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Diffusion of renewable energy technology on Spanish farms: drivers and barriers

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Abstract
The aim of this paper is to identify the drivers and barriers of on-farm adoption of renewable energy systems (RES) in Spain and to determine how the existing mix of policies (subsidies, regulation and communication) affected the decisions of the farmers. The analysis is based on the results of a national survey that was completed by 719 farmers, representing the main types of farms and production regions. Statistically significant correlations have been observed between the probability of on-farm RES adoption and variables such as the use of contract farming, interest in new technologies and risk tolerance. Findings suggest that the diffusion of on-farm RES was at an early stage. Farmers are hesitant to adopt RES because the level of economic and regulatory uncertainty is perceived as too high in relation to the return and payback time typical of RES investments. Tailored business models and financing solutions should be implemented and promoted to overcome the described issues. Furthermore, relevant and reliable information should be available within farmers' most common professional networks such as cooperatives and farmers' associations. These aspects should be combined or even prioritized over providing direct economic incentives when producing on-farm RES supporting policies.

Keywords Renewable energy · Diffusion of innovation · On-farm RES · Energy policy Spain · Sustainable farming · Decarbonizing farming

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1 Introduction

Farms and agribusinesses in Spain consume large amounts of energy as a basic input of their production processes. Energy is used to power machinery and transport, irrigation systems, illumination, coolant pumps and temperature-control machinery for sheds and greenhouses among other things. Furthermore, the modernization of farms by introducing new technologies and practices tends to increase energy consumption, both in absolute and relative terms (Martinho, 2016). Thus, Spanish farms consumed 2458 Ktoe in 2018, equivalent to 2.8% of the total primary energy consumption of the country in that year (MAPAMA, 2020). Energy costs represent more than 10% of Spanish farmers' average expenses and in some cases, such as those farms that rely on irrigation systems, it can represent up to 50% of production costs (Lorenzo et al., 2018). As consequence, the carbon footprint of Spanish farming is also very relevant, as it is estimated that the sector was responsible for 11.9% of the country's greenhouse gas emissions in 2018 (MAPAMA, 2020). The use of renewable energy systems (RES) can improve the long-term economic and environmental sustainability of the Spanish agrarian sector by producing a significant part of the energy consumed on most farms, creating gains both for the farmer and for the local communities (Pedroli & Langeveld, 2011; Sutherland et al., 2015) while facilitating compliance with the international commitments that require significant increases in the use of clean energy technologies in every sector of the economy.

Spanish farms are especially well-suited to installing photovoltaic systems (PVS) for the production of electricity for self-consumption purposes, as solar radiation is high in most parts of the country. Potential savings obtained by PVS are especially relevant for farms where the consumption curve matches the production curve of PVS, so no batteries are required. This is the case for many farms that require irrigation for their crops or livestock farms that require ventilation to control the temperature in sheds, especially during the central hours of the day in the warmer months of the year. In particular, PVS' potential to generate a relevant share of the electricity consumed for pumping water in irrigation systems presents a remarkable opportunity for Spanish farmers (Lorenzo et al., 2018), given that the 3.8 million ha. of irrigated land produces nearly 60% of the final agrarian output of the country (MAPAMA, 2020).

Poultry, pig and bovine farms are increasingly concerned with controlling climate conditions in sheds (Franke, 2000) while the use of sophisticated electrically powered equipment, including robots, is also on the rise (Steidle, 2021; John et al., 2016). For example, in many regions of Spain, long and warm summers mean the need to operate large fans to ventilate sheds with PV systems, as the peak times for consumption conveniently match the peak moments of solar irradiation. Heat is also an important input in many farming production processes including greenhouses (Esen & Yuksel, 2013; Mostefaoui, 2019) sheds and stables (Franke, 2000), and those with heating requirements (Abdelhady et al., 2018; Rosillo-Calle, 2012).

A significant part of the Spanish 2020 energy objectives was to be achieved by installing renewable energy systems (RES) that are considered to be reliable and cost-efficient alternatives to conventional energy sources. Specifically, 268 Ktoe of the planned savings by 2020 were to be related to irrigation and in-door farming where on-farm RES could provide up to 60% savings in relation to non-RES technologies (Abdelhady et al., 2018; Lorenzo et al., 2018). To achieve these goals, the Spanish agrarian sector should have introduced RES to provide at least 22% of its energy needs, meaning that at least 37% of farms should have introduced RES by the end of 2020.

The aim of this paper is to identify the drivers and barriers of on-farm RES adoption in Spain and to determine how the existing mix of policies (subsidies, regulations and communication) affected the decisions of the farmers. Intermediate adoption rates, characteristics and drivers of farmers who installed RES, and barriers that could have impeded general policy goals are evaluated using data from a survey completed by 719 farmers as part of the RESFARM project, funded by the European Commission's Horizon 2020 programme. RESFARM was undertaken between 2015 and 2018 by an international coalition of research institutions, farming associations and governmental agencies with the aim of facilitating on-farm RES introduction. The project allowed for the design and dissemination of materials and tools such as technical manuals, assessment methodologies and best practices to support on-farm RES projects. RESFARM activities were targeted to Mediterranean agriculture and specific working groups were established to focus on Spain, Italy and Greece. This paper is based on the activities of the group focused on Spain.

Due to its relevance in relation to climate and agricultural policy action, the identification of the drivers and barriers of on-farm RES adoption has been carried out for several contexts, including the USA (Borchers et al., 2014), China (Li et al., 2021) the Netherlands (Trujillo-Barrera et al., 2016), Germany (Schaffer & Düvelmeyer, 2016) and the UK (Barnes et al., 2022). Nevertheless, equivalent insights are not available for the Mediterranean Agriculture in general and, in particular, for Spain. This is a gap that this paper aims to fill, as Mediterranean farming presents its own specific technological, economic and cultural drivers. Furthermore, in order to provide useful insights in order to design on-farm RES promotion actions, a special focus has been put on the analysis of the communication channels which are being used to disseminate relevant information and to establish those which might be more effective. This is an issue which, to our knowledge, has not been thoroughly considered in existing literature.

This paper is divided into five parts. After this introduction, Sect. 2 discusses data collection and analysis. Section 3, presenting main results, is divided into two parts. The first part presents the results and estimations of the level of diffusion of on-farm RES, the characteristics and drivers of early adopters and the dissemination channels that are already in place. The second part lists barriers that have been identified for the diffusion of on-farm RES as well as the communication channels that can be used to efficiently disseminate new technologies to farmers. Section 4 contains a discussion of the survey results, and actions are suggested to overcome the identified barriers, including policy recommendations. Finally, Sect. 5 consists of the paper's conclusions.

