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THE CONTRIBUTION OF AGRICULTURAL HOLDINGS LOCATED IN THE MOUNTAINOUS AREAS TO THE ENERGY TRANSITION: REFLECTIONS FROM ITALY

O CONTRIBUTO DAS EXPLORAÇÕES AGRÍCOLAS LOCALIZADAS NAS ZONAS MONTANHOSAS PARA A TRANSIÇÃO ENERGÉTICA: REFLEXÕES DE ITÁLIA

Giorgia BRESSAN
University of Udine
giorgia.bressan@uniud.it

Giorgia SCOGNAMIGLIO
University of Rome, MEMOTEF
giorgia.scognamiglio@uniroma1.it

Resumo

A União Europeia estabeleceu objectivos ambiciosos de neutralidade carbónica através do Pacto Ecológico Euopeu e de medidas subsequentes. Consequentemente, a necessidade urgente de dedicar novas terras à transição energética exige que se considere a melhor forma de integrar os objectivos energéticos na paisagem. Mesmo as zonas de montanha, frequentemente consideradas excepcionais pelo seu elevado valor natural e cultural, estão a tornar-se cada vez mais o local de implantação de infraestruturas de energias renováveis intermitentes. Contudo, os factores geográficos nas zonas de montanha podem não incentivar a presença de projectos de energias renováveis. Este é um desafio no Sul da Europa, por exemplo, onde uma proporção significativa do território não é plana.
Este estudo examina se os vinculos geográficos podem influenciar a distribuição espacial dos investimentos na produção de energias renováveis. O Recenseamento Italiano geral da Agricultura 2020 fornece dados municipais sobre as explorações agrícolas envolvidas em actividades remuneradas relacionadas com a produção de energias renováveis. Estes dados permitem uma análise detalhada da integração dos objectivos de descarbonização no sector agrícola. Foram utilizados testes estatísticos múltiplos e modelos de regressão para investigar potenciais diferenças entre municípios de montanha e de planície. Os resultados preliminares mostram diferenças significativas, com os municípios de montanha a apresentarem níveis mais baixos de investimento em actividades rentáveis de produção de energia renovável nas explorações agrícolas do que os seus homólogos das planícies. Estes resultados sublinham a contribuição desigual das diferentes actividades de produção de energia renovável nas explorações agrícolas.

Palavras chave: Montanha, Agricultura, Energias renováveis

Abstract

The European Union has set ambitious targets for carbon neutrality through the Green Deal and subsequent measures. As a result, the urgent need to devote new land to energy transition requires consideration of how best to integrate energy objectives into the landscape. Even mountain areas, often considered exceptional for their high natural and cultural value, are increasingly becoming the location of intermittent renewable energy infrastructure. However, geographical factors in mountain areas may not encourage the presence of renewable energy projects. This is a challenge in Southern Europe, for example, where a significant proportion of the territory is not flat.
This study examines whether geographical constraints can influence the spatial distribution of investments in renewable energy production. The Italian Agricultural Census 2020 provides municipal data on agricultural holdings engaged in remunerative activities related to the production of renewable energy. These data allow detailed analysis of the integration of decarbonisation targets with the agricultural sector. Multiple statistical tests and regression models were used to investigate potential differences between mountain and plain municipalities. Preliminary results show significant differences, with mountain municipalities showing lower levels of investment in profitable renewable energy production activities on farms than their counterparts in the plains. These results highlight the uneven contribution of different areas

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within a country to the energy transition goals. However, factors such as belonging to the province of Bolzano dominate the predictive power, suggesting that although mountain status is a critical factor, contextual factors strongly influence the commitment to renewable energy.

Keywords: Mountain, Agriculture, Renewable Energy

1- Introduction

The European Union has set ambitious targets for carbon neutrality through the Green Deal and subsequent measures. Renewables are the future of European countries, not only because the continent is a key player in the global fight against climate change, but also because they are fundamental to tackling the energy insecurity problem following the invasion of Ukraine by Russian troops in February 2022. The increasing reliance on renewables is not without consequence from a geographical perspective (Deshaies, 2020). They are characterized by lower power density compared to fossil fuels (Smil, 2015); consequently, a problem of identifying new surfaces to install such energy infrastructure emerges. Fragile environments such as mountainous areas are not excluded from this challenge, especially if an equality perspective is taken and there is an objective of reducing winter electricity import dependency. Mountains are generally known as a source of biomass and hydroelectric energy, but as there are limits to further capacity expansion, it is important to assess the contribution of mountainous areas to the development of modern renewable energy.

