

Energy behaviour of selected agri-food business and potential savings from collective self-consumption

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Abstract— Agriculture and energy use are increasingly linked, especially as farms' energy needs grow. Renewable Energy Communities (RECs) help farmers, particularly in remote areas, access affordable surplus energy from other producers, while sellers gain extra revenue. This study focuses on the creation of RECs as a sustainable and economically viable solution for small and medium-sized agribusinesses to address their energy challenges. We explore the complementarities and potential benefits of RECs from the experience learned in the Tools4AgriEnergy project, using RECreation digital platform for the management of RECs. A case study is used, based on the Alqueva region in Portugal with six members that develop different agri-food sector activities. Using tariffs compliant with Portuguese regulations, results indicate that the development of self-consumption activities can achieve significant energy cost savings annually.

Index terms—renewable energy communities, collective self-consumption, agri-food sector, digital platforms.

I. INTRODUCTION

Agriculture and energy consumption are deeply intertwined, with rising energy demands in small and medium enterprises (SMEs) driven by the evolution of agricultural processes [1], [2], [3]. Farmers are increasingly adopting energy-efficient measures and renewable energy sources (RES) like photovoltaic (PV) systems to reduce costs and environmental impact [4]. Renewable Energy Communities (RECs) present a sustainable solution for farmers, especially those in remote areas or lacking resources to invest in Distributed Energy Resources (DERs) [5]. By joining RECs, farmers can access surplus energy at reduced costs, while sellers benefit from new revenue streams [6].

A REC key aspect is the energy complementarities of its members in energy generation and consumption. Complementary energy involves the strategic combination of energy sources and consumption patterns to ensure more stable and efficient energy management, tailored to specific operational needs. For instance, solar energy combined with batteries allows for energy storage during peak generation and its use during low-generation periods [7]. Similarly, floating solar and hydropower can complement each other by using water reservoirs to store and release energy as needed [8]. Another example is the combination of solar and biomass, where biomass can offset fluctuations in solar energy availability to meet demand consistently [9]. The study in [10] proposes a deterministic method for integrating solar PV, energy storage, and an anaerobic digestion biogas power plant to minimize energy imbalances while achieving the lowest Levelized Cost of Energy (LCOE). In terms of energy consumption, complementarities can maximize local energy usage by aligning operational processes with energy availability [11]. For example, in agribusinesses, irrigation systems can be scheduled to operate during periods of peak solar generation, maximizing self-consumption and reducing reliance on the grid. Cold storage facilities for perishable

goods can optimize energy use by pre-cooling during high-generation periods, reducing demand during off-peak hours [12]. Additionally, hybrid operations combining automated and manual labor can adapt energy-intensive tasks to periods of lower energy costs, improving overall efficiency [13]. These synergies ensure energy reliability while addressing strategic objectives like cost reduction and sustainability.

Thus, the main contributions of this study are:

- Address the gap, which is still limited in the literature, regarding the relationship between complementarities in the agri-food sector and energy use.
- Assess the energy exchanges, financial interactions, and potential savings of RECs for agribusinesses, using the RECreation digital platform [14] for REC management, and the Mixed-Integer Linear Programming (MILP) of its energy management system (EMS) for simulations studies.
- Support informed decision-making through the simulation of different scenarios in the agrifood sector.

II. COMPLEMENTARITIES IN AGRIFOOD SECTORS

Integrating complementary energy sources into agricultural practices offers benefits such as energy independence, cost savings, and environmental sustainability. By adopting renewable energy solutions, farmers can reduce reliance on traditional power grids and fossil fuels, leading to more resilient and eco-friendly operations [15], [16].