2 Materials and methods

2.1 Characteristics of the surveyed sample

Understanding the diffusion of on-farm RES was among the objectives of the RESFARM project. In this framework, the need to obtain a detailed picture of the situation of on-farm RES adoption in quantitative and qualitative terms was identified. In particular, it was necessary to identify the barriers and drivers of on-farm RES adoption and the implications of the findings in relation to the effectiveness of existing public support measures and the achievement of related policy goals. For this purpose, it was decided to carry out a survey addressed to farmers and managers of farming cooperatives regarding the introduction of on-farm RES in Spain. In order to design the survey, in-person, open interviews with 32

Table 1 Structure of the sample and of the population of the Spanish farming sector by type of production

Farm type	No.	(%)	Population*	Pop. (%)
Cereal	35	4.8	136,517	16.6
Cow	230	32	64,969	7.9
Fruit	29	4	131,583	16
Grassland	19	2.6	148,031	18
Greenhouse	75	10.4	16,448	2
Olive	17	2.3	188,328	22.9
Poultry	55	7.6	8,224	1
Sheep	68	9.5	41,942	5.1
Swine	66	9.2	6,579	0.8
Vegetable	40	5.6	18,093	2.2
Vineyard	86	12	61,679	7.5
Total	719	100	822,392	100

*Spanish Agrarian Census 2009 (INE, 2009)

experts in different areas related to on-farm RES objectives were carried out by researchers from the University of A Coruña. Based on the results of this preliminary work, it was decided to focus the scope of the survey on the general level of awareness of potential adopters, the characteristics of early adopters, the factors affecting the decision process of on-farm RES adoption and the communication channels that were available to disseminate relevant information among the farmers. As result, a questionnaire with 44 questions was produced to collect both information regarding the characteristics of the farm and the farmer and information specifically related to on-farm RES adoption.

The first part of the questionnaire produced a detailed description of the farm and of the characteristics of the farmer. The second part of the questionnaire was related to the level of on-farm RES introduction, the reasons and information sources that influenced those who had already installed RES, the level of awareness and interest of farmers in RES and, for those who consider their farms suitable for RES but who have not yet installed these technologies, what barriers are dissuading them from adopting RES. Finally, a number of control questions were included. The questions required the farmers to respond to what extent they agreed or disagreed with the question on a Likert scale ranging from 1 to 5 with 1 being strongly disagree, 3 somewhat agree and 5 totally agree.

After a pre-test of the draft questionnaire, carried out with 5 farmers, slight amendments were made. 21 survey-givers were trained among the staff of the agrarian associations of the RESFARM consortium with broad experience in working with farmers. To obtain a representative sample of the entire farming sector of Spain, 11 type of farms in terms of type of production were established as a first level of stratification, representing more than 96.5% of the total agrarian output in the country. Due to the level of geographical specialization of farming in Spain related with the variety of climate and physical conditions, a multistage sampling technique was used to select the sample farmers. A minimum target of 15 surveyed farms of each type was established to be chosen using random sampling in the databases of the farming associations (Hibberts et al., 2012). The fact that the farmers' association which collaborated in the study represent more than 70% of the total population (more than 600,000 farmers) allowed for the obtention of a stratified sample, made up of 3 types of farms in terms of size and 3 geographical/specialization areas, in proportions similar to those observed in the population of farms in Spain, as shown in Table 1. The size of the sample needed to produce estimations with a 95% confidence level was of 394 observations. Then, a sample within each group was randomly selected from the databases of the farmers' organizations and the contact details of the farmers were assigned to the nearest survey giver. In order to ensure that such at least 394 observations were available, it was decided to contact double that number of farmers (788). The details of the potential participants were distributed to local offices of the associations in 15 regions of Spain to directly contact the selected farmers in order to proceed with the survey. The final sample is biased towards medium and large farms and towards cattle (especially cows) rather than crops. This bias is related with the geographical location and production specialization of the farming unions that carried out the survey. This bias has been corrected by weighing the cases by size and type of farm in order to reflect the actual structure of the Spanish farming sector.

The rate of response was high, as the questionnaire was answered by 719 farmers and cooperative managers out of the 788 contacted (91.24%). This high level of response can be related to the pre-existing relationships of collaboration and trust between the farmers' and the local branches of the farming associations. The survey was carried out between November 2015 and March 2016 and was conducted by the survey givers during telephone interviews with the sampled farmers. After completing each questionnaire, survey givers had to evaluate to what extent the surveyed farmers understood the meaning of the questions and responded accordingly. Survey takers also had to evaluate the perceived level of collaboration and understanding that the farmer showed during the interview.

Most (680) of the 719 farms included in the final sample were personal enterprises, 30 were limited partnerships and there were 9 cooperatives. All the farmers included in the survey were directly responsible for investment decisions on their farms. Also, most of the surveyed farmers obtained all or most of their income from the farm (80.4% of the sample). All the surveys were directly filled in by the trained survey givers. The main characteristics of the population and the sample are shown in Table 1.

The final sample includes farms representing the different farming regions of Spain as presented in Fig. 1.

2.2 Methods

Following relevant literature (Borchers et al., 2014; Glenk, 2014; Tate et al., 2012), a farmer's decision to introduce a new technology can be analysed by assuming that the adoption is a categorical dependent variable of a binomial logistic model. This allows for establishing the influence of a number of independent variables with the probability of adoption. A common modelling framework to analyse technology diffusion under this framework is a binary choice model (Rao & Kishore, 2010), usually a probit or logistical specification. Such a model is appropriate if participation fits into a dichotomous choice, essentially taking on values of zero and 1 (i.e. whether a respondent of the survey has or has not introduced on-farm RES). We used a logistic, binary choice model to estimate the probability of a farmer adopting on-farm RES in Spain. It should be noted that the use of logistic distributions has an advantage over other models in the analysis of dichotomous outcome variables; binary logistic models do not rest on the assumption of linearity between dependent and independent variables and do not assume homoscedasticity. The logistic model used in this analysis is specified below:

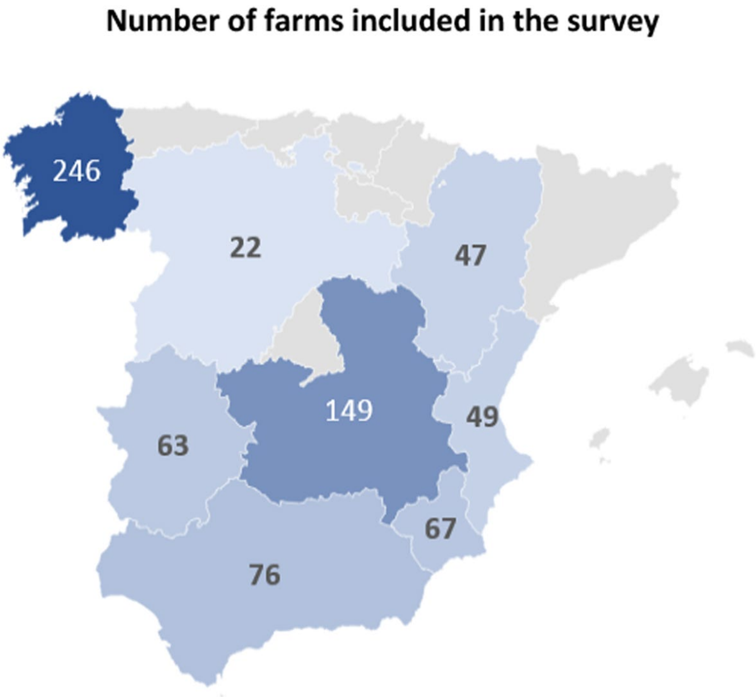

Fig. 1 Geographical distribution of the farms including in the survey. The 719 farms included in the survey represented the different climatic areas of Spain, corresponding to different types of farming

$$\text{Prob}\left(Y_i = 1\right) = P_i = F\left(Z_i\right) = F(\alpha + \sum \beta_1 X_i) = \frac{1}{1 + e^{-Z_i}} \tag{1}$$

where P_i is the probability that a farmer adopts on-farm RES; X_i represents a set of explanatory variables and α and β are parameters to be estimated.

