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Optimising multi-target policies with Machine Learning: the case of Agro-energy

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Abstract

The paper applies Machine Learning techniques to FADN farm-level data for predicting the factors that influence the likelihood of establishing a renewable energy production activity in the Italian agricultural sector. Despite policy efforts, concerns remain, in fact, that farmers may miss out on opportunities in the renewable energy market. ML's predictive capacity can offer valuable insights for evidence-based policy design supporting sustainable energy transitions in the next CAP after 2027.

Keywords: *Machine Learning; farm-level data; agroenergy (maximum 6).*

1. Introduction

The EU set an ambitious objective of becoming a climate-neutral economy by 2050. Therefore, increasing renewable energy is a straightforward, tangible aim of the EU political agenda. The REPowerEU[1] strategy, within the updated EU Industrial Strategy, highlights the urgency of a green and digital transition, with renewable energy sources (RES) central to reducing dependence on fossil fuels (EC, 2022a; EC, 2022b; Roege et al., 2014). Within this framework, the agrifood ecosystem is expected to play a key role in renewable electricity generation, particularly in rural areas where renewable deployment may also foster socio-economic resilience (EC, 2024).

The linkage between agriculture and the energy system has been recognised as strategically important for renewable energy (Hahn *et al*., 2025). Several actors of the agrifood sector are involved in the so-called *agri-energy systems*, referring to energy obtained from renewable

[1] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, REPowerEU Plan.

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sources by agricultural, livestock, and forestry enterprises, as well as by the agro-industrial sector. How agriculture can provide such contributions is manifold, ranging from the installation of RES-based systems (e.g., photovoltaic, agri-voltaic, wind power) to the reuse of processing waste, by-products, and residues from production activities, and extending to the cultivation and processing of dedicated energy crops.

The 2023-2027 Common Agricultural Policy (CAP) encourages *agri-energy systems*, and, post-2027, it will continue offering a strong toolbox for improving the energy contribution of agrifood producers (EC, 2025). As reported by the EC, in the future "*the measures [*of National and Regional Partnership (NRP) Plans] *should focus on […] promoting renewable energy generation"* (COM(2025) 565 final, p. 18).

While agricultural policy agendas have accelerated the roll-out of RES, concerns remain regarding the possibility of producers missing out on the renewable energy market. Limited empirical evidence exists on the micro-level factors shaping farms' decisions to invest in renewable energy production.

For instance, Hahn et al. (2025) have recently studied the motivations behind investing in on-farm RES, but the analysis was limited to 172 farmers in Sweden and conducted by desk interviews (only 11 farmers with in-depth interviews). Wagner et al. (2024) have conducted a similar analysis by analysing the willingness to use agrivoltaics of 214 German farmers.

This paper contributes to this literature by applying machine learning (ML) techniques to farm-level data for predicting the factors that influence the likelihood of establishing a renewable energy production activity in the Italian agricultural sector. ML's predictive capacity can offer valuable insights for evidence-based policy design supporting sustainable energy transitions.

2. Data and research methodology

The analysis relies on the Italian Farm Accountancy Data Network (FADN) dataset (source: CREA, downloaded 2025), which comprises a representative sample of Italian farms within the agrifood sector. The FADN represents a distinctive micro-level dataset, being the sole official EU system that collects farm-specific information through standardised accounting rules applied uniformly across all Member States. We selected those farms which were present in the sample for the last two years covered by the dataset (2021-2022) for a total of 8,521 different individuals. The analysis relies on the 2022 wave (the 2021 wave has been used to calculate time lags). The target variable of our classification exercises is a dichotomous variable, which assumes the value one if the farm in 2022 had produced at least 1 EUR of renewable energy and zero otherwise. The dependent variable is, in fact, defined as the probability of producing within the holding at least 1 EUR of energy from renewable resources that can be sold (Gross Saleable Production). The Gross Saleable Production is the economic measure commonly used

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in agricultural economics, given that it accounts for the revenues strictly connected with the agricultural activity.

First, we implemented five different ML algorithms and a rebalancing procedure (He et al., 2008). We divided our sample into 70% for train and 30% for test. Moreover, for tuning parameters, we implemented a repeated five-fold cross-validation. Random forest outperforms all the other predictive algorithms.
Once verified that it is possible to make out-of-sample predictions regarding the probability for farms to engage RES production (i.e., technical feasibility), we moved our analysis to what the most predictive features are that lead to this choice. To do so, we ordered our features in terms of their predictive importance.

In addition, given that feature importance alone does not indicate the direction of the relationship between features and the target variable, to better understand whether a feature has a positive or negative impact on the predictions, we performed a SHAP (SHapley Additive exPlanations) analysis (Lundberg et al., 2017).
Lastly, to further analyse the relationship which occurs from the choice to invest in RES and our primary features, we performed several partial dependence plots (PDPs) which graphically disentangle the functional relation between features and our target variable.