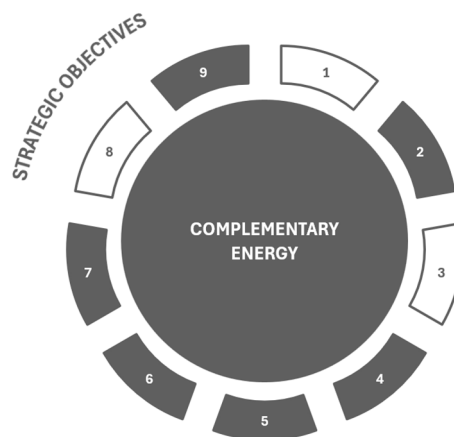


Figure 1 Strategic objectives for complementary energy

Complementary energy in energy systems address several strategic objectives:

1. Stabilizing energy generation to ensure continuity when renewable sources are not producing energy.
2. Maximizing the use of renewable energy sources.
3. Integration of other technologies, such as biomass, to

generate energy during periods of low renewable output.

4. Increasing operational efficiency across activities.
5. Exploring potential avenues for additional revenue generation.
6. Reducing dependency on grid energy.
7. Minimizing CO₂ emissions.
8. Identifying business model integrations or new models to guide infrastructure investments and operational strategies, maximizing economic and environmental benefits.
9. Reducing costs.

These strategic objectives are often connected. For the purposes of this paper, the focus mainly impacts the following objectives 2, 4, 5, 6, 7 e 9. In objective 4, for example, increasing energy efficiency reduces waste by optimizing the use of already available resources more intelligently, helping to balance energy supply according to seasonal, regional, and business-type variations.

To support the effective implementation of RECs, the RECreation digital platform [14] [17] enables the planning, operation and simulation of RECs, including local energy exchanges and financial interaction among members. Its EMS implements a MILP to dispatch the REC flexible assets and simulate local energy trades including the provision of flexibility to third parties [6] [18]. To optimize the energy use in agri-food businesses, RECreation also support Distributed Energy Resources (DERs) sizing based on the energy behaviour and opportunity costs of the members, leading to data-driven decision-making based on historical energy patterns. By embracing these community-driven approaches, agri-food businesses can create more efficient, sustainable, and economically viable energy solutions.

III. CASE STUDY

A. Case study description

The Tools4AgriEnergy [19] pilot concept, Figure 2, aims to establish a REC with EDIA—the company responsible for the development and infrastructure of Alqueva—serving as both the REC manager and investor. EDIA is deploying floating PV panels on water reservoirs to power their water distribution pumps and share the surplus generation with the REC members, that may also have their own generation facilities.

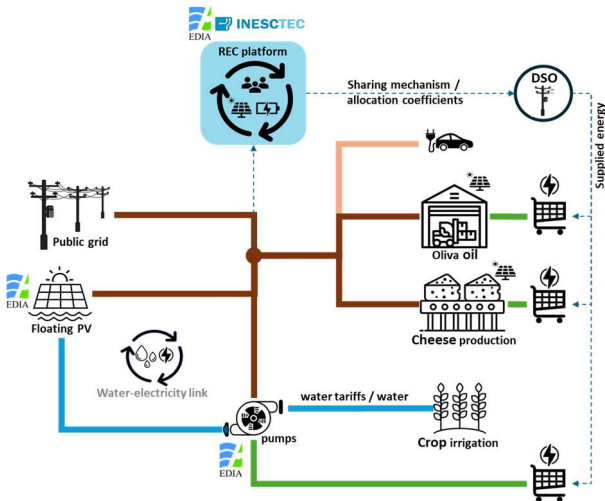


Figure 2. Synergies in the Tools4AgriEnergy pilot concept.

Based on historical data, and using RECreation, we assess

the complementarities of the potential REC members and possible investments to minimize the energy costs. To do so the options selected for the REC configuration are in Table I [20].

TABLE I RECREATION REC CONFIGURATION OPTIONS

Settings	Values
Type of Allocation Coefficients [21]	Proportional-to-Consumption
Local Price Calculation [20]	Intermediate Market Rate
Supply Voltage Level	Medium Voltage
Tariff Cycle	Four-Week Cycle
Use of Public Grid	Yes
Assets Ownership Percentage	100%
Supply Contracts	Indexed to The Spot
Network Access Tariff [22]	As per ERSE regulations
Self-Consumption Tariff	As per ERSE regulations
Contracted Power Tariff	As per ERSE regulations

Given the historical data, for the simulations, the contracted power (P_c) for each meter was defined from E_{max} , the maximum registered energy (kWh), as follows:

$$P_c = \frac{E_{max}}{0.25 h \times 0.9} \times 1.1 \quad (1)$$

Where 0.25 h represents the measurement period (equivalent to 15 minutes or a quarter of an hour), 0.9 is the power factor (or $\cos \varphi$) required since the contracted power is given in kVA and the energy data in kWh, and 1.1 accounts for a 10% tolerance factor.

