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THE ROLE AND PERFORMANCE OF WIND AND SOLAR ENERGY POLICY IN ENERGY TRANSITION PROCESS IN GERMANY AND POLAND

Rozprawa doktorska

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THE ROLE AND PERFORMANCE OF WIND AND SOLAR ENERGY POLICY IN ENERGY TRANSITION PROCESS IN GERMANY AND POLAND

ABSTRACT

Wind and solar energy sources have developed rapidly during the last few decades, as conventional fossil fuels' global dominance looks to be coming to an end. Furthermore, these two renewable energy technologies are in the centre of global 'modern' energy transition, based on carbon-free sustainable system. While renewables like wind and solar energy have recently become a widespread object of discussion on political, economic, social, and other levels, they are strongly considered as a major force in tackling global problems such as energy scarcity, environmental pollution, or global warming.

Last but not least important is the role played by support policies in speeding up deployment of clean energy sources. Despite some criticism centred in the realization and expediency of such measures, there is a consensus in the literature that policy instruments are one of the main catalysts of wind, solar and other renewable energy sources. Understanding of the main features and effects of support policies can contribute to a better use of financial resources and boost the development of renewable energy markets. Also, assessment and monitoring performance of support instruments is very important, as different dimensions (e.g., socio-economic, environmental) should be considered.

Measuring effectiveness and efficiency of renewable energy policies is one of the main discussions in the literature regarding energy economics. Despite growing interest in the topic, there is an agreement among scholars that more research must be done in this area. This stems from multiple factors such as recent energy shock[1], the growing significance of energy security and transition etc. Also, a dynamic expansion of wind and solar energy markets led to seismic changes in many areas including political, social, and economic aspects. This forces governments to continuously update their goals and improvements in terms of policies that support these RE sources. Within this context, there is a need for reliable and up-to-date research in the mentioned area. This thesis aims to fill that gap by providing a comprehensive study on policy performance of wind and solar energy technologies. While concentrating on

[1] here is meant price surge on EU energy market, as a result of Russian aggression in Ukraine in 2022.

the case study countries of Poland and Germany, other European Union (EU) member states were also included in the analysis during the periods of 2005-2021.

Based on the conducted literature review, methods including the indicator-based approach, DEA (Data Envelopment Analysis) and regression modelling were applied. As a result of the empirical research carried out in this work, the following patterns were summarized: 1) Germany compared to Poland was much more effective in the context of wind energy policy; 2) Germany conducted also a more effective policy regarding solar energy, while Poland made considerable progress during the maturity phase of 2016-2021; 3) countries, where feed-in tariffs and quotas were dominant, they contributed strongly to policy effectiveness of wind and solar energy especially in early stages of their development; 4) as a market-based policy instrument, tenders became an effective mechanism to support both wind and solar energy during the maturity period of 2016-2021, indicating a higher competitiveness of these clean energy technologies; 5) Poland and Germany were quite inefficient with below-average rankings in terms of wind and solar energy polices; 6) countries, in which feed-in tariffs were the dominant policy instruments, have been quite inefficient in terms of wind energy; 7) countries with main instruments such as feed-in tariffs, quotas, tenders, tax incentives and investment grants - all having a significant and positive impact on the efficiency of solar energy policies; 8) the significant and positive relationship was also recorded between average solar power theoretical potential and the efficiency of solar energy policy.

Additionally, findings of the present work indicate that even the same policies promoting wind and solar energy sources can perform differently across various countries. That is why there is a strong need for an in-depth analysis of support frameworks to maintain constant improvement of policy support in each stage of technology development. The study also provides valuable insights for policymakers and researchers. While results are explained in the most accessible way, special attention is also paid to the data collection process. Furthermore, limitations and avenues for further research are highlighted.

Keywords: Energy security, energy transition, sustainable development, wind and solar energy, renewable energy policy, effectiveness, efficiency, indicator-based method, DEA, regression, feed-in tariffs, quotas, tenders

ROLA I SKUTECZNOŚĆ POLITYKI ENERGII WIATROWEJ I SŁONECZNEJ W PROCESIE TRANSFORMACJI ENERGETYCZNEJ W NIEMCZECH I POLSCE

STRESZCZENIE

Energia wiatrowa i słoneczna rozwijały się bardzo szybko w ciągu ostatnich dziesięcioleci. Jednocześnie era globalnej dominacji konwencjonalnych paliw kopalnych dobiega końca. W tym czasie te dwie technologie energii odnawialnej stały się popularnym przedmiotem dyskusji na poziomie politycznym, gospodarczym i społecznym. Co więcej, energia wiatrowa i słoneczna znajdują się w centrum globalnej transformacji energetycznej, opartej na zrównoważonym systemie bezemisyjnym. Dyskurs ten dotyczy ich przeznaczenia, mianowicie są one przedstawiane jako rozwiązywanie globalnych problemów, takich jak deficyt energii, zanieczyszczenie środowiska czy globalne ocieplenie.

Ostatnią, ale nie mniej ważną rolę w przyspieszeniu rozwoju odnawialnych źródeł energii odgrywa polityka i mechanizmy jej wsparcia. Pomimo krytyki, skoncentrowanej na realizacji lub celowości takich środków w ogóle, w literaturze przedmiotu panuje zgoda co do tego, że instrumenty polityki wsparcia są jednym z głównych katalizatorów energii wiatrowej, słonecznej i pozostałych odnawialnych źródeł energii. Zrozumienie głównych cech i skutków takich polityk może przyczynić się do lepszego wykorzystania zasobów finansowych i przyspieszenia rozwoju rynku energii odnawialnej. Bardzo ważna jest również ocena i monitorowanie skuteczności mechanizmów promowania w kontekście różnych wymiarów, przykładowo w ujęciu społeczno-ekonomicznym i środowiskowym.

Ocena skuteczności (ang.: effectiveness) i efektywności albo wydajności (ang.: efficiency) polityki w zakresie energii odnawialnej jest jedną z głównych debat w literaturze dotyczącej gospodarki i polityki w domenie energii. Pomimo rosnącego zainteresowania tematem wśród naukowców panuje zgoda co do tego, że istnieje potrzeba dodatkowych badań w tym obszarze. Wynika to z wielu czynników, takich jak niedawny szok gospodarczy[2] i rosnące znaczenie bezpieczeństwa oraz transformacji energetycznej. Ponadto dynamiczny rozwój rynków energii wiatrowej i słonecznej zmienił w znaczący sposób obszary, m.in. polityczne, społeczne i gospodarcze. Obliguje to rządy państw do ciągłego aktualizowania swoich celów i ulepszeń w zakresie polityk wspierających te źródła energii odnawialnych. Ze

[2] Chodzi o wzrost cen na rynku energii UE będący efektem rosyjskiej agresji na Ukrainę w 2022 roku.

względu na to istnieje potrzeba rzetelnych i aktualnych badań we wspomnianym obszarze. Niniejsza rozprawa ma na celu wypełnienie tej luki badawczej poprzez dostarczenie kompleksowego studium na temat wyników polityki wsparcia w zakresie energii wiatrowej i słonecznej. Pomimo skupienia się na Polsce i Republice Federalnej Niemiec, do analizy włączono również inne państwa członkowskie Unii Europejskiej. Za okres badawczy wybrano lata 2005-2021.

