11.83	3.29	8.26
	2	-37.48	53.11	35.17	49.20	57.96	20.12	7.77	14.15
	3	-18.02	42.06	34.56	41.40	74.80	10.88	4.03	10.28
	4	41.62	24.49	8.76	25.12	76.59	9.86	3.46	10.08
	5	-26.45	51.60	32.36	42.49	73.89	10.69	3.94	11.48
	6	-36.26	55.32	55.41	25.52	73.06	10.65	10.60	5.69
	7	-30.96	51.69	53.02	26.25	73.45	10.08	11.07	5.39

Based on the contribution shares displayed in Table 27, the aggregate community costs (displayed as negative values) and profits (displayed as positive values) are distributed, and the results are presented in Tables 28 – 30.

Due to the absence of prosumers in scenario A, and as only the energy resources generated by the collective system are distributed, all community members are charged with increased costs in both seasons (Table 28). The results are especially unfavorable for residential agents in winter since the distribution of collective costs leads to the duplication of energy costs on some of the simulation days. For example, in the summer season, each residential agent would pay, on average, €4.19/day. However, if the proposed cost-sharing scheme was implemented, this daily cost would increase to €9.14/day. In the case of winter, these average costs would be €4.80 /day and €9.99/day, respectively. In the case of SMEs, costs also increase. In the summer season, the primary school would increase costs by 35.8%, the restaurant would pay about 35.5% more, andthe office building would also pay about 35.3% more. In winter, the final electricity bill would increase 35.5% for the school, 33.7% for the restaurant and 35% for the office building. These results show that, under these conditions, it would not be beneficial for these members to be involved in an energy community.

Table 28 Community cost and profit sharing in Scenario A.

		Scenario A							
		Homes		Schoo		Restaurant		Office	
	Day	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]
Summer	1	-411.18	-862.17	-197.71	-301.38	-79.56	-108.46	-152.88	-224.64
	2	-414.70	-869.69	-205.87	-311.66	-80.06	-121.78	-144.22	-218.51
	3	-415.28	-869.80	-185.89	-280.68	-69.20	-105.01	-175.06	-264.66
	4	-444.81	-917.50	-180.94	-276.69	-63.34	-97.60	-185.87	-284.07
	5	-405.62	-952.83	-175.69	-284.71	-65.03	-106.02	-189.42	-306.73
	6	-438.99	-960.08	-166.72	-264.18	-174.25	-272.56	-89.17	-141.29
	7	-405.70	-963.39	-159.69	-262.42	-185.05	-299.50	-85.41	-140.35
Winter	1	-496.07	-1079.46	-132.92	-217.07	-52.71	-76.09	-103.37	-162.15
	2	-491.47	-1048.66	-138.59	-218.17	-53.13	-83.88	-97.28	-153.24
	3	-454.17	-925.83	-125.09	-187.96	-45.96	-69.27	-117.95	-177.32
	4	-469.02	-948.88	-121.83	-183.94	-42.12	-63.91	-125.05	-188.54
	5	-502.18	-1069.83	-118.25	-187.02	-43.22	-68.60	-127.53	-201.43
	6	-495.19	-1019.02	-112.42	-173.30	-116.46	-177.04	-60.12	-92.68
	7	-453.75	-901.65	-107.73	-160.37	-123.66	-181.45	-57.62	-85.77

When analyzing the results for Scenario B, some changes are observed (Table 29). In this scenario, results show that residential agents receive profits in some simulation days. Still, after the distribution of the community costs and profits, these amounts are reduced in response to the costs that the community has from buying power from the grid. Although greater generation capacity is installed in this scenario, the generated resources are not enough for satisfying the demand of all the members. Therefore, a considerable amount of power is still required from the grid, which represents costs for the community system. By taking this issue into account, when the contribution of residential agents is assessed, the profit repaid to these members is lower. In the winter season, and as in Scenario A, the low PV availability leads to much of the community's demand being met by buying power from the grid. This leads to residential agents being charged at a price almost twice as high as they would pay if they were not in the community.

There is a slight difference between the costs initially predicted and the costs after the cost sharing scheme. In summer, the primary school costs increase only 24%, 25% for the restaurant and 23% for the office building. In winter, costs increase 35, 32 and 34%, respectively. This shows that although members' costs increase by bearing the community costs, the larger presence of prosumers allows for anticipating that a higher renewable generation capacity installed could lead to the achievement of higher economic advantages.

Table 29 Community cost and profit sharing in Scenario B.

		Scenario B							
		Homes		Schoo		Restaurant		Office	
	Day	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]
Summer	1	60.02	4.39	-197.71	-241.15	-79.56	-91.67	-152.88	-182.95
	2	55.49	-21.68	-205.87	-255.54	-80.06	-99.65	-144.22	-179.10
	3	83.92	13.29	-185.89	-230.33	-69.20	-85.99	-175.06	-217.07
	4	-173.01	-420.81	-180.94	-257.44	-63.34	-90.71	-185.87	-264.32
	5	75.38	-28.61	-175.69	-236.56	-65.03	-87.91	-189.42	-254.91
	6	40.76	-80.14	-166.72	-228.01	-174.25	-236.07	-89.17	-121.94
	7	69.34	-57.82	-159.69	-230.40	-185.05	-263.82	-85.41	-123.22

		Scenario B							
		Homes		Schoo		Restaurant		Office	
	Day	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]
Winter	1	-459.44	-984.54	-132.92	-209.87	-52.71	-74.09	-103.37	-157.12
	2	-243.01	-584.04	-138.59	-206.07	-53.13	-79.20	-97.28	-144.73
	3	-439.47	-912.31	-125.09	-190.06	-45.96	-70.05	-117.95	-179.30
	4	-478.77	-947.19	-121.83	-182.69	-42.12	-63.47	-125.05	-187.26
	5	-452.20	-999.13	-118.25	-189.57	-43.22	-69.54	-127.53	-204.17
	6	-426.28	-898.29	-112.42	-172.91	-116.46	-176.66	-60.12	-92.47
	7	-389.01	-777.42	-107.73	-157.52	-123.66	-178.33	-57.62	-84.25

The results of Scenario C (Table 30) are by far the best ones for members. Since all residential agents are prosumers, and as it is not possible to take advantage of the entire generation for self- consumption or storage, large amounts of power are injected and sold. Thus, significant profits are obtained. As collective profits are distributed on a contribution basis, the final profits for these members increase almost 37% in the summer season. In this season, PV availability is so significant that SMEs also benefit from being in the community as part of their demand is supplied by collective resources as well as by having profits made by the sale of local generation surpluses. Thus, the primary school reduces its costs by about 11%, the restaurant 12% and the office building 7%. The winter season remains unfavorable for members as their individual costs are increased due to the distribution of collective costs. In this setting, alternative solutions can be formulated in future approaches to solve the increased costs in the winter season. First, the inclusion of wind generation may be considered since it can help to soften the peak demand at night. Second, instead of distributing the community profits in the summer season among members, these profits can be used to compensate for the costs in the winter season. Other potential application of the profits is to fund extra storage capacity, indispensable to increase self-consumption shares and to reduce the power requested from the grid. Third, the potential for developing and implementing customized DR mechanisms (notably through tariff schemes) to match the periods of renewable energy generation and consumption should be assessed.

Table 30 Community cost and profit sharing in Scenario C.

		Scenario C							
		Homes		School		Restaurant		Office	
	Day	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]	Initial cost [€]	Final cost [€]
Summer	1	542.21	1 012.62	-197.71	-160.14	-79.56	-75.35	-152.88	-126.23
	2	532.17	953.26	-205.87	-162.23	-80.06	-78.52	-144.22	-111.37
	3	558.17	972.67	-185.89	-157.59	-69.20	-60.64	-175.06	-135.74
	4	65.28	4.89	-180.94	-216.48	-63.34	-76.06	-185.87	-222.32
	5	550.98	784.09	-175.69	-156.47	-65.03	-69.66	-189.42	-183.39
	6	533.54	851.52	-166.72	-162.47	-174.25	-170.21	-89.17	-84.64
	7	544.48	757.64	-159.69	-121.06	-185.05	-108.59	-85.41	-84.63
Winter	1	-419.44	-912.08	-132.92	-209.00	-52.71	-73.85	-103.37	-156.51
	2	-424.74	-975.48	-138.59	-173.38	-53.13	-66.57	-97.28	-121.74
	3	-402.43	-811.62	-125.09	-184.62	-45.96	-68.03	-117.95	-174.17
	4	-487.20	-1013.94	-121.83	-189.65	-42.12	-65.92	-125.05	-194.39
	5	-381.43	-813.00	-118.25	-180.67	-43.22	-66.26	-127.53	-194.60
	6	-341.38	-718.77	-112.42	-167.41	-116.46	-171.19	-60.12	-89.54
	7	-328.98	-677.55	-107.73	-155.58	-123.66	-176.20	-57.62	-83.21

Concluding remarks

This work illustrated how distinct entities may benefit from belonging to an energy community. In collective settings, prosumers have access to extra sources of power generation that can be used to minimize their energy dependence on external suppliers, whereas consumers can profit from collective energy sources to minimize their energy bills. Thus, in the proposed model, SMEs benefited from being in the community as they were able to minimize their energy costs by benefitting from the collective resources. In turn, the community system also benefited from having commercial entities that absorbed a large part of the local generation due to the matching of their activities with the PV generation period. Thus, self-consumption was maximized, contributing to maximize community self-sufficiency.

The work also examined the importance of fairly sharing community costs and profits. In the proposed model, a community coordinator agent was included to manage the collective energy resources. By being managed by a coordinator agent endowed with optimization rationality, the collective energy resources were distributed in such a way that all members of the community benefit from them. Since different community participants contribute differently to the system self-sufficiency, fairness in collective energy resources distribution is ensured since each member have access to collective energy resources based on its contribution to the community demand.

The results also showed that belonging to a community is especially advantageous if the installed renewable generation capacity is enough to supply part of the demand and if surplus generation is sold to the grid. However, economic, and regulatory dimensions must be considered as a larger generation capacity means a higher investment and the regulatory framework can curb the generation capacity installed in a given system. In fact, special attention should be paid to the installed generation capacity in a community setting, as the European directives are clear regarding the non-profit nature of these arrangements. Additionally, although storage systems are still expensive technologies, they must be promoted as indispensable to increase self- consumption shares, especially in the residential segment.

4.2.5. COLLECTIVE SELF-CONSUMPTION IN MULTI-TENANCY BUILDINGS[M]

Overview

The work presented in this section aimed at to assess to what extent consumers' individual cost and comfort related objectives are influenced by the collective project overall cost minimization and autonomy maximization objectives. For this purpose and to assess how it would work in a multitenancy building, the MAS embedded with optimization algorithms described previously was adjusted. A generic representation of the MAS framework developed to model the multi-tenancy building collective renewable self-consumption (CRSC) operation is displayed in Fig. 46.

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[m] This section is based on Research paper V.

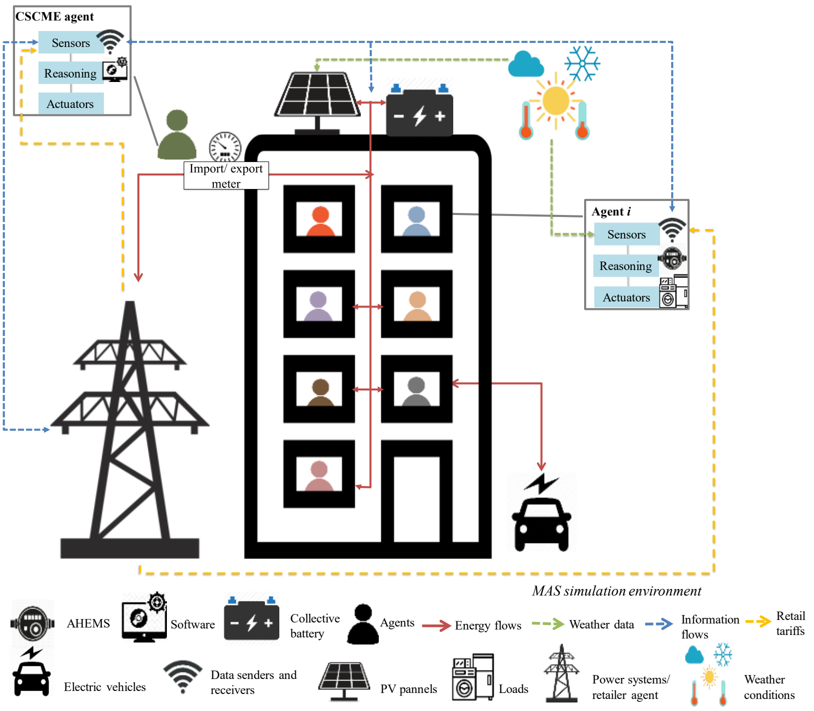


Fig. 46 Layout of the proposed collective renewable self-consumption model.

The model includes a set of PV panels that generate the energy to be used in the building. The generation assets are coupled to a static storage system, which can store self-generated energy as well as the energy bought from the grid when retail prices are attractive. These systems are managed by an agent with management, coordination, communication, and optimization capabilities - the coordinator agent. Loads modeling and individual optimization processes are like the ones presented in previous sections. Still, some differences must be highlighted. First, by the time residential agents perform their first optimization processes, no data on energy generation is assumed. The energy generated and stored in the collective system is distributed according to demand. Thus, by the time these agents perform their optimization processes, they are yet not aware of how the collective energy resources will be shared by the coordinator agent. Therefore, individual optimization processes are run considering that all the required energy is procured from the retailer agent and the cost minimization objective function only includes the load consumption costs (due to loads) and the energy exported and sold to the grid, which is only possible for EV owners who can use the energy stored in the EV battery to reduce the total amount of energy requested from the grid or the collective system (perceived as self-consumption) and to sell the energy stored in the EV batteries back to the grid.

The residential agents' optimization processes generate individual demand profiles (and energy export profiles for EV owners) that are sent to the coordinator agent. This agent, in addition to knowing the individual demand of residential agents, also receives information regarding the collective PV generation forecast and the collective battery SoC. Based on these data, a GA-based algorithm implemented in the coordinator agent architecture decides on how to use the collective energy resources (generation and storage), i.e., how to distribute the self-generated and stored energy and when to interact with network operators, represented by a retailer agent, to negotiate the remaining energy deficit or surplus.