3. Discussion of the results

The results show that it is possible to make out-of-sample predictions and diagnose the precise factors characterising agrifood producers involved in renewable energy production. In the case under analysis, the degree of involvement in diversification activities different from RES production, investments (i.e., the expense for plant and equipment) and whether or not the farm is managed by young entrepreneurs emerge as specific actors' characteristics that work successfully in tandem and have a beneficial effect when applied in producing RES.
The partial dependent plots show that farms more involved in diversification activities and making it the core strategy of the farm in terms of economic value are more likely to be involved in RES production. This positive link emerges also in the case of investments in new plant and equipment, suggesting the relevance of being a farm prone to invest in new technologies and facilities.
Results also show that farms with higher expenditures on agritourism services are more involved in RES production. Also in this case, it is possible to assume that those farms have a broadening diversification nature and follow a multi-activity and multifunctional strategy.

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4. Main conclusions

By investigating the key characteristics of farms that influence the RES's production effectiveness, the paper makes two main contributions to literature: one for researchers and practitioners interested in policy analysis, and another for policymakers working on agrifood and energy-related policies.

Starting from the policy analysis perspective, the main finding of this study is the validity of the ML to make out-of-sample predictions and thus predict which farms are more likely to be involved in RES production, even without having a specific target policy so far.

This evidence could inform policymakers of the validity of adopting such an approach to conduct an ex-ante preliminary investigation, during a policy design, on the potential beneficiaries of the policy that they would implement. Such a sort of policy validation might minimise inefficiency and political discontent. In the case of CAP, for example, this may help to reduce the perceived favouritism towards specific groups of producers.

The research also contributes to the political debate on the effects of RES-oriented policies in supporting sustainable economic development. The use of *agri-energy* supports, in fact, not only the diversification of renewable energy sources and the reduction of greenhouse gas emissions, but also the promotion of more sustainable agricultural practices, the closure of on-farm resource cycles, and the diversification of farm income. However, findings highlighted that producing RES is affected by farms' characteristics, especially those related to their historical engagement in diversification activities. The diversification variables are, in fact, related to previous years (lag variables), highlighting a sort of path dependence between producing RES and being involved in diversification activities, also those that are not explicitly connected to renewable energy. The choice of implementing a diversification strategy plays a significant role in farms' capacity to produce RES. Such evidence can be linked to the different forms of business adopted by producers and the fact that those that are already involved in diversification activities become more prone to exploiting revenue opportunities.

Conversely, however, diversified farms tend to be more market-oriented, to be less focused on agricultural production, and often to be bigger from both economic and physical perspectives. In the long run, such a dynamic might enhance a polarisation of the sector, putting small producers at a competitive disadvantage in terms of economic opportunities. This evidence invites, therefore, a reflection on how, and under which criteria, to incentivise RES production within the agrifood sectors. A concrete example is the new Italian D.l. 63/2024 of May 15, 2024 (*i.e., Decreto Agricoltura*) that introduced new limitations for the installation of new ground-mounted photovoltaic systems, as well as on the territorial expansion of existing ones, in

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agricultural areas.[2] For producers remain the possibility of adopting agro-photovoltaic systems remains, which allow for agricultural production below. While on the one hand, this regulation limits the possibility of changing the destination use of agricultural land, preserving agricultural land from exploitation, it reduces the diffusion of RES in Italy (i.e., solar energy) and, in tandem, the competitiveness of the country on the RES markets. At the same time, some exemptions for installing photovoltaic systems have been introduced. In particular, they refer to the so-called *advanced photovoltaic*, energy communities and the projects that have already been financed by the NRRP. Due to these changes, what could emerge in the long run is a potential polarisation of the market. On the one hand, those who can adopt photovoltaic systems and who are the biggest actors, who are often originally not farmers, for whom investing in advanced technologies is affordable and who succeed in participating in an NRRP project. On the other hand, those producers who will rely only on agri-photovoltaic systems and that, therefore, will be less competitive in the energy market. Through this opaque authorisation allocation mechanism, a sort of rent-seeking position is, therefore, created. The results of this paper capture such risk highlighting, in fact, an insufficient differentiation effect of the formulation of EU policies, since all producers have, at least in principle, the same opportunities, but only a specific group of them succeed in converting them into economic opportunities.

Lastly, this paper contributes to the present policy debate on the relevance of accounting for the characteristics of local enterprises to design incentive policy mechanisms for economic transitions that apply to all the ecosystems involved from a technical, economic, financial, and fiscal perspective. An underestimation of beneficiaries may generate a concentration of funds towards those actors that are more capable, for different reasons, of attracting funds (e.g., economic dimension) at the expense of small and medium enterprises.

Such a reflection could be particularly relevant in this era of transition toward the proposal of a unique EU Fund, merging Cohesion and Rural Development objectives, where the governance should become more centralised and recall a top-down mechanism (Rodríguez-Pose, 2025). The empirical evidence provided confirms that there may be implications for the overlap of these policies in terms of beneficiaries (Calegari et al., 2021). While on the one hand, combining different sources of funds can increase the complementarity in the use of funds and support large-scale projects, on the other hand, this may favour bigger participants at the expense of the smallest ones, while introducing allocation inefficiency and monopolistic behaviours.

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[2] Disposizioni urgenti per le imprese agricole, della pesca e dell'acquacoltura, nonché' per le imprese di interesse strategico nazionale.». (24A03724) (GU Serie Generale n.163 del 13-07-2024).

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