The theme is particularly relevant in Europe, as mountains characterize the landscape of many European countries. It is perhaps trivial to recall that mountainous areas are very diverse in terms of climate, ecology, economy and other characteristics. Gløresen et al. (2004) describe that, for example, there are large differences in land cover. In northern Europe, grassland is proportionally more important, as is barren land and permanent ice and snow in Scandinavia. In central and southern Europe, arable land is much more important than grassland. Mediterranean scrub is important in Greece and over much of the Iberian Peninsula. Thus, an increased presence of renewables in these environments would interfere differently with the current land uses, but if the installation concerns are already artificial surfaces, this diversity will become less significant and a European-wide approach to the problem becomes relevant. In addition, the climate change problem is common.

The purpose of this study is to investigate whether geographical constraints can influence the spatial distribution of investments in renewable energy production. The context of the research is Italy, which was chosen for two main reasons. Firstly, because a gross production of 143.03 TWh from gas is the highest value in Europe in 2022 (European Union, 2024). Considering that Italy is a gas importer, the above-mentioned data underline the fact that its energy needs are mainly met by territorial transformations taking place outside its borders. The ongoing energy transition will change this picture and will increasingly require clean energy production to take place domestically. Specifically, the ambitious targets set out in Italy's Integrated Energy and Climate Plan call for the installation of around 40 GW of new capacity by 2030,

almost exclusively from wind and photovoltaic sources[6]. The Italian case study is also interesting because the 2020 Agricultural Census provides for the first time municipal data on agricultural holdings engaged in remunerated activities related to the production of renewable energy. These data allow for a detailed analysis of the integration of decarbonisation targets in the agricultural sector. A common way to increase renewable capacity in this sector is to use the roofs of stables to install solar photovoltaic panels, for instance. This is particularly interesting, as it does not imply a major transformation of the landscape, as is the case where energy infrastructure occupies large open areas. This note is quite important because social obstacles such as public reservations linked to changes in landscape aesthetics and habitat quality, rather than technical constraints, pose the greatest limits to the development of intermittent renewable energy (Pasqualetti, 2011).

This article aims to contribute to the growing literature on the transformation of southern European landscapes due to renewables (cfr. Bressan, 2024). It examines whether the presence of permanent natural handicaps due to topographical constraints negatively influences the development of renewable energy in agricultural holdings in such areas. This is a particularly relevant issue for the European context as a whole, given that a consistent part of its territory is not flat, in addition to the fact that the solutions where energy infrastructures are integrated with existing functions should be privileged.

The paper is structured as follows. The next section discusses the contribution of mountainous areas to the energy transition. Then, the data and the approach used in the analysis are presented. Subsequently, statistical tests and analyses are carried out to investigate potential differences between mountain and plain municipalities. The final section wraps up the research.

2 – The energy transition in the Italian mountainous area

Despite the advantages of renewables from a greenhouse gas emission perspective, public reservations on type of energy source might surge (Grilli et al., 2017). It is well known that there are two main ways to expand renewables capacity: by occupying large open areas with ground-mounted installations, for instance, or using artificial surfaces such as rooftops. Consequently, renewable energy infrastructures can cause a remarkable change not only in the material appearance of the landscape and in terms of nature conservation and wildlife, but also in the way people living nearby perceive that new environment. The great demand for space linked to the current energy transition must include mountain spaces in the discussion. Mountainous areas are special environments and are of vital importance in their countries in many ways: as “water towers”, especially in summer; as centers of biological and cultural diversity; as providers of recreational and tourist opportunities based on natural features and the local

[6] Source: https://www.terna.it/it/sistema-elettrico/ruolo-terna/insight (last accessed: 18 December 2024).

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heritage. However, there are conditions under which such environments are suitable to host renewable energy projects.

Especially in the twentieth century, mountainous areas were very important for energy production from forest biomass and hydroelectric power. However, the contribution of the latter may change drastically in the next years due to climate change. According to the statistics published by Terna[7] - the Italian company operating the electricity transmission networks - the gross production from hydroelectric power passed from 47,478.4 GWh in 2021 to 30,290.7 in 2022, which means an annual reduction of 36,2%. The same Terna[8] explains that this outcome was due to natural conditions which contributed to the drop in reservoir levels in many months, remaining below historical levels, with an average reduction of 20% in rainfall and 40% in snowfall. In general, the issue of climate change creates a very worrying scenario for the electricity generation system, as the exceptional conditions of high temperatures and low rainfall have potentially negative and multiplying effects on the adequacy of the system. These features simultaneously affect both demand (e.g. higher request for air-conditioning) and generation capacity, due to the reduction in available capacity linked to the effects of high temperatures on the phenomenon of derating and limits for cooling the plants.