This case study also differs from the previous ones because residential agents do not make direct decisions regarding the management and distribution of energy generated in the PV system. This responsibility is assigned to the coordinator agent and rules for sharing collective self-generated and stored resources, a critical issue in collective self-consumption, were studied. The simplest forms of distribution are based on fixed sharing coefficients (all users are entitled to receive the same amount of energy) or on consumption requirements (more energy from the collective system is supplied to the users with higher consumption profiles). Both approaches have issues balancing efficiency and fairness in the distribution of resources: the coefficient-based approach is fairer if the investment is made equally but can result in wasted energy for participants with lower consumption profiles; the consumption-based approach can raise issues of fairness as participants who consume the most may not have been those who invested more in the system. In the scope of this work, a consumption-based distribution approach was adopted, which accounts for both individual objectives (as the demand profiles are already designed according to the personal agents' objectives regarding cost and dissatisfaction minimization) and collective objectives (since the coordinator agent algorithm pursues collective objectives). Although it may raise fairness issues, this approach allows for the most efficient use of local energy resources (generation and storage).

Depending on the motivations of the project developers, the coordinator agent algorithm may pursue two main goals: overall cost minimization (Scenario A) and minimization of surplus generation exports, used as a proxy for self-consumption maximization (Scenario B). The problem formulation at this level is single objective but presents similarities with the one implemented at the consumer agents' level. The coordinator agent problem is described as follows.

$$OF = min \sum_{t=1}^{T} \Big(\big(BPt \cdot \Delta t \cdot (PDe_t + \textstyle\sum_{s=1}^{k} P_{st} - SCT_t) \big) - \big(SPt \cdot \Delta t \cdot PST_t \big) \Big) \, [EUR] \qquad (33)$$

s.t.

$$PG_t = PGeGr_t + PGeL_t + PGeS_t \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (34)$$

$$PIn_t = PInL_t + PInGr_t + \textstyle\sum_{s=1}^{k} PInS_{st} \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (35)$$

$$PGeS_{st} + PGrS_{st} + PInS_{st} = PSGr_{st} + PSL_{st} + P_{st} \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (36)$$ [32]

$$PST_t = PGeGr_t + \textstyle\sum_{s=1}^{k} PSGr_{st} + PInGr_t \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (37)$$

$$SCT_t = PGeL_t + PInL_t + PSL_{st} \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (38)$$

$$SOC_s^{min} \leq SOC_{st} \leq SOC_s^{max} \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (39)$$

$$SOC_{st} = SOC_{s(t-1)} + \left(\frac{\eta_{sch} \cdot P_{st} \cdot \Delta t}{Cap_s} \right) - \left(\eta_{sdch} \cdot \frac{(PSGr_{st} + PSL_{st}) \cdot \Delta t}{Cap_s} \right) \quad s=1, \ldots, k;\ t=1, \ldots, T \qquad (40)$$

---

[32] At each t, the static battery is in a single state (self-consuming; exporting surplus; idle; charging from the grid, from the self-generated power or from the power exported by residential agents). Therefore, the respective constraints and auxiliary binary variables required to guarantee this condition were considered.

In these expressions, the following definitions were considered:

Parameters

PDe_t: aggregated power demanded by all the residential agents at t [kW];
PIn_t: aggregated power exported by residential agents at t [kW];
k: number of static batteries (s=1,…,k);
SOC_s^{min}, SOC_s^{max}: minimum and maximum SoC of static battery s, respectively [%];
PG_t: expected PV generation at t [kW];
η_{sch}/η_{sdch}: charging/discharging efficiency of the static battery s [-];
Cap_s: capacity of static battery s [kWh].

Decision variables

P_{st}: power requested by static battery s at t [kW];
SCT_t : total power used for self-consumption at t [kW];
PST_t : total power sold (to the retailer) at t [kW];
$PGrL_t$: power supplied by the retailer for feeding loads at t [kW];
$PGrS_{st}$: power supplied by the retailer used to charge the static battery s at t [kW];
$PGeL_t$: power from PV generation used for feeding loads at t [kW];
$PGeGr_t$: PV power exported into the grid at t [kW];
$PGeS_{st}$: PV power used for feeding the static battery s at t [kW];
$PInL_t$: power exported by EV owners used to feed the loads at t [kW];
$PInGr_t$: power exported to the grid by EV owners at t [kW];
$PInS_{st}$: power exported by EV owners used to feed the static battery s at t [kW];
PSL_t: power from the static battery s used to feed the loads at t [kW];
$PSGr_{st}$: power exported (to the grid) by the static battery s at t [kW];
SOC_{st}: SoC of static battery s at t [%].

The cost minimization objective function of the coordinator (Eq. 33) was adapted from Eq. 10 and is used for exploiting both collective objectives: minimization of collective cost and minimization of surplus generation exported to the grid. The coordinator objective function (Eq. 33) accounts for the costs associated with the energy demanded by all consumer agents and the power requested by the collective battery. At this level, the energy demanded by consumer agents is perceived as a constant to ensure residential objectives are not compromised. Similarly to what happens to EV batteries, the collective battery can be supplied by self-generated energy, energy purchased from the grid or exported to the grid by the EV owners (Eq. 36). The second component of Eq. 33 represents the self-consumed energy (computed according to Eq. 38), which can either be supplied by the self-generation system or the storage (collective and individual) system. The third term of Eq. 33refers to the energy exported and sold to the grid, which can also be supplied by the individual and collective energy resources (calculated according to Eq. 37). Both the self-generated energy (Eq. 34) and the energy made available by the EV owners (Eq. 35) can be used to supply the collective battery and loads and be exported to the grid. Eqs. 39 and 40 model the SoC restrictions of the collective battery as well as its charging and discharging processes.

In the proposed model, the building internal electric networks are used to transfer the energy generated to the consumption sites; therefore, the payment for the use of public networks is not due. Public networks are used to export surpluses and supply deficits and, therefore, must be paid accordingly. Thus, the deficit energy requested from the grid is charged according to the ToU tariff used in residential optimization, which already includes the tariff components due for the use of public networks. Correspondingly, the surplus energy that is sent to the grid is remunerated according to the same selling tariff used in the optimization of residential agents, defined in accordance with Article 27-D of the Portuguese Decree-Law 76/2019, which also accounts for all tariff components.

The distinction between both collective objectives was considered at the implementation level by adapting the fitness function. The fitness function aims to assess how good a solution is considering the objective functions. For the cost minimization objective function, the best solutions are the ones producing the lowest cost. However, for the grid export minimization objective function, this rationale is not so direct as, at each instant, there may (or may not) be energy available to export to the grid. In case of energy being sent into the grid, the quality of the solutions is associated with the amount of energy being exported; therefore, the solutions corresponding to the least export amounts are selected. If there is no energy being exported, the solutions must be distinguished through cost. In this situation, an arbitrarily high value *H* is subtracted from the cost value associated with these solutions to shift the fitness region such that the fitness values of exporting and not exporting solutions do not overlap. Therefore, the region with positive fitness values is reserved for the exporting solutions whereas the negative fitness region is reserved for the non-exporting solutions, ensuring that whenever an exporting solution is compared with a non-exporting one, the latter is selected.

The outcomes of the coordinator agent optimization are communicated to the actuators in the generation and storage devices which, in turn, trigger the distribution of the collective energy among consumer agents and the energy procurement/selling with the retailer. Residential agents receive their respective amounts and recalculate their expected costs, considering energy imports/exports with the retailer and the collective self-consumption.

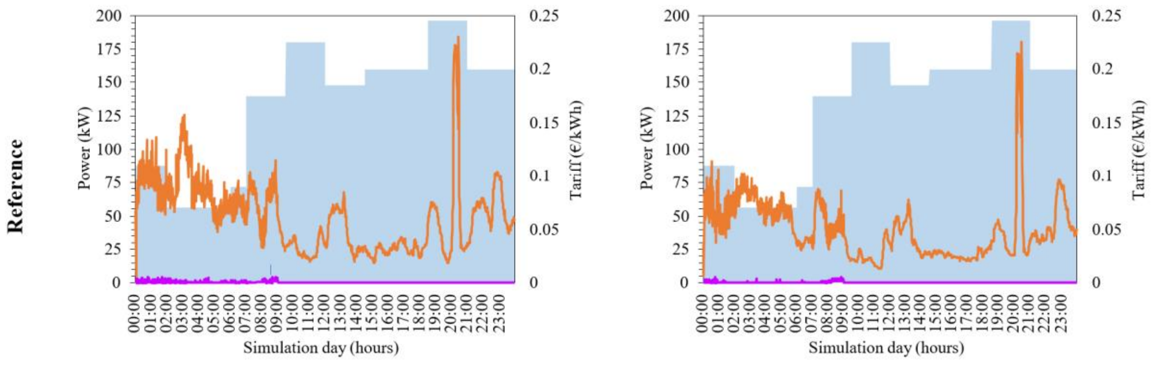
Results and discussion

OVERALL POWER PROFILES

Figure 47 displays the daily power profile for three scenarios:

- Reference scenario (without generation and storage systems);
- Scenario A (overall cost minimization);
- Scenario B (overall self-consumption maximization).

These profiles include the overall energy requested from the retailer, the energy to be exported to the grid and the self-consumed energy. The results were discretized for a typical winter (a) and summer (b) day to better understand the influence of seasonality (outdoor temperature and solar PV availability) on the system performance. The results are also described in Table 31, where the main characteristics of the scenarios are displayed, as well as the summary of the amounts of energy traded daily with the grid (bought and sold) and used for self-consumption.



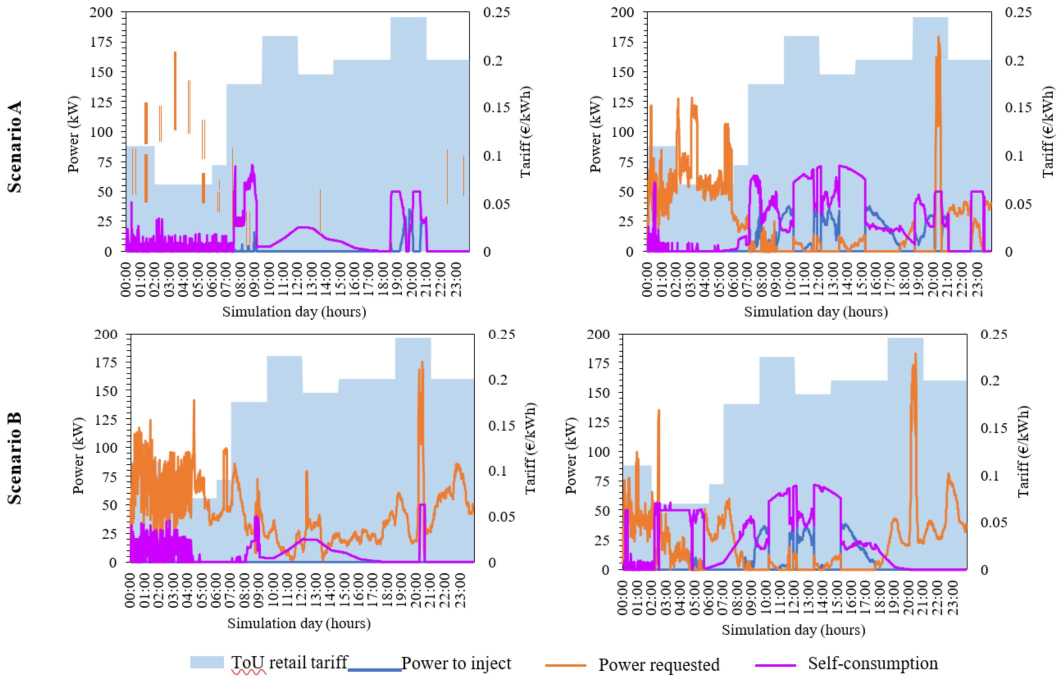


Fig. 47 Power profiles in a typical winter (left) and summer (right) day in the three scenarios.

Table 31 Comparison of the daily performance of scenarios. Legend: W: Winter; S: Summer.

	Available energy resources			Energy imported from the grid [kWh/day]		Energy exported to the grid [kWh/day]		Energy self-consumed [kWh/day]	
Scenario	Local generation	Static storage	EV storage	W	S	W	S	W	S
Reference	-	-	✓	1201.70	948.91	52.38	22.26	6.81	3.45
A	✓	✓	✓	1118.74	573.34	26.75	184.60	257.60	614.24
B	✓	✓	✓	1056.28	513.96	0	105.09	259.76	643.23

As the reference scenario does not consider collective energy generation and storage assets (only EV batteries are available for some agents), all the consumers' demand must be supplied by the grid and, therefore, the overall power requested is noticeably high (Table 31). Also, in this scenario, the available energy used for self-consumption and grid exports is limited to the EV batteries, which are only available during night/dawn periods since, in general, residents are not at home during the day due to work or school. Thus, as consumer agents aim to minimize their overall energy costs, EV owners privilege the sale of part of the energy stored in the EV battery to the grid, as they are remunerated for it, to the detriment of self-consumption. In the remaining scenarios, demand peaks are smoothed due to the sharing of the collective self-generated and stored energy. Also, the shares of self-consumption (mainly in Scenario B) and the energy exported to the grid (mainly in Scenario A) significantly increase, according to the optimization objectives considered in each scenario. The results differ considerably between seasons due to the higher PV availability during summer.

The performance of the collective battery also deserves further investigation as it provides insights about how collective resources are being managed by the coordinator agent (Fig.48). By comparing the collective battery SoC with the tariff of purchasing energy from the grid (on the left), the energy being sent to the grid by consumer agents and the local generation (on the right), similar patterns are visible in both scenarios. Whenever there is storage capacity available, the battery is either charged by the PV panels (during the periods of solar availability), the energy made available by the EV owners (only during

EV availability periods) or the energy procured from the grid, especially in the early morning periods (when the price is lower). The results reveal distinct trends in the collective battery SoC. First, in winter, due to the scarcity of solar availability, the collective battery must be mainly charged with energy from the grid. In these circumstances, the stored energy is preferably consumed to supply the consumers' loads, avoiding the high price periods, especially at the end of the day. Second, in scenario A, the periods with more energy stored in the collective battery are shorter compared to scenario B. This happens since, in scenario A, stored energy is exported to the grid and sold to the retailer agent to improve the cost objective function. In turn, scenario B prioritizes the storage of self-generated energy by discouraging the interactions with the retailer agent. Consequently, the battery remains at a higher SoC for longer periods.