Na podstawie przeglądu literatury przedmiotu stworzyłem własne podejście ilościowe, które obejmuje metody oparte na wskaźnikach, DEA (*Data Envelopment Analysis*) i regresji. Dzięki badaniom empirycznym przeprowadzonym w tej pracy doszedłem do następujących wniosków: 1) Niemcy w porównaniu z Polską były znacznie bardziej skuteczne pod względem polityki energii wiatrowej; 2) Niemcy prowadziły bardziej skuteczną politykę energii słonecznej, podczas gdy Polska poczyniła znaczne postępy w fazie dojrzałości technologicznej (2016-2021); 3) kraje, w których dominowały taryfy gwarantowane oraz kwoty, silnie przyczyniły się do wzrostu skuteczności polityki w zakresie energii wiatrowej i słonecznej, zwłaszcza na wczesnych etapach ich rozwoju; 4) rynkowy instrument polityki przetargowej stał się skutecznym mechanizmem wsparcia zarówno energii wiatrowej, jak i słonecznej w fazie dojrzałości technologicznej (2016-2021), wskazując na wyższą konkurencyjność tych dwóch czystych technologii energetycznych; 5) Polska i Niemcy w porównaniu z innymi krajami członkowskimi były dość nieefektywne, z rankingami poniżej średniej pod względem polityki wsparcia energii wiatrowej i słonecznej; 6) kraje, w których taryfy gwarantowane były dominującymi instrumentami, były nieefektywne we wdrażaniu energii wiatrowej; 7) kraje z głównymi instrumentami, takimi jak taryfy gwarantowane, kwoty, przetargi, ulgi podatkowe i dotacje inwestycyjne, miały znaczący i pozytywny wpływ na wydajność polityki w zakresie energii słonecznej; 8) odnotowano istotną i pozytywną zależność między średnim teoretycznym potencjałem energii słonecznej a efektywnością polityki w tym zakresie.

Ponadto wyniki niniejszej pracy wskazują, że nawet prowadzenie tych samych polityk wsparcia energii wiatrowej i słonecznej może działać inaczej w zależności od kraju. Dlatego też istnieje silna potrzeba dogłębnej analizy polityk wsparcia w celu utrzymania ciągłego doskonalenia działań politycznych na każdym etapie rozwoju technologicznego. Praca doktorska dostarcza cennych spostrzeżeń politykom i badaczom. Podczas gdy wyniki są wyjaśnione w najbardziej przystępny sposób, szczególną uwagę zwraca się również na proces gromadzenia danych. Dodatkowo, w pracy podkreślono ograniczenia obecnych opracowań i wskazano kierunki dalszych badań.

Słowa kluczowe: Bezpieczeństwo energetyczne, transformacja energetyczna, zrównoważony rozwój, energia wiatrowa, energia słoneczna, polityka energii odnawialnej, skuteczność, efektywność, metoda oparta na wskaźnikach, DEA, regresja, taryfy gwarantowane, kwoty, przetargi.

DIE ROLLE UND LEISTUNG DER WIND- UND SOLARENERGIEPOLITIK IM ENERGIEWENDEPROZESS IN DEUTSCHLAND UND POLEN

ABSTRAKT

Die Wind- und Solarenergie hat sich in den letzten Jahrzehnten sehr schnell entwickelt, als die Ära der globalen Dominanz der konventionellen fossilen Brennstoffe zu Ende zu gehen scheint. Während diese beiden Technologien für erneuerbare Energien in letzter Zeit zu einem beliebten Diskussionsgegenstand auf politischer, wirtschaftlicher, sozialer und anderer Ebene geworden sind, werden sie stark als wichtige Kraft bei der Bewältigung globaler Probleme wie Energieknappheit, Umweltverschmutzung oder globale Erwärmung angesehen. Nicht zuletzt spielt die Förderpolitik eine wichtige Rolle bei der Beschleunigung des Einsatzes erneuerbarer Energiequellen. Trotz einiger Kritiker, die sich auf die Umsetzung oder Zweckmäßigkeit solcher Maßnahmen konzentrieren, besteht in der Literatur ein Konsens darüber, dass Politikinstrumente einer der wichtigsten Katalysatoren für Wind- und Solarenergie sowie andere erneuerbare Energiequellen sind. Ein Verständnis der Hauptmerkmale und Auswirkungen von Fördermaßnahmen kann zu einer besseren Nutzung der finanziellen Ressourcen beitragen und die Entwicklung des Marktes für erneuerbare Energien vorantreiben. Sehr wichtig ist auch die Auswertung und Überwachung der Leistung von Förderinstrumenten, da verschiedene Dimensionen (z.B. sozioökonomische und ökologische) berücksichtigt werden sollten.

Die Messung der Wirksamkeit und Effizienz von Maßnahmen im Bereich der erneuerbaren Energien ist eine der wichtigsten Debatten in der Literatur zur Energiewirtschaft. Trotz des wachsenden Interesses an diesem Thema sind sich die Wissenschaftler einig, dass in diesem Bereich mehr Forschung betrieben werden muss. Dies ist auf mehrere Faktoren zurückzuführen, wie den jüngsten Energiepreisschock[3], die wachsende Bedeutung der Energiesicherheit und der Energiewende. Außerdem hat die dynamische Expansion der Wind- und Solarenergiemärkte zu seismischen Veränderungen in vielen Bereichen geführt, einschließlich politischer, sozialer und wirtschaftlicher Aspekte. Dies veranlasst die Regierungen, ihre Ziele und Verbesserungen in Bezug auf die Politik zur Förderung dieser

[3] Gemeint ist damit ein Preisanstieg auf dem EU-Energiemarkt als Folge der russischen Aggression in der Ukraine im Jahr 2022.

erneuerbaren Energiequellen ständig zu aktualisieren. Vor diesem Hintergrund besteht ein Bedarf an zuverlässiger und aktueller Forschung in dem genannten Bereich. Die vorliegende Arbeit soll diese Lücke füllen, indem sie eine umfassende Studie über die politische Leistung von Wind- und Solarenergietechnologien erstellt. Obwohl der Schwerpunkt auf den Fallstudienländern Polen und Deutschland liegt, wurden auch andere Mitgliedstaaten der Europäischen Union (EU) in die Analyse einbezogen, da der Zeitraum von 2005 bis 2021 gewählt wurde.