The RECreation also requires the certified power P_{cert} used to ask for corresponding grid connection permits computed for each meter as follows:

$$P_{cert} = \frac{E_{max}}{0.25 h} \quad (2)$$

For the purposes of the simulation, the following variables are also defined below:

$$S_n^{CSC-ISC} = Rev_n^{CSC} - Rev_n^{ISC} \quad (3)$$

Where $S_n^{CSC-ISC}$ is the REC's savings computed by subtracting the collective REC revenue Rev_{CSC} with the sum of the revenues of the REC members under individual self-consumption, Rev_{ISC} . Then, the REC financial balance, FB_n includes the revenue from selling surplus energy within the REC and to the external aggregator and the contracted power tariff λ_n^{cont} :

$$Rev_n^{CSC} = FB_n - \lambda_n^{cont} \quad (4)$$

The energy E_n^{SALE} sold locally by member n with surplus energy for collective self-consumption of member m :

$$E_n^{SALE} = \sum_m E_{n,m}^{SALE} \quad (5)$$

where n refers to the DSO smart meters of the REC members.

The energy E_n^{PUR} purchased locally by member n with energy deficit from member m for collective self-consumption:

$$E_n^{PUR} = \sum_m E_{n,m}^{PUR} \quad (6)$$

Finally, the total energy E^{SLC} self-consumed in the REC is

given by:

$$E^{SLC} = \sum_m E_{n,m}^{PUR} = \sum_m E_{n,m}^{SALE} \quad (7)$$

From the pilot concept of Figure 2, a REC was simulated using the RECreation platform. The REC has members linked to 6 agri-food activities: Olive Oil, WDUtility (water distribution utility), Pistachios, Wines, Milk and dairy and Viticulture. The simulation considered real data collected by EDIA from local partners for a period of 1 year.

B. Results and analysis

Figure 3 shows the monthly percentual consumption of the REC members referred to the local generation set to 100%. Absolute values were avoided due to confidentiality issues.

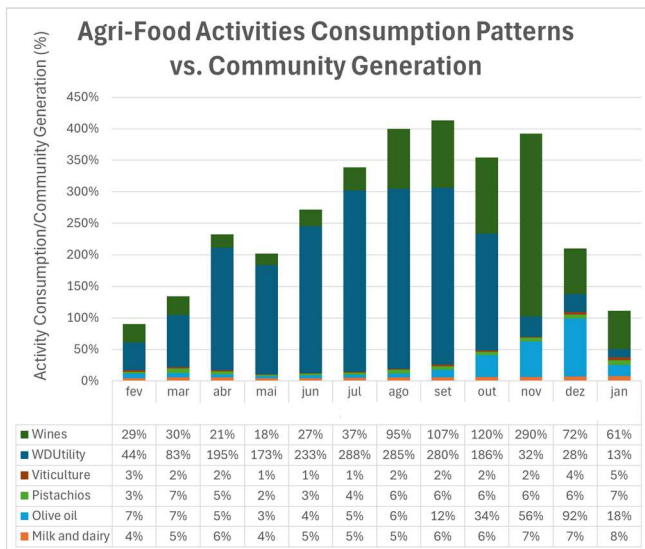


Figure 3 Agri-food activities consumption patterns

As shown, utilities electricity consumption can reach high levels especially in warmer months, with 288% in July and above 280% from until September, revealing a strong seasonal demand, possibly linked to intensive irrigation usage that take place during these warm period. WDUtility consumption drops sharply to 13% in January, reflecting reduced energy needs in winter months. The high summer consumption suggests potential efficiency improvement, by increasing the local PV generation, optimizing the water and electricity consumption considering the local supply and watering requirements.