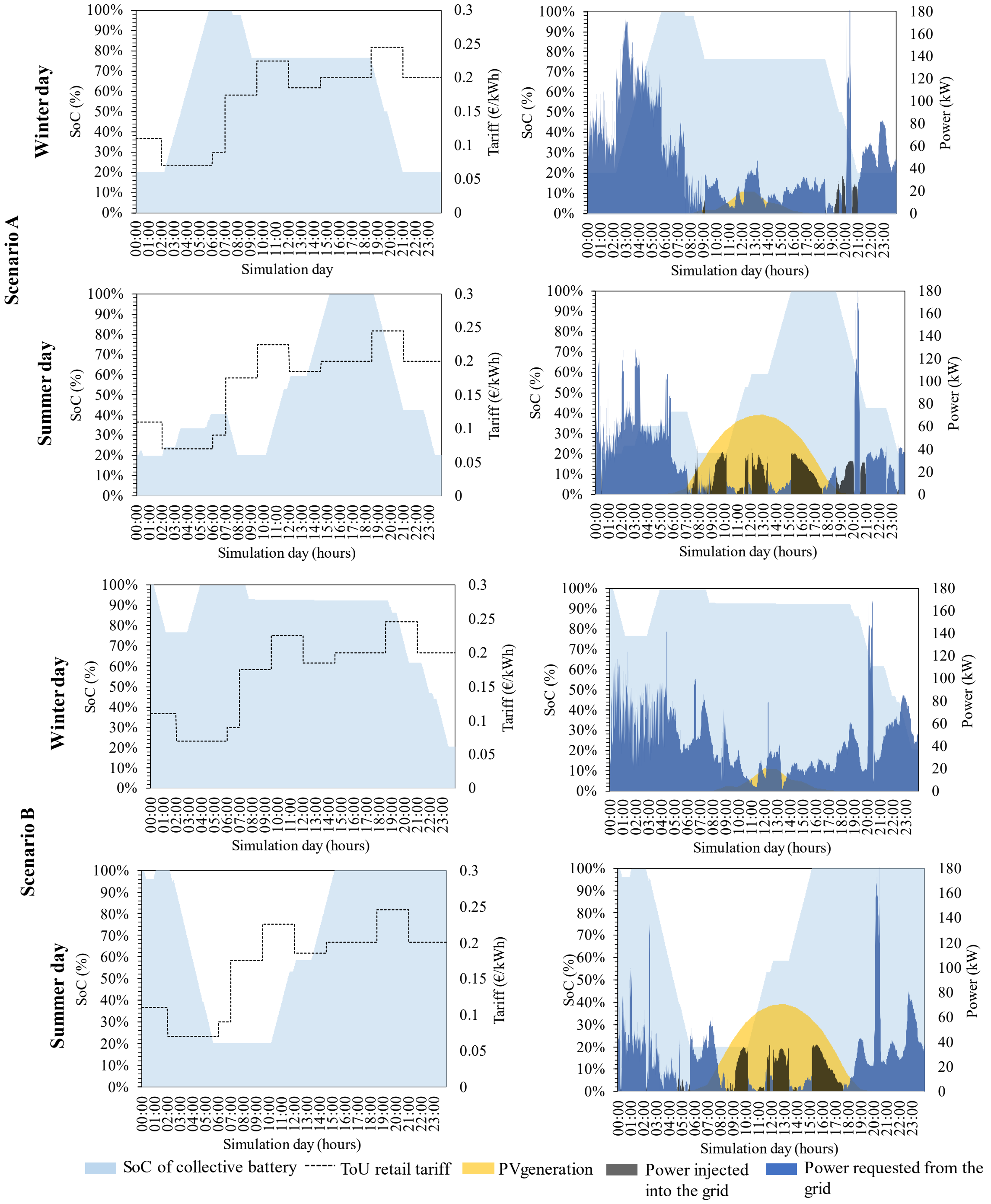


Fig. 48 Collective battery performance in typical summer and winter days.

ENERGY INDICATORS

Key performance indicators (KPI) are used to compare scenarios (A and B) regarding a reference one, assumed to be an alternative setting in which there is still no collective generation and storage. KPI are measurable metrics that reflect the performance of different dimensions (economic, environmental, social, etc.) in a given context and express the achievement of broader objectives (DEFRA 2006; Hristov and Chirico 2019; May et al. 2013). Scenarios are compared through energy KPI, based on Viti et al. (2020) and Luthander et al. (2019).

The project energy performance may be assessed by computing two main indicators, namely, the system's self-sufficiency (SS) and the generation-demand (GD) ratios (Luthander et al. 2019; Viti et al. 2020). The first expresses the level of energy autonomy from external suppliers and is calculated by the ratio between the total energy self-consumed and the total demand (Eq. 41) (Viti et al. 2020). The second correlates the local energy generation and demand (Eq. 42)(Luthander et al. 2019).

$$SS = \frac{Total\ energy\ self-consumed}{Total\ energy\ demand}[\%] \tag{41}$$

$$GD = \frac{Total\ energy\ generated}{Total\ energy\ demand}[\%] \tag{42}$$

In the scope of this work, it could also be relevant to assess the self-consumption rate reflecting the relationship between self-consumed and locally generated energy. This would be a relevant KPI to understand the real autonomy of the project with respect to the electricity grid. However, as it was decided to account for the impact of individual and collective storage in reducing the energy requested from the grid, and the energy stored in collective and EV batteries can be supplied by local generation or the grid, it would be difficult to disentangle the provenance of the stored energy. Then, the accounting of the self-consumption rate would bring little value for the analysis since it would skew the self-consumption results. Furthermore, the cost and dissatisfaction values resulting from the optimization processes are used to compare scenarios, translating the economic and comfort dimensions which are also relevant in this setting. Fig. 49 shows the monthly variation of the SS and generation-demand ratio (GD) indexes in the different scenarios and Table 32 summarizes them quantitatively on an annual basis.

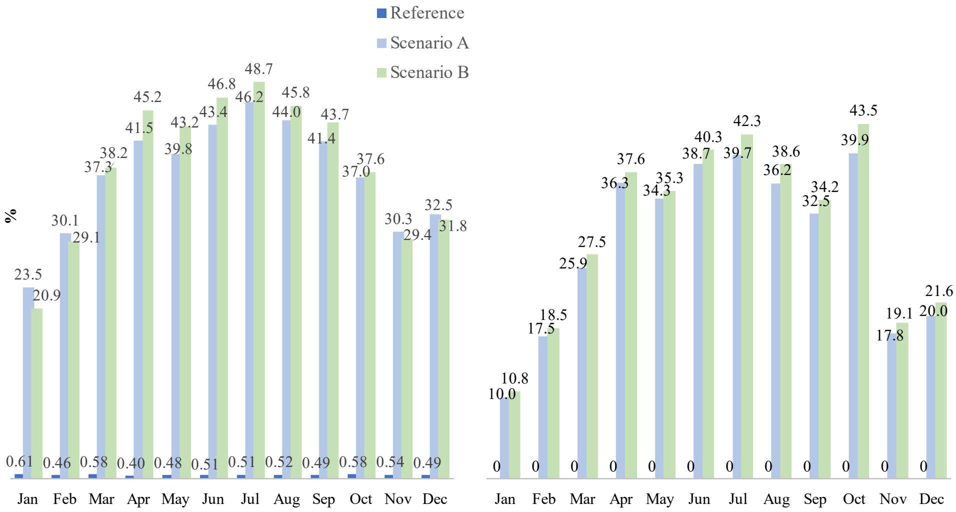


Fig. 49 GD (left) and SS (right) indexes per month.

Table 32 Energy indexes comparison.

Scenario	Energy self-consumed [MWh/year]	Energy imported from the grid [MWh/year]	Energy exported to the grid [MWh/year]	Energy self-generated [MWh/year]	SS [%]	GD [%]
Reference	2.11	405.55	8.80	0	0.52	0
A	184.12	314.96	46.95	135.98	36.89	27.25
B	238.39	291.45	25.15	135.98	44.99	25.66

As the energy generated and stored in collective systems is solely used to supply users' demand and not to feed the common areas of the building[33], the energy demand is only created by the loads of residential agents to which the energy purchased from the grid to charge the static battery is added, in scenarios A and B. Therefore, in these two scenarios, the total energy demand is higher than the reference scenario. However, as in A and B, local generation is available for self- consumption, the total amount of energy required from the grid decreases. The amount of self- consumed energy varies significantly between scenarios since in the reference situation only the energy stored in EV batteries (and procured from the grid) is used for this purpose, while in the other two scenarios the energy supplied by the generation and collective battery systems is also used for supplying the loads.

As explained before, the SS indicator reflects the relationship between the energy consumed locally, which varies considerably between scenarios and seasons, and the total energy demand, which in this case results from the sum of the self-consumed energy and the energy requested from the grid. Given this relationship, scenario B is the one that presents a higher SS index since the collective objective explored by the coordinator agent promotes the local consumption of generation and storage resources. In turn, in scenario A, more energy is made available for grid export to enhance overall cost solutions. The GD indicator correlates the energy generated locally, which is null in the reference scenario and equal in the two other scenarios, and the total building demand. As local generation is not considered in the reference scenario, the GD index is null. For the two other scenarios, the GD index is quite similar. Its slight variation is due to the objectives pursued in each scenario, which creates variations in the amounts of energy required from the grid, self-consumed, and exported to the grid. Both indices fluctuate seasonally due to the PV availability and the consequent variations in the energy self-consumed. In addition, both indicators are relatively low (< 50%) in both scenarios, which may indicate an insufficient installed generation capacity.

DISSATISFACTION AND COST OUTCOMES

The economic and comfort results are directly calculated by the optimization processes and allow to assess the real impact of collective optimization goals for the CRSC users. These results are presented considering the agents' sensitivity to cost and comfort as displayed in Fig. 50 and Table 33. Daily average results are presented across the simulation months to show the seasonality effect. Standard deviation results are also provided to show the variability of results obtained within the same cost/comfort sensitivity profile due to the differences on the household size.

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[33] This decision was made to facilitate the modeling process.

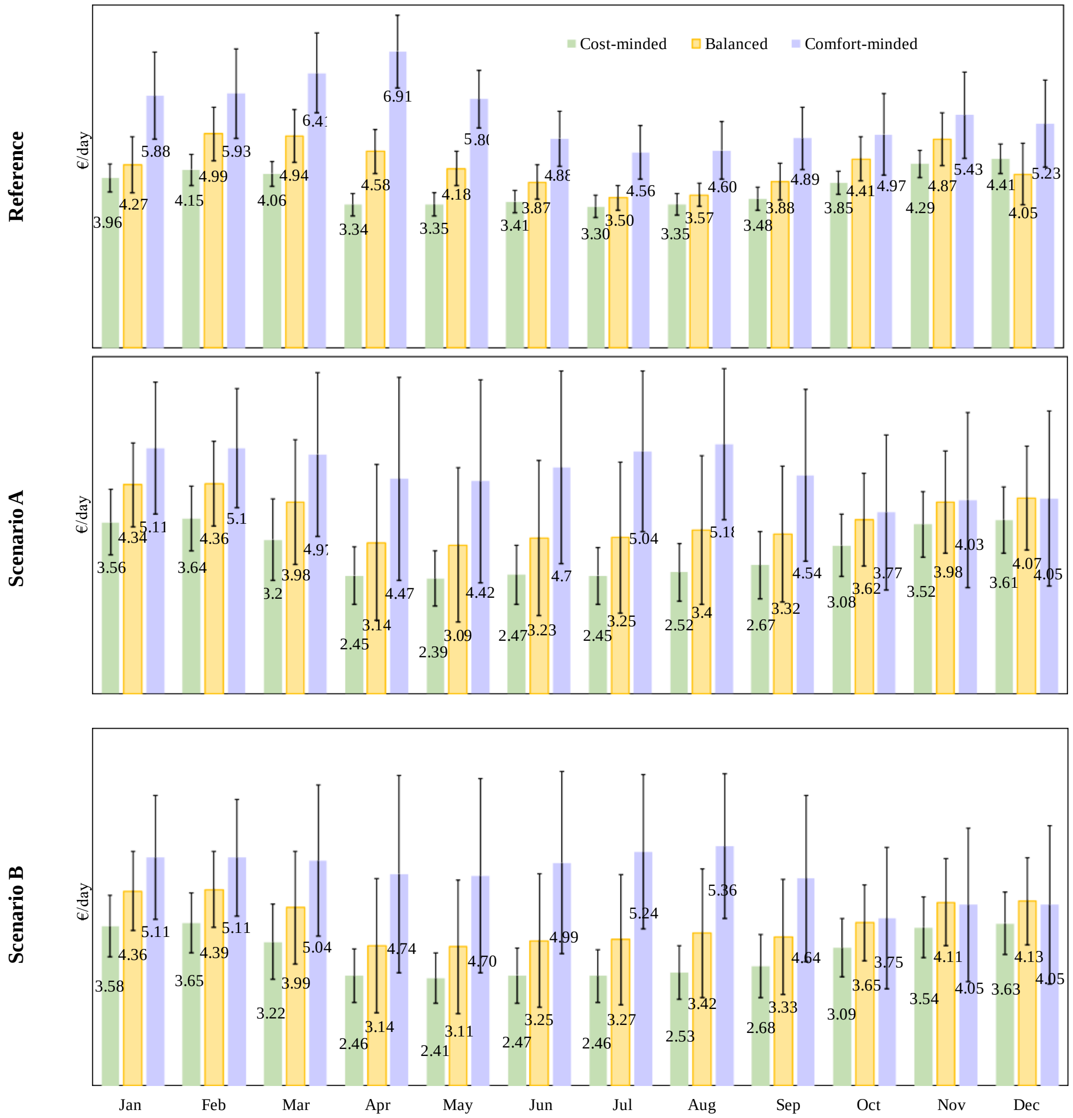

Fig. 50 Daily average costs [€/day] per month. Bars represent the average costs and error bars signify the standard deviation.

Table 33 Dissatisfaction results. Larger bars - worst results; smaller bars – best results.