Auf der Grundlage der durchgeführten Literaturrecherche wenden wir Methoden wie den indikatorbasierten Ansatz, DEA (Data Envelopment Analysis) und Regressionsmodelle an. Dank der empirischen Forschung, die in dieser Arbeit durchgeführt wurde, können wir die folgenden Muster zusammenfassen: 1) Deutschland war im Vergleich zu Polen viel effektiver in der Hinsicht der Windenergiepolitik; 2) Deutschland führte auch eine effektivere Politik in Bezug auf Solarenergie durch, während Polen in der Reifephase (2016-2021) einen beträchtlichen Fortschritt machte; 3) Länder, in denen Einspeisetarife und Quoten vorherrschten, trugen stark zur politischen Effektivität von Wind- und Solarenergie bei, besonders in den frühen Phasen ihrer Entwicklung 4) ein marktbasiertes politisches Instrument - Ausschreibungen - wurde zu einem effektiven Mechanismus, um sowohl Wind- als auch Solarenergie während der Reifephase (2016-2021) zu unterstützen, was auf eine höhere Wettbewerbsfähigkeit dieser sauberen Energietechnologien hinweist; 5) Polen und Deutschland waren ineffizient, mit unterdurchschnittlichen Platzierungen im Kontext der Windenergie- und Solarenergiepolitik. 6) Länder, in denen Einspeisetarife die vorherrschenden politischen Instrumente waren, waren ineffizient beim Einsatz von Windenergie. 7) Länder mit Einspeisetarife, Quoten, Ausschreibungen und Steuerliche Anreize hatten einen signifikanten und positiven Einfluss auf die Effizienz der Solarenergiepolitik; 8) Die signifikante und positive Beziehung wurde auch zwischen dem durchschnittlichen theoretischen Solarstrompotenzial und der Effizienz der Solarenergiepolitik festgestellt.

Außerdem zeigen die Ergebnisse der vorliegenden Arbeit, dass selbst dieselben politischen Maßnahmen zur Förderung von Wind- und Solarenergie in den verschiedenen Ländern völlig unterschiedlich wirken können. Aus diesem Grund ist eine gründliche Analyse der Fördermechanismen dringend erforderlich, um eine ständige Verbesserung der politischen Unterstützung in jeder Phase der Technologieentwicklung zu gewährleisten. Die Studie liefert wertvolle Erkenntnisse für politische Akteure und Forscher. Die Ergebnisse werden auf möglichst verständliche Weise erläutert, wobei auch dem Prozess der Datenerhebung besondere

Aufmerksamkeit gewidmet wird. Darüber hinaus werden Einschränkungen und Möglichkeiten für weitere Forschung aufgezeigt.

Stichworte: Energiesicherheit, Energiewende, nachhaltige Entwicklung, Wind- und Solarenergie, Politik für erneuerbare Energien, Effektivität, Effizienz, indikatorbasierte Methode, DEA, Regression, Einspeisetarife, Quoten, Ausschreibungen

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ABBREVITION	DEFINITION
AT	Austria
BCC	Banker-Charnes-Cooper
BE	Belgium
BG	Bulgaria
BMWK	Federal Ministry for Economic Affairs and Climate Action (*from German*: Bundesministerium für Wirtschaft und Klimaschutz)
CAP	Installed Capacity
CBA	Cost-Benefit Analysis
CCR	Charnes-Cooper-Rhodes
CEER	Council of European Energy Regulators
CO_2	Carbon Dioxide
CY	Cyprus
CZ	Czech Republic
DE	Germany
DEA	Data Envelopment Analysis
DK	Denmark
DMU	Decision Making Unit
DW	Deutsche Welle
e.g.	Example Given
EC	European Commision
EDGAR	Emissions Database for Global Atmospheric Research
EE	Estonia
EEA	European Environmental Energy
EEG	Renewable Energy Act (*from German* :Erneubaren-Energie-Gesetz)
EL	Greece
ENV	Environmental Aspect (Indicator)
ES	Spain
ESMAP	Energy Sector Management Assistance Program
ETS	Emission Trading System
EU	European Union
EU-27	27 European Union Members States
EurObserv’ER	Monitoring Project of RE Development in the EU
Eurostat	European Statistical Office
FI	Finland
FIP	Feed-in Premium
FIT	Feed-in Tariff
FR	France
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GW	Gigawatt
H	Hypothesis
HR	Croatia
HU	Hungary
ICAT	Initiative for Climate Action Transparency
IE	Ireland
IEA	International Energy Agency

IMPORT	Import
IOŚ-PIB	Institute of Environmental Protection – National Research Institute (*from Polish*: Instytut Ochrony Środowiska – Państwowy Instytut Badawczy)
IRENA	International Renewable Energy Agency
IT	Italy
JOB	Employment (Direct and Indirect Jobs)
kWh	Kilowatt Hour
LCA	Lifecycle Costs Analysis
LCOE	Levelized Cost of Electricity
LT	Lithuania
LU	Luxemburg
LV	Latvia
MAAS	Modern Applied Statistics with S
MI	Malmquist Index
MLN	Millions
MT	Malta
Mt	Million Tonnes
MToE	Million Tonnes of Oil Equivalent
MW	Megawatt
MWh	Megawatt Hour
N2O	Nitrous Oxide
NL	Netherlands
NREAP	National Renewable Energy Action Plan
OECD	Organisation for Economic Cooperation and Development
PEI	Policy Effectiveness Indicator
PFCs	Perfluorocarbons
PII	Policy Impact Indicator
PL	Poland
PR	Production (Generation)
PSEW	Polish Wind Energy Association (*from Polish*: Polskie Stowarzyszenie Energetyki Wiatrowej)
PT	Portugal
PTE	Pure Technical Efficiency
PV	Photovoltaic
PV_potential	Average solar power theoretical potential
QUOTA	Quota-Based Instruments
R&D	Research and Development
RE	Renewable Energy
REC	Renewable Energy Certificates
RED	Renewable Energy Directive
REN21	Renewable Energy Policy Network for the 21st Century
RES	Renewable Energy Sources
RES-LEGAL	Database on RE policies in EU member states
RO	Romania
RPS	Renewable Portfolio Standards
RTS	Returns to Scale
S	Solar energy
SE	Sweden
SEC	Energy Security Aspect (Indicator)

SK	Slovakia
SL	Slovenia
SUP	Cost of Support Policy
TAX_INV	Tax Incentives and Investment Grants
TEP	Techno-Economic Potential
TGCs	Tradable Green Certificates
TNDR	Tender
TWh	Terawatt Hour
UN	United Nations
USA	Unites States of America
USD	United States Dollar
VIF	Variance Inflation Factor
VRS	Variable Return to Scale
W	Wind Energy
W_speed	Mean Wind Speed
WEF	World Economic Forum
WEO	World Economic Outlook

INTRODUCTION

The demand for energy has been gradually growing for many years, which is strongly linked to rapid economic and technological development. The necessity to keep up with the strong economic potential of many countries has led to a search for new alternative energy sources. At the beginning of the 21st century, the global energy market was still completely dominated by conventional fossil fuels with cloudy prospects for renewables. However, the renewable energy (RE) market has been developing very fast during the last two decades, whereas a growing role in energy transition is attributed to wind and solar energy sources. Given the recent global threats and challenges on economic (global implications of COVID-19), energy (drastic increase in power prices) and political domain (the Russian invasion of Ukraine in 2022), the role of wind and solar energy technologies grows on importance, as countries look for alternative ways to tackle these issues.