Wines' production consumption increases significantly from 95% in July to 290% in October, suggesting also a strong seasonal pattern, possibly tied to the period of harvest and processing activities. In January and February, electricity consumption is relatively low, opening potential for energy storage (although seasonal storage may be economically unfeasible), or integration with complementary sources in case of own generation surplus. Wines peak in October-November, while Olive Oil peak later in December, suggesting that these activities might not compete directly for local generation.

Olive oil consumption starts increasing in the second half of the year, peaking at 92% in December, suggesting strong energy needs for processing and extraction activities. Energy use is significantly lower in January, following its December

peak. Since Olive Oil peak after Wines, again there seem to be opportunities for staggered energy consumption, reducing demand pressure during months with the highest demands.

Pistachios electricity consumption shows a slight increase between July and October but remains relatively low compared to other activities. It is relatively constant throughout the year (3%-7%), meaning it does not contribute significantly to seasonal energy imbalances and there may be opportunities to integrate other sources such as biomass. The stable consumption of Dried Fru with activity could help improve energy predictability and act as a baseline consumption load for the REC. The predictable and moderate energy demand makes this activity less dependent on seasonal adjustments.

Milk and dairy exhibits stable energy consumption (between 4%-8%) throughout the year, with minor fluctuations. Similarly, as Pistachios, this activity does not show significant seasonal variation, allowing for better forecasting but lower complementarities. Such stable activities may benefit from larger PV and storage to flatten the net supply.

Viticulture consumption maintains the lowest and most stable energy consumption of all sectors (between 1%-5%), indicating a lower reliance on electricity, or mainly only indirect through water pumping, which consumption is reflected in the WDUtility measurements. With such low energy usage, it does not contribute directly to energy surplus or deficit periods. The activity's low energy demand suggests flexibility potential, meaning its operations could be adjusted to accommodate energy peaks or optimize self-consumption strategies. However, the impact on the electricity needs for water pumps must not be forgotten.

Figure 4 represents the energy exchanges among the REC members and their financial results, i.e., savings (S), financial balance (FB), energy sold (E-sale), energy purchased (E-pur) and self-consumed energy (E-slc) according to equations (3) to (7), computed also with the RECreation platform, and presented as percentages of participation of members and their activities in the REC.

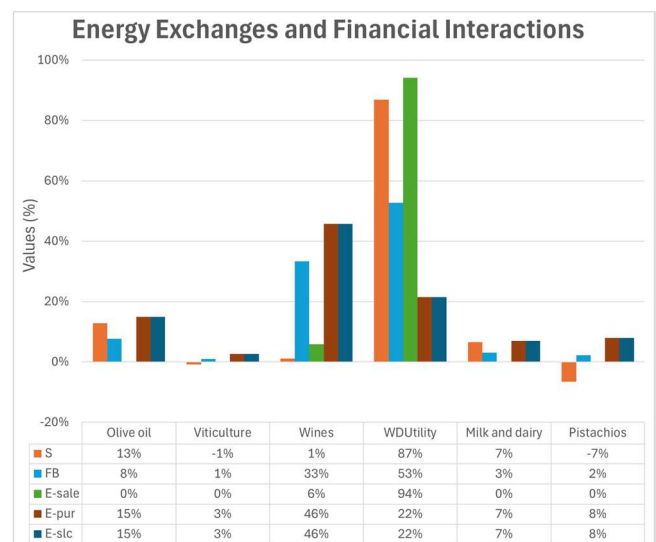


Figure 4 Energy exchanges and financial interactions

To evaluate these results for each activity and members, the following analysis was divided into three parts: energy exchanges, financial impact, and participation in savings.

1) Energy exchanges

Regarding energy exchange, WDUtility stand out as the largest consumer within the REC but also shared 94% of energy, corresponding to different behaviors depending on the temporal periods considered.

Wines have a high level of shared energy received (46%), indicating that it heavily depends on the REC's surplus energy. Despite this, it provides 6% of energy, contributing relatively little to the system.