		Jan		Feb		Mar		Apr		May		Jun		Jul		Ago		Sep		Oct		Nov		Dec	
Scenario	**Agent type**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Reference	Cost-minded	2.36	0.68	2.23	0.66	2.29	0.69	2.31	0.65	2.29	0.65	2.31	0.65	2.33	0.65	2.19	0.68	2.32	0.65	2.19	0.71	2.19	0.70	2.29	0.67
	Balanced	1.07	0.89	0.97	0.86	0.98	0.87	0.98	0.86	0.97	0.64	0.93	0.84	0.98	0.86	0.99	0.88	0.99	0.86	0.89	0.82	0.89	0.80	0.92	0.78
	Comfort-minded	0.09	0.05	0.09	0.05	0.12	0.05	0.17	0.05	0.11	0.63	0.09	0.05	0.09	0.05	0.34	0.70	0.21	0.50	0.09	0.05	0.19	0.31	0.39	0.41
A	Cost-minded	2.20	0.67	2.18	0.65	2.22	0.68	2.21	0.64	2.21	0.86	2.22	0.64	2.22	0.64	2.15	0.67	2.20	0.64	2.13	0.70	2.17	0.69	2.20	0.66
	Balanced	0.90	0.87	0.87	0.84	0.88	0.85	0.88	0.84	0.87	0.84	0.87	0.82	0.88	0.84	0.92	0.86	0.91	0.84	0.85	0.75	0.83	0.78	0.82	0.76
	Comfort-minded	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.78	0.07	0.05	0.07	0.05	0.30	0.69	0.15	0.49	0.07	0.80	0.18	0.30	0.31	0.40
B	Cost-minded	2.18	0.82	2.16	0.64	2.20	0.62	2.22	0.65	2.16	0.05	2.20	0.62	2.21	0.65	2.16	0.63	2.20	0.62	2.15	0.62	2.20	0.69	2.25	0.76
	Balanced	0.89	0.85	0.89	0.89	0.88	0.84	0.88	0.79	0.85	0.05	0.88	0.83	0.88	0.79	0.85	0.78	0.88	0.84	0.82	0.21	0.78	0.75	0.84	0.85
	Comfort-minded	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.07	0.05	0.15	0.05	0.20	0.22	0.20	0.24

Regarding the cost outcomes, cost-minded agents are the ones who achieve the best results in all scenarios. These agents reach average costs of €3.75/day in the reference scenario, which decrease to around to €2.96/day and €2.97/day in scenarios A and B, respectively. On the contrary, comfort-minded agents are the ones with the highest cost solutions. These agents have average daily costs of €5.46/day in the reference scenario. Daily costs are also reduced for comfort-minded agents in scenario A (€4.62/day) and in scenario B (€4.69/day). In the reference scenario, as all the energy needed to supply the residential loads is sought from the retailer agent, the overall costs are the highest. In turn, in scenarios A and B, as collective energy is distributed, the total amount of energy requested from the retailer is lower and, therefore, the costs decrease.

From the cost optimization point of view, scenario A is the one that leads to better results as it seeks for solutions minimizing the collective costs. Additionally, in the reference scenario, the seasonal variability of costs is less evident as it depends only on the load utilization dynamics. In turn, in the remaining scenarios the cost variability is more visible due to the distribution of collective self-generated and stored energy (more abundant in summer). It is also worth to mention that the household size variability is more expressive (higher standard deviations are registered) for comfort-minded agents as their energy costs are higher.

As for dissatisfaction (Table 33), cost-minded agents are the ones who get the worst results in contrast to the comfort-minded ones that achieve the best solutions. There are slight improvements in results in scenarios A and B due to the greater amount of collective resources (generation and storage) available to satisfy the energy needs of residential agents.

Concluding remarks

These results disclose the potentialities of CEI in multi-tenancy scenarios, providing insights for both policymakers and project developers to design offers encompassing technical and financing services. To sum up, the following conclusions can be drawn:

- *Regardless of the project collective objective, local energy generation and distribution in MTB is advantageous for participants who can reduce their energy costs in both scenarios (average reductions of 16.7% in scenario A and 15.4% in scenario B).*
- *The implementation of a collective energy generation and storage system allows reducing the overall power requested from the grid of about 22.3% and 28.1% in scenarios A and B, respectively. Such reductions are doubly valuable as they translate an increase in the project self-sufficiency and a reduction of consumers' energy costs.*
- *Scenario B generates the best levels of energy self-sufficiency. Energy self-sufficiency is one of the value propositions of CRSC projects and special attention should be paid to this indicator, which denotes the capacity of the energy system to operate without external energy supply.*
- *As in both scenarios consumers are economically benefited (although greater savings are obtained in scenario A), the project collective objective should incorporate the participants' and developers' motivations. Therefore, if the motivations are exclusively economic and the quick recovery of the investment is a priority, the minimization of collective costs (scenario A) is the most favorable. In turn, if the project motivations are self-sufficiency, scenario B is the most favorable. Since both options are currently allowed by the regulatory framework, it is therefore up to each project to define its course.*
- *Some of the assumptions that most influence the results obtained, namely the ones related to the tariffs to be charged, storage, electric mobility, installed PV capacity, translate the current legislation in force and, therefore, the results must be understood as illustrative. The influence of these factors on the results could be assessed through a sensitivity analysis (which is beyond the scope of this work). Additionally, the assumptions considered for the Portuguese case study have direct effects on the results and, also in this case, different assumptions could have been made. Still, the methodological approach remains valuable since these assumptions are parameterizable and can be easily adjusted, allowing for the reproducibility of the model in other contexts.*

4.2.6. *HOW CAN VULNERABLE CONSUMERS BE INCLUDED IN COMMUNITY-BASED ENERGY MARKETS?*[N]

Overview

This work aims to address the gap related with the disregard of the role of vulnerable consumers in energy modeling by proposing a community-based electricity exchange scheme in which this type of consumers is prioritized. This work advances the previous research on the topic in three ways. First, a diversified set of agents, including vulnerable consumers, which are typically excluded from energy modeling, and prosumagers is modeled. A MAS embedded with optimization algorithms is proposed to model a community-based electricity exchange scheme with different shares of prosumagers and vulnerable consumers to assess how each type of agent influences the overall system performance. Agents with distinct flexibility profiles, preferences and goals are considered. Second, a community-based electricity exchange scheme is developed and the buying and selling processes within the LEC are modeled by considering an intra- community pricing structure that reflects demand and supply patterns. Third, the work investigates the interactions between prosumagers and vulnerable consumers, which unveil valuable clues for the implementation of real LEM.

The proposed MAS framework, including the agents and the respective interactions, is displayed in Fig. 51. Four different categories of agents are considered, namely, a retailer, a community manager, prosumagers and vulnerable consumers. The retailer agent plays a passive role in the model as it does not take any active decision or action. In turn, the community manager agent (CMA), the prosumager agents (PA), and the vulnerable consumer agents (VCA) are assumed as active rational goal-oriented agents, since they deliberatively choose to perform actions towards the achievement of their objectives.

A total of 30 residential agents is considered and different shares of VCA and PA are tested to demonstrate to which extent the characteristics of the participants and how the role they play may influence the LEC performance. Two main scenarios are evaluated (Table 34): in scenario A, an ideal situation with only PA is considered and in Scenario B, different shares of PA and VCA are tested.

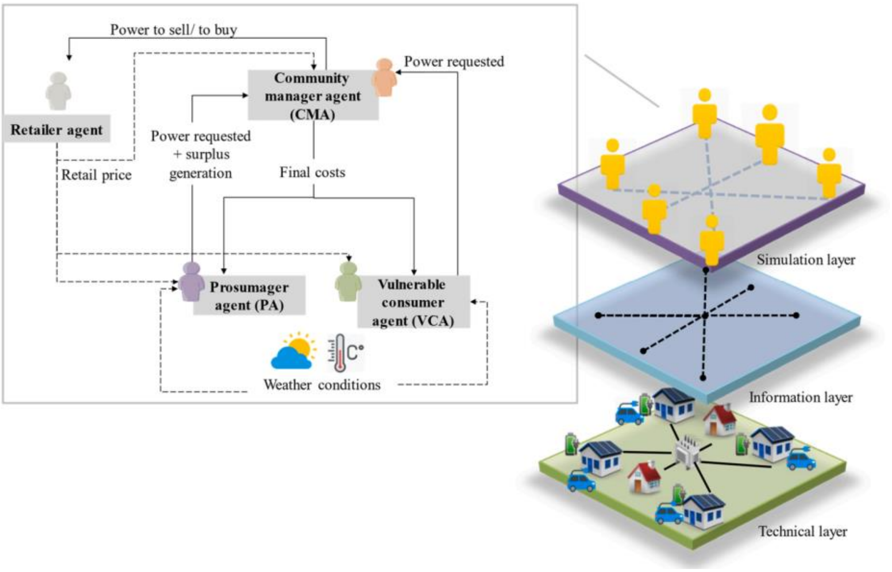

Fig. 51 Overview of the proposed MAS framework. Solid black lines: information exchanged between agents; dashed black lines: input data from the environment.

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[n] This section is based on Research papers IV and IX.

Table 34 Summary of tested scenarios.

Scenario	Weather conditions		Type and number of agents	
	Summer	Winter	VCA	PA
A	X	X		30
B1	X	X	15	15
B2	X	X	20	10
B3	X	X	10	20

The community operation is described as follows. Residential agents, both vulnerable consumers and prosumagers, are assumed as being LEC members willing to participate in an electricity trading scheme to sell their generation surpluses and to buy deficits. These agents are physically linked to each other and with the retailer agent through the low voltage distribution network. To reach their collective purpose, residential agents are assumed as being willing to prioritize electricity exchanges within the LEC boundaries. Virtually, agents are also linked to a software- based CMA, with which information is exchanged.

Once the use of energy resources (loads, generation, and storage) is individually decided (through the optimization processes fully described in previous sections), power profiles are sent to the CMA, which can recognize the sender (VCA or PA). The CMA is responsible for managing the LEC electricity trading scheme by matching buyers (VCA and PA) and sellers (PA) to maximize the power traded within the LEC, while prioritizing the transactions involving VCA. Therefore, although LEC participants do not know with whom they are trading their electricity, they trust the decisions made by the CMA are in the best collective interest (self-sufficiency) and ensure the mitigation of potential biases in exchanges matching. Also, if the electricity available to be shared is not enough to supply the needs or if there are still generation surpluses available, the CMA interfaces with the retailer agent to manage these transactions. Lastly, residential agents are informed about their final expected costs, already considering the exchanges within LEC and with the retailer.

Demand modeling was carried out as in the remaining case studies. Still, to keep coherence, load ownership between PA and VCA was differentiated. In the proposed model, PA are assumed to own all the loads, whereas VCA are only presumed to own the baseload, shiftable loads, the fridge and the EWH. As the range of VCA electric appliances is restricted, their exploitable demand flexibility is also reduced. A second difference among PA and VCA concerns the ownership of generation and storage assets. PA are assumed as owning solar PV systems coupled to static batteries and able to use EV batteries as storage, while VCA are not expected to own these assets, further limiting their demand flexibility.

Despite the differences distinguishing PA and VCA, all agents are assumed as being optimization-oriented, meaning that their decisions on electricity use and resource allocation are optimized by the AHEMS. Residential agents, whether PA or VCA, aim to minimize their electricity costs and care for the dissatisfaction AHEMS decisions impose in daily routines. To explore trade-off solutions in the bi-objective optimization setting, differences in comfort and cost sensitivity were considered by creating three cost/comfort sensitivity profiles, namely: 1) the cost-oriented profile, 2) the balanced profile and 3) the comfort-oriented profile. This feature is randomly assigned to each agent. Due to their specific characteristics, the sensitivity to cost and comfort of PA and VCA was supposed as being different: while PA were randomly assumed to be one of the three profiles (the prevalence of each profile in the model is ensured with a similar probability of occurrence, i.e., one third of agents are cost-oriented, one third are comfort-oriented and the rest are balanced), all the VCA were assumed to be cost-oriented.

Proposed energy trading scheme

The CMA receives the information on the expected day-ahead power supply deficit and surplus generation of VCA and PA. Then, based on this information, it coordinates the electricity exchanges by matching sellers (PA) and buyers (PA and VCA). The generic algorithm describing how energy exchange in LEC is processed is presented in Fig. 52, in which some comments wereadded to assist understanding.

```
LEC energy exchanging algorithm
Input: power requested ($PR_t$) and injected ($PI_t$) by each agent; set of PA; set of VCA
for $t$ in $T$ do
  $SPA_t$ = Sum of the power available to sell by the set of PA; // Check the availability to share
  $TPR_t$ =Sum the power requested by PA and VCA; // Check the LEC need
    Compute LEC price;
    Identify Sellers within the set of PA;
    Identify Buyers within the set of VCA and PA;
    while $SPA_t > 0$ and $TPR_t > 0$ do
      Randomly select a PA from Sellers and identify its power available to sell ($PI_t$); // Random choice of a Seller within PA
      if VCA are within Buyers then // Prioritization of VCA
        Select a random VCA from the set of VCA in Buyers and its respective power requested ($PR_t$);
      else
        Select a random PA from the set of PA in Buyers and its respective power requested ($PR_t$);
      end if
      Determine transaction quantity: $min(PI_t, PR_t)$; // As the availability is limited, the transaction quantity is constrained by the minimum value of $PI_t$ and $PR_t$
      Perform transaction;
      Update $SPA_t$ ; // Subtract the amount traded to the SPAt;
      Update $TPR_t$ ; // Subtract the amount traded to the TPRt;
    end while
end for
Output: Return the power injected/requested from the grid and between LEC members
```

Fig. 52 Pseudocode of the CMA algorithm.

The power profiles sent by the VCA and PA to the CMA are compiled and the total amount of electricity available to sell and buy is computed by the CMA algorithm. At each interval of the planning period, whenever there is electricity to sell, the CMA algorithm checks the PA which are selling and randomly selects one of them to initialize the process. By randomly selecting a PA among the set of selling PA, it is guaranteed that some agents are not benefited over others. Similarly, the set of buyers including PA and VCA is checked and whenever VCA are among this pool, priority is given to them. Once again, randomness in considered to ensure the same agents are not repeatedly selected and, thus, benefited. Only when there is no VCA within the buyers' pool, transactions between PA are allowed. After matching, transactions are performed and the remaining amounts of electricity to buy and sell are updated so that the process is repeated for the next time intervals. Also, the algorithm checks if the power requested by each agent is fully supplied by the matchings. If not, the remaining amount is requested from the retailer agent. Atthe end of these processes, the amounts of electricity supplied by the different sources (other agents and retailer) are known as well as the expected final costs for each agent, considering the transactions carried out.