Mountainous areas like the Alps, which are characterized with great seasonal weather variability together with geographical isolation, are not per se the ideal context for solar photovoltaic production. However, as illustrated by Đunkan et al. (2024), beside options such as hydro dam walls and floating infrastructure on lakes, the installation of photovoltaic plants above the winter cloud and fog cover could be a viable solution in some high-altitude mountain areas, albeit with risks and revenue uncertainties. Wind technologies are also not the best option for mountainous areas. On this aspect, Grilli et al. (2017) points out that they guarantee several benefits in terms of return on investment, efficiency of the technology and the capacity factor of the power plants; however, when focusing on the environmental consequences and public perceptions the evaluation is different. The scarce adoption of intermittent renewable energy in the Italian mountainous area, as illustrated in Terna's regional data, reflects these issues. However, it cannot be excluded that other places besides large open areas can host the infrastructure for the energy transition.

[7] Source: «Dati statistici sull'energia elettrica in Italia 2023», available at https://download.terna.it/terna/Terna_annuario_statistico_energia_elettrica_Italia_2023_8dd211b3585b028.pdf (last accessed 28 December 2024).
[8] Source: «La corsa a due velocità dell'Italia nel 2022», available at https://download.terna.it/terna/corsa-due-velocita-italia-2022_8db77058d6a9ed5.pdf (last accessed 28 December 2024).

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3 – The approach

3.1- Data

The identification of the mountainous area is made in this research using the geographical layer provided by the European Environmental Agency, which covers the 38 member countries of the European Environment Agency network plus the United Kingdom, Andorra, and San Marino[9]. The layer was intersected with the cartography of the Italian municipalities in order to identify the municipalities where this feature is present.

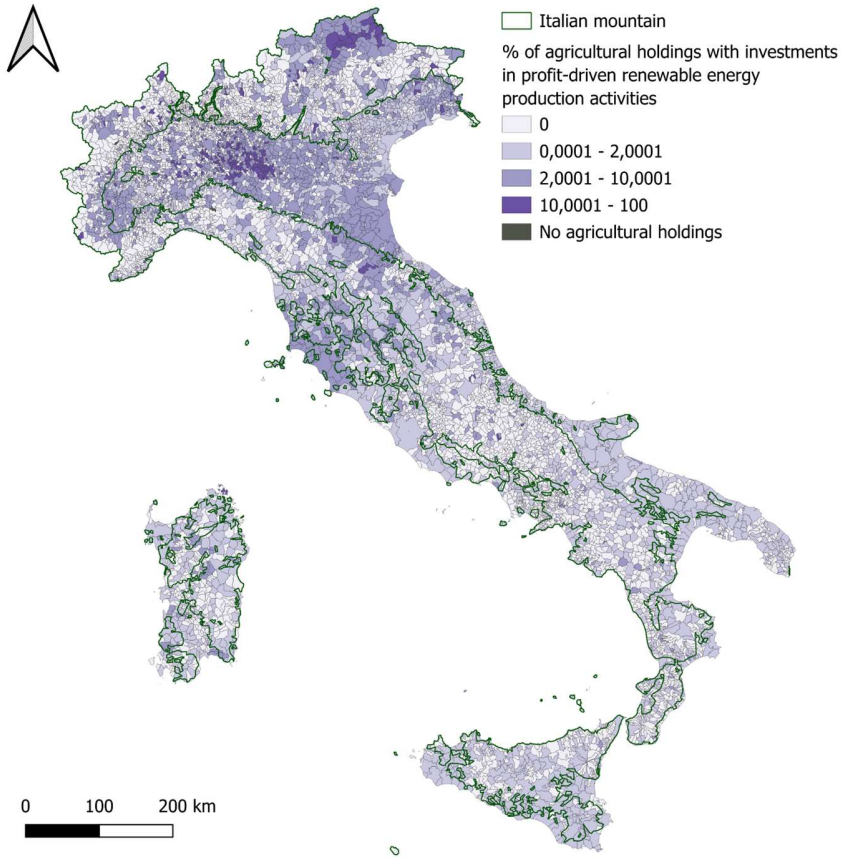


Figure 1 - Thematic map concerning the percentage agricultural holdings in each Italian municipality where there are investments in profit-driven renewable energy production activities
Source: Authors' elaboration

[9] Data source: https://www.eea.europa.eu/en/datahub/datahubitem-view/48b6f8a7-9e5a-4865-bd05-59c29348b5fb (downloaded on 25 February 2024). According to the information provided in the web page "the delineation of European mountainous areas was carried out by using digital elevation models, considering different criteria combination of thresholds of altitude, climate, and topography variables".