Pistachios and Olive Oil receive 8% and 15% of shared energy, respectively, demonstrating that they consume part of the REC's surplus energy. However, these activities do not contribute to the surplus energy.

Milk and dairy and Viticulture have low participation in surplus energy sharing, suggesting that they have a more stable consumption pattern.

2) Financial impact

Following for the financial impact analysis, WDUtility has a balance of 53%, the highest among all sectors, suggesting that it generates significant revenue from selling its surplus energy, with a strong financial impact within the REC.

Wines has a balance of 33%, indicating that despite consuming a considerable amount of energy from the REC, it still manages to maintain a relatively positive financial balance.

Olive oil and Pistachios have lower values, 8% and 2%, respectively, indicating that they do not have a significant financial impact within the REC.

Viticulture and Milk and dairy have the lowest values, 1% and 3%, respectively, suggesting a low financial interaction within the collective self-consumption model.

3) Savings participations

The REC's savings participations show that WDUtility has the highest savings, 87%, indicating that it benefited the most financially from participating in the collective self-consumption model.

Olive oil and Milk and dairy also had positive savings, 13% and 7%, respectively, demonstrating that they gained some advantage by sharing energy within the REC.

Wines has savings between 0 and 1%, meaning that it obtained virtually no significant financial benefits.

Pistachios and Viticulture show negative values, -7% and -1%, respectively, suggesting that under current conditions, these sectors do not seem to be taking advantage of the REC model, as they present negative savings.

C. Qualitative analyses

As a general and somehow expected conclusion, dry and wet seasons tend to present opposite behaviors. In the dry season it is common to have more PV generation and more consumption due to watering pumps and thermal loads, and a reduced agricultural activity intensity since crops and farm processing usually has not started yet. In the wet season, there is usually lower PV generation, lower consumption since watering is not needed, and a higher agricultural activity intensity resulting in greater energy consumption of agrifood

industries. This is summarized in TABLE II.

TABLE II GENERAL PATTERN OF ENERGY BEHAVIOUR BY SEASON

Dry Season	Wet Season	Behavior
▲	▼	Generation from photovoltaic panels
▲	▼	Consumption by pumping systems
▼	▲	Agricultural activity intensity

Comparing energy consumption patterns identified for specific types of agricultural activities allows to make strategic decisions about including, replacing or supporting members with similar agricultural operations. By aligning members with compatible energy profiles, the REC can enhance overall efficiency and effectiveness.

For example, in this pilot concept, since irrigation occurs predominantly during dry months (typically summer), and agribusinesses reach peak activity afterwards, it is important to pinpoint the phases when:

- The electricity demand of the pumping system decreases;
- Photovoltaic electricity generation remains high;
- Local businesses' energy consumption increases.

By analyzing the energy consumption profiles of businesses that could utilize the surplus electricity, the focus can shift to periods of heightened activity, particularly when irrigation needs are minimal or non-existent (post-summer). For example, this helps define the window of complementary energy, namely, the periods when:

- There is a PV surplus (exceeding the needs for pumping);
- Local business demand increases (after the irrigation period).

To simplify this analysis, where the conditions are most favourable, some approaches can be defined. For example, thus:

- A smaller absolute error might reflect greater complementary energy;
- A lower correlation also might indicate higher complementary energy.

TABLE III summarizes in a simple way of using energy consumption and generation patterns through agricultural activities to find energy complementarities. By integrating these objectives, conditions and considerations, agri-food businesses can better align their energy use with renewable generation, optimize costs, and strengthen their energy resilience while fostering sustainability.

TABLE III ASPECTS TO FIND ENERGY COMPLEMENTARITIES

Aspect	Description
Critical phases for energy complementarities	- Decrease in the electricity demand of the pumping system. - High photovoltaic energy generation. - Increase in local businesses' energy consumption.
Window of energy complementarities	- PV surplus exceeding the pumping system's needs. - Increased local business demand after the irrigation period.
Approach to defining greater energy complementarities	- Lower absolute error between energy generation and consumption, indicating higher complementarity. - Lower correlation between generation and consumption, suggesting greater complementarity.