As electricity transactions can occur both inside and outside the LEC boundaries (with the retailer), we explicitly distinguished it through pricing. As mentioned previously, transactions with the retailer are paid according to a ToU tariff and remunerated through a FiT. In turn, the energy exchanges between LEC members are governed by an inter-community pricing structure that varies according to demand and supply.

According to the EU directives, LEC must be responsible for the payment of the public network components they use. Based on the tariff structure in force in Portugal (used as a reference), as this LEC relies on the retailer to supply and absorb its remaining electricity, participants must pay the tariff components related to the global use of the system, retailer change operator and electricity (remuneration of large producing centers) (ERSE 2020a). However, since during local energy exchange, only the LV distribution grid is used, the transmission, high and medium distribution network components (which in the current Portuguese tariff scheme represent about 12% of the final price charged to end-users (ERSE 2020b)) were subtracted from the ToU retail tariff, allowing these transactions to be carried out at a lower price. This pricing scheme is henceforth referred to as the LEC tariff. To further simulate the behavior of a real bidding arrangement subject to fluctuations in demand and supply, an adjustable pricing scheme was adopted, varying within predefined bounds. This allows sellers to maximize their sales is some periods while buyers can benefit from more competitive prices in other periods. To ensure that the prices charged within the LEC do not create imbalances, the ToU retail tariff and the FiT considered in individual optimization processes were stipulated as the LEC tariff maximum and minimum price bounds, respectively. With these underlying assumptions, for each interval *t* of the planning period, the LEC tariff is determined as follows:

$$\frac{\sum_{t=1}^{T} BQ_t}{\sum_{t=1}^{T} BQ_t + \sum_{t=1}^{T} SQ_t} \times (Pf_{max} - Pf_{min}) + Pf_{min} \tag{43}$$

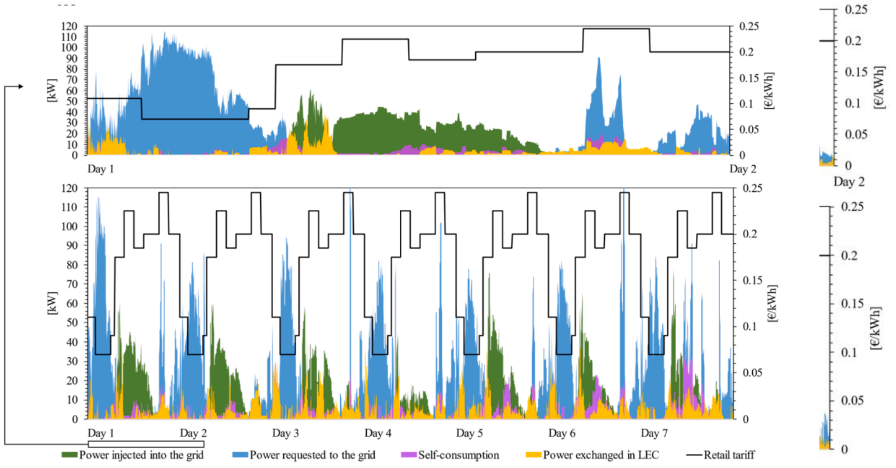
In this expression, BQ_t is the total amount of energy that all LEC participants want to buy [kWh] while SQ_t is the total amount of energy available to sell [kWh]. Pf_{max} and Pf_{min} are the upper and lower price band limits [€/kWh] at which LEC transactions are carried out, respectively. To avoid the price ranges to fully coincide with the maximum and minimum bounds, parameterizable distance factors were applied. In this case, a 1% factor was used, which means that, at the upper limit, the LEC trading price can reach 99% of the ToU and, at the lower limit, it can reach 81%. The proposed pricing mechanism allows that, when there is more demand, prices may vary between the LEC tariff and the upper bound. Conversely, when more surplus generation is available, prices may fluctuate between the LEC tariff and the lower bound. Lastly, when demand and generation are equivalent, the price charged is the one defined by the LEC tariff.

Results and discussion

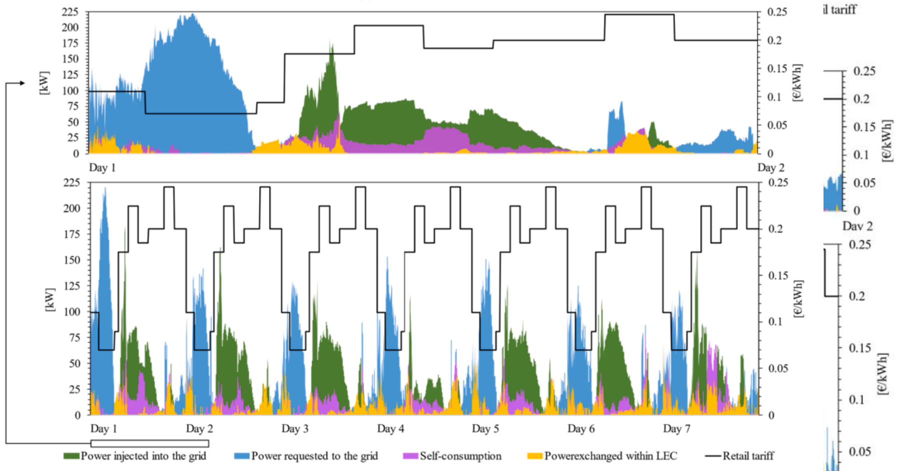
OVERALL LEC PROFILES

Fig. 53 illustrates the overall community profile over the different scenarios during the summer, after the LEC electricity trading. The patterns across simulation days are shaped by the retail tariff dynamics. As residential agents aim to minimize costs, aggregated demand peaks are created in periods of lower prices. Conversely, injection peaks coincide with the PV availability periods. During these periods, as the aggregated LEC demand is low due to residential dynamics and the load scheduling optimized by the AHEMS, most generation surplus is injected into the grid and agents are remunerated for that. This only happens because injection and selling to the grid is permitted and remunerated, contributing to minimize costs while self-consumption is not enforced. In fact, in this setting, electricity cost minimization does not necessarily mean maximizing self-consumption, as in certain circumstances it may be economically advantageous to sell self-produced electricity rather than to consume it. Thus, as the periods of higher tariff pricing match the periods of higher PV generation, the optimization process may lead to selling self-generation instead of consuming or storing it. Also, during daytime, storage is limited to the static battery capacity since EV storage is not available, simulating a real situation in which users (and EV) are not at home. Therefore, depending on the SoC of static batteries, much of the electricity generated by PA can be injected into the grid or shared with other LEC participants, since neither demand nor storage are able to use it.

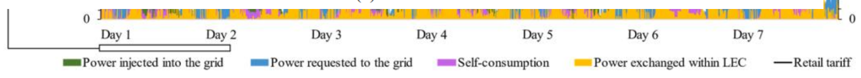
The larger presence of PA in scenarios A and B3 justifies the greater amount of power requested, injected, and self-consumed. These agents own the more energy demanding loads, as EV and AC. For this reason, considering more PA leads to increased self-consumption levels since these agents use part of their self-generation for supplying their own loads. The results of these two scenarios anticipate better cost solutions for PA. In turn, in the presence of more VCA in the LEC, the results show that more power is available to be shared and less overall power is requested from and injected into the grid. These results seem to reveal that VCA may play a key role in LEC, by absorbing locally generated resources, thus contributing to enhance self-sufficiency.



(c) Scenario B2



(d) Scenario B3



(b) Scenario B1

Fig. 53 Overview of the LEC profile over the different scenarios in the summer season.

VARIATION OF THE LEC TRADING TARIFF

Considering the electricity requested to the grid and available to sell in each scenario, as well as the price adjustment expression (Eq. 43), the LEC trading pricing fluctuation is showed in Fig. 54 (the results are similar across the different scenarios, and therefore only the results of scenario A are detailed). As expected, at time periods of higher demand and lower supply – typically corresponding to night/dawn – the LEC prices get close the upper limit, which allows PA to profit from selling their surpluses. As these periods do not match PV generation, PA with larger amounts of stored electricity (in the static or EV battery), and willing to sell it, benefit the most. Conversely, the periods of greater PV availability and lower demand – daytime – are characterized by the proximity of LEC prices to the lower price bound. These periods are the most interesting for buyers as they can purchase cheaper electricity. Due to the agents' cost minimization objective, the AHEMS shifts the operation of the most energy demanding loads to the low ToU price periods (night/dawn). In turn, due to their characteristics and the energy services they provide, other loads (as the fridge, the EWH, the non-manageable loads) still need to be supplied during the daytime, when the ToU prices are higher. Thus, at the first sight, this model configuration may not seem very adequate to promote the inclusion of VCA, as most of their loads must operate during high price periods. Indeed, the ToU retail tariff penalizes agents with lower demand flexibility. However, a closer look reveals that all agents benefit from this configuration. First, because by trading electricity (selling or buying) within the LEC, agents automatically benefit from price reductions created by the removal of unused grid tariff components. Second, the proposed LEC price adjustment scheme allows for the trading price to approach the lower limits during the daytime. Thus, much of the non-manageable demand of VCA can be supplied by the energy exchange scheme at lower prices than those charged by the energy retailer.

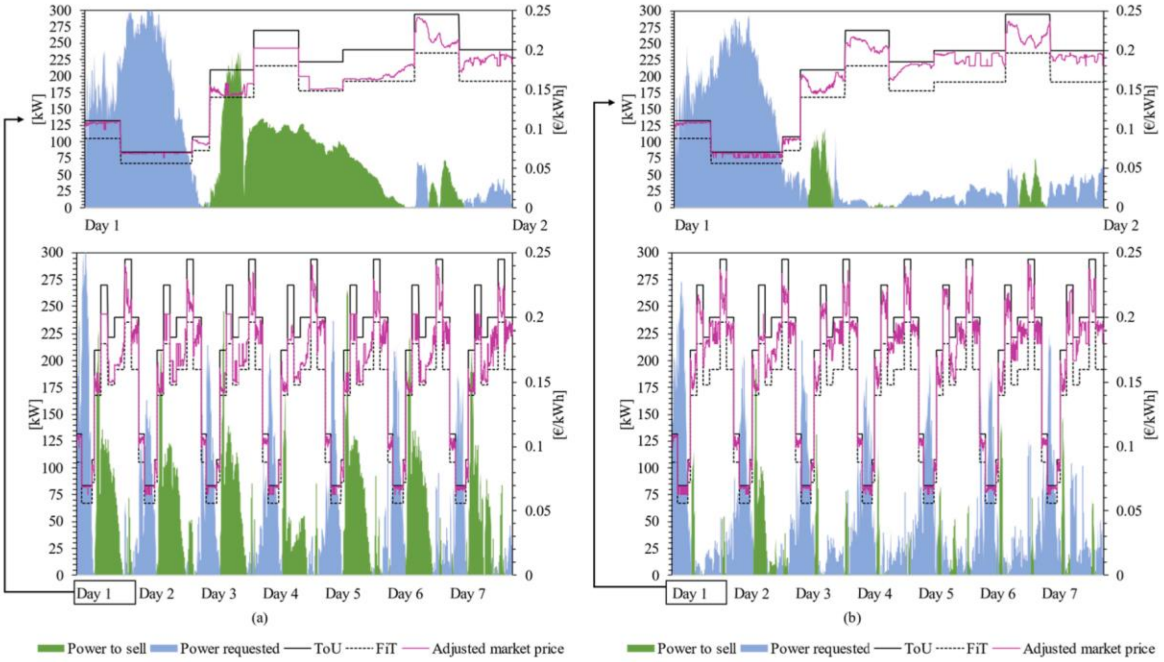


Fig. 54 LEC pricing fluctuation in Scenario A in summer (a) and winter (b) seasons.

COMPARISON OF SCENARIOS

Each scenario is evaluated regarding costs, comfort, and energy balance results. The economic and comfort dimensions reflect the nature of the agent (cost-oriented, balanced or comfort- oriented) and are directly computed by the optimization processes. The energy performance is evaluated through a set of indicators aiming to characterize the effectiveness of the energy sharing scheme. The following indicators were considered: the number of matchings/ transactions defined by the CMA; the amount of electricity locally shared; and the LEC self- sufficiency. The two first indicators were designed for this setting and allow to understand if the CMA indeed prioritizes the VCA in the buying/selling matches, what are the buying/selling patterns formed and between what kind of agents. In turn, the self-sufficiency index was adapted from Mengelkamp et al. (2018) allowing to measure how much community demand can be supplied by local resources when local electricity trading is promoted.

Starting with the costs and dissatisfaction results, the average daily costs (represented by negative values) and benefits (shown as positive values) expected before and after the participation in the LEC trading model, as well as the dissatisfaction in the different scenarios during the simulation period, are presented in Tables 35 and 36.

Table 35 Economic results over the different scenarios.

			Summer				Winter			
			A	B1	B2	B3	A	B1	B2	B3
Average daily costs before sharing [EUR/day]	VCA		–	-2.36	-2.39	-2.24	–	-2.31	-2.43	-2.36
	PA	Cost-oriented	4.09	6.18	3.33	4.24	-1.72	-0.50	0.20	-1.77
		Balanced	3.30	2.72	1.77	3.70	-2.70	-1.53	-1.42	-2.69
		Comfort-oriented	1.46	-1.05	1.21	0.67	-5.30	-4.41	-3.84	-5.24
Average daily costs after sharing [EUR/day]	VCA		–	-2.21	-2.29	-2.11	–	-2.21	-2.34	-2.24
	PA	Cost-oriented	4.27	6.51	3.62	4.44	-1.46	-0.24	0.56	-1.50
		Balanced	3.50	3.03	2.06	3.95	-2.35	-1.27	-1.13	-2.36
		Comfort-oriented	1.87	-0.49	1.51	1.00	-4.70	-3.88	-3.45	-4.64
Weekly Δ [EUR/day]	VCA		–	1.00	0.69	0.91	–	0.65	0.64	0.85
	PA	Cost-oriented	1.27	2.32	2.01	1.54	1.84	1.81	2.46	1.92
		Balanced	1.44	2.25	2.04	1.79	2.46	1.86	2.04	2.32
		Comfort-oriented	2.86	2.81	2.09	2.33	4.23	3.68	2.75	4.18

Table 36 Dissatisfaction results over the different scenarios (average daily results). Legend: green, lowdissatisfaction; yellow; average dissatisfaction; red: high dissatisfaction.

