Argumenta Oeconomica
Year 2025, Vol. 55, No. 2
ISSN 2720-5088
journals.ue.wroc.pl/aoe

Taxonomic analysis of photovoltaic technology diffusion processes in European countries

Marcin Salamaga

Department of Statistics, Krakow University of Economics, Poland

e-mail: salamaga@uek.krakow.pl

ORCID: 0000-0003-0225-6651

Quote as: Salamaga, M. (2025). Taxonomic analysis of photovoltaic technology diffusion processes in European countries. *Argumenta Oeconomica*, *2*(55), 21-33.

DOI: 10.15611/aoe.2025.2.02

JEL: Q42, Q55, C38

Abstract

Aim: The aim of the article was to compare the processes of diffusion of innovations in photovoltaic technologies in European countries.

Methodology: The study used the Bass model, and on the basis of individual estimates of the parameters of this model for each of the compared countries, their taxonomic analysis was carried out.

Results: The innovators in the field of photovoltaic technologies turned out to be countries with high GDP and elevated expenditure on research and development, as well as countries whose favourable geographical location ensures a sufficiently large number of sunny days per year. This is followed, in turn, by countries with limited solar energy market potential located mainly in Central and Eastern Europe and some Scandinavian countries.

Implications and recommendations: The results presented in the article may support decision-makers in creating an appropriate system for the synchronisation and coordination of policies and activities aimed at creating an electricity system with a high share of renewable energy sources. Comparative studies of the diffusion of solar technologies are also important from the point of view of assessing the effectiveness of actions aimed at creating zero-emission economies and possible adjustments to the European Green Deal.

Originality/value: The article presents an original comparative analysis of the diffusion profiles of innovations in photovoltaics in European countries, thus the research results fill the research gap in this area.

Keywords: renewable energy sources, photovoltaics, Bass model, learning curves, Ward's method

1. Introduction

Gradually moving away from energy sources based on fossil fuels and replacing them with renewable energy sources is one of the most important tools to stop unfavourable climate changes and their effects (Dooley, & Kartha, 2018). Renewable energy sources are free from most of the disadvantages of fossil fuels (Lindman, & Söderholm, 2016; Grubb et al., 2021). This applies in particular to the impact of energy sources on the natural environment and human health. Renewable energy sources are ecological, as most renewable energy sources do not emit harmful combustion by-products into the environment, thus improving the climate. One must also remember about the limited resources of fossil fuels, which are found only in certain regions of the world. Moreover, the limited supply and high demand for fossil fuels make their prices very unstable and constantly increasing (Dooley, & Kartha, 2018; Grubb et al., 2021).

Importantly, renewable energy sources allow to increase the available energy options, diversify energy sources and reduce the energy market's dependence on unstable fossil fuel prices. Taking into account the need to stop negative climate changes, which are largely a consequence of the use of emission-intensive energy sources, limited fossil fuel resources, but also the need to protect the natural environment, the UN member states under the Paris Agreement committed to reducing greenhouse gases (Markard et al., 2020). The European Commission has introduced a package of political initiatives – the so-called European Green Deal – which aims to achieve ecological transformation and, ultimately, climate neutrality by 2050. Its long-term goal is to transform the EU into a fair and prosperous society with a modern and competitive economy. As part of the European Green Deal, member countries were obliged to gradually eliminate mined energy sources in all economic sectors and replace them with renewable energy sources (Almeida et al., 2023). The values of renewable energy use indicators and the time in which they are to be achieved in individual sectors of the economy have been determined. At the same time, an EU financing mechanism has been developed to help countries achieve individual and collective renewable energy goals (Sikora, 2021). An inherent element of the energy transformation is innovation and an appropriate innovation policy (at national and EU level), which support technologically advanced devices and installations based on renewable energy sources.

One of the key sources of renewable energy is solar energy which is used in three ways: through photovoltaic conversion, chemical conversion or photochemical conversion (Alharbi, & Kais, 2015). Photovoltaic conversion taking place in photovoltaic cells enables the conversion of solar energy into electricity, which can be directly consumed by prosumers, stored and transferred in the form of a surplus to the power grid and settled under the price discount system.

Innovations in photovoltaic technologies include activities aimed at improving the efficiency of PV operation, reducing the costs of electricity production, increasing the durability of installations and better adapting the technology to various applications. Examples of such activities include the search for new materials and photovoltaic cells (thin-film, organic cells – OPV), development of the structure of silicon cells (use of Passivated Emitter and Rear Cells – PERC), integration of photovoltaics with other technologies (Building Integrated Photovoltaics – BIPV), integration with energy storage facilities (e.g. lithium-ion batteries, flow batteries), new and efficient methods of recycling photovoltaic panels (technologies allowing to recover silicon, silver and other materials from end-of-life panels) (Allouhi et al., 2022; Panda et al., 2023). The attractiveness of solar energy obtained from photovoltaic panels (PV) is rapidly increasing and some experts predict that solar energy will gradually dominate global electricity markets (Nijsse et al., 2023; Bessi et al., 2024).

Innovations in renewable energy sources based on solar energy are subject to diffusion, i.e. spreading in individual economic sectors, industries and society, which generally follows an S-shaped curve over time (as is the case with most other innovations), yet the rate of this phenomenon or the level of technology saturation may vary between countries and sectors (Bessi et al., 2024; Skoczkowski et al., 2019; Zhang et al., 2020). This is due to many factors, e.g. different market potential of individual countries, as well as different levels of absorption of new technologies. Regarding the diffusion of renewable energy technologies based on solar energy, the angle of incidence of sunlight and the number of sunny days per year also play a significant role.