The technology cost of the two intermittent clean energy sources has been dropping drastically during the last few years, making them a strong force in competition with fossil fuels. The existence of this and other factors makes wind and solar energy technologies a decisive factor in facilitating a modern energy transition based on a climate friendly system, in which problems of air pollution and global warming won't exist anymore. However, the ongoing energy transition is a complex process which covers numerous dimensions: economic, social, technological, political, environmental etc. Furthermore, a complete energy transformation can only happen when domination of renewables is achieved not only in power, but also in heat and transport sectors.

Many countries have taken various measures to enhance the energy transition process during the last two decades. One of them is support policy (or policy instruments) directed to promote RE sources. Governments take different measures to promote renewables like wind and solar technologies with a goal to bridge a gap between them and conventional fossil fuels. Despite emerging consensus on the high importance of RE support, many still question the expediency and feasibility of such measures. As policymakers constantly look for new solutions to improve RE policy mechanisms, this topic has also been an object of intense discussion among scholars. Against this context, a comparative assessment of RE policy performance is very important, as it does not only make it possible to spot 'best' or 'worst' support frameworks, but also answers the question why they are successful or not.

While measuring performance of RE support is popular among scholars, there is a lack of comprehensive and structural research which provides policymakers with robust results. Furthermore, relevant studies usually focus on RE sources in general, as less popular is the approach where separate clean energy technology (e.g., wind, solar or biomass) is an object of research. Besides that, one can indicate a problem of a short time span or out-of-date research periods, as well as old data sets, that questions the actuality of the analysis of some studies. Also, scholars often take an approach which covers only one dimension (usually economic or environmental). Overall, there is a consensus in the literature that indicates a lack of studies on the topic. These and other research gaps indicate that a need for comprehensive research in the area of RE economics and policy is very strong.

Motivation

The biggest inspiration behind writing this doctoral dissertation lies in the ambitious plans of the European Union (EU) to facilitate energy transition in the upcoming decades. The recent agreements on making the European community a carbon-neutral zone by 2050 could serve as an example for other countries and regional organizations on their way to a new era of a sustainable world, in which an energy mix consists of clean and climate-friendly technologies. As a recent example, European Commission (EC) has already adopted a legislative initiative, aimed at reducing greenhouse gases (GHG) by at least 55% until 2030, compared with 1990, with a goal to become carbon-natural by 2050 (*EC, 2021a*). The adoption of the so-called 'Fit for 55' package (*KPMG, 2021*) means that renewable energy sources are going to play a pivotal role in EU energy and environmental transformation. There is a wider and deeper rationale for addressing the topic, starting from active measures of some countries in supporting RE sources and ending with growing importance of aspects such as energy security, global warming and environment pollution.

First of all, one should point out the energy transition policy in Germany (in literature it is called 'Energiewende'), which is an unprecedented nationwide project. One of the main goals of 'Energiewende' is a strong promotion of RE sources and reducing the dominant role of fossil fuels. Another aspect of motivation lies in strong dependency on coal and the problem of smog in some countries. As more and more governments adjust their energy policies in favour of RE technologies, Poland's large reliance on conventional fuels such as coal is still dominant at the present time. Such strong dependency on fossil fuels can decrease the competitiveness of national economies, while contributing to increasing prices for consumers. It could be especially harmful considering the presence of the EU trading scheme called emission trading system (ETS). Overall, rising global concerns in the form of climate change, problems of air pollution and the current dominant role of fossil fuels were also considered while writing this doctoral dissertation.

One should also pay attention to the aspect of energy security whose sense has recently grown from strong to significant during the last few years. The Russian invasion of Ukraine in February 2022 demonstrates not only political miscalculations which led to a dramatic energy dependence of many countries, but also a misguided approach of keeping faith in fossil fuels, which will be a significant challenge for European and global energy markets during the next years.

On the other side, the failure of some member states to maintain safe and reliable gas and oil supplies could be a major boost for clean energy technologies. By fostering RE sources, countries without large resources can, at the same time, reduce its dependence on foreign fossil fuel supplies, while also depriving dominant energy players, such as the Russian Federation, of financing its military industry to sustain its war capabilities. Overall, trends and concerns regarding energy security will have further reflection within this doctoral dissertation.

Importance of research

One can name many reasons behind the significance of the research. Some categories such as air pollution and global warming have already been cited earlier. From here, the main aspects will be described which will demonstrate the importance of this research.

First, wind and solar energy technologies have become a significant force on global energy markets as their technology costs have been constantly decreasing during the last two decades. An analysis was also conducted which emphasizes the magnitude of expansion of these two RE sources across the EU during the last two decades. Such evolution of these two clean energy sources implies that more and more governments assign them a very significant role. Also, many scholars acknowledge the economic feasibility of wind and solar energy technologies as they look to dominate the global energy mix in the near future and for decades to come.

Second, support policies to foster development of renewables have been a constant object of discussion among scholars. The role and effects of such policies are cited in many studies, as a need for more research in this area exists. Despite some critics, many scholars admit that RE sources like wind and solar energy technologies have benefited strongly from policy measures. As different countries have been using different support instruments to boost their RE market, the main discourse addresses the fact of which policy mechanism or the combination of instruments is better.

Third, assessment of effectiveness and efficiency of support measures can be considered as a substantial contribution of this study. Insights from such analysis can be especially important as policymakers look for works on policy performance for improvement purposes. As this study presents important findings on the effectiveness and the efficiency of wind and solar energy policies across EU countries, a deeper clarification of the results is depicted for Poland and Germany. Furthermore, additional analysis is conducted in order to find out why some countries and their policies have been successful or not during the defined period. Also, further research can be built on the methodological frameworks and results from the present work.

Fourth, an in-depth literature review was conducted which sums up all major valuable insights on the topic. Also, analysis of peer-related studies, which used similar methodological framework to assess policy performance, was also performed. Based on the abundance of studies and interdisciplinary nature of the topic, such analysis of literature can be especially useful for those who attempt to familiarize themselves with perceived problems in energy policy or those who create and devise their own research in this area.