The other main source of data is the Italian 2020 Agriculture Census, provided by the Italian Institute of Statistics (ISTAT). This makes it possible to identify the number of agricultural holdings in each Italian municipality where there are investments in profit-driven renewable energy production activities. It could be energy from renewable non-fossil sources, i.e. wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas[10]. Figure 1 is a thematic map of Italy with the percentage of agricultural holdings having such a feature.

It is possible to observe that in most Italian municipalities, there are no agricultural holdings with this type of investment. High values of this variable are observed in the plain area of North Italy, and in the municipalities of the Tyrrhenian coast of Tuscany and Latium. It is also interesting to note the very high values in the northernmost part of Italy, in the province of Bolzano, on the border with Austria.

Finally, for the statistical analysis, we have considered a set of variables that can allow demographic and economic characterization of the Italian municipality. Table 1 shows the variables considered in this paper.

Table I - List of variables

Acronym	Variable	Source
PER_R_C	**Percentage of agricultural holdings where there are investments in profit-driven renewable energy production activities**	**ISTAT, Agriculture Census, Municipal level**
SUP	Surface (kmq)	ISTAT, Municipal level
POP_RES	Population	ISTAT, Municipal level
DENS	Population density	ISTAT, Municipal level
URBAN	Degree of urbanization (1=cities; 2=towns; 3=rural areas)	ISTAT, Municipal level
LAND_CON	Percentage of consumed soil on total municipal area	ISTAT, Municipal level, Municipal Fragility Index
ACCES_SE	Accessibility index for essential services	ISTAT, Municipal level, Municipal Fragility Index
ACCESS_STRA	Accessibility index for motorway network	ISTAT, Municipal level
PROT_NAT	Percentage of the municipal area covered by terrestrial protected areas included in the Official List of Protected Areas or in the Natura 2000 Network	ISTAT, Municipal level, Municipal Fragility Index
ARU	Utilised agricultural areas (hectares)	ISTAT, Agriculture Census, Municipal level
HO	Number of agricultural holdings	ISTAT, Agriculture Census, Municipal level

[10] Data source: https://esploradati.istat.it/databrowser/#/it/censimentoagricoltura/categories/CENSAGR/CENSAGR_STRCHAR/IT1,DCAT_CENSAGRIC2020_GAIN,1.0 (downloaded on 16 May 2024).

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DIM_EC_C	Number of agricultural holdings with an economic dimension over 100,000 euros	ISTAT, Agriculture Census, Municipal level
PERC_EC_C	Percentage of agricultural holdings with an economic dimension over 100,000 euros	ISTAT, Agriculture Census, Municipal level
IRR	Solar radiation (kWh/m2)	JRC (mean value)
BOLZ	Municipality pertaining to the Bolzano province (=1)	ISTAT, Municipal level
SUD	Municipality located in the South of Italy (=1)	ISTAT, Municipal level
STAT	Municipalities in special (=1) or ordinary (=0) statute regions	ISTAT, Municipal level
PERC_IMP_ATT	Percentage of firms active in the agricultural sector	Chambers of commerce, provincial level
PERC_ADD	Percentage of employees in the agricultural sector	Chambers of commerce, provincial level
RED	Average taxable income	Ministry of Economy and Finance, Municipal level
IST	Population aged 25-64 with no more than lower secondary education or vocational training	ISTAT, Municipal level
OCC	Employment rate (20-64 years)	ISTAT, Municipal level

3.2- Methodology

The analysis employed multiple statistical methods to evaluate how agricultural holdings in mountainous areas contribute to the energy transition. The methodological framework was designed to evaluate whether the geographical classification of a municipality (specifically, whether it is mountainous or not) affects investment in renewable energy activities. Methods included exploratory statistical tests for differences to compare renewable energy activities between mountainous and non-mountainous municipalities, and regression models to further explore this relationship and identify influencing factors.