$$\text{Prob}\left(Y_i = 0\right) = 1 - \text{Prob}\left(Y_i = 1\right) = \left(1 - P_i\right) = \frac{1}{1 + e^{-Z_i}} \tag{2}$$

From Eqs. (1) and (2), we get,

$$\frac{\text{Prob}\left(Y_i = 1\right)}{\text{Prob}\left(Y_i = 0\right)} = \frac{P_i}{1 - P_i} = e^{Z_i} \tag{3}$$

where P_i is the probability that Y_i takes the value 1 and then $(1 - P_i)$ is the probability that Y_i is 0 and e is the exponential constant. Now taking the natural log of both sides of Eq. (3), we get,

$$Z_i = \ln\left(\frac{P_i}{1 - P_i}\right) = \beta_0 + \beta_1 x_{i1} + \cdots + \beta_k x_{ik} + u_i \tag{4}$$

Also, in this paper, an estimation of the level of awareness and interest of those potential adopters among Spanish farmers hesitant to introduce RES is obtained. This is a relevant issue

Table 2 Distribution of the sample of farmers by age, dedication, succession plans, size of the farm and location within Spain

Categories	Sample (*n*)	% (*n*)	Population*(%)
Age			
< 40	123	17.1	9.1
40–54	300	41.7	35.0
55–64	256	35.6	25.0
> 64	40	5.6	30.9
Dedication			
Full time	578	80.4	69.4
Part time	141	19.6	30.6
Succession/long-term continuity guaranteed			
Yes	497	69.1	58.0
No	222	30.9	42.0
Farm size			
Small	445	61.9	74.8
Medium	113	15.7	20.6
Large	161	22.4	4.5
Location (within Spain)			
North	187	26.0	15.7
Centre	206	28.7	34.9
South/Mediterranean	326	45.3	49.4

*Spanish Agrarian Census 2009

in order to analyse the results of the survey and the effectiveness of existing policy support measures. Details are provided regarding the barriers that are perceived by this group of surveyed farmers for the introduction of on-farm RES. Then, information is provided regarding the communication channels that are disseminating relevant information among early adopters. Finally, the communications channels that can be used to reach the majority of the farmers are described. The results have been weighed in order to extrapolate the estimations to the population of farmers in Spain.

Table 2 presents the demographic characteristics of the surveyed sample and of the population of farms in Spain. As can be observed, the surveyed farmers are on average, younger than the average farmer in the population, are more likely to be full-time farmers, already have plans for the continuity of the farm and also have larger farms. This is due to the fact that the statistics of the farming sector include a relevant number of part-time farmers who tend to be older and with smaller farms than full-time farmers. As the objective of the study is to produce relevant information to support the promotion of on-farm RES, a special focus has been put on full-time farmers. In order to obtain estimations for the Spanish farming sector on the basis of the results of the survey, post-stratification weighing was applied, on the basis of type of farm and its size following the weights presented in Table 2.

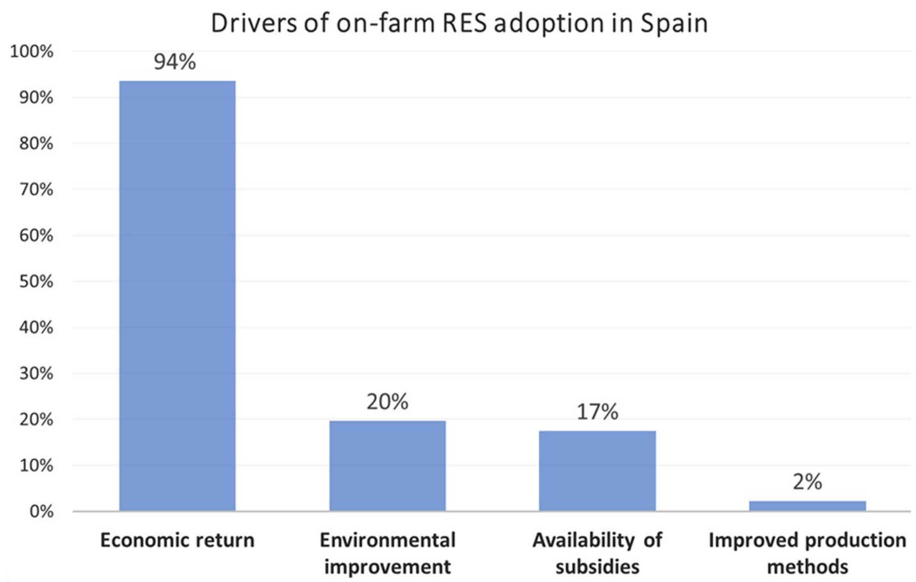

Fig. 2 The expectation to secure economic gains has been the main driver of on-farm RES adoption in Spain

3 Results

3.1 Drivers of on-farm RES adoption in Spain

The proportion of farmers who have adopted RES technology in Spain by 2016 is estimated at 7.99% (confidence interval (CI) at 95%: 5.14–10.85%), a level of introduction lower than that observed in similar surveys in European countries (Ruiz-Fuensanta, 2019; Schaffer & Düvelmeyer, 2016; Tate et al., 2012). The main driver of early adopters of on-farm RES in Spain is to obtain economic benefits. This factor was key for 93.5% (CI 95%: 86–100%) of early adopters, a much higher figure than the second most important factor: reducing the environmental impact of the farm. That is estimated to be very relevant for 19.6% (CI 95%: 7.6–31.4%). The existence of grants was very relevant for an estimated 17.4% (CI 95%: 6–28.7%) of on-farm RES adopters, while other improvements in production methods (for example producing a "higher quality" sort of heat for poultry farms as a result of using biomass instead of propane), is estimated to have been relevant for just 2.2% (CI 95%: 0–6.5%) of early adopters. Figure 2 presents these results.

In order to analyse which characteristics differentiate early adopters from the average farmer, a logit regression model has been produced. The dependent variable was the adoption of RES and the independent variables were the individual characteristics of the farm and of the farmer. At farm level, the factors that were included were: the size of the farm, the production orientation (crops or livestock), its profitability, the farm using contract farming, the existence of a succession mechanism, the level of debt and the level of technological advance of the farm. At farmer level, the factors included were: the expected evolution of his production, the level of risk aversion and the self-perception that the farmer has of his degree of early adoption of technologies, social activity and a management style focused on continuous improvements of the farm. The variables included in the analysis were selected on the basis that they have been previously associated with the probability of early adoption in the framework of DIT literature. The variable "farming using contract farming" was included as a result of a preliminary correlation analysis of the data recorded during the survey.[1] Summary statistics and explanation of the variable with the hypothesized effects are presented in Table 3.