Fifth, developed countries are emphasized more often in literature of RE economics. Against this background, Poland was chosen which is rarely depicted in theoretical or empirical studies in the context of RE policy. Also, insights from this research could be transferred to less developed countries which may learn from good or bad practices as far as policy performance is concerned.

Research purpose, questions, and hypotheses

The main objective of this doctoral dissertation is evaluation of comparative policy effectiveness and efficiency in terms of solar and wind energy in Germany and Poland (on background of EU member states). First, policy effectiveness for the researched countries will be measured with the help of an indicator-based approach. Second, policy efficiency is assessed by employing DEA (Data Envelopment Analysis) and regression methods. In addition, while conducting analysis between the above-mentioned countries, also assessment of the impact of selected external factors (e.g., average wind speed) have on the policy performance in the past, has been carried out. Such an analysis is intended to better interpret assessment of the policy performance and provide reliable insights for policymakers. Considering the scope and objectives of the present work, an attempt will be made to answer the following questions:

How wind and solar markets evolved in Poland and Germany during last few decades on the background of other EU countries? What main policy instruments have been implemented to support mentioned RE technologies in the EU? What criteria should be employed to measure cross-country policy performance of wind and solar energy sources? How Germany and Poland rank in terms of policy effectiveness and efficiency in the presence of other EU countries? Which types of policy instruments have been most and least effective and efficient among analysed countries? What are effects of some external factors such as wind speed and solar power theoretical potential?

In order to answer the research questions, a methodological concept was used which has been selected with help of a general literature review of the problematic and an in-depth analysis of previous studies on policy performance. The selected methods mainly address effectiveness and efficiency as criteria. Also, in order to deliver strong empirical research, the most up-to-date and suitable data sets for the mentioned methodological concept have been employed.

The assumed research objectives of the doctoral dissertation, as well as the analysis of the literature on the subject, developed the formulation of the following main and auxiliary hypotheses:

H1: German wind and solar energy policies are more effective and efficient in comparison with those of Poland. In order to conduct in-depth research, the following effectiveness metrics has been applied: Policy Effectiveness Indicator (PEI). This indicator estimates the degree of the achieved goal - in other words, the real progress of both RE technologies against their realizable of potential and are compared across the mentioned countries. To the best of available knowledge, this dissertation is the only study to conduct such research whose geographical scope addresses predominantly Poland and Germany. The average and cumulative scores of PEI during the period of 2005-2021 will show the quantitative difference between the two countries in terms of wind and solar energy support policy. Also, an analysis on effectiveness based on diffusion theory of energy transition and calculated with help of PEI was conducted by dividing researched period of 2005-2021 into three main stages (early, take-off and maturity phases).

As mentioned above, Germany embarked on an unprecedented energy transition three decades ago with its vast amount of private and public spending. This led to a rapid development of wind and solar energy markets. Nevertheless, the country has been an object of constant critics, pointing out the low effect of its RE policy. As for Poland, the progress in the context of wind and solar energy development could be only noted during last years, as the country has been strongly dependent on its conventional energy resources, like coal. Such comparative analysis in terms of effectiveness is an important stage in measuring policy performance. However, due to its limitation, another part of research was initiated, which addresses efficiency.

Assessment of policy efficiency will provide more solid outlines if German transformation can be acknowledged as successful or not. A similar evaluation is conducted for Poland. As analysis of policy efficiency is carried out by dividing technology diffusion process into three periods, research on policy efficiency applies to dimensions such as environment, employment, and energy security. Despite difference in the scope of RE policies in Poland and Germany, it is assumed that the latter performs better in terms of wind and solar energy policy efficiency. As already mentioned, research on efficiency has been conducted with the help of DEA and regression models. The comprehensive cross-country analysis on policy effectiveness and efficiency has been extended to other selected EU member states with a goal to discover how Poland and Germany are compared with other countries, that can also bring more valuable results.

H2: Countries with FIT (feed-in tariff) and quota-based instruments deliver better results than the ones with tenders. An attempt is made to provide a comprehensive analysis by presenting which groups of countries (by taking an assumption of main (dominant) policy instruments applied) are more successful in terms of wind and solar energy. While measuring policy effectiveness, additional insights which support mechanisms performed better have been obtained. Furthermore, by selecting out most dominant policy instruments (FIT, quotas, tenders, or tax incentives) across the EU, regression models were employed with a goal to quantify their impact on policy efficiency of wind and solar energy across researched countries (with the main focus on Poland and Germany). Based on this approach evidence has been extracted and conclusions made on which policy instruments delivered better results.

H3: Resource endowment has a positive impact on efficiency of wind and solar energy policies. It is important not only to measure the performance of certain policies, but also to find out why they are successful or not. Average wind speed and solar power theoretical potential are employed as explanatory variables to investigate their impact on policy efficiency of wind and solar energy policies. More robust evidence is obtained in this area as EU member states are also included in the analysis.

Dissertation outline

The present work is outlined into the following chapters:

Introduction: presents importance of research, objectives, questions, and hypotheses. Additionally, motivation and structure of the doctoral thesis is highlighted.

Chapter 1: Theoretical background and status of energy transition, covers main aspects and status of energy transition in case study countries of Poland and Germany. Additionally, a role and status of wind and solar energy sources in EU countries has been described. This chapter also summarizes main types and features of RE policy instruments in EU countries. A strong focus is also placed on regulatory initiatives in EU.

Chapter 2: Literature review on the performance of RE energy policy, presents a comprehensive analysis of literature on the topic. In addition, aspects of monitoring and assessment of RE policy performance are discussed. The chapter also highlights the role of wind and solar energy policy and provides a selection process of the research criteria. The main focus of the chapter addresses main literature streams regarding popular policy instruments and their performance.

Chapter 3: Methodological aspects of measuring RE policy performance, provides a review of peer-related studies on researched methods and presents methodological framework applied in the dissertation. The chapter also covers data collection process and selected data sets.

Chapter 4: Performance assessment of wind and solar energy policy in Poland and Germany on background of EU countries, covers main results on policy effectiveness and efficiency of the researched countries. A verification and conclusion regarding the results is presented.

Chapter 5: Discussion, contribution, limitations and recommendations for further research, presents summary, discussion, implications, and significance of findings. The chapter also highlights avenues for further research and limitation of the present work.

1. THEORETICAL BACKGROUND AND STATUS OF ENERGY TRANSITION

1.1. Role and status of wind and solar energy sources in EU

Conventional fuels started to gain significance during the industrial revolution in the seventeenth century and since then have grown into a major force on the world energy market (*Sovacool, 2016*). Their dominance reached a peak in the twentieth century as demand on energy started to boom (*Ritchie & Rosado, 2020*). New technologies to extract fossil fuels on a massive scale were applied, being a catalyser for many national economies. Even the worst sceptics could not predict that coal, oil, or gas could face any competition in the long run. However, aspects of high exploitation, ecological implications, and resource scarcity - publicly known drawbacks of conventional energy led to a search for new technologies. Furthermore, energy crises, manifestations against air pollution and price manipulations in the 1970s - 1980s (*Yergin, 1991*) were signals that the countdown of fossil fuels' era had just begun.