As shown previously energy complementarity can occur when the different consumption patterns of agricultural activities align with the appropriate periods of renewable energy generation in the REC. If the renewable generation of this REC follows a predictable seasonal pattern that meets the agricultural production requirements, complementarity opportunities can be improved to reduce waste and dependence on the power grid. In this context, the understanding of improving local energy use was based on four key quadrants (flexibility or load redistribution, energy storage, energy exchanges, complementary sources) as shown in the Figure 5 and were applied methodologically in a basic manner in the analysis of the section B, Results and analysis.



Figure 5 Improvements to complementarities

The analyses using these four quadrants were intended to generate suggestions and were conducted at a superficial level. More specific and detailed evaluations are required for a comprehensive or specific assessment.

1) Flexibility or Load Redistribution

It could be effective if consumption patterns were predictable, demand could be adjusted without compromising operations, and financial incentives existed for shifting energy loads to periods of lower demand.

2) Energy Storage

It could be used if significant discrepancies between energy generation and consumption occurred, requiring enhanced self-sufficiency and resilience. Its implementation would be particularly relevant if economic and technical conditions justified the investment in storage systems.

3) Energy Exchanges

It could be feasible if an appropriate infrastructure were available, complementary consumption profiles existed among different consumers, and economic advantages could be gained from redistributing excess energy within the community.

4) Complementary sources

The integration of alternative energy sources would be necessary if local renewable generation were insufficient to meet demand. This strategy would require the availability of complementary energy sources, along with technical and financial viability assessments to ensure a cost-effective and reliable energy supply.

IV. CONCLUSION

The study underscores the transformative potential of RECs in addressing energy challenges in agri-food businesses, including complementary energy. The results obtained through the RECreation platform show that agri-food companies can achieve cost savings, improve energy resilience and adopt sustainable practices. The Alqueva case study highlights tangible benefits, including annual savings for REC participants. Future efforts should focus on scaling REC adoption and refining simulation tools to maximize benefits for the agri-food sector. However, a more detailed analysis may be required for this purpose, considering the expertise within each agricultural activity.

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REFERENCES

- [1] "EU agricultural outlook 2024-35: A resilient sector adapts to climate change, sustainability concerns, and shifting consumer demand - European Commission." Accessed: Feb. 04, 2025. [Online]. Available: https://agriculture.ec.europa.eu/news/eu-agricultural-outlook-2024-35-resilient-sector-adapts-climate-change-sustainability-concerns-and-2024-12-11_en
- [2] F. Mocera, A. Somà, S. Martelli, and V. Martini, "Trends and Future Perspective of Electrification in Agricultural Tractor-Implement Applications," *Energies*, vol. 16, no. 18, Art. no. 18, Jan. 2023, doi: 10.3390/en16186601.
- [3] M.-A. Kourtis *et al.*, "Energy Efficiency in Agriculture through Tokenization of 5G and Edge Applications," *Energies*, vol. 16, no. 13, Art. no. 13, Jan. 2023, doi: 10.3390/en16135182.
- [4] "Agrivoltaics: Combining solar panels and agriculture into a win-win result." Accessed: Feb. 04, 2025. [Online]. Available: <https://www.statkraft.com/newsroom/explained/agrivoltaics-combining-solar-panels-and-agriculture/>
- [5] S. O. M. Boulanger, M. Massari, D. Longo, B. Turillazzi, and C. A. Nucci, "Designing Collaborative Energy Communities: A European Overview," *Energies*, vol. 14, no. 24, Art. no. 24, Jan. 2021, doi: 10.3390/en14248226.
- [6] R. Rocha *et al.*, "A Three-Stage Model to Manage Energy Communities, Share Benefits and Provide Local Grid Services," *Energies*, vol. 16, no. 3, Art. no. 3, Jan. 2023, doi: 10.3390/en16031143.
- [7] A. Zahedi, "Maximizing solar PV energy penetration using energy storage technology," *Renewable and Sustainable*