The results are shown in Table 4, where those variables which make a significant unique contribution to the probability of on-farm RES early adoption in Spain are marked in bold type. The likelihood ratio (LR) chi-square statistics, and pseudo-R-square values reported at the bottom of Table 4 indicate that our model specification provides a reasonably good fit of the data. The logistic model correctly predicts 97.2% of the sample observations (98.5% of observed 0 and 66.2% of observed 1). At farm level, the variables identified with statistically significant relations with on-farm RES adoption were, in order of relevance: the existence of a succession plan/farmer already in place, use of contract farming and the profitability of the farm. Non-statistically significant relations, but close to that level, were found for the size of the farm and (negative) for the level of indebtedness. The production orientation of the farm and its level of technological advance showed no relation to on-farm RES adoption.

At farmer level, the variables with a statistically significant relation to early adoption were, in order of relevance: the planned increase in production, the focus on asset/farm improvement, the self-evaluated level of the early adoption of technology and the level of risk tolerance. A negative, non-statistically significant relationship was estimated for social activity.

The identification of the communication channels that were used by early adopters to obtain information related to on-farm RES is especially relevant in the framework of DIT to establish the underlying driving forces of the process. The most relayed source is other farmers who have direct experience with RES. Word-of-mouth is estimated to be a key communication channel by 53.1% (CI 95%: 37–69%) of early adopters. This result is coherent with some evidence that indicates that technology adoption is strongly influenced by the social network of individuals, especially by opinion leaders within those networks (Valente Thomas, 1995). The second most relevant channel has been assessment from independent experts, estimated to be very relevant for 35.4% of early adopters, (CI 95%; 19.9–50.84%) followed in importance by salesmen 22,4%, (CI 95%: 8.95–35.85%). Other sources that are estimated to be less relevant include exhibitions/conferences, 12.5% (CI 95%: 1.8–23.18%), cooperatives and associations, 5.5% (CI 95%: 0–12.8%), or agricultural extension services, 1.5% (CI 95%: 0–5.4%). Figure 3 shows these results:

3.2 Barriers to on-farm RES diffusion

While the results of the survey suggested low adoption levels of RES in the farming sector, extrapolation of the results indicates that 85.2% (CI 95%: 81–89%) of those farmers

[1] Contract farming is an agreement established between farmers and processing or distribution companies for the supply of agricultural products under forward agreements usually at predetermined prices. The purchaser also provides production support to the farmer like input supply and technical advice.

Table 3 Description of variables included in the model, their means, standard deviation (SD) and hypothesized effects

Variables	Description	Mean	SD	Hypothesized effects
Dependent variable				
RES already installed	1 if a RES system has already been installed on the farm, 0 otherwise	0.08	0.20	
Independent variables				
Farm characteristics				
Size of the farm	1 = less than 16 ESU*; 2 = 16 < ESU < 100, 3 = more than 100 ESU	1.61	0.83	+
Livestock farm	1 if the farm is mainly focused on cattle (more than 50% of the activity), 0 otherwise	0.31	0.46	+
Farm profitability	1 to 5 in Liker scale agreement with the sentence "my farm is a very profitable business"	3.15	1.26	+
Contract farming	1 if the farmer has signed production contracts for at least 40% of its output, 0 otherwise	0.24	0.43	+
Technologically advanced (self-considered)	1 to 5 in Liker scale agreement with the sentence "Compared to other farmers in my neighbourhood, my farm uses a lot of technology"	3.06	1.42	+
Debt level	1 to 5 in Liker scale agreement with the sentence "I have too many loans related to my farm"	2.22	1.14	–
Farmer characteristics				
Succession planned	1 if a successor or long-term continuity plan for the farm is envisaged, 0 otherwise	0.69	0.46	+
Planned increase of production	Planning to modify farming activities. 1 to 5 scale;1 It will decrease a lot, 2 It will decrease, 3 Will remain stable, 4 It will increase, 5 It will increase a lot	3.32	0.60	+
Risk aversion	1 to 5 in Liker scale agreement with the sentence "I take out insurance for farm activities"	2.91	1.40	–
Early adopter (self-considered)	1 to 5 in Liker scale agreement with the sentence "It is important to keep up with latest farming methods"	3.01	0.86	+
Socially active (self-considered)	1 to 5 in Liker scale agreement with the sentence "I participate in very few social activities with neighbours"	3.17	1.28	+
Focus on improvements (self-considered)	1 to 5 in Liker scale agreement with the sentence "I share thoughts about the business with family and try to get them to support the work"	2.42	1.38	+

*European size unit, abbreviated as ESU, is a standard gross margin of € 1,200 that is used to express the economic size of an agricultural holding or farm

Table 4 Logistic model estimates of the factors determining the adoption of on-farm RES

Variables in the Equation	B	S.E	Wald	Sig.	Exp(B)
Size of the farm	1.029	.539	3.649	.056	2.798
Livestock farm	.214	.660	.105	.746	1.238
Farm profitability	**.662**	**.325**	**4.145**	**.042**	**1.938**
Contract farming	**1.373**	**.577**	**5.659**	**.017**	**3.948**
Succession planned	**1.801**	**.799**	**5.083**	**.024**	**6.058**
Debt level	− .447	.237	3.561	.059	.640
Planned increase of production	**.873**	**.378**	**5.329**	**.021**	**2.394**
Risk aversion	**− .510**	**.201**	**6.423**	**.011**	**.600**
Early adopter (self-considered)	**.731**	**.269**	**7.398**	**.007**	**2.076**
Technologically advanced (self-considered)	− .220	.249	.778	.378	.802
Socially active (self-considered)	− .470	.249	3.573	.059	.625
Focus on improvements (self-considered)	**.811**	**.315**	**6.611**	**.010**	**2.250**
Constant	− 13.570	2.925	21.527	.000	.000

χ^2	− 2 Log likelihood	Cox and Snell R Square	Nagelkerke R Square
149.76	120.055	.197	.426

Figures marked in bold indicate statistically significant differences at the 95% confidence level