Municipalities were classified based on the EU_MOUN variable, with mountainous areas coded as 1 and non-mountainous as 0. The primary variable of interest, PER_R_C (percentage of agricultural holdings with activities related to the production of renewable energy), was compared between the two groups using three statistical tests: Wilcoxon's test, Somers' Delta test, and Levene's test (Agresti and Finlay, 2009; Field et al., 2012; Hollander, 2013).

- Wilcoxon's test is a non-parametric test used to compare the distributions of a variable between two independent groups. By focusing on medians rather than means, it avoids the assumption of normality, making it suitable for skewed data. A significant result indicates a difference in central tendency between groups (Mann and Whitney, 1947).
- Somers' Delta quantifies the strength and direction of the association between variables. Values range from -1 (perfect negative association) to +1 (perfect positive association), with 0 indicating no association (Somers, 1962).

- Levene's test is used to assess the homogeneity of variances (homoscedasticity) between two or more groups. It determines whether the variability of renewable energy activities in agricultural holdings significantly differs between mountainous and non-mountainous areas. A significant result ($p \leq 0.05$) suggests unequal variances, and the F-value quantifies the extent of variance differences, with larger values typically indicating greater discrepancies (Levene, 1960).

Regression analyses incorporated a set of control variables to account for potential confounding factors, such as demographic, economic, and infrastructural factors, such as degree of urbanization, population density, accessibility, and regional characteristics (e.g., protected natural areas and energy policies in specific areas like Bolzano) (see Table I). Least Absolute Shrinkage and Selection Operator (LASSO) regression identified key predictors by imposing a penalty on the size of the coefficients to reduce model complexity and minimize overfitting (Tibshirani, 1996). A Logit regression model was employed to examine the likelihood of a municipality being classified as mountainous (EU_MOUN=1) based on the percentage of agricultural holdings engaged in renewable energy activities (PER_R_C), using odds ratios for interpretation. Ordinary Least Squares (OLS) regression with bootstrap analysis (999 replicates) was performed with PER_R_C as the dependent variable and EU_MOUN as the primary independent variable to assess the stability of the coefficient. Bootstrapping, a statistical resampling method, estimates the distribution of a parameter (e.g. a coefficient) by simulating multiple samples from the observed distribution, enabling the derivation of confidence intervals and robust variability estimates (Efron and Tibshirani, 1993). Multicollinearity was tested using Variance Inflation Factors (VIF) and the condition index (Belsley et al., 2005). These measures ensured that the observed relationships were not significantly influenced by collinearity among predictors.

4 – Results and discussion

Exploratory Analysis and Test for Differences

The exploratory analysis revealed significant differences in renewable energy activities between mountainous and non-mountainous municipalities. The Wilcoxon test (*p-value*: <2.2e-16) showed a highly significant difference in the distributions, indicating that agricultural holdings in mountainous areas are less likely to engage in renewable energy activities. Somers' Delta (Δ = -0.2626323) showed a negative association between mountain classification (EU_MOUN=1) and engagement in renewable energy activities. Levene's test (F-value: 404.62, *p-value*: < 2.2e-16) confirmed significant differences in the variability between the two groups, highlighting non-uniform distributions across territorial types. Table II provides a summary of these results.

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Table II - Statistical tests comparing mountainous (EU_MOUN=1) and non-mountainous (EU_MOUN=0) municipalities for PER_R_C.

Test	Value	p-value
Wilcoxon	8508838	< 2.2e-16 ***
Somers' Delta	-0.2626323	-
Levene	404.62	< 2.2e-16 ***

Source: authors elaboration in R environment, *stats*, *DescTools,* and *car* packages.

LASSO Regression and Variable Selection

LASSO regression identified EU_MOUN (β=−0.496) as a key negative predictor of renewable energy activities, with BOLZ (β=3.909) showing the strongest positive effect. Other influential variables included PERC_EC (β=1.362), RED (β=0.315), and URBAN (β=0.280), while variables like PERC_IMP_ATT (β=−0.224), DENS (β=−0.138), and IST (β=−0.137) exhibited negative associations. SUP (β=−0.035) and POP_RES (β=0.018) showed minimal coefficients, leading to their exclusion from further analysis. The model explained a modest variance (R^2 = 0.2025) but effectively isolated the most relevant predictors, confirming the utility of LASSO for reducing dimensionality and enhancing interpretability in complex datasets. Outputs are provided in Table III.

Table III LASSO Regression Output. Predictors ordered from most influential to least influential.