There was a research gap in the literature in this area, due to the lack of studies that would comprehensively compare the processes of diffusion of innovations in renewable energy sources based on solar energy in Europe. However, there are numerous studies on the diffusion of renewable energy innovations in non-European countries, such as China, India and some developing countries. However, it should be emphasised that the structure of the economies of these countries is generally different than that of most countries in Europe. The aim of this article was to compare the processes of diffusion of innovations in photovoltaic technologies in European countries, serving to test the following research hypothesis: innovators in the field of PV technology and diffusion of photovoltaic technologies may be technologically advanced countries, even if they have worse climatic conditions (little sunlight), as well as countries with low R&D expenditure on renewable energy, provided they have favourable climatic conditions (abundant sunlight).The basic tool used by the author was the Bass model **(BM)**. Based on the results of this model estimated for individual European countries (including non-EU countries), regularities between the obtained indicators of innovation, imitation and market potential were determined. Additionally, the authors conducted a taxonomic analysis of European countries with respect to the numerical characteristics of the diffusion processes of solar technology innovations.

2. Literature review

In research on innovations in renewable energy technology, two trends are clearly visible: the analysis of the dynamics of technology dissemination over time, and the second focused on the presentation of the effect of learning through experience. The first trend analyses, among others: technology cycles and predicts when innovation saturation occurs; s-shaped curves are most often used for this purpose (Meade, & Islam, 2006; Zhang et al., 2020). The second approach generally uses a curve that refers to the cost reduction of a standard product within one company (learning curve) or a curve that describes the cost of non-standardised products at global, regional or national level (experience curve) (Dan, & Simon, 1983). The former is based on the diffusion of technology, with one of the basic theories of diffusion being that of Rogers (1983), who defined diffusion as a process in which an innovation (e.g. a new technology) is characteristic of a specific element over time belonging to a member of a social system. Rogers identified four key elements that come together for diffusion: innovation, communication channel, time and social system.

Among the models used in diffusion analysis, the logistic function and the Bass model are relatively common. Harris et al. (2018), for example, used four-parameter multi-cycle logistic growth curve models to forecast constant conditions for energy production and consumption in the USA up to 2040. The study also assessed the sources of energy production in terms of their ability to meet demand in the US market.

Hansen et al. 2017 showed that technologies using, among others, solar energy are subject to diffusion according to the logistic curve. The authors showed that, contrary to popular belief, the growth dynamics of energy from photovoltaics (and also from wind turbines) has decreased in recent years. In turn, Cong (2013) proved that the use of solar energy in the Chinese economy was growing relatively steadily, and also predicted a decrease in the unit cost of investment in this form of energy. Bessi et al. (2024) studied trends in the diffusion of photovoltaic technologies in the Italian economy, and showed a strong correlation between the degree of acceptance of this type of technology by society and the use of public incentives and the implementation of various types of incentive programmes. The authors used the BM in their research, and conducted the analysis separately in different periods and under different energy market development scenarios.

The Bass model was also used in the analysis of the spread of photovoltaic systems in Colombia by Radomes and Arango (2015), where the adoption rate was a function of awareness campaigns and social interactions. The model takes into account both subsidy and feed-in tariff policies, and their results proved that an appropriate investment subsidy combined with a feed-in rate together provided the highest marginal increase in the diffusion of solar technologies. De La Tour et al. (2013) used annual data on PV module prices, total production, R&D knowledge resources, and silicon and silver raw material prices to build an experience curve model based on which they predicted a 67% decline in the price of PV modules in 2011–2020. Thus, they showed that the cost of electricity generated from photovoltaics would reach the level of conventional energy by 2020 in the sunniest countries, such as Italy and Spain. A learning curve for system balance costs in photovoltaics for over 20 countries was also constructed by Elshurafa et al. (2018), who provided a detailed analysis of the rate of decline in the capital costs of solar PV that facilitates effective renewable energy planning. An analysis of the costs of photovoltaics in South Korea based on the learning curve was conducted by Hong et al. (2015). Using two-factor learning curve (2FCL) analysis, they showed that for each doubling of cumulative photovoltaic energy production, the cost decreased by 2.33%. The Bass curve was used in modelling photovoltaic energy generation technology in China by Zhang et al. (2020). Their research indicated that high costs remain a significant obstacle to the development of large-scale photovoltaics, and also showed that domestic economic activity, the intensity of policy incentives and other factors had a limited impact on the development of photovoltaic generation.

Skoczkowski et al. (2019) used logistic curves to describe the diffusion of solar technologies and predicted that the share of energy production in the EU, depending on the scenario considered and the model used, would reach saturation with photovoltaics at a level of 20% to 60%. The authors carried out projections of the development of photovoltaic energy until 2100, however the results of these studies were presented for the entire EU-28 not allowing for a comparative analysis of the diffusion of innovations in solar technologies between individual member states. Factors influencing the diffusion of innovation in PV in Australia were studied by Simpson and Clifton (2017). They showed, among others, that financial incentives, technical and environmental aspects of solar energy, and proper education allowing potential recipients of new technologies to understand the benefits of solar energy were important in the process of adopting solar technologies. Learning curves in conjunction with appropriate econometric models were also used to investigate the role of sustainability factors in the diffusion of photovoltaic technologies.