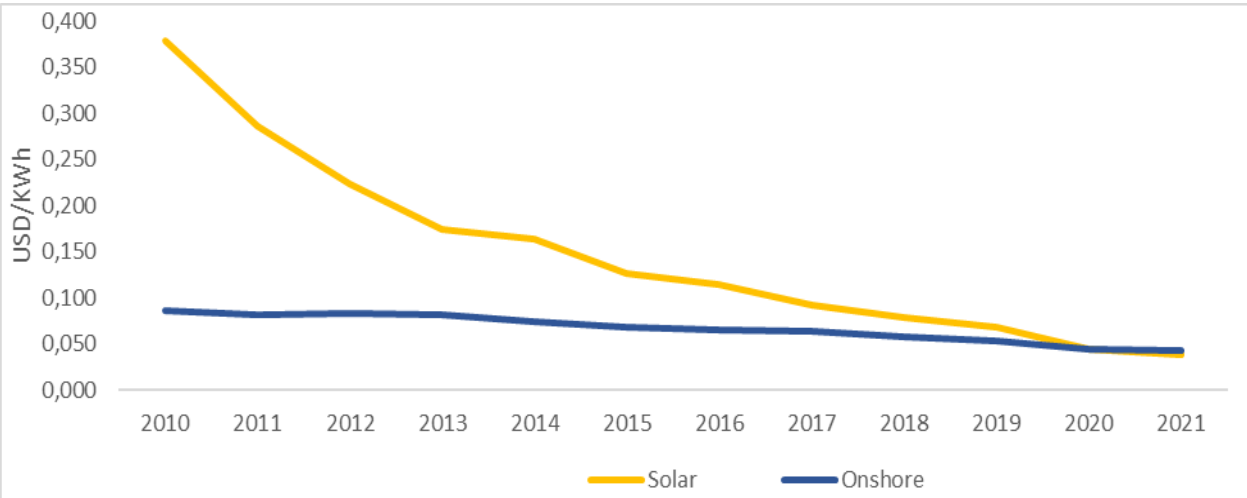
The issue of global warming and ecological threats are new trends on the political and social agenda constitute a consensus on adverse effects by conventional energy. Emergence of renewable energy (RE) sources even deepened that discussion, forcing a process of phase-out of fuels like coal in some countries (e.g., Germany). As more research indicates a diminishing role of fossil fuels in the upcoming decades (e.g., *Pedraza, 2014*), energy transition, with renewables in the core, could not be seen as fiction anymore, but reality, happening now. However, the question of how fast this transformation can proceed is still open. There are many bottlenecks which can hinder this process starting from lobby of fossil fuels and ending with a problem in energy storage.

As public opinion towards conventional energy started to change noticeably during the last few decades, renewable energy sources gained even more popularity for their climate- and environment-neutrality status. However, renewables were not considered seriously as many critics indicated that they were not economically viable. During the last few years an exponential drop in technology cost (Figure 1.1) has seen some RE sources as a driving force in the global energy market. Even though fossil fuels oil and gas are still dominant, a global share of renewables doubled within last two decades, accounting for around 14% in 2022 (*Ritchie et al., 2022*).

The European Union is regarded not only as a leader, but also as a pioneer in terms of clean energy technologies. Development of renewables has been one of the main economic and political priorities of most EU member states. Despite some differences in energy policies, the EU plans to build its economy on RE sources, among which a special place is assigned to wind and solar energy. Given the recent rapid development (see Appendix A.1), these clean technologies will play an even more important role in facilitating European carbon-free energy transition.

Despite a consensus on terms and characteristics of 'renewable energy', 'renewables' or 'RE sources' in the literature, no commonly accepted definition exists. One should single out a general definition mentioned in the statute of the International Renewable Energy Agency. According to it (*IRENA, 2009, p.4-5*), "renewable energy means all forms of energy produced from renewable sources in a sustainable manner, which includes bioenergy; geothermal energy; hydropower; ocean energy, including inter alia tidal, wave and ocean thermal energy; solar energy; and wind energy". A more general definition of renewable energy is presented by United Nations (UN), labelled as "energy derived from natural sources that are replenished at a higher rate than they are consumed" (*UN, 2023b*).

Figure 1.1. Global weighted average LCOE[4] and auction cost of wind and solar energy for years 2010-2021



Note: LCOE values are presented for years 2010-2019, later period 2020-2021 refers to auction cost.
Source*:* Based on data from *IRENA, Global LCOE and Auction values*.

Among RE sources one can pay special attention to wind and solar energy sources which have seen an unprecedented growth during last two decades. Due to decreasing technology cost (see Figure 1.1) and environment-friendly nature, these two types of renewables have gained

[4] Levelized Cost of Electricity (LCOE) - a method of measuring cost (in Euro/kWh) of a certain technology unit (e.g., solar power farm) during the whole period of its exploitation (see *Mir-Artigues & del Río, 2016, p.126*).

more popularity among investors. Furthermore, they already constitute a large share in energy mixes of many countries thus gradually crowding out fossil fuels.

According to *UN (2023b)* “solar technologies can deliver heat, cooling, natural lighting, electricity, and fuels for a host of applications. Solar technologies convert sunlight into electrical energy either through photovoltaic panels or through mirrors that concentrate solar radiation”. As for a definition provided for wind energy, “it harnesses the kinetic energy of moving air by using large wind turbines located on land (onshore) or in sea- or freshwater (offshore)” (*Ibidem*).

The role of RE sources is difficult to underestimate in the future. From one side, the share of RE sources is growing fast globally which can cover rising demand in the short run (*REN21, 2021*). From the other side, the huge supply of potential of renewables could replace fossil fuels in the near future (*Pedraza, 2014*). What looked impossible to imagine a few years ago, recent economic and ecological threats could pave a way for wind and solar technologies to dominate the global energy market.

The advantages such as low technology cost (see *REN21, 2020; IRENA, 2020*) and infinite resources are key to the interest in wind and solar energy technologies. However, there is still a strong discussion regarding their caveats. One of the most publicly known fact is that no energy can be produced when no wind blows or there is no sun. The problem of intermittent performance of some renewables such as wind and solar energy and their low degree of market maturity in some countries are often qualified by scholars as barriers to a scalable diffusion. Also, seeing fossil fuels as being dominant on the energy market for a very long time requires additional political efforts to promote clean technologies. Despite these and other barriers, wind and solar energy have already outperformed some conventional energy sources by the amount of electricity production in some countries, for example in Germany and Denmark (*REN21, 2020*). Additionally, the fact that wind and solar technologies have enormous potential based on their innovative unlimited and environment-friendly nature, gives them the edge over old fossil conventional coal or oil (*Koruga, 2011*).