		Summer				Winter			
		A	B1	B2	B3	A	B1	B2	B3
VCA		–	🟡 1.92	🟡 1.96	🟡 2	–	🟡 2.24	🟡 1.91	🟡 2.2
PA	Cost-oriented	🔴 10.21	🟡 2.63	🟡 2.35	🔴 6.9	🟡 2.32	🟡 2.27	🟡 2.46	🟡 2
	Balanced	🟡 3.79	🟢 0.65	🟢 0.53	🟡 3.16	🟢 0.65	🟢 0.73	🟢 0.7	🟢 0.47
	Comfort-oriented	🟢 0.84	🟢 0.13	🟢 0.29	🟢 0.61	🟢 0.08	🟢 0.16	🟢 0.54	🟢 0.06

In Scenario A, the available generation in the summer allows for all agents to obtain profits. These results are further enhanced after local electricity trading as agents may sell and procure electricity at better prices. In turn, in winter, costs are recorded for all agents since the available local generation is insufficient to supply most loads. However, also in this case, all agents can reduce their expected electricity costs. Exceptional results are verified on the second day of simulation in winter due to an atypical day of solar availability, which allows surplus to be sold. This unusual generation availability allows PA (especially the cost-oriented ones) to improve their profits by selling more. Similar conclusions can be drawn from Scenarios B1, B2 and B3, in which results show that VCA do benefit from participating in the LEC trading scheme, while PA (especially the cost-oriented and balanced ones) are also able to improve their costs and benefits.

As the energy needs of VCA are low due to the nature of the loads considered, their costs are also reduced. Thus, the savings achieved do not seem very attractive. However, they can be enough to alleviate the economic shortages that most of these consumers may suffer. Comfort-orientedPA are the only ones slightly lowering their results (when compared to Scenario A, which proves to be the best setting for these agents), since they compete for the electricity available in the exchanging scheme, which is preferably provided to VCA.

In general, in all scenarios, cost-oriented agents achieve the best cost solutions as they sell more electricity by sacrificing partially their comfort standards (as confirmed by the worst comfort results). The balanced PA reach intermediate cost and comfort results, while the comfort- oriented agents register the worst (highest) cost solutions. Due to their comfort requirements, these agents need to procure more electricity in the LEC trading scheme to satisfy their higher comfort levels. Still, they are also the ones who benefit most from trading electricity locally. These results are further confirmed by the energy indicators presented in the next sections. The results also show that, in LEC with high generation capacity installed, the existence of consuming entities (as VCA and comfort-oriented PA) is crucial to balance generation and demand. Thus, the best results for VCA are obtained when there is a balance (Scenario B1) or more surplus generation (Scenario B3) and, therefore, more resources are available.

Regarding comfort, the worst results are obtained for VCA and cost-oriented PA, while better solutions are registered for the comfort-oriented agents. The slightly worst comfort results in summer are explained by the large temperature lag between outdoor and reference temperatures, which the AC system cannot fully cope with.

Concerning energy indicators, as explained before, three indexes are assessed: the number of matchings, the electricity flows, and the model self-sufficiency. The number of transactions in the LEC trading scheme (Fig. 55) reveal that in most scenarios (except B2), more trades are completed in the winter. At the first glance, these outcomes may seem unexpected since this season is generally characterized by a lower PV availability, which should be translated in less electricity available to share and, consequently, less transactions being matched. However, transactions are only scheduled when demand and supply can be matched and, in summer, due to the presence of PA and the high PV generation capacity considered, the amount of electricity made available to trade locally cannot be absorbed by the existing demand. This happens due to several reasons. First, as the agents' main goal is cost minimization, the AHEMS avoids scheduling loads in periods of higher local generation since these periods represent higher costs. Thus, in such periods, the existing demand is insufficient to match supply. Second, in this season, the levels of self- consumption are slightly higher; therefore, fewer buying requests are created and less transactions are matched. In turn, in winter, as locally self-generated electricity is less plentiful and, consequently, less of this energy can be used for self-consumption, the buying requests increase, and more matchings can be assigned.

In Scenario A, in the summer season, on average, about 13,000 transactions were daily made and in winter the number raises to almost 17,000. All these transactions are made between PA, since this scenario only includes these agents. In scenarios including VCA (B1, B2 and B3), the daily average number of transactions increases significantly since these agents are always available for matching, creating a greater pressure on the demand side. In Scenario B1, in summer, on average, more than 22,350 transactions are daily established, and, in winter, the number rises to 22,600. In Scenario B2, the daily average number of transactions is around 22,000 in summer and 17,500 in winter, while in Scenario B3 around 19,300 daily transactions are established in summer and over 20,400 in winter. As a result of CMA prioritization rules over VCA, most of the transactions in these three last scenarios are made between these agents. In Scenario B1, 83% of daily transactions in summer are made with VCA, which rises to 93% in Scenario B2 representing 71% of transactions in Scenario B3. Similarly, in winter, about 75% of daily transactions in Scenario B2 involve VCA, rising to 89% in Scenario B2 and decreasing to 60% in Scenario B3, which has a lower presence of these agents.

The electricity flows traded between agents in each scenario and season are shown in Table 37. The predominance of electricity flows exchanged in Scenario A stands out. In this scenario, together agents trade about 235kWh/week in summer and 349kWh/week in winter. Although these values may seem high, this setting is fully composed by PA, which make large amounts of self-produced electricity available for sale but also request larger amounts of electricity to supply more demanding loads (such as EV). In summer, less electricity is traded since larger shares of self-consumption are registered. The situation is reversed in the winter season, in which more transactions are matched, and larger amounts of energy are traded.

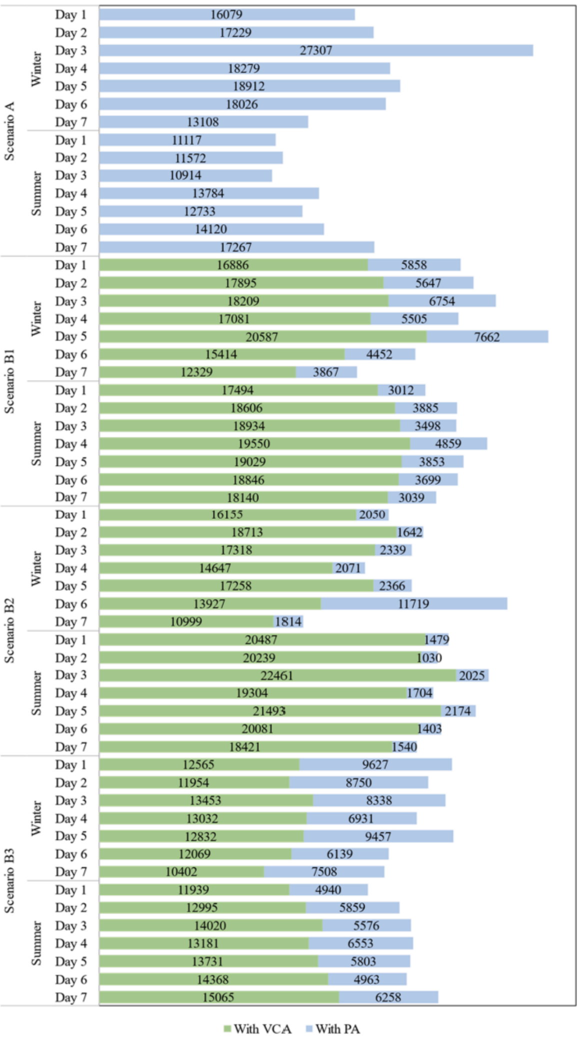
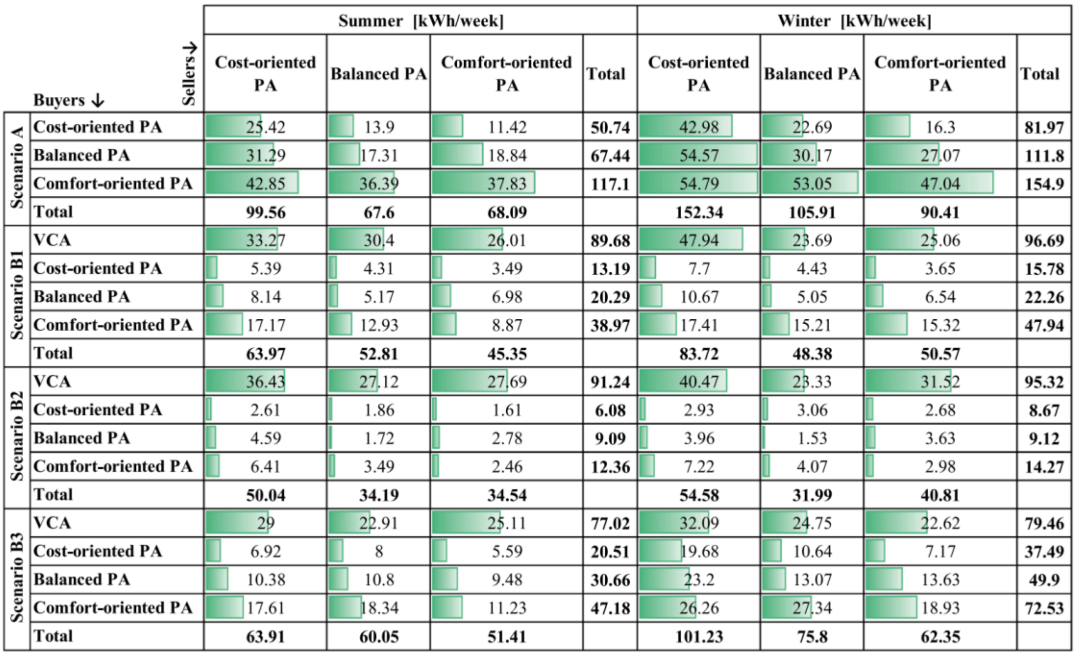


Fig. 55 Average number of transactions between LEC members.

Electricity flows within the LEC decrease considerably with the participation of VCA in the LEC. In Scenarios B1, B2 and B3, in the summer, 31.1%, 49.5% and 21.2% less electricity is exchanged between LEC members, respectively. Following the same trend, in winter, these three scenarios trade less 47.6%, 63.5% and 28.5%, respectively. This decrease is due to the presence of agents with a much lower electricity demand; thus, although more transactions are matched, less electricity is effectively traded. When investigating the biggest sellers and buyers, the results confirm the higher selling trend of cost-oriented PA, which are deeply involved in local exchanging as they seek to sell their self-generated and stored energy to obtain better cost solutions. The higher buying tendency of comfort-oriented agents can also be verified as these agents take advantage of their participation in the LEC energy exchanges to seek electricity at more competitive prices. The differences among agents with the same price sensitivity reflect the household size, i.e., PA establishing larger transactions correspond to larger households, with higher energy demand profiles or who have an EV with a larger battery capacity. The results must also be interpreted considering the scenarios regarding the presence of VCA versus PA.

Table 37 Electricity flows between agents over the different scenarios.



		Summer [kWh/week]				**Winter [kWh/week]**			
	Buyers ↓ / **Sellers→**	**Cost-oriented PA**	**Balanced PA**	**Comfort-oriented PA**	**Total**	**Cost-oriented PA**	**Balanced PA**	**Comfort-oriented PA**	**Total**
Scenario A	**Cost-oriented PA**	25.42	13.9	11.42	**50.74**	42.98	22.69	16.3	**81.97**
	Balanced PA	31.29	17.31	18.84	**67.44**	54.57	30.17	27.07	**111.8**
	Comfort-oriented PA	42.85	36.39	37.83	**117.1**	54.79	53.05	47.04	**154.9**
	Total	**99.56**	**67.6**	**68.09**		**152.34**	**105.91**	**90.41**	
Scenario B1	**VCA**	33.27	30.4	26.01	**89.68**	47.94	23.69	25.06	**96.69**
	Cost-oriented PA	5.39	4.31	3.49	**13.19**	7.7	4.43	3.65	**15.78**
	Balanced PA	8.14	5.17	6.98	**20.29**	10.67	5.05	6.54	**22.26**
	Comfort-oriented PA	17.17	12.93	8.87	**38.97**	17.41	15.21	15.32	**47.94**
	Total	**63.97**	**52.81**	**45.35**		**83.72**	**48.38**	**50.57**	
Scenario B2	**VCA**	36.43	27.12	27.69	**91.24**	40.47	23.33	31.52	**95.32**
	Cost-oriented PA	2.61	1.86	1.61	**6.08**	2.93	3.06	2.68	**8.67**
	Balanced PA	4.59	1.72	2.78	**9.09**	3.96	1.53	3.63	**9.12**
	Comfort-oriented PA	6.41	3.49	2.46	**12.36**	7.22	4.07	2.98	**14.27**
	Total	**50.04**	**34.19**	**34.54**		**54.58**	**31.99**	**40.81**	
Scenario B3	**VCA**	29	22.91	25.11	**77.02**	32.09	24.75	22.62	**79.46**
	Cost-oriented PA	6.92	8	5.59	**20.51**	19.68	10.64	7.17	**37.49**
	Balanced PA	10.38	10.8	9.48	**30.66**	23.2	13.07	13.63	**49.9**
	Comfort-oriented PA	17.61	18.34	11.23	**47.18**	26.26	27.34	18.93	**72.53**
	Total	**63.91**	**60.05**	**51.41**		**101.23**	**75.8**	**62.35**	

The energy system self-sufficiency expresses its level of autonomy from external suppliers and is computed as the ratio between the electricity self-consumed and the demand (Viti et al. 2020). In this model, electricity is withdrawn from the grid to be stored in EV and static batteries whenever this leads to lower costs for agents and used to supply loads (self-consumption). Therefore, the overall LEC self-sufficiency cannot be assessed directly, and the results presentedmust be understood as illustrative. The amount of electricity self-consumed within the LEC is different before and after the electricity trading scheme. Before trading, self-consumption is strictly narrowed to PA, which use part of their self-produced electricity to reduce external demand and minimize costs. When the electricity is shared between the LEC elements, these flows can also be counted as self- consumption since they are traded locally. Thus, in addition to the economic benefits for the participants, the proposed exchange scheme also contributes to improving the LEC levels of self-sufficiency in all the scenarios and seasons, as shown in Fig. 56.

In general, the scenarios with a greater presence of PA (A and B3) can reach higher levels of self-sufficiency due to the contribution of the individual self-consumption of these agents. The results also show the seasonal variation in PV availability, with higher levels of solar radiation (and therefore more energy available for consumption and exchanging) in summer and the greater scarcity in winter. Significant improvements are registered in the scenarios with VCA (B1, B2 and B3), due to the contribution of these agents to keep the electricity generated within the LEC boundaries.