Aponte et al. (2023) showed their significant impact on the installed capacity in all analysed photovoltaic technologies, and that the cost reduction of photovoltaic modules depended largely on the learning outcomes and the analysed period. Although the issue of diffusion of solar energy innovations is relatively popular in scientific research, studies of a comparative nature in relation to a larger group of countries are rarely conducted. Yet, this type of research is necessary to assess the progress of various EU countries in implementing the European Green Deal policy and to compare the capabilities of their economies in absorbing new renewable energy technologies. The author of this article met these expectations and tried to fill the existing research gap. Data for calculations came from the Our World in Data[1] database available under an open licence. The research included data on energy production based on photovoltaic panels in 32 European countries[2]. The basis for building models of the diffusion of photovoltaic technology innovations were time series of annual energy production (in TWh) covering the years 1985–2023.

[1] https://ourworldindata.org/

[2] The data included the total energy production generated by all PV installations (both from home prosumer installations and from large photovoltaic farms) in each country based on reports from national power systems.

3. Methodology

The Bass model was used to analyse the process of proliferating solar technology innovations, successfully applied to assess the diffusion of innovations, including those related to renewable energy. In the analysis of the diffusion of solar technologies, the BM was employed by, among others, Radomes and Arango (2015) and Zhang et al. (2020). Moreover, the BM was chosen as the most suitable for this research due to its simplicity, traceability and ease of interpretation of the obtained parameters.

This model was estimated for 32 different European countries (including non-EU countries)[3], and the comparative analysis of its parameters, i.e. innovation indicators, imitation and market potential, combined with cluster analysis allowed the identification of regularities occurring in the processes of diffusion of these innovations, among others in spatial terms. The basic form of this model can be written in the following differential equation (Bass, 1969, 2004; Guidolin, 2023):

$$\frac{dN(t)}{dt} = \left[p + q\frac{N(t)}{m}\right][m - N(t)], \tag{1}$$

where *N(t)* – total number of users of the innovation in time *t*, *m* – number of potential and current users of the innovation (market potential), *p* – innovation coefficient reflecting the influence of potential and current users of innovations, *q* – imitation coefficient responsible for the impact of replicating (imitation) innovations.

Parameter *p* belonging to the interval [0;1] can be interpreted as the percentage of users who adopt the innovation (Da Silva et al. 2020). In turn, component $q\frac{N(t)}{m}$ in formula (1) means the percentage share of users of the innovation, scaled by imitation coefficient *q*.

The solution to equation (1) has the form of function *N(t)*:

$$N(t) = m\frac{1-\exp(-(p+q)t)}{1+\frac{q}{p}\exp(-(p+q)t)}, \; t > 0 \tag{2}$$

The graph of this function is an S-curve, and taking into account formula (2), the equation of the immediate innovation diffusion process (the first derivative of the cumulative number of users)takes the form:

$$N'(t) = m\frac{p(p+q)\exp(-(p+q)t)}{[p+q\exp-(p+q)t^2}, \; t > 0 \tag{3}$$

The time after which the maximum number of new users occurs (the maximum of the immediate diffusion process) is: $t^* = \frac{\ln\left(\frac{q}{p}\right)}{(p+q)}$, and this maximum number of new users is equal to: $N(t^*) = \frac{m}{2} - \frac{p}{2q}$. The results of the BM estimates were used to group European countries using taxonomic methods. For this purpose, a two-dimensional analysis (taking into account pairs of BM parameters) and Ward's method with Euclidean distance (taking into account all BM parameters) were used. The obtained clusters made it easier to identify regularities in the development of the diffusion processes of solar technologies in European countries.

4. Results

First, the Bass model (1) was estimated for 32 European countries. The diffusion models were estimated based on annual energy production from PV based on time series from 1985-2023. The results are presented in Table 1.

[3] The research included only those countries for which complete data on PV energy were available from the Our World in Data database.

Table 1. Bass model estimation results

Country	Mark	Parameters		
		p	*q*	*m*
Austria	AUT	0.0019	0.0152	1710.6942
Bulgaria	BLR	0.0008	0.0599	258.8275
Belgium	BEL	0.0035	0.0626	90.7379
Belarus	BGR	0.0007	0.1420	286.3502
Czechia	CZE	0.0011	0.0442	126.4385
Denmark	DNK	0.0014	0.0319	105.1744
Estonia	EST	0.0012	0.0773	15.1111
Finland	FIN	0.0007	0.0153	656.5753
France	FRA	0.0049	0.0480	2965.6112
Germany	DEU	0.0033	0.0267	1423.0448
Greece	GRC	0.0020	0.0252	860.6942
Hungary	HUN	0.0009	0.0309	17.0423
Ireland	IRL	0.0005	0.7106	29.1437
Italy	ITA	0.0041	0.0962	3305.6121
Latvia	LVA	0.0014	0.0152	220.0084
Lithuania	LTU	0.0012	0.0319	28.7542
Luxembourg	LUX	0.0020	0.2178	4.3679
Netherlands	NLD	0.0029	0.3543	124.7815
North Macedonia	MKD	0.0001	0.3198	7.9688
Norway	NOR	0.0000	0.4785	21.9372
Poland	POL	0.0003	0.5215	130.2703
Portugal	PRT	0.0041	0.2988	50.8273
Romania	ROU	0.0001	0.4988	160.8273
Russia	RUS	0.0011	0.1751	29.6388
Slovakia	SVK	0.0018	0.0705	24.2462
Slovenia	SVN	0.0005	0.1681	19.0671
Spain	ESP	0.0023	0.2585	1894.6102
Sweden	SWE	0.0004	0.5015	10.0011
Switzerland	CHE	0.0015	0.0202	22.7619
Ukraine	UKR	0.0002	0.0824	55.3558
Great Britain	GBR	0.0025	0.3850	948.9271
Croatia	HRV	0.0037	0.3109	2.4153

Source: own calculations.