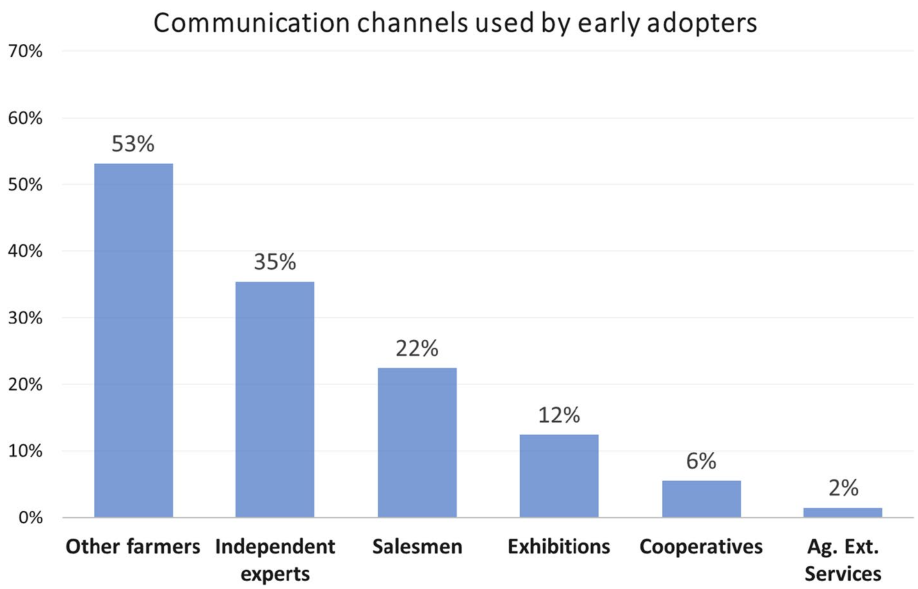

Fig. 3 Informal social networks, such as other farmers and independent experts, are the predominant communication channels that early adopters rely on in Spain to obtain relevant information regarding on-farm RES

who have not yet installed RES consider that their farm would be well-suited to the technology. This figure is similar to results reported in other studies (Tate et al., 2012; Beckman & Xiarchos, 2013). High interest levels, however, contrast with low level of

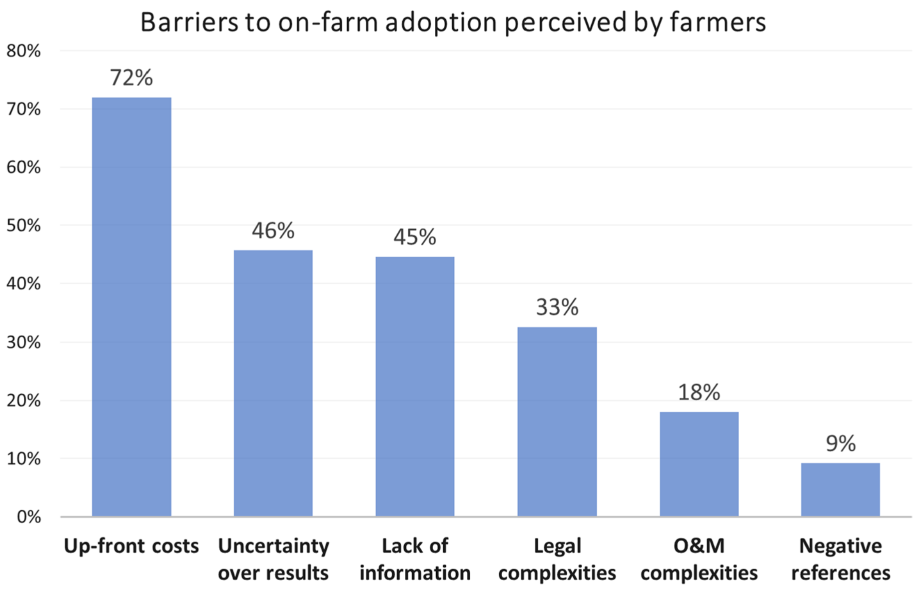

Fig. 4 High up-front cost, uncertainty over the results of the investment and lack of tailored offers to farmers' needs are the main barriers identified by those hesitant to adopt RES. The legal and administrative framework of RES in Spain is also perceived as a major deterrent

adoption and it is important to identify barriers for RES uptake. The surveyed group of farmers classified as "suitable but without RES" indicated that the upfront cost required for RES is, by far, the main barrier that discourages them from installing on-farm RES (72%, CI 95%: 67–72%). The second most important barrier mentioned by farmers was a high level of uncertainty over the results (45.7%, CI 95%: 40–52%), including uncertainty about the expected economic savings, doubt regarding the capacity of RES to produce the energy required by the farm in a reliable manner and uncertainty regarding the actual burden that operation and maintenance activities of the systems may cause. The lack of information and tailored offers to farmers' needs are also perceived as important barriers (44.6%, CI 95%: 39–51%). Barriers following in importance are legal and administrative complexities (32.6%, CI 95% 27–38%) and O&M complexities (18%, CI 95% 14–23%). Negative references from farmers who have already installed RES are considered to be a discouraging factor by 9.2% (CI 95%: 6–13%) of potential users. Figure 4 presents these estimations.

Scale effects were observed regarding the barriers to on-farm RES and farm size. Smaller farms are almost exclusively concerned about up-front costs (100%), while medium and large farms are much more concerned about legal and administrative complexities, uncertainty over results and the lack of relevant information and offers (Fig. 5 below shows these scale effects).

Finally, the survey allows for the estimation of the communication channels that can be used to disseminate RES among potential users. Thus, information and assessment about new technologies provided by farmers' associations and cooperatives is the most cited source (73%, CI 95%: 68–78%) followed by technology providers (61%, CI 95%: 56–67%), independent experts (53.9%, CI 95% 48–60%), and other farmers (44.3%, CI 95% 38–50%). Large farms rely more on independent experts and less on technology providers. Small

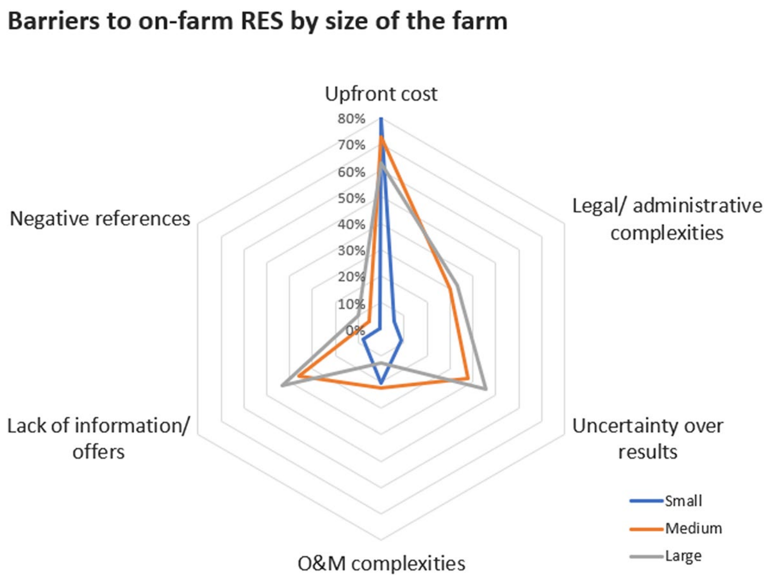

Fig. 5 The barriers perceived by farmers to on-farm RES introduction present scale effects and two groups of farms can be identified. The first group includes small farms which are almost exclusively concerned with the cost of the systems. The second group includes medium-sized and large farms, and they are relatively more concerned with non-economic factors