An increasing global energy demand can be considered as one of the biggest challenges nowadays. Some analyses already state that conventional fossil fuels may not be enough and express urgency in fast deploying of new energy technologies. This fact gives a boost to technologies like wind and solar energy that can be a solution in light of a surge in energy consumption in the upcoming years and decades (*Rosales-Calderon & Arantes, 2019*).

One of the strongest rationales behind preferring renewables to fossil fuels lies in relation to the environment. Renewables unlike conventional energy cause minimum pollution to the environment, while emitting no greenhouse gases (GHG) (*Piwowar & Dzikuć, 2019*). A common fact that clean technologies like wind and solar energy sources are friendly to the environment leads to a conclusion that a complete phase-out of fossil fuels is inevitable, even though the latter may be still effective from financial or economic perspectives. However, as mentioned previously, long-term dominance of conventional energy and strong political lobby still present a strong resistance to clean energy technologies in many countries. Despite a strong agreement in science regarding the fact that RE sources are clean and pollution-free, some scholars reveal that even wind and solar energy can indirectly cause damage to the environment. For example, production and transportation of details for wind turbines or utilization of photovoltaic (PV) panels can be harmful to the ecology (see *Mir-Artigues & del Río, 2016*). Nevertheless, renewables are called economic friendly and are recognized as carbon-free energy sources in policies of many countries, whose goal for the upcoming decades is the energy mix, which completely or almost completely excludes the existence of fossil fuels.

Besides air pollution and ecological damage, closely related factors are global warming and climate change (*Fouquet & Pearson, 2012*). It has already been proven that conventional fossil fuels not only pollute the atmosphere, but also have a negative impact on the climate. Based on this fact, one can single out a historical international consensus between scientists and politicians, reflected in the Paris Agreement[5] in 2015 (*UN, 2023a*), which obliged almost all countries in the world to curb the speed of climate change. It was one of the first times when a decision about cutting GHG and reducing fossil fuels was made. The agreement also encompassed additional measures directed at the acceleration of global RE development.

As a result, renewables have another strong advantage over fossil fuels as they are carbon-free and don’t contribute to global change. Even though RE sources, like wind and solar technologies can still be more expensive compared with fossil fuels in some countries, this drawback can be seen as negligible. The fact that a quick deployment of renewables is key to the solution of global problems like air pollution and climate change (*Fouquet & Pearson, 2012*) means that wind, solar and other clean technologies are going to dominate global energy markets in the next decades.

Investors start to build more new wind farms in water, mostly at sea in light of rigorous legislative frameworks as well as addressing available sites on land in some countries. Such trends have been especially noticeable during the last few years. Also, solar energy sources have been developing very fast recently thanks to drastic downward trend in technology cost. As

[5] A historical agreement took place in Paris in 2015. According to it, a growth in world average temperature by the end of 21st century is fixed to a level not exceeding 1,5°C with 196 countries signing under Paris Agreement.

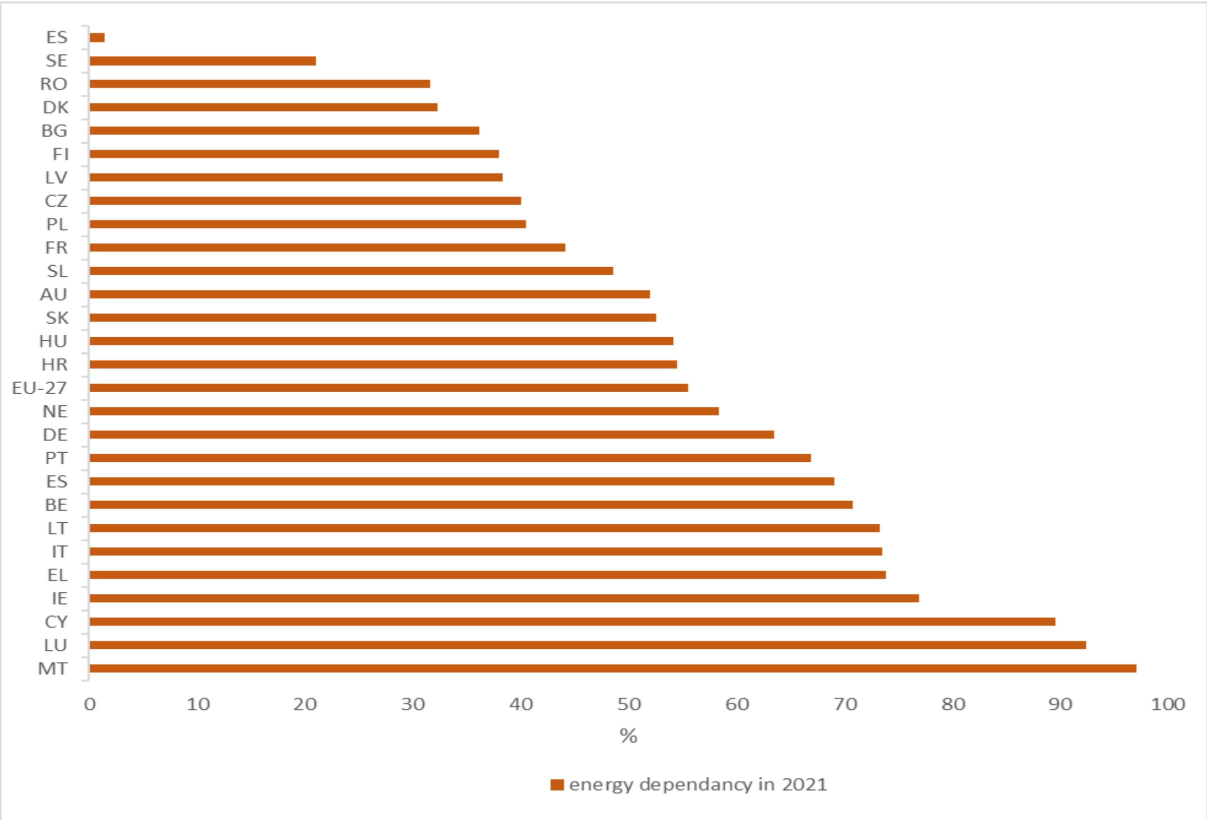
investors look for new business opportunities, households also seek ways of becoming energy efficient and dependent. Solar energy farms or modules could serve as suitable modern solution in such undertaking.