In order to effectively compare the obtained results between countries, the next three figures present two-dimensional summaries of the values of all pairs of BM parameters, i.e. *p* and *q*, then *m* and *p* and *m* and *q*. This made it easier to identify countries where the diffusion of innovations in photovoltaics was similar and to determine any regularities occurring between the parameters of the BM in different groups of countries.

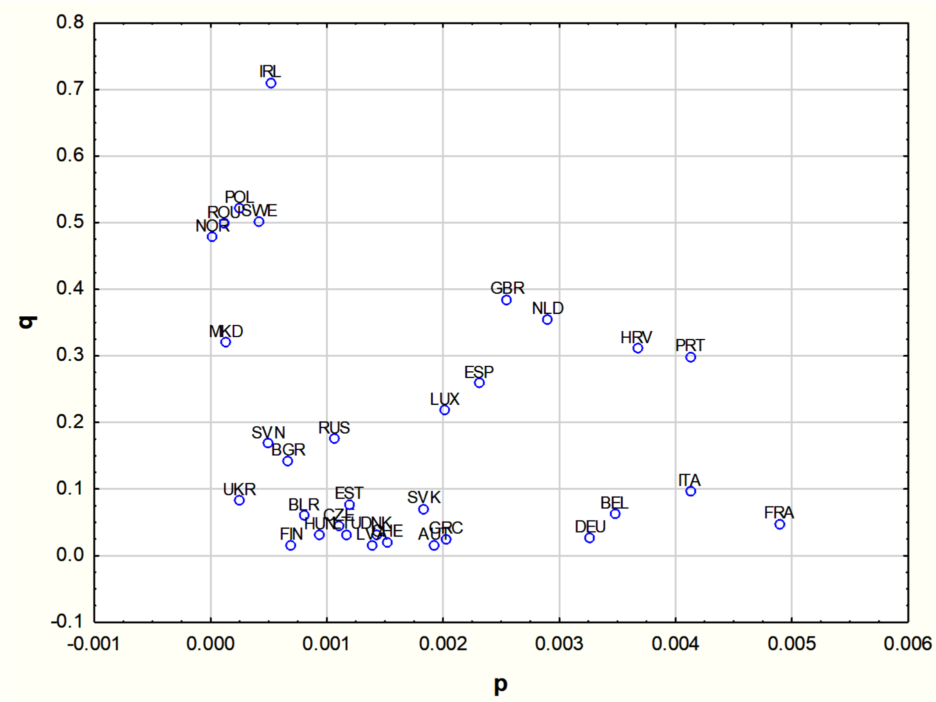

Fig. 1. The values of parameters *p* and *q* in the BM describing the diffusion of innovations in photovoltaics in European countries

Source: own calculations.

Figure 1 shows that most countries were characterised by a low innovation rate and a low imitation rate – primarily Central and Eastern European countries such as Ukraine, Russia, Belarus, Bulgaria, the Czech Republic, Estonia, Latvia and North Macedonia, but also, which may seem surprising, Greece, Austria, Denmark and Switzerland. However, the latter three had a higher innovation rate ($q > 0.001$), which allowed to consider them as early innovators when it comes to solar technologies, whereas the remaining countries were seen as late adopters of innovation. Another clearly distinguishable group of countries are 'imitators', characterised by low innovation and high levels of the imitation index, namely Ireland, Sweden, Norway, Romania and Poland. Therefore, with some exceptions, countries with a low R&D spending base or with a location in higher latitudes (resulting in less exposure to the sun and fewer days of sunshine per year) were less interested in innovative activities in the area of solar technologies and more likely to become imitators of this type of innovation. Countries that can be considered innovators in the field of photovoltaic technologies with a higher level of innovation index ($p > 0.002$) and a low level of imitation index were mainly Western European countries, i.e. Germany, France, Belgium, the Netherlands, Italy, Spain, Portugal, Great Britain, but also Croatia. Some of these countries with a particularly high innovation rate can be considered pioneers of photovoltaic technologies. Note that these are generally countries with high GDP and high levels of expenditure on research and development (Germany, France, Great Britain), and some of them enjoy a favourable geographic location ensuring a sufficiently high number of sunny days (Croatia, Italy, South of France), which enables the effective use of solar technologies in the production of electricity and heat.

Figure 2 presents market potential indicators (m) of European countries and innovation indicators (p).

As can be seen from Figure 2, among the compared countries dominant those with a low market potential index ($m < 500$) and late adopters of solar technologies ($p < 0.002$). These are mainly Central European countries, both EU and non-EU. Among the countries with a low market potential but with a high innovation rate are the Netherlands, Belgium, Croatia and Portugal. Out of the compared countries, four clearly showed high market potential ($m > 1000$) and are pioneers of innovation in photovoltaic technologies, namely France, Italy, Spain and Germany.