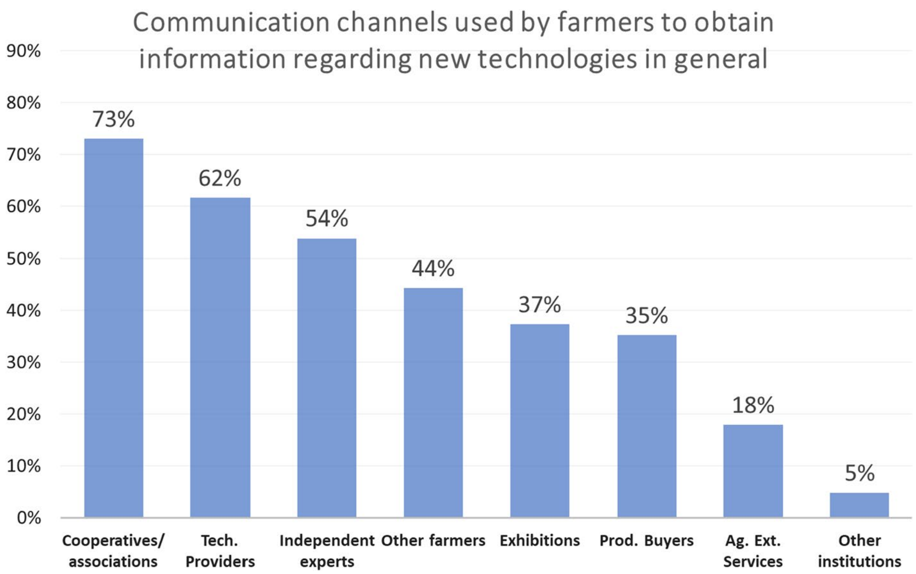

Fig. 6 Farmers rely on their formal networks to obtain relevant information regarding new technologies that can be introduced in their holdings, including farmers' associations and cooperatives and sellers/providers of the technology. These channels must be used to disseminate on-farm RES information in order to reach the majority of potential adopters

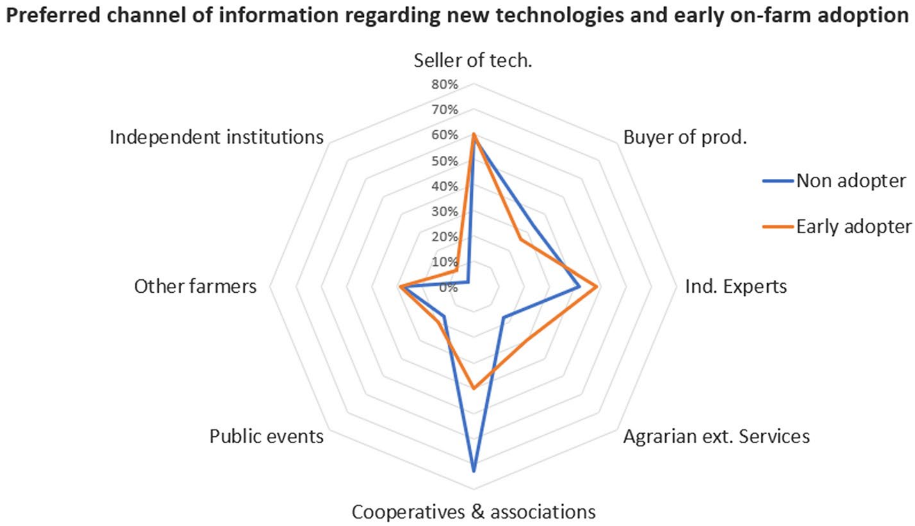

Fig. 7 The sources that early adopters used to obtain information regarding new technologies differ from those of non-adopters. This effect may indicate that cooperatives and farmers associations may play a larger role in disseminating on-farm RES

farms rely more on information provided by farming associations/cooperatives and other farmers. These results are presented in Fig. 6.

Farmers that already installed RES report different pattern of information acquisition, identifying cooperatives and farming associations as important sources regarding the introduction of new technologies, as can be seen in Fig. 7. For non-adopters, cooperatives and farmers' associations were recognized as the most important communication channel (72.7%), whereas for early adopters, technology sellers were the source of information of reference (60%).

4 Discussion

The results indicate that the diffusion of RES technology in Spain was far below the policy targets, as only 8% of farmers adopted the technology by 2016 while Government's target for that time was of 20%. Even in the upper level of the confidence interval, the results show a deviation of around 50% from the planned target. The observed deviation indicates the limited success of the policies that have been implemented to reach on-farm RES targets. Importantly, the results suggest that the low level of diffusion of on-farm RES in Spain is not primarily caused by a lack of awareness or interest by farmers regarding on-farm RES, as an estimated 85% of the farmers who have not installed RES are aware of the technology and consider that it may be suitable for their farm.

Nevertheless, a number of findings indicate that on-farm RES was still in the early stages of its technology diffusion process (Rogers, 2010), suggesting that most farmers were using a "wait and see" approach rather than actively adopting it. This can explain the high relationship shown between risk tolerance and on-farm RES adoption which suggest that most of the farmers who were introducing the technology can be classified as "innovators". To explain this lack of progress, it is relevant to analyse the drivers and barriers found by farmers in relation to the adoption of on-farm RES as well as the communication channels that are acting to disseminate the technology.

The main driver for on-farm RES adoption in Spain was the farmer's expectation to obtain positive economic returns on the investment, whether by saving in energy bills or by selling the energy produced. This result is consistent with most of the literature available on the issue (Borchers et al., 2014; Yaqoot, 2016; Ackrill & Abdo, 2020). Environmental concerns were less of a relevant factor while the availability of grants, the cornerstone of the Spanish supporting policy, was a decisive element for only 17.4% of the farmers that had introduced on-farm RES. This result indicates the relatively reduced relevance of grants as a driver for on-farm RES adoption, an issue that has been already reported elsewhere (Borchers et al., 2014; Tate et al., 2012; Reise, 2012). Thus, the accumulated evidence contradicts the widespread perception that grants and subsidies are the main driver of investments in farming and that consequently, these types of actions should be the most important piece of supporting policies for on-farm RES.

The survey also showed that the probability of early adoption is statistically related with the availability of a succession mechanism for the farm and with the willingness of the farmer to carry out long-term investments, relationships that have been previously reported (Calus, 2008; Sutherland, 2016; Pedroli & Langeveld, 2011). Thus, Spanish farmers consider that on-farm RES will only pay-off in the long term, so only those willing to assume long payback times are interested in the solution. Nevertheless, for on-farm RES to be massively introduced, it is necessary that it offers a clear value proposition for the farmers, not only in the long term, but also in the short and medium term. In this regard, business models that deliver positive returns from day one, while reducing the riskiness of the investment, can be expected to be more suited for the majority of farmers. This is the case of third party ownership-based (TPO) business models (Drury et al., 2012), such as those based on energy services companies (ESCO), where the RES is owned and operated by specialized entities. In TPO, the results are guaranteed by the operator and, in most cases, no upfront payments are required, so most of the financial, legal and technical complexities and risks are transferred from the farmer to the ESCO. TPO models also have the capacity to attract a higher level of investment to RES and to introduce price transparency and technical quality to the market (Joshi, 2012; Mendelsohn et al., 2015).