Coefficients for Selected λ=0.00681292	
Variable	*Coefficient (β)*
const	0,658
BOLZ	3.909
PERC_EC	1.362
EU_MOUN	-0.496
RED	0.315
URBAN	0.280
PERC_IMP_ATT	-0.224
IST	-0.137
DENS	-0.138
STAT	0.138
PERC_ADD	0.160
IRR	-0.104
PROT_NAT	-0.073
OCC	0.075
SUD	0.122
LAND_CON	-0.058
ACCES_SE	-0.048
ACCES_STRA	-0.036
SUP	-0.035
POP_RES	0.018
BOLZ	3.909
Additional Model Information	

Cross-validation folds	10
Number of observations	7,904
λ (Minimized MSE)	0,00681292 (*)
Training Data R2	0.1104
Largest λ within one SE of the minimum	1,000000

Source: authors' elaboration in R environment, *stat* package.

Logit Regression Analysis

The Logit regression model revealed that increased renewable energy production by agricultural holdings (PER_R_C) reduces the probability of a municipality being mountainous. An odds ratio of 0.948 (p-value < 0.0001) indicates that a 1% increase in PER_R_C reduces the likelihood of a municipality being mountainous by 5.1%, holding other variables constant. The variable BOLZ was automatically excluded from the logistic regression because every municipality where BOLZ = 1 is classified as mountainous (EU_MOUN = 1) with 100% certainty. These results highlight potential geographical disparities in renewable energy investments, suggesting that mountainous areas may face structural and economic challenges in adopting renewable energy. Outputs are provided in Tables IV and V.

Table IV - Logit Regression Output: coefficients, significance, and summary statistics

	Coefficient (B)	*Std.Error*	*z*	*p-value*	
const	2.30492	0.223114	10.33	<0.0001	***
PER_R_C	**−0.0526402**	**0.0125115**	**−4.207**	**<0.0001**	*******
URBAN	−0.329061	0.0823511	−3.996	<0.0001	***
STAT	0.939680	0.108587	8.654	<0.0001	***
SUD	−0.412206	0.112639	−3.660	0.0003	***
ACCES_SE	0.774688	0.0579015	13.38	<0.0001	***
LAND_CON	−1.44815	0.0812768	−17.82	<0.0001	***
PROT_NAT	0.355488	0.0502792	7.070	<0.0001	***
PERC_EC	−0.845921	0.0426207	−19.85	<0.0001	***
PERC_IMP_ATT	−0.406183	0.0716922	−5.666	<0.0001	***
PERC_ADD	0.371785	0.0729933	5.093	<0.0001	***
IRR	−1.03740	0.0725889	−14.29	<0.0001	***
DENS	0.723437	0.0629792	11.49	<0.0001	***
RED	−0.300471	0.0550620	−5.457	<0.0001	***
IST	−0.412097	0.0434816	−9.478	<0.0001	***
OCC	−0.735584	0.0706714	−10.41	<0.0001	***
Summary Statistics					
Mean Dependent Variable	0.685016		Log-Likelihood	−2834.307	
Sum of Squared Residuals	0.464539		Akaike Criterion (AIC)	5700.615	
Adjusted R2	0.421044		Schwarz Criterion (BIC)	5812.213	

Source: authors' elaboration in R environment, *stat* package.

Table V - Logit Regression Output: Odds ratios and confidence intervals

Variable	*Odds Ratio*	*Std. Error*	*95% Confidence Interval*
PER_R_C	**0.948721**	**0.01187**	**[0.925740, 0.972273]**
URBAN	0.719599	0.05926	[0.612341, 0.845645]
STAT	2.55916	0.277891	[2.06856, 3.16612]
SUD	0.662188	0.074588	[0.531010, 0.825771]
ACCES_SE	2.16991	0.125641	[1.93712, 2.43068]
LAND_CON	0.235004	0.0191	[0.200398, 0.275587]
PROT_NAT	1.42688	0.071742	[1.29297, 1.57465]
PERC_EC	0.429162	0.018291	[0.394768, 0.466552]
PERC_IMP_ATT	0.666188	0.047761	[0.578858, 0.766693]
PERC_ADD	1.45032	0.105864	[1.25699, 1.67339]
IRR	0.354375	0.025724	[0.307379, 0.408555]
DENS	2.06151	0.129832	[1.82212, 2.33234]
RED	0.74047	0.040772	[0.664719, 0.824852]
IST	0.66226	0.028796	[0.608159, 0.721174]
OCC	0.479225	0.033868	[0.417238, 0.550421]

Source: authors' elaboration in R environment, *stat* package.