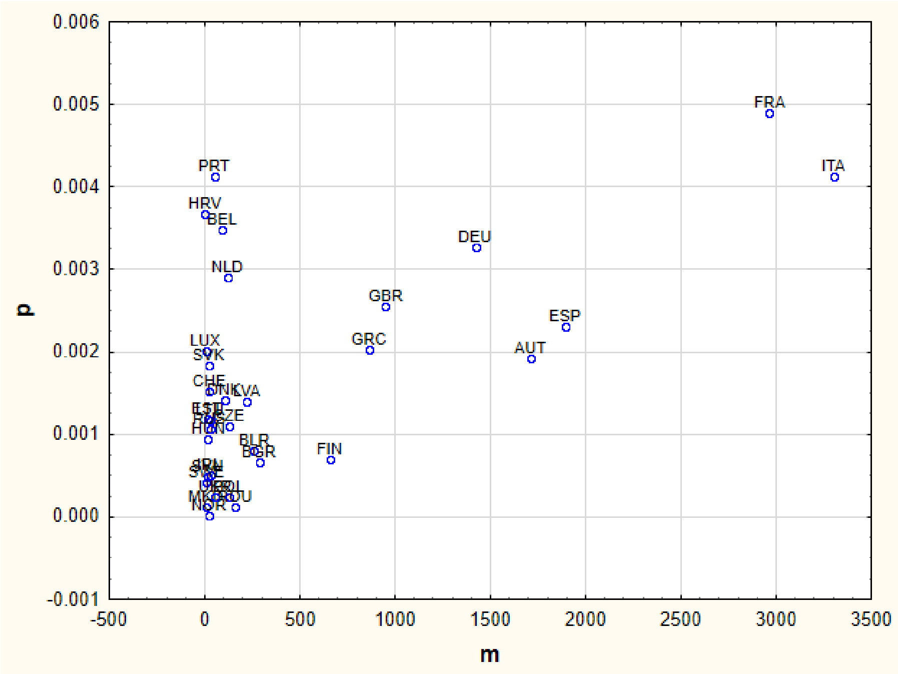

Fig. 2. The values of parameters *m* and *p* in the BM describing the diffusion of innovations in photovoltaics in European countries

Source: own calculations.

Figure 3 presents the market potential indicators (*m*) of European countries and the adaptation indicators (*p*) for the compared European countries.

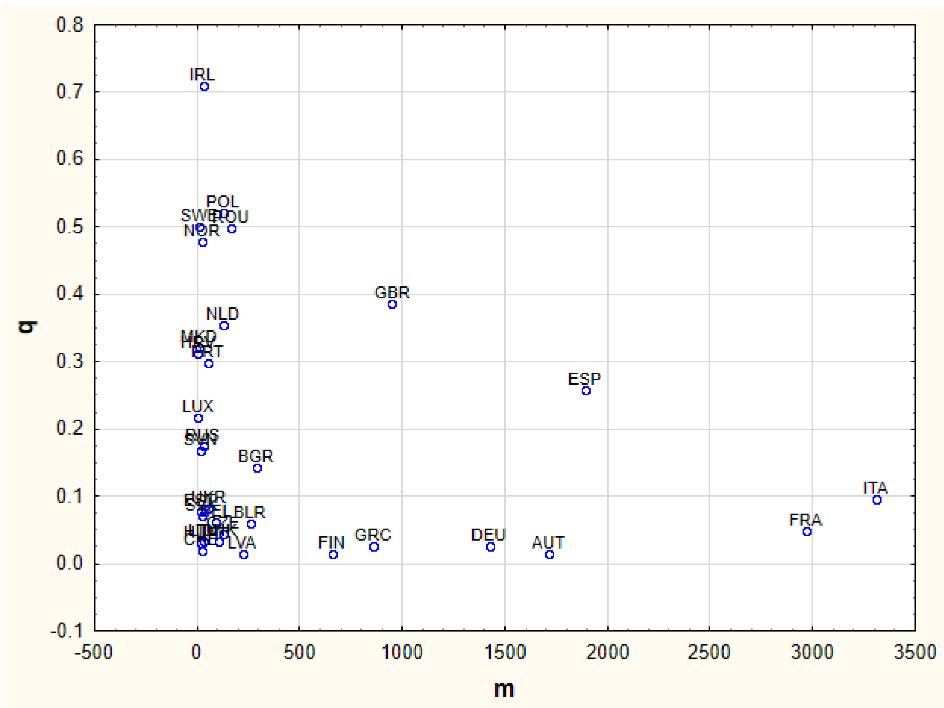

Fig. 3. The values of parameters *m* and *q* in the BM describing the diffusion of innovations in photovoltaics in European countries

Source: own calculations.

Based on Figure 3, it can be concluded that the leading imitators of photovoltaic technologies were countries with a low market potential for this type of technology, i.e. Norway, Sweden, Poland, Ireland and Romania. Countries with a high market potential (*m*>1000) were usually poor imitators of innovators in photovoltaic technologies (i.e. Spain, France, Italy, Germany, Austria).

The dominant group were countries with a low market potential and low imitation rates. Using the values of parameters *m*, *p* and *q* obtained in the Bass model, grouping of all the compared countries was carried out using the Ward's method with Euclidean distance. This made it possible to identify clusters of countries with the most similar profiles of innovation diffusion in photovoltaic technologies. The results of this grouping are presented in a dendrogram (Figure 4).