Another relevant result is the strong positive relationship found between contract farming and on-farm RES introduction. Contract farming facilitates long-term planning and is seen by many farmers as a risk mitigation strategy (Glover & Kusterer, 2016) which can somehow compensate for the additional risks of introducing on-farm RES. Contract farming also allows farmers to introduce new technology and to learn new skills as well as to have access to credit lines from the purchaser or other financial providers. The positive relationship between contract farming and on-farm RES adoption can be considered in the design of supporting measures for on-farm RES, for example by combining standardized production contracts for the agrarian output of the farm with standardized power purchase agreements for the energy output resulting from on-farm RES.

Regarding the barriers of on-farm RES adoption, the most relevant barrier is the high up-front costs that are required to install on-farm RES. This barrier has been highlighted by more than 70% of farmers. Long payback time, together with the novelty of the technology, introduces uncertainty regarding the results of the investment, so the assessment of return and reward is considered to be insufficient for most farmers. The lack of confidence regarding the actual performance of installed on-farm RES can also be related to the limited track record of the solution within the personal network of most farmers, due to the low diffusion level of the technology.

In the case of Spain, uncertainty over long-term results of RES could have been compounded with the unstable regulatory framework that negatively affected the profitability of many projects (Dusonchet & Telaretti, 2015; Alonso, 2016). Indeed, the legal and administrative framework of RES in Spain is also perceived to be a barrier, rather than as a driver for many farmers, a result that puts into question the effectiveness of the related policies implemented by the Spanish Government. Thus, while only an estimated 17.4% of farmers who introduced on-farm RES considered that the availability of subsidies and grants were a relevant factor for adoption, an estimated 32.6% of potential adopters considered the related legal and regulatory framework as a main barrier to adoption. The negative impact of RES-related regulation, also found in other studies (Morris & Bowen, 2020; Ackrill, 2020) indicate that ill-designed and unstable regulation more than offsets the availability of subsidies and grants.

Scale effects have been observed in the perceived barriers to on-farm RES. The survey showed small farms listing different barriers to medium-sized and large-sized farms. Thus, the former were almost exclusively concerned with the up-front cost of the systems, meaning that supporting measures based on subsidizing this cost could be more efficient when engaging small farms in on-farm RES. Larger farms requires more comprehensive on-farm RES supporting measures, aimed at reducing uncertainty and providing a stable regulatory and administrative framework. Regarding the existence of scale effects and the introduction of on-farm RES, existing literature shows contradictory findings. Results found in Spanish farms (Ruiz-Fuensanta et al., 2019) and in Dutch horticulture farms (Aramyan et al., 2007), for example, suggest that large farms are more likely to invest in energy-saving measures than small-scale farmers, as they are consuming more energy. These results contrast with those reported in greenhouse farming (Pietola & Lansink, 2006), indicating that small farms are more likely to invest in such technologies. In our dataset, no correlation between farm size and investments in RES installations was found.

Finally, the analysis of the communication channels that have been used by early adopters indicates that the on-farm RES dissemination process has been mainly driven by word of mouth and by direct contact among farmers. Thus, the communication channel that has been more active in disseminating on-farm RES in Spain has been "other farmers". Nevertheless, the results also show that non-adopter farmers, who are the majority, mainly rely on farmers' associations and cooperatives to obtain relevant information much more than adopters do.

It appears that the relevant "know-how" for on-farm RES adoption is not available precisely in the place where most farmers are used to obtaining such information (Skaalsveen, 2020). Also interestingly, a negative correlation (Sig. 0.59) has been found between the level of social and professional networking activity of the farmer and early adoption, which can also indicate that on-farm RES adoption has not been driven as a result of information or experiences that have occurred within the farmers' main professional network: the farmers associations and cooperatives. The described findings suggest that reinforcing the capacity of farmers' associations and cooperatives to provide relevant information regarding on-farm RES could be an effective strategy to facilitate its dissemination. This can be done by supporting these types of entities, for example, by training their staff in on-farm RES related issues or by carrying out pilot experiences whose results can then be disseminated among members.

5 Conclusion

Despite the existence of suitable solutions and dedicated supporting measures and policies, the level of diffusion of on-farm RES in Spain is much lower than the level established by the Spanish Government. This mismatch has been caused by a number of non-technological barriers which are preventing most of the potential adopters to install on-farm RES.

Farmers' perceived uncertainty over the results of on-farm RES projects was too high to convince them to assume the high up-front costs and long pay-back times which are characteristic of RES investments. Furthermore, relevant information regarding the available solutions is missing precisely in the places where farmers are more used to searching for it when adopting new practices. The observed combination of economic and legal uncertainties that surround RES is compatible with a potential lock-out for the technology. In such context, subsidies and grants, which are the basis of existing supporting policies, have a limited impact on promoting on-farm RES adoption and further action might be necessary.

Thus, in order to facilitate the diffusion process of on-farm RES, tailored solutions must be implemented to better manage on-farm RES related risks and financing. In this regard, the development and promotion of tailored business models for on-farm RES based on task and risk allocation can be especially effective. Also, actions can be taken to ensure that relevant and reliable information is available within the most frequently used communication channels of the farmers such as cooperatives and associations. Furthermore, it is important to ensure a coherent policy framework for on-farm RES which could act as driver rather than as a barrier of on-farm RES. This policy framework does not necessarily have to be based on direct subsidies for RES investments, but in establishing a legal and administrative framework which is especially necessary to reduce uncertainty regarding the results of long-term investments, such as on-farm RES.

This analysis has a number of limitations that must be taken into consideration. Firstly, the sample used is entirely composed by Spanish farms, so its extrapolation to the rest of Mediterranean agriculture is not straightforward, especially in the case of smaller farms which tend to be more affected by local factors. Secondly, it should be noted that new communication channels based on web-based social networks are being rapidly adopted by farmers. Such communication channels have not been considered for this research so it could be a relevant issue for future work. Other issues that also deserve further attention in future research in on-farm RES adoption include the assessment of the effectiveness of alternative supporting measures to encourage new projects, the detailed identification of the risk factors perceived by the farmers and analysis of the impact of existing on-farm RES in the sustainability of the agricultural holdings and the rural communities where they belong.

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Authors' contributions Results of a survey of Spanish farmers on sustainable energy adoption are presented. The level of introduction of sustainable energy technology was much lower than the policy targets for the sector. The diffusion process of on-farm RES is locked in an early stage where only innovators are willing to adopt the technology. A high level of uncertainty regarding the results of the investment is the main barrier for most farmers. On-farm RES supporting measures should focus on reducing such uncertainty and on improving access to reliable and relevant information.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Abdelhady, S., Borello, D., & Shaban, A. (2018). Techno-economic assessment of biomass power plant fed with rice straw: Sensitivity and parametric analysis of the performance and the LCOE. *Renewable Energy, 115*, 1026–1034.

Ackrill, R., & Abdo, H. (2020). On-farm anaerobic digestion uptake barriers and required incentives: A case study of the UK east midlands region. *Journal of Cleaner Production, 264*, 121727.

Alonso, P. M., Hewitt, R., Pacheco, J. D., Bermejo, L. R., Jiménez, V. H., Guillén, J. V., et al. (2016). Losing the roadmap: Renewable energy paralysis in Spain and its implications for the EU low carbon economy. *Renewable Energy, 89*, 680–694.