- Energy Reviews*, vol. 15, no. 1, pp. 866–870, Jan. 2011, doi: 10.1016/j.rser.2010.09.011.
- [8] G. Kakoulaki *et al.*, “Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe,” *Renewable and Sustainable Energy Reviews*, vol. 171, p. 112989, Jan. 2023, doi: 10.1016/j.rser.2022.112989.
- [9] M. C. Cameretti, “Modelling of a Hybrid Solar Micro-Gas Turbine fuelled by biomass from agriculture product,” *Energy Reports*, vol. 6, pp. 105–116, Feb. 2020, doi: 10.1016/j.egy.2019.10.026.
- [10] C. S. Lai and M. D. McCulloch, “Sizing of Stand-Alone Solar PV and Storage System With Anaerobic Digestion Biogas Power Plants,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 3, pp. 2112–2121, Mar. 2017, doi: 10.1109/TIE.2016.2625781.
- [11] B. V. Miranda, G. F. A. Monteiro, and V. P. Rodrigues, “Circular agri-food systems: A governance perspective for the analysis of sustainable agri-food value chains,” *Technological Forecasting and Social Change*, vol. 170, p. 120878, Sep. 2021, doi: 10.1016/j.techfore.2021.120878.
- [12] E. Beard, “Using Cold Storage as a Battery: A Smart Energy Strategy,” *Leading Edge Energy*. Accessed: Feb. 04, 2025. [Online]. Available: <https://www.leadingedgeenergy.com.au/blog/using-cold-storage-as-a-battery-a-smart-energy-strategy-for-cold-storage-businesses/>
- [13] W. Chen, J. Wang, G. Yu, and Y. Hu, “Energy-Efficient Hybrid Flow-Shop Scheduling under Time-of-Use and Ladder Electricity Tariffs,” *Applied Sciences*, vol. 12, no. 13, Art. no. 13, Jan. 2022, doi: 10.3390/app12136456.
- [14] T. Tavares *et al.*, “Operation and simulation of a renewable energy community based on a local post-delivery pool market,” in *2023 19th International Conference on the European Energy Market (EEM)*, 2023, pp. 1–6. doi: 10.1109/EEM58374.2023.10161761.
- [15] “3 unusual ways renewable energy is giving farming a boost,” *World Economic Forum*. Accessed: Feb. 07, 2025. [Online]. Available: <https://www.weforum.org/stories/2023/10/agriculture-farmers-renewable-energy/>
- [16] J. Jurasz, F. A. Canales, A. Kies, M. Guezgouz, and A. Beluco, “A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions,” *Solar Energy*, vol. 195, pp. 703–724, Jan. 2020, doi: 10.1016/j.solener.2019.11.087.
- [17] *INESC TEC RECreation. Platform for the management of energy communities — Proposta Projetos Em Copromoção*. INESC TEC. [Online]. Available: <https://www.inesctec.pt/en/projects/recreation>
- [18] L. Rodrigues, J. Mello, K. Ganesan, R. Silva, and J. Villar, “Building Flexibility Bidding Curves for Energy Communities,” in *2024 20th International Conference on the European Energy Market (EEM)*, Jun. 2024, pp. 1–6. doi: 10.1109/EEM60825.2024.10608874.
- [19] “Tools4AgriEnergy.” Accessed: Nov. 22, 2024. [Online]. Available: <http://www.tools4agrienergy.com/>
- [20] J. Mello, C. de Lorenzo, F. A. Campos, and J. Villar, “Pricing and Simulating Energy Transactions in Energy Communities,” *Energies*, vol. 16, no. 4, Art. no. 4, Jan. 2023, doi: 10.3390/en16041949.
- [21] J. Mello, J. Villar, R. J. Bessa, A. R. Antunes, and M. M. Sequeira, “Decarbonized and Inclusive Energy: A Two-Fold Strategy for Renewable Energy Communities,” *IEEE Power and Energy Magazine*, vol. 22, no. 4, pp. 49–63, 2024, doi: 10.1109/MPE.2024.3396442.
- [22] “ERSE - Tarifas e preços - eletricidade.” Accessed: Oct. 02, 2021. [Online]. Available: <https://www.erse.pt/atividade/regulacao/tarifas-e-precos-eletricidade/#periodos-horarios>