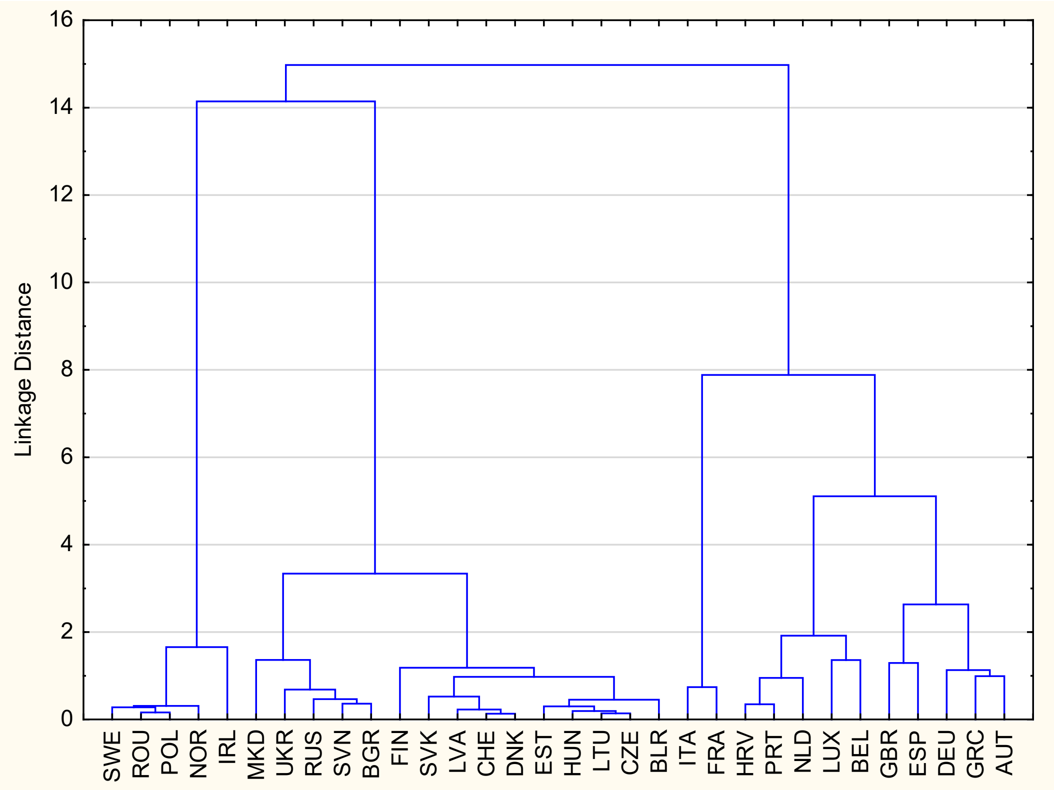

Fig. 4. Results of grouping European countries using the Ward's method according to the values of parameters *p*, *q* and *m* obtained in the BM

Source: own calculations.

Using the criterion of the first clear increase in agglomeration distance, the dendrogram was cut off at the height of link 4 and, as a result, the following homogeneous clusters of countries were obtained:

- group one: Sweden, Romania, Poland, Norway, Ireland,
- group two: North Macedonia, Ukraine, Russia, Slovenia, Bulgaria, Finland, Slovakia, Latvia, Switzerland, Denmark, Estonia, Hungary, Lithuania, Czechia, Belarus,
- group three: France, Italy,
- group four: Croatia, Portugal, the Netherlands, Luxembourg, Belgium,
- group five: Great Britain, Spain, Germany, Greece, Austria.

The results of this clustering confirmed the more detailed results of the bivariate analysis presented earlier. The first group of countries were imitators with a limited market potential. Common determinants of the development of photovoltaics in the countries belonging to this group resulted from global and regional trends, as well as from EU policy and local socio-economic conditions. These were primarily the climate policy established by the EU, the use of EU funds (especially by Poland and

Romania) and public financial support, the growing ecological awareness of societies, and the development of micro-installations. Nevertheless, each country set its own priorities in the field of energy transformation, taking into account geographical and climatic conditions, the existing energy infrastructure and its technological advancement, with related country-specific determinants of photovoltaics' development. For example, in Sweden and Norway sunlight is low, especially in winter, which results in the limited development of photovoltaics, instead they focused on the development of hydropower and wind energy. Photovoltaic farms are typical of Ireland and Romania, and micro-installations of Poland. In terms of renewable energy priorities, in Norway and Sweden the emphasis is on smart grids and technological innovations. Pro-consumer programmes are popular in Poland, and high investment in R&D prevail in Sweden (Simson et al., 2024; Wardal et al., 2024).

The second group of countries with low potential demonstrates its technological backwardness in the field of solar energy and imitates innovations in photovoltaics to a limited extent. This group included countries with similar sunlight conditions: those with moderate sunlight (e.g. Bulgaria, Hungary, Slovakia) or with long days in summer (e.g. Finland, Estonia). The countries belonging to this group were characterised by an increasing importance of photovoltaics as an alternative energy source in the context of reducing dependence on imported energy raw materials, especially important for countries such as Ukraine, Estonia, Lithuania and Slovakia, which want to become independent from gas and oil supplies from Russia.

Moreover, the EU countries such as Slovakia, Latvia, Lithuania and Bulgaria benefited from structural funds and EU programmes (e.g. Horizon Europe Programme) that support investment in photovoltaics, while Ukraine, North Macedonia and Belarus received international support (e.g. from the World Bank and the EBRD). The decreasing prices of photovoltaic panels and installation of PV systems were also important, which contributed to the popularisation of such solutions (Simson et al., 2024). A specific country in this group was Russia, with its vast area and an economy based on the oil, gas and coal industries. Nevertheless, photovoltaics is being developed in regions far from the power grid, where providing fossil fuels is expensive, e.g. isolated settlements in Siberia and the Far East, where it reduces the costs associated with transporting fuels (Agyekum et al., 2021).

The third group includes countries with very large market potential that are pioneers in the solar technology market (e.g. Italy and France), characterised by high levels of sunlight, especially in the southern regions, which favours the development of photovoltaics. Both countries offer many forms of support for photovoltaics, in particular subsidies, feed-in tariffs and tax breaks for prosumers and investors. As part of the energy transformation, the governments of both countries strive to diversify energy sources: France is reducing dependence on nuclear energy in favour of renewable energy sources, including photovoltaics, while Italy is striving to reduce its dependence on gas and oil imports, which motivates the development of renewable energy sources (Wardal et al., 2024).