OLS Regression and Bootstrap Analysis

OLS regression (Table VI) confirmed a negative association between being mountainous (EU_MOUN) and renewable energy activities (β = −0.470, p < 0.0001). Other variables showed very significant effects: degree of urbanization (URBAN), location in the province of Bolzano (BOLZ), percentage of agricultural holdings with an economic dimension over 100,000 (PERC_EC), percentage of employees in agriculture (PERC_ADD), and average income (RED) positively influence renewable energy production, while factors like percentage of agricultural holdings (PERC_IMP_ATT) and low education level (IST) are negatively associated. The consistency of the key results with the Logit model reinforces the reliability of the analysis, while the multicollinearity check, through VIF values (1.05 - 6.43), confirmed the robustness of the model.

Table VI - OLS regression output

Variable	*Coefficient (β)*	*Std. Error*	*t*	*p-value*	
EU_MOUN	**−0.470044**	**0,106514**	**−4.413**	**<0.0001**	***
URBAN	0.507845	0.0330009	15.39	<0.0001	***
STAT	0.223155	0.118756	1.879	0.0603	*
BOLZ	3.88687	0.375683	10.35	<0.0001	***
SUD	0.221247	0.123812	1.787	0.0740	*
PROT_NAT	−0.0853226	0.0436355	−1.955	0.0506	*

LAND_CON	0.00184139	0.0891717	0.02065	0.9835	
ACCES_SE	−0.0962177	0.0536855	−1.792	0.0731	*
ACCES_STRA	−0.0662411	0.0506319	−1.308	0.1908	
PERC_EC	1.37371	0.0462300	29.71	<0.0001	***
PERC_IMP_ATT	−0.319892	0.0791951	−4.039	<0.0001	***
PERC_ADD	0.244602	0.0825554	2.963	0.0031	***
IRR	−0.115878	0.0509412	−2.275	0.0229	**
ARU	−0.00761223	0.0400875	−0.1899	0.8494	
POP_RES	0.0436009	0.0458039	0.9519	0.3412	
SUP	−0.0350381	0.0475711	−0.7365	0.4614	
DENS	−0.147950	0.0802663	−1.843	0.0653	*
RED	0.336364	0.0637974	5.272	<0.0001	***
IST	−0.153177	0.0478433	−3.202	0.0014	***
OCC	0.0778711	0.0718665	1.084	0.2786	
Model fit					

Mean dependent variable	1.156140	SQM dependent variable	3.882662
Residual Sum of Squares	95001.07	Standard Error reg.	3.471731
R-squared	0.202396	P-value(F)	0.000001
F (20, 7882)	143.8213	Akaike	42115.38
Log-likelihood	-21037.7	Schwarz	42163.16

Source: authors' elaboration in R environment, *stat* package.

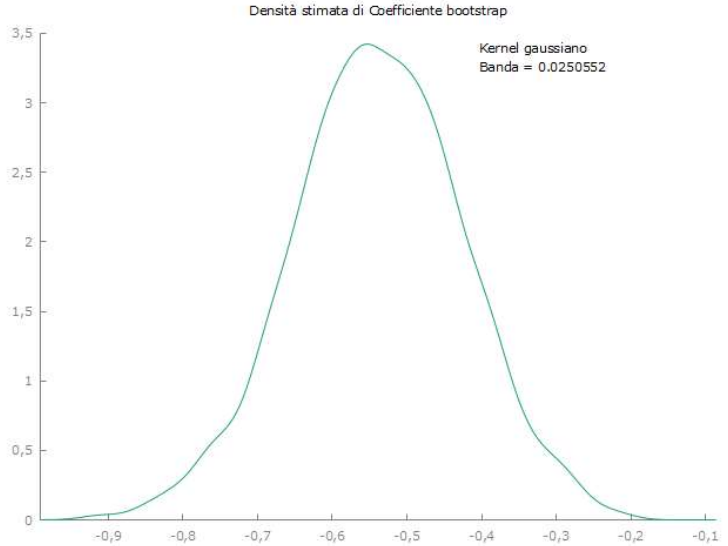


Figure 2 - Estimated density of the bootstrap coefficients.
Source: authors' elaboration in R environment, *glmnet* package.