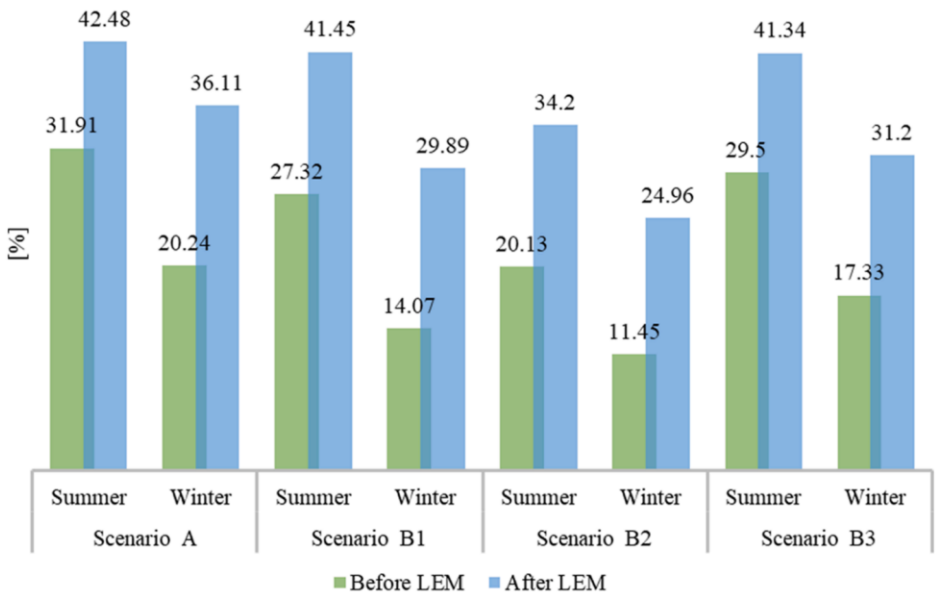


Fig. 56 LEC self-sufficiency.

Concluding remarks

The results indicate that, first, it is beneficial for participants to consume the self-generated electricity within the LEC boundaries, as it increases the community self-sufficiency while providing economic benefits for all members. By legal definition, LEC should not be created for profit-making; thus, local generation capacity should be projected to satisfy demand and not to generate surpluses. However, if any, generation surpluses should be traded locally, reducing the bi-directional electricity flows with the grid and the costs related with the payment of upstream network tariffs. The results showed that, although more transactions are made when vulnerable consumers are present, less electricity is effectively traded within the LEC, which reflects vulnerable consumers' lower energy demand. Thus, in LEC with significant surpluses, self- consumption maximization (which may not be the same of the agents individual cost minimization objective), the exploitation of storage systems and the inclusion of agents with higher energy demand are key to enhance self-sufficiency. Therefore, in addition to vulnerable consumers, the presence of more energy demanding users, as comfort-oriented ones, is also crucial to balance LEC demand and supply and enhance self-consumption. Second, although vulnerable consumers are economically benefited in all the proposed scenarios, the savings obtained may appear to be of little significance. The profiles characterized by reduced demand and lack of demand flexibility mean that the economic benefits of these agents, although existing, are not noteworthy. Though, given the social characteristics of this consumer segment, the savings reached can be enough to mitigate situations of energy poverty. To enhance this positive effect, future approaches should focus on the potential benefits achieved by such consumers under different pricing schemes as a way of improving the design of more adequate tariff structures to be implemented in electricity trading mechanisms aiming to fight *energy poverty. Third, relevant clues about how users with different features, roles and goals behave in a community setting are raised. From a general point of view, vulnerable consumers contribute to increase the amount of locally self-generated energy consumed within the limits of the LEC and benefit from the larger presence of prosumagers in the arrangement since more electricity is available for trading. In turn, prosumagers benefit differently from the community exchange scheme depending on their sensitivity to cost and comfort. The comfort-oriented agents achieve better results in situations where there is more surplus generation to sell/buy (more prosumagers). In turn, cost-oriented agents benefit from contexts where there is more demand as these agents seek to maximize their sales. These results can be used as guidelines for tuning LEC to achieve specific goals, such as maximizing self-consumption or self-sufficiency and reveal the need to include entities with complementary profiles and roles to balance demand and supplylocally.*

5. CONCLUSIONS AND FUTURE WORK

In a nutshell, considering the outcomes discussed in Chapter 5, the main conclusions of this work are as follows. First, despite some countries, as Portugal, are taking the first steps on collective energy initiatives, the main stakeholders are aware of the benefits of these projects and are committed to work collaboratively with policymakers to circumvent existing barriers and create an enabling framework for the dissemination of such projects. Second, different, and innovative business models may emerge in collective energy settings exploiting value-added products and services as long as the regulatory framework is in place and is flexible enough to support developers and investors in this regard. Third, from a modeling point of view, flexible simulation tools are requested to be able to simulate the complex decision-making process in an energy community setting facing dynamic pricing signals. Fourth, price signals may have a relevant role in the operation of a collective energy initiative since, although profit making is not the main purpose of energy communities, energy bill reduction and return on investment are key factors influencing community participation. Thus, relevant clues were raised on how community projects must be balanced in terms of participants (including cost-driven and not cost-driven) and objectives to pursue (cost minimization vs. self-consumption maximization). Fifth, the benefits of managing efficiently the existing energy resources in configurations with community members with different roles and features in the model (i.e., residential - vulnerable consumers, regular consumers, prosumers, prosumagers - non-residential, cross-sectoral, etc.) were showed and the role of collective energy initiatives on energy poverty mitigation was addressed.

This chapter focuses on highlighting the contributions of this thesis (section 5.1), answering the research questions raised in the Chapter 1 (section 5.2) and list future research avenues (section5.3).

5.1. CONTRIBUTIONS OF THE THESIS

In recent years, energy communities and collective self-consumption projects have emerged and gained relevance in both the scientific literature and at the political level, with a prominent place in the current European regulatory landscape. Despite this, and although some European countries have already a comprehensive national regulatory framework and a long tradition on CEI, innovative and successful projects are falling short, especially in countries with no tradition in such initiatives. In this context, this Ph.D. research aimed to draw a broad framework on collective energy projects to foster the discussion on several dimensions, including conceptualization, design, and modelling. Special focus was given to the modeling issues since the literature shows that technical, organizational, behavioral, and social dynamics in community settings, underlying an optimizing rationality, must be comprehensively simulated to assess the performance of different community configurations before putting them into practice.

To date, few works have modeled energy communities to explore, in an integrated way, the energy demand flexibility necessary for these projects to be self-sufficient. Thus, the first contribution provided by this Ph.D. work to the existing scientific literature on collective energy projects was the conceptualization and modeling of different aspects and activities on energy community settings, addressing several potentialities announced in European directives and still poorly promoted in real applications, by combining multiagent systems modeling and optimization techniques, i.e., the agents are endowed with optimization rationality simulating the deployment of energy management systems based on low-cost microprocessor hardware. This research argues that automated devices assisting decision-making (to both users and system operators) and optimizing energy resources management are key to fully exploit the potential ofdecentralized energy initiatives and promote a smart and efficient energy transition. In additionto the modernization of the buildings and equipment (to exploit features as on/off, settings adjustment, etc.), an upgrade of ICT technologies and communication and metering networks are required as well as the reinforcement of data management structures on the side of system operators. Only in this way it will be possible to bring “smartness” to these projects and explore demand side flexibility to its full potential, with advantages for users and system operators, thusopening of doors for the emergence of new business models and value streams.

The second main contribution provided by this research is the integration of different sectors exploiting the complementary nature of electricity demand into the modeling and the exploitation of a wide range of roles played by residential users in community settings since to date only residential settings, with very little variability in the modeled agents, was present in the literature. The rationale for including non-residential members is twofold: first, these members have distinctive flexibility profiles which can be beneficial in community contexts aiming to achieve some degree of self-sufficiency; second, energy communities have been described in literature as purely residential arrangements, although European directives include SMEs as potential members. Therefore, the modeling of non-residential members in a community setup aims to be a step forward in the existing literature as more mixed configurations are expected in the next future. In turn, residential users with different characteristics (e.g., prosumers, consumers, prosumagers, vulnerable consumers) were modeled to assess the extent to which energy communities are truly inclusive, as announced at the regulatory level, and how they are prepared for participating entities playing different roles. This research discusses and shows thatthe heterogeneity of participants with different (and complementary) demand profiles and flexibility, playing different roles (consumers, prosumers, prosumagers) and driven by different objectives, is beneficial to optimizing the use of collective resources, which should be considered by both policymakers and market stakeholders.

To keep coherence and ensure the validity of the modeling, and thus allow for the contributions described above, different dimensions that strongly influence energy demand flexibility were considered. First, the behavioral dimension associated with decision-making in residential settings. To address this issue, different consumption profiles (using energy audits data) were created and preferences regarding loads’ usage and daily practices (gathered through surveys) were considered into the modeling. Also, the sensitivity to cost and to discomfort was included in the modeling by considering three behavior profiles: cost-based, neutral, comfort-based, representing people willing to reduce energy costs, people willing to moderate energy costs andmaintain some comfort, and people privileging comfort, respectively. Second, the complexity and organizational dimensions related with SMEs. Commercial entities are part of real communities, and their demand profiles are quite diverse depending on the activity performed, the occupancy patterns and the use of different types of loads. Due to this heterogeneity and the lack of publicly available electricity consumption data, this sector is often excluded from modeling experiments. Still, examples of representative commercial activities were selected, and the assumptions maderegarding loads flexibility considered the services provided. Third, the technical dimension was considered throughout the modeling stage in all the demand, generation and storage resources as physically-based models, data gathered through energy audits and manufacturers’ specifications were assumed. Lastly, the social dimension was assured in the managing of multiple entities interacting in a collective setting by establishing relationships through a community coordinating entity.

The third contribution this research aims to provide to both academia and market stakeholders is the categorization of a set of energy community business model archetypes, shaping the discussion on the most promising business developments at the light of the current regulatory and technological frameworks. This contribution is expected to systematize innovative configurations announced in the European directives but still underdeveloped from the implementation point of view, highlighting their value-added as well as warning regarding the existing barriers hampering their implementation, ensuring they are safeguarded from a technical and regulatory point of view.

Lastly, this work intends to address the energy vulnerability issue as collective energy initiatives are being promoted as cost-effective energy solutions aimed at increasing local energy generation and self-consumption in a democratic and equity-enhancing way. CEI are expected to actively contribute to energy justice by engaging vulnerable and underrepresented groups of citizens and providing them access to cheaper renewable energy, energy efficiency and other valuable energy-related services, helping to alleviate situations of energy poverty. Notwithstanding the limited scope of the analysis performed, innovative projects emerging in Portugal showing how collective renewable energy projects can be designed to include vulnerable groups of citizens in the energy transition were found and the main barriers and success factors were discussed.

By proposing a comprehensive modeling approach for smart renewable-based energy communities, informed by a preliminary Problem Structuring methodology developed to clarify the framing of energy communities in the electricity sector, their relationships with other system stakeholders and the expectations of each of them regarding these projects, and considering a wide range of possible configurations and business models, this research expects to make a contribution to support policy and decision-makers in the design of new energy policies and regulations focused on energy communities, collective self-consumption arrangements and other decentralized structures with the aim to shape a more reliable and sustainable energy system, as well as to support market stakeholders in the identification of new business model opportunities and value streams.

5.2. ANSWERING THE RESEARCH QUESTIONS

This section aims to answer the four research questions enunciated to frame this research.

RQ1: *What is the influence of different demand-side flexibility profiles on the overall collective energy initiative performance?*

In collective settings, prosumers have access to extra sources of power generation that can be used to minimize their energy dependence on external suppliers, whereas consumers can profit from collective energy sources to minimize their energy bills. Also, demand-side flexibility is greater the more flexible loads (e.g., thermostatically controlled loads) and storage assets agents own. Thus, residential prosumager agents benefit the most (financially) from being in a collective energy project while vulnerable consumers, SMEs or cross-sectoral activities with reduced demand flexibility continue to benefit, but less, from these initiatives. In turn, the community system benefits from having only-consuming entities (either residential or commercial) that absorb local generation surpluses due to the matching of their activities with the PV generation period. By having these entities in the community, local self-consumption is maximized, lowering the transactions with external agents, and contributing to maximize the community self- sufficiency.

RQ2: *What decisions should be taken individually by each of the agents and what decisions should be taken at community level?*

At an individual level, agents should decide on their main goals and preferences regarding loads' usage. The adequate coordination of residential demand requires the consideration of several aspects ranging from demand needs, operational constraints, integration of intermittent renewable generation sources and increasingly dynamic retail pricing. Due to the complexity of these issues, automated home energy management systems are required to decide the load control actions to implement, reducing end-user's intervention while considering their preferences regarding energy services. Automated home energy management systems are assumed to be implemented in the residential agents' reasoning modules, aiming to schedule demand management actions, deciding on when and how to operate loads, informing agents about their expected electricity demand and/or supply deficit and generation surpluses. These decisions, which are made based on optimization algorithms, aim to individually minimize costs while accounting for the dissatisfaction such actions may cause to users (e.g., associated with changing the normal periods of appliances operation to profit from time-of-use tariffs). These decisions must be taken at an individual level to make sure households' energy usage behaviors and preferences are maintained.

In turn, in the proposed modeling, once the use of energy resources (loads, generation and storage) is individually decided, power profiles are sent to a community coordinator entity, endowed with management, coordination, communication, and optimization capabilities. The existence of this entity is foreseen in the regulatory framework of some countries, as Portugal. In addition to assist end-users' daily decisions (as the distribution of self-generated electricity), this entity is also responsible for ensuring the commercial relationships with network operators and establishing selling and procurement contracts with market and last resort retailers. In the model, this entity is in charge of managing collective generation and storage assets (if existing); based on these data and on the power profiles received from residential agents, it decides on how to use the collective energy resources (generation and storage), i.e., how to distribute the self- generated and stored energy and when to interact with network operators, represented by a retailer agent, to negotiate the remaining energy deficit or surplus. These decisions are taken considering the collective goals of the project which can be, for instance, the overall cost minimization (most common) or the overall self-consumption maximization. The overall project goals are established at the beginning of the project by the promoters. By concentrating these decisions at the coordinator entity level, impartiality, and equity in the distribution of energy resources is maintained.