The fourth group includes countries with a low market potential and relatively high innovation in the field of photovoltaics. The common determinants of the development of photovoltaics in countries from this group are primarily obligations arising from the EU climate policy, and similar solutions in terms of forms of support for investors and prosumers, such as subsidies, tax breaks, feed-in tariffs and settlement mechanisms (e.g. net-metering or net-billing). The key differences resulted mainly from the level of sunlight (higher in Croatia and Portugal) and the available space for PV installations. In countries with a limited territory (e.g. Luxembourg, Belgium, the Netherlands), roof installations and floating PV technologies (photovoltaics on water) are being developed, whilst in Croatia and Portugal, where rural areas are more available, investments are being made in the construction of large photovoltaic farms. In the Netherlands, Belgium and Luxembourg, despite moderate sunlight, the development of PV is supported by advanced technologies and favourable support mechanisms (Simson et al., 2024; Wardal et al., 2024).

Finally, the fifth group includes countries with high market potential and high innovation, with the common feature of using similar mechanisms for implementing commitments to reduce greenhouse gas emissions under the Paris Agreement and national plans for climate neutrality by 2050. Spain, Germany, Greece and Austria are additionally involved in the implementation of EU goals in the field of renewable energy, while the UK, despite Brexit, consistently implements its energy policy assumptions. These countries are investing in modernising power grids to better integrate unstable energy sources such as photovoltaics, in effort to reduce their dependence on fossil fuels: Germany is intensively moving away from coal and nuclear energy, Spain and Greece are reducing the share of coal and gas, Great Britain is focusing on renewable energy to become independent from gas imports, whilst Austria is historically based on hydropower but is diversifying its energy mix with a growing share of photovoltaics (Simson et al., 2024; Wardal et al., 2024).

To check which parameters contributed significantly to the differentiation of the resulting clusters, a one-way ANOVA was used, which showed that at the significance level of 0.001, all the parameters (p, q, m) significantly differentiated the resulting clusters, with the largest contribution to the differentiation of country clusters being the potential of the solar energy market (m), for which the value of F statistic was 108.5511, and the smallest contribution had an imitation index F=18.6017.

5. Discussion and conclusions

Solar energy is undoubtedly a serious alternative to the traditional energy sector, and in many countries it plays an increasing role in the decarbonisation of this sector. However, the effective implementation and improvement of photovoltaic technologies require the appropriate research resources, capital, appropriate information and education policy and state support for entities investing in renewable energy sources. Creating an appropriate system of synchronisation and coordination of policies aimed at building an electricity system with a high share of renewable energy sources requires detailed analyses in each country.

In many cases the share of photovoltaics in national energy systems can be increased and its importance strengthened, but this requires a coordinated energy policy both at national and EU levels. Its elements should include: financial mechanisms and investment support (subsidies for investors, preferential credits and loans, tax relief), adaptation of technical infrastructure (construction of energy storage facilities, expansion of power grids), legal regulations requiring the use of renewable energy sources, greater support for prosumerism (dynamic tariffs for prosumers) and joint cross-border projects regarding the construction of large-scale PV installations, developing a mechanism of inter-country energy solidarity.

The presented results fill the research gap in the field of comparative analysis of innovation diffusion profiles in photovoltaics in European countries. The innovators were countries with a high level of GDP and high expenditure on research and development, as well as those whose favourable geographical location ensured a sufficiently large number of sunny days per year. Therefore, the research hypothesis formulated in the introduction should be considered positively verified.

The so-called imitators were countries with limited solar energy market potential, located mainly in Central and Eastern Europe and in the north of Europe, with less sunlight than in the south of the continent. In these countries, priority is given to other sources of renewable energy, e.g. wind energy. The resulting division was therefore, first of all, consistent with the geographical conditions of the countries (determining exposure to the sun), and secondly, reflected the differences in their economic potential (determining the level of technological development and absorption capacity for innovation). The process of diffusion of innovation in solar technologies presented in this article was confirmed by the results obtained in similar studies by other researchers (Skoczkowski et al., 2019; Aponte et al., 2023), who generally did not conduct comparative analyses between countries allowing for the identification of groups and profiles of countries with similar characteristics of the diffusion of innovations in photovoltaic technologies.

The presented research proposal based on learning curves has its limitations. First of all, this type of innovation diffusion modelling does not take into account a number of endogenous factors that may influence the pace and size of innovation diffusion (e.g. legal regulations, market conditions, environmental conditions, price conditions and others). Therefore the obtained results can be supplemented with endogenous models in future research and possibly extrapolated from the level of development of photovoltaic technologies in individual countries.

References

Agyekum, E. B., Kumar, N. M., Mehmood, U., Panjwani, M. K., Alhelou, H. H., Adebayo, T. S., & Al-Hinai, A. (2021). Decarbonize Russia − A best–worst method approach for assessing the renewable energy potentials, opportunities and challenges. *Energy Reports*, *7*, 4498-4515.

Alharbi, F. H., & Kais, S. (2015). Theoretical limits of photovoltaics efficiency and possible improvements by intuitive approaches learned from photosynthesis and quantum coherence. *Renewable and Sustainable Energy Reviews*, *43*, 1073-1089.

Allouhi, A., Rehman, S., Buker, M. S., & Said, Z. (2022). Up-to-date literature review on solar PV systems: Technology progress, market status and R&D. *Journal of Cleaner Production*, *362*, 1-19.