The bootstrap analysis revealed an estimated density for EU_MOUN centered at −0.537. The 95% confidence interval (−0.743 to −0.317) and the symmetrical distribution of the coefficient (Fig. 2) reinforced

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the robustness and stability of the findings, as well as the significance and reliability of EU_MOUN as a predictor. Regardless of the specific sample used, the coefficient consistently exhibits a negative effect on the dependent variable. However, the observed variability suggests that the "mountain effect" can fluctuate depending on the sample, possibly due to the presence of particularly high-performing mountainous municipalities, such as those in the province of Bolzano, where favorable conditions may encourage renewable energy investments. These outliers contribute to the observed fluctuation and highlight the heterogeneity among mountainous areas.

In brief, the results indicated a clear negative relationship between mountainous municipalities and renewable energy engagement among agricultural holdings, as evidenced by multiple complementary statistical methods.

The explanatory analysis revealed a significant difference between mountainous and non-mountainous municipalities in terms of renewable energy activities, highlighting a strong geographical gap. LASSO regression provided a robust basis for variable selection, identifying EU_MOUN as a significant negative predictor. However, factors such as belonging to the province of Bolzano (BOLZ) dominate the predictive strength, suggesting that, although mountain status is a critical factor, contextual peculiarities (e.g. policies, economic conditions) strongly influence engagement to renewable energy mitigating the "mountain effect".

The Logit model reinforced these findings, revealing that municipalities with higher levels of renewable energy investment are less likely to be mountainous, likely due to structural and economic limitations that inhibit such activities in these areas. The OLS analysis, supported by bootstrap procedures, further validated the negative association and highlighted the validity of the coefficient EU_MOUN. Again, the variability observed in the bootstrap coefficient, particularly in relation to high-performing municipalities like those in Bolzano, suggests that exceptions exist within mountainous areas that may require further exploration.

Future research could focus on understanding the factors that make some mountainous municipalities outliers in terms of renewable energy investments. Further analysis could involve testing the robustness of these findings by excluding exceptional municipalities, as well as by replicating the models with alternative definitions of “mountain”. Additionally, it would be valuable to explore the interaction effects between mountainous status and other socio-economic or environmental factors, such as agricultural productivity, or access to renewable energy incentives, to better understand the drivers of investment disparities in renewable energy across different territorial contexts. In particular, the structural characteristics of the agricultural sector should be greater considered in order to interpret these findings. Finally, employing spatial models (e.g., spatial Logit) could account for spatial dependencies and spillover effects, offering a more comprehensive understanding of the geographical dynamics influencing renewable energy engagement.

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5 – Conclusion

The research presented in this paper consists of an original analysis focusing on the integration of decarbonisation targets with the agricultural sector. In Italy, statistical data at the municipal level on the presence of renewables are rare. Consequently, the data used in this paper, collected in the context of the Italian Agriculture Census, offer a unique opportunity to analyze a particular aspect of the energy transition at a very low geographical scale. The special focus of this paper is on mountainous areas that, despite their permanent natural handicaps due to topographical and climatic constraints, can make their important contribution to the energy transition.

To wrap up the paper, we would like to emphasize two aspects. The first observation comes from Figure 1. The presence of investments in renewables in agricultural holdings, although limited, shows that agricultural landscapes are increasingly equipped with infrastructures for the production of renewable energy. They highlight that the landscape, even one as fragile as the mountainous one, is destined to change significantly due to the demand for energy, which will be satisfied more and more at a domestic level. On the other hand, statistical findings reveal significant disparities across the Italian territory, with mountainous municipalities exhibiting lower levels of investments in profit-driven renewable energy production activities within agricultural holdings than their counterparts in the plains. These results show the unequal contribution of different territories within the same country to the energy transition. However, the very high values in the mountainous area of Bolzano testify that the geographical factors alone are not per se barriers to the development of renewables.

The next step is to reflect whether these results can help policymakers to design energy policies that encourage the development of renewable capacity in the mountainous region. The variable weather conditions of these geographical contexts justify the government's support to tackle the financial risks. It's clear that promoting renewable energy investments in mountainous areas is not without consequences for the environment and people living there. One priority is that these policies should strike a balance between development and preservation, given the special features of mountainous areas. If one of the main problems of renewable energy development is social, then the objective should consist in minimizing the territorial impacts by avoiding an increase in the artificial soil. In this light, investments made in rooftops of agricultural holdings or in other artificial surfaces should be privileged by policymakers.

The research presented in this paper can be further developed from a methodological perspective, as discussed in the previous section, but it can also be extended spatially. The energy transition is a challenge that affects the whole of Europe, that is why experiences in one country should be compared with those in another. Clearly, the availability of data at a low geographical level is crucial to allow the analysis to be replicated elsewhere.

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