RQ3: *How can conflicting preferences and goals be incorporated into the modeling process?*

The Problem Structuring methodology developed to clarify the framing of collective energyinitiatives in Portugal allowed to unveil the different perspectives of the stakeholders. These results, informed by literature review and direct contact with the main stakeholders (through online surveys and semi-structured interviews) allowed to draw conclusions on the goals of different actors regarding community projects which were represented in simulation. In addition, the exploitation of residential agents' conflicting goals (sensitivity to cost and comfort), revealedto benefit differently these agents. On average, the comfort-oriented agents achieve better results in situations where there is more surplus generation to sell/buy (more prosumers/ prosumagers in the model). In turn, cost-oriented agents benefit from contexts where there is more demand as these agents seek to maximize their sales. These results can be used as guidelines for tuning CEI seeking to achieve specific goals, such as maximizing self-consumption or self-sufficiency and reveal the need to include entities with complementary profiles and roles to balance demand and supply locally.

RQ4: *What is the best configuration of the energy community from a modeling and a real implementation point of view considering the current regulatory framework and the emerging business models?*

From a modeling point of view, both energy communities based on individual and collective generation and storage assets showed to be relatively easy to simulate. Configurations with individual distributed generation and storage systems are marked by an additional number of devices which need to be considered and which give rise to a slightly higher computational effort. However, the comparison (for the same number of agents) with a centralized configuration is negligible. The inclusion of a coordinating entity, although it creates an additional layer of decision-making and complexity, helps to clarify the relationships established between community members and with retailers.

5.3. FUTURE WORK

This research started in a time when no legal definition for energy communities existed and has followed and evolved at the same time as the European and national regulatory frameworks in this area were created. Therefore, although this research aimed to open doors to the conceptualization and modeling of smart renewable-based energy communities, the challenges in this area have only now begun to emerge.

From the obtained results, the following research directions are raised.

As for the chosen modeling approach, MAS tools proved to be adequate to deal with both the dynamics and complexity of energy communities with many different agents and energy assets as well as to incorporate the optimization component representing the rationality of the agents. However, a limitation of this research is related to the validation of the results and conclusions drawn. Despite the valuable insights this work unveils, it presents conceptual collective configurations, supported by a set of assumptions informed by the existing literature on energy communities and the authors experience on smart grids, as well as behavioral and technical demand response research and practice. As the configurations this work aims to model have notbeen materialized, there is no real basis for comparison that allows to discuss how far the model outcomes are to represent the behavior of the target system (correctness) or to what extent the conceptual framework of the model and the target system match (consistency). Therefore, results must be understood as experimental and exploratory. In future approaches, data from real energy communities can be used to calibrate and validate the modeling results.

Additionally, in the current versions, the modeling assumes that agents decide based on perfect forecasts. In fact, there may be considerable differences in renewable generation, prices (if more dynamic pricing schemes are considered) and residential demand. Thus, accounting for the robustness of solutions in face of different uncertainty sources is worth further study. Also, the results obtained are biased by the time-of-use tariff used to reproduce the grid price signals. This tariff was designed considering the current characteristics of the electrical system and not a future scenario largely dependent on renewables. For this reason, the results should be interpreted as illustrative and future approaches should focus on the design of tariff schemes that more closely reproduce what is expected to be the power systems of the future.

A final consideration regarding modelling concerns the need to introduce further diversity, either by considering agents with different characteristics (different SMEs, industry, etc., different loads and generation assets) or by exploiting larger settings (more agents). Heating and cooling district networks, one of the main issues considered in the creation of positive energy districts (PEDs) - a growing trend at European level and to where CEI are rapidly moving – can also be exploited in future approaches. Additionally, the optimization framework can be refined, for instance, to consider batteries' degradation effect, which is not directly considered in this work but can become an increasingly relevant issue as storage devices become more affordable. This effect can be used in the optimization approach by, for instance, considering an additional term in the dissatisfaction objective function, penalizing the number of charging/discharging cycles.

Regarding the regulatory framework itself and the dissemination of energy communities, given the current geo-political circumstances and the European focus on the need to reduce dependence on fossil sources and accelerate the energy transition, great expectations are being created around these new energy models. A proof of this growing interest is the considerable increase in funding available to support the dissemination of CEI. For instance, the first call to support the implementation of Renewable Energy Communities and Collective Self-Consumption was launched recently in Portugal under the Recovery and Resilience Program with an amount of 30M€. This call will reinforce the capacity in self-consumption and CER in the residential, public administration and commercial sectors by at least 93 MW. The creation of this investment lines will certainly reinforce the interest of different stakeholders in these models and may give rise to new business models that must be monitored.

In addition, as the regulatory framework seems to be stabilizing in most European countries and the first projects start to emerge in the field, it becomes increasingly relevant to assess the implementation costs not only in terms of the required technical infrastructure (i.e., PV panels, smart meters, etc.), but also including the costs incurred by the community coordinating entity ("entidade gestora do autoconsumo" in Portuguese). This analysis is relevant to further realize the potential benefits of collective energy projects for members through a cost-benefit perspective.

Lastly, it is relevant to analyze what the emergence of concepts such as *positive energy districts,* defined as energy-efficient urban areas with net-zero energy imports and striving towards local renewable energy surpluses, mean for energy communities. The growing tendency to look at neighborhoods and cities in an integrated way, considering energy efficiency needs (buildings renovation, replacement of equipment and energy vectors, etc.), in addition to energy generation, has led to an emerging focus on positive energy districts which are understood as fundamental to cities' energy system transformation towards carbon neutrality. Collective energy initiatives can be complementary to positive energy districts in the sense that they complement the energy generation issues and boost the required citizens engagement. However, CEI business models should be rethought so that the profits obtained are channeled towards energy efficiency measures which may attract different stakeholders.

APPENDIX 1

This appendix presents the script of the online survey used to exploit stakeholders' expectations and perceived implementation barriers regarding energy communities in Portugal.

INVITATION EMAIL

As explained before, participants were informed and invited to participate in this study. Below, the email sent is presented.

Assunto: Convite para participar num estudo sobre comunidades de energia e iniciativas de autoconsumo coletivo

Caro(a) Participante,

Convidamo-lo a participar num estudo que visa ajudar os órgãos de decisão/planeamento/regulação a perceber como os modelos coletivos de energia (comunidades de energia e projetos de autoconsumo coletivo) estão a ser implementados em Portugal. Para isso, pretendemos reunir a opinião dos diferentes stakeholders com interesse nesta temática, pois consideramos que podem trazer pistas relevantes para facilitar o processo de aceitação e implementação destas iniciativas.

Este estudo é realizado no âmbito de um projeto de investigação do INESC Coimbra e da investigação conducente á elaboração de uma tese de doutoramento em Sistemas Sustentáveis de Energia na Universidade de Coimbra.

Porque foi selecionado(a)?

Foi selecionado(a) devido à sua colaboração com uma entidade com interesse nesta problemática. A sua participação neste estudo permitir-nos-á obter perspetivas valiosas para o apoio à definição de políticas nacionais nesta matéria.

A sua participação é voluntária e sigilosa. As suas respostas serão apenas identificáveis pela equipa de investigação que se compromete a tratá-las de forma confidencial. Poderá abandonar o questionário em qualquer momento do processo. Contudo, as suas respostas serão apenas consideradas se responder a todas as questões do questionário.

Como decorrerá o estudo e o que envolve?

Algumas questões de resposta aberta ser-lhe-ão colocadas. Estas questões pretendem avaliar as motivações e expectativas das entidades em relação à difusão de comunidades de energia e projetos de autoconsumo coletivo em Portugal, assim como compreender as barreiras percebidas pelas entidades à implementação destes projetos.

Pedimos-lhe que preencha o questionário eletrónico e submeta as respostas nas próximas 2 semanas.

O que acontecerá aos resultados deste estudo?

Os resultados serão possivelmente, apresentados em artigos e conferências científicas.

Como aceder ao questionário?

Por favor siga o link abaixo para iniciar a sua resposta ao questionário:

Clique aqui para aceder ao inquérito:

https://ls.uc.pt/index.php/278821?token=BdwqEuiKRRv5EVZ&lang=pt

Se não quiser participar deste inquérito e não deseja receber mais convites clique p.f. na seguinte ligação: https://ls.uc.pt/index.php/optout/tokens/278821?token=BdwqEuiKRRv5EVZ&langcode=pt

Informações

Para esclarecer qualquer dúvida ou obter mais informações sobre o estudo, por favor, entre em contacto com os autores do estudo:

Inês Reis (inesfreis@deec.uc.pt), Marta Lopes (mlopes@esac.pt), Carlos Henggeler Antunes (ch@deec.uc.pt)

Antecipadamente gratos pela sua colaboração.

SURVEY SCRIPT

The online survey was implemented in LimeSurvey, a simple, quick and anonymous online survey tool (https://www.limesurvey.org/en/) and included a set of five questions. The script is presented as follows.

Bem-vindo(a)

As questões seguintes têm o objetivo de recolher a sua opinião pessoal enquanto representante de uma entidade com interesse na implementação de iniciativas coletivas de energia em Portugal.

Por favor, responda a todas as questões apresentadas.

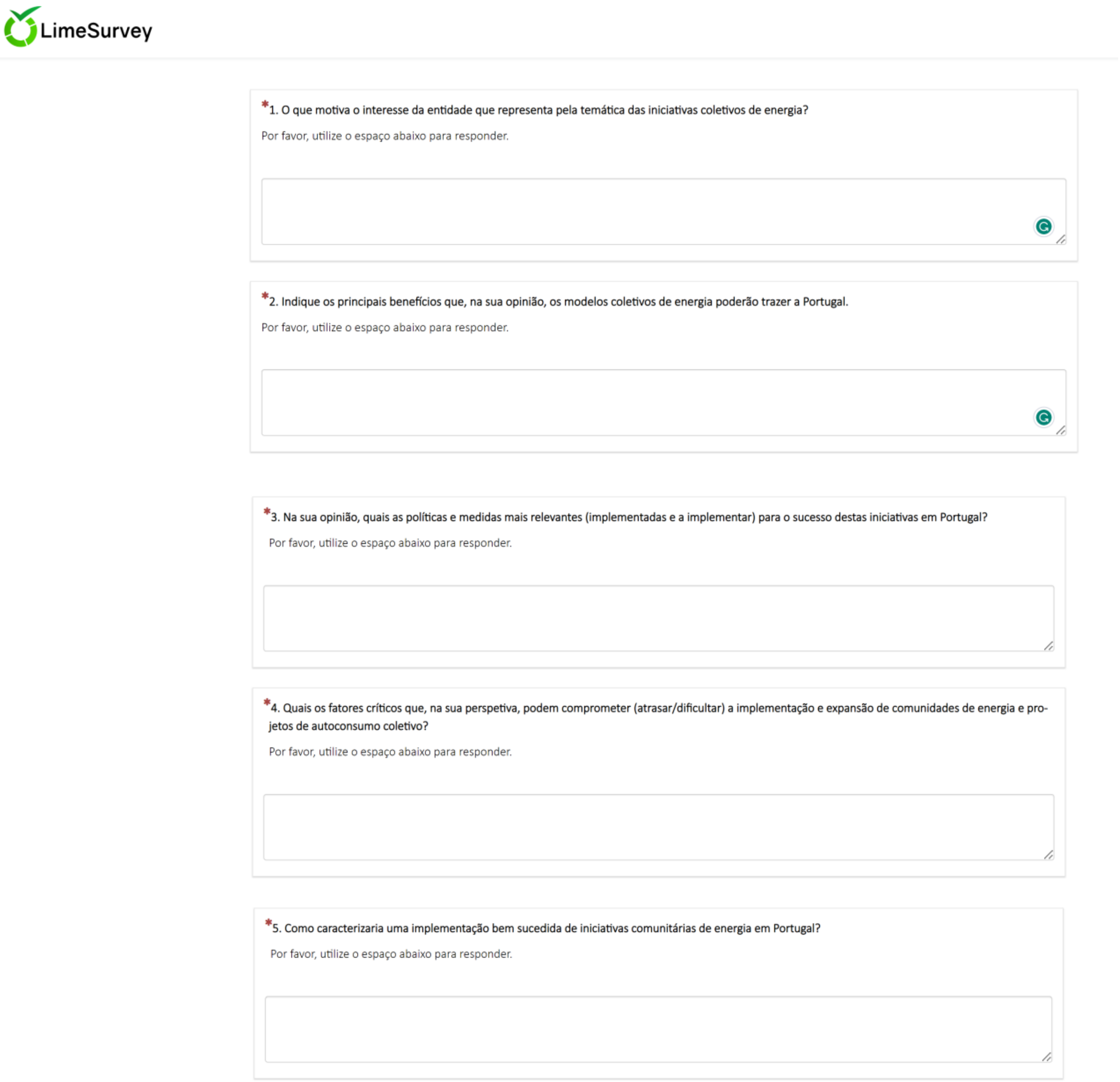
Relembramos que a sua participação é voluntária e sigilosa. As suas respostas serão apenas identificáveis pela equipa de investigação que se compromete a tratá-las de forma confidencial. Poderá abandonar o questionário em qualquer momento do processo, contudo as suas respostas serão apenas consideradas se responder a todas as questões do questionário.

Para esclarecer qualquer dúvida ou obter mais informações sobre o estudo, por favor, entre em contacto com os autores:

Inês Reis (inesfreis@deec.uc.pt), Marta Lopes (mlopes@esac.pt), Carlos Henggeler Antunes (ch@deec.uc.pt)

Mais uma vez agradecemos a sua colaboração!

Existem 5 perguntas neste questionário.



*1. O que motiva o interesse da entidade que representa pela temática das iniciativas coletivos de energia?

Por favor, utilize o espaço abaixo para responder.

*2. Indique os principais benefícios que, na sua opinião, os modelos coletivos de energia poderão trazer a Portugal.

Por favor, utilize o espaço abaixo para responder.

*3. Na sua opinião, quais as políticas e medidas mais relevantes (implementadas e a implementar) para o sucesso destas iniciativas em Portugal?

Por favor, utilize o espaço abaixo para responder.

*4. Quais os fatores críticos que, na sua perspetiva, podem comprometer (atrasar/dificultar) a implementação e expansão de comunidades de energia e projetos de autoconsumo coletivo?

Por favor, utilize o espaço abaixo para responder.

*5. Como caracterizaria uma implementação bem sucedida de iniciativas comunitárias de energia em Portugal?

Por favor, utilize o espaço abaixo para responder.

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