Almeida, D. V., Kolinjivadi, V., Ferrando, T., Roy, B., Herrera, H., Gonçalves, M. V., & Van Hecken, G. (2023). The “greening” of empire: The European green deal as the EU first agenda. *Political Geography*, *105*, 1-16.

Aponte, F. R., Wiebe, K. S., & Luttikhuis, N. (2023). The role of sustainability characteristics in the diffusion of renewable energy technologies. *Sustainable Energy Technologies and Assessments*, *57*, 1-12.

Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science*, *15*(5), 215-227.

Bass, F. M. (2004). A new product growth for model consumer durables. *Management Science*, *50*(12), 1825-1832.

Bessi, A., Guidolin, M., & Manfredi, P. (2024). Diffusion of solar PV energy in Italy: Can large-scale PV installations trigger the next growth phase? *Energies*, *17*(3), 1-23.

Cong, R. G. (2013). An optimization model for renewable energy generation and its application in China: A perspective of maximum utilization. *Renewable and Sustainable Energy Reviews*, *17*, 94-103.

Dan, H., & Simon, L. S. (1983). Advertising and the diffusion of new products. *Marketing Science*, *2*(1), 1-17.

Da Silva, H. B., Uturbey, W., & Lopes, B. M. (2020). Market diffusion of household PV systems: Insights using the Bass model and solar water heaters market data. *Energy for Sustainable Development*, *55*, 210-220.

de La Tour, A., Glachant, M., & Ménière, Y. (2013). Predicting the costs of photovoltaic solar modules in 2020 using experience curve models. *Energy, 62*(C), 341-348.

Dooley, K., & Kartha, S. (2018). Land-based negative emissions: Risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, *18*, 79-98.

Elshurafa, A. M., Albardi, S. R., Bigerna, S., & Bollino, C. A. (2018). Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations. *Journal of Cleaner Production*, *196*, 122-134.

Guidolin, M. (2023). *Innovation Diffusion Models: Theory and Practice*, Wiley.

Grubb, M. et al. (2021). The new economics of innovation and transition: evaluating opportunities and risks. *Economics of Energy Innovation and System Transition*, University of Exeter, the Report, https://eeist.co.uk/download/557/

Hansen, J. P., Narbel, P. A., & Aksnes, D. L. (2017). Limits to growth in the renewable energy sector. *Renewable and Sustainable Energy Reviews*, *70*, 769-774.

Harris, T. M., Devkota, J. P., Khanna, V., Eranki, P. L., & Landis, A. E. (2018). Logistic growth curve modeling of US energy production and consumption. *Renewable and Sustainable Energy Reviews*, *96*(C), 46-57.

Hong, S., Chung, Y., & Woo, C. (2015). Scenario analysis for estimating the learning rate of photovoltaic power generation based on learning curve theory in South Korea. *Energy*, *79*, 80-89.

Lindman, Å., & Söderholm, P. (2016). Wind energy and green economy in Europe: Measuring policy-induced innovation using patent data. *Applied Energy, 179*(C), 1351-1359.

Markard, J., Geels, F. W., & Raven, R. (2020). Challenges in the acceleration of sustainability transitions. *Environmental Research Letters*, *15*(8), 1-6.

Meade, N., & Islam, T. (2006). Modelling and forecasting the diffusion of innovation – A 25-year review. *International Journal of Forecasting*, *22*(3), 519-545.

Nijsse, F. J., Mercure, J. F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., & Pollitt, H. (2023). The momentum of the solar energy transition. *Nature Communications*, *14*, 1-10.

Panda, A., Dauda, A. K., Chua, H., Tan, R. R., & Aviso, K. B. (2023). Recent advances in the integration of renewable energy sources and storage facilities with hybrid power systems. *Cleaner Engineering and Technology*, *12*, 1-17.

Radomes Jr., A. A., & Arango, S. (2015). Renewable energy technology diffusion: An analysis of photovoltaic-system support schemes in Medellin. *Journal of Cleaner Production*, *92*, 152-161.

Rogers, E. M. (1983). *Diffusion of Innovations*. 3rd edition. Free Press.

Sikora, A. (2021). European Green Deal – legal and financial challenges of the climate change. *ERA Forum*, *21*, 681-697.

Simpson, G., & Clifton, J. (2017). Testing Diffusion of Innovations Theory with data: Financial incentives, early adopters, and distributed solar energy in Australia. *Energy Research & Social Science*, *29*, 12-22.

Simson, K., Jørgensen, D. J., Garribba, M., Wörsdörfer, M., & Baldwin, M. (2024). State of the energy union report 2024. Directorate-General for Energy, European Commission, https://energy.ec.europa.eu/publications/state-energy-union-report-2024-country-fiches_en

Skoczkowski, T., Bielecki, S., & Wojtyńska, J. (2019). Long-term projection of renewable energy technology diffusion. *Energies, 12*(22), 1-24.

Wardal, W. J., Mazur, K., Barwicki, J., & Tseyko, M. (2024). Fundamental barriers to green energy production in selected EU countries. *Energies*, *17*(15), 3664.

Zhang, X., Li, H., Liu, Q., & Tan, X. (2020). A study on the technology diffusion of China's solar photovoltaic based on Bass and generalized Bass model. *IOP Conference Series: Earth and Environmental Science*, *571*, 012016. https://doi.org/10.1088/1755-1315/571/1/012016

Received: September 2024, revised: November 2024

Acknowledgement: *The article presents the result of the Project no 091/EIT/2024/POT financed from the subsidy granted to the Krakow University of Economics.*