Aramyan, L. H., Lansink, A. G. O., & Verstegen, J. A. (2007). Factors underlying the investment decision in energy-saving systems in Dutch horticulture. *Agricultural Systems, 94*, 520–527.

Barnes, A. P., McMillan, J., Sutherland, L., Hopkins, J., & Thomson, S. G. (2022). Farmer intentional pathways for net zero carbon: Exploring the lock-in effects of forestry and renewables. *Land Use Policy, 112*, 105861.

Beckman, J., & Xiarchos, I. M. (2013). Why are Californian farmers adopting more (and larger) renewable energy operations? *Renewable Energy*, *55*, 322–330.

Borchers, A. M., Xiarchos, I., & Beckman, J. (2014). Determinants of wind and solar energy system adoption by US farms: A multilevel modeling approach. *Energy Policy, 69*, 106–115.

Brudermann, T., Reinsberger, K., Orthofer, A., Kislinger, M., & Posch, A. (2013). Photovoltaics in agriculture: A case study on decision making of farmers. *Energy Policy, 61*, 96–103.

Calus, M., Van Huylenbroeck, G., & Van Lierde, D. (2008). The relationship between farm succession and farm assets on Belgian farms. *Sociologia Ruralis, 48*, 38–56.

Drury, E., Miller, M., et al. (2012). The transformation of southern California's residential photovoltaics market through third-party ownership. *Energy Policy, 42*, 681–690.

Dusonchet, L., & Telaretti, E. (2015). Comparative economic analysis of support policies for solar PV in the most representative EU countries. *Renewable and Sustainable Energy Reviews, 42*, 986–998.

Esen, M., & Yuksel, T. (2013). Experimental evaluation of using various renewable energy sources for heating a greenhouse. *Energy and Buildings, 65*, 340–351.

Franke, G. (2000). Trends in House Climate Control. *Landtechnik, 55*, 412–413.

Glenk, K., Eory, V., Colombo, S., & Barnes, A. (2014). Adoption of greenhouse gas mitigation in agriculture: An analysis of dairy farmers' perceptions and adoption behaviour. *Ecological Economics, 108*, 49–58.

Glover, D., & Kusterer, K. (2016). *Small farmers, big business: Contract farming and rural development*. Springer.

Hibberts, M., Burke Johnson, R., & Hudson, K. (2012). Common survey sampling techniques. In *Handbook of survey methodology for the social sciences* (pp. 53–74). New York, NY: Springer.

Instituto Nacional de Estadística (INE), (2009). Censo Agrario 2009.
John, A., Clark, C., Freeman, M., Kerrisk, K., Garcia, S., & Halachmi, I. (2016). Review: Milking robot utilization, a successful precision livestock farming evolution. *Animal, 10*, 1484–1492.
Joshi, J. (2012). Renewable energy finance and securitization. *Journal of Structured Finance, 17*, 174.
Li, B., Ding, J., Wang, J., Zhang, B., & Zhang, L. (2021). Key factors affecting the adoption willingness, behavior, and willingness-behavior consistency of farmers regarding photovoltaic agriculture in china. *Energy Policy, 149*, 112101.
Lorenzo, C., Almeida, R. H., Martínez-Núñez, M., Narvarte, L., & Carrasco, L. M. (2018). Economic assessment of large power photovoltaic irrigation systems in the ECOWAS region. *Energy, 155*, 992–1003.
MAPAMA, (2020). Informe Anual de Indicadores: Agricultura, Alimentación y Medio Ambiente 2019.
Martinho, V. J. (2016). Energy consumption across European Union farms: Efficiency in terms of farming output and utilized agricultural area. *Energy, 103*, 543–556.
Mendelsohn, M., Urdanick, M., Joshi, J., (2015). Credit enhancements and capital markets to fund solar deployment: Leveraging public funds to open private sector investment.
Morris, W., & Bowen, R. (2020). Renewable energy diversification: Considerations for farm business resilience. *Journal of Rural Studies, 80*, 380–390.
Mostefaoui, Z., & Amara, S. (2019). Renewable energy analysis in the agriculture–greenhouse farms: A case study in the mediterranean region (sidi bel abbes, algeria). *Environmental Progress and Sustainable Energy, 38*(3), e13029.
Pedroli, G.B.M., Langeveld, H., (2011). Impacts of Renewable Energy on European Farmers.Creating benefits for farmers and society.
Pietola, K., & Lansink, A. O. (2006). Energy-saving Technology Choices by Dutch Glasshouse Firms. *Journal of Agricultural Economics, 57*, 129–144.
Rao, K. U., & Kishore, V. V. N. (2010). A review of technology diffusion models with special reference to renewable energy technologies. *Renewable and Sustainable Energy Reviews, 14*, 1070–1078.
Reise, C., Musshoff, O., Granoszewski, K., & Spiller, A. (2012). Which factors influence the expansion of bioenergy? An empirical study of the investment behaviours of German farmers. *Ecological Economics, 73*, 133–141.
Rogers, E. M. (2010). *Diffusion of innovations*. Simon and Schuster.
Rosillo-Calle, F., Woods, J., (2012). The biomass assessment handbook: Bioenergy for a sustainable environment, Earthscan.
Ruiz-Fuensanta, M. J., Gutiérrez-Pedrero, M., & Tarancón, M. (2019). The role of regional determinants in the deployment of renewable energy in farms. The case of spain. *Sustainability (basel, Switzerland), 11*(21), 5937.
Schaffer, A., & Düvelmeyer, C. (2016). Regional drivers of on-farm energy production in Bavaria. *Energy Policy, 95*, 361–363.
Skaalsveen, K., Ingram, J., & Urquhart, J. (2020). The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems, 181*(102824), 69.
Steidle Neto, A. J., & Lopes, D. D. C. (2021). Technical analysis of photovoltaic energy generation for supplying the electricity demand in brazilian dairy farms. *Environment, Development and Sustainability, 23*(2), 1355–1370.
Sutherland, L., Peter, S., Zagata, L., (2014). On-farm renewable energy: A 'classic case'of technological transition. Transition Pathways towards Sustainability in Agriculture: Case Studies from Europe, 127.
Sutherland, L., Toma, L., Barnes, A. P., Matthews, K. B., & Hopkins, J. (2016). Agri-environmental diversification: Linking environmental, forestry and renewable energy engagement on Scottish farms. *Journal of Rural Studies, 47*, 10–20.
Tate, G., Mbzibain, A., & Ali, S. (2012). A comparison of the drivers influencing farmers' adoption of enterprises associated with renewable energy. *Energy Policy, 49*, 400–409.
Trujillo-Barrera, A., Pennings, J. M., & Hofenk, D. (2016). Understanding producers' motives for adopting sustainable practices: The role of expected rewards, risk perception and risk tolerance. *European Review of Agricultural Economics, 43*, 359–382.
Valente Thomas, W. (1995). *Network models of the diffusion of innovations*. Cresskill.
Yaqoot, M., Diwan, P., & Kandpal, T. C. (2016). Review of barriers to the dissemination of decentralized renewable energy systems. *Renewable and Sustainable Energy Reviews, 58*, 477–490.