Another factor, why renewables like wind and solar energy sources will play an even more important role is a factor of social acceptance. Many years ago, people didn't care much about which type of energy they used or how much pollution it caused. Given a strong diffusion of clean energy sources in some countries, knowledge about sustainability and environment has had a strong effect on society's preferences. For example, in the first decade of the 2000s, when the cost of wind and solar energy technology was much higher to compare with most expensive conventional sources, taxpayers in some countries (e.g., Denmark or Germany) were aware of the importance to support the development of renewables, even though it led to a rise in their electricity bills (*Nkomo, 2018*). The rapid deployment of RE sources has been supported by different policy measures which became popular in many countries ever since (*IRENA, 2014a*). However, pushing renewables is connected to various potential problems perceived by citizens and consumers. For example, very popular is an issue of the proximity of wind farms to the nearest communities (*DW, 2019*). The fact that turbines make noise and are dangerous for some species of birds could mean a challenge for this type of energy that might demand more creativity in legislative initiatives.

One should also pay attention to a trend in growing energy imports by some countries, leading to a strong dependence on deliveries from abroad. Especially, EU member states have conducted a policy of buying gas and oil mostly from autocratic regimes such as Russia. Such dependence (see Figure 1.2) led to disastrous consequences, jeopardizing all energy systems of the community. Even worse, on one hand, some fossil fuels have been used as a political instrument, which eventually destabilized global energy markets and prices. For example, Russia's war with Ukraine is being financed from the sale of oil and gas. A dependency on Russian fossil fuels in some EU countries became so strong that member states became prisoners of their own situation. Understanding these disastrous implications, some countries were not able to resign from imported fuels in the short term.

Many would agree that a matter of energy security in the world and especially nowadays in Europe has never been so vital since the Russian invasion in Ukraine in 2022. By focusing on short-term solutions based on deliveries of cheap gas and oil from the country-aggressor, European governments failed in realization of their energy policy in the middle and long term. Instead of investing in their own clean energy technology, a policy relied on import of cheaper fossil fuels has been extremely visible during the period of last two decades. Not every country has abundant conventional energy sources. However, when the choice comes to renewables, no strong political efforts in areas of wind or solar energy exist. Against this background, RE sources could be a massive tool in light of growing energy dependency and insecurity. Even though renewables still have some challenges, their development can help to diversify and stabilize domestic energy markets, while also protecting from major threats such as electricity shortages or price surges on global markets (*Adamczak, 2016*).

Figure 1.2. Energy import dependency of EU countries in 2021

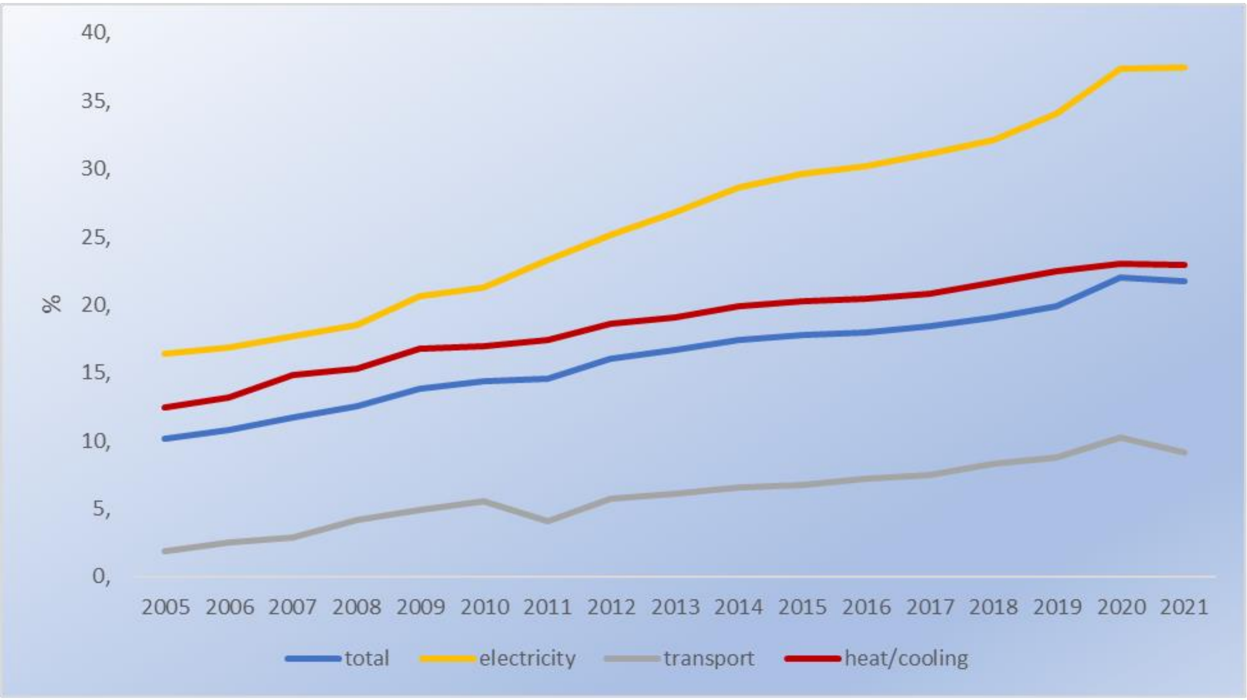


Source: Based on data from *Eurostat.*

Renewables can also have positive economic and social implications. With the rapid development of RE sources, many jobs are being created, that can also give a boost for local economies (*IRENA/IEA/REN21, 2018*). There are many articles in the literature devoted to the topic of employment in RE sector. Even though most scientists agree that clean technologies contribute to a job market, there are also different analyses. For example, critics indicate that the development of renewables leads to the loss of jobs in the conventional energy market. As RE sources like wind and solar technologies become more competitive, they can take a dominant role over some fossil fuels. This may lead to higher unemployment in other sectors, which could adversely affect a local economy.

Thus, considering a high level of social acceptance from society, growing energy demand, and positive ecological and climate effects, RE sources can be crucial in accelerating the world's economy on the way towards sustainability. Also, the pace of technology, cost reduction, unlimited resource base and growing interest from investors means that wind and solar technologies will play an even more crucial role in energy systems and policies of many countries. These clean technologies gradually become more economically viable (*Pedraza, 2014*), as some international reports such as *IRENA* (*2020*) or *REN21* (*2020*) already acknowledge that they can compete with conventional fossil fuels. As an example, in some countries the cost of wind and solar technologies is lower than coal. This aspect is so important, as such RE sources draw attention from private investors, at the same time saving public financial resources which can be used for other purposes.

Figure 1.3. Share of RE sources (%) in total energy mix by sector in EU-27[6] for years 2005-2021



Source: Based on data from *Eurostat*.

There are other rationales behind the growing role of renewables in the EU and other parts of the world. The dominance of technologies like wind and solar energy could also lead to better economic life or modernization of grid connections. Thanks to renewables, poorer

[6] 27 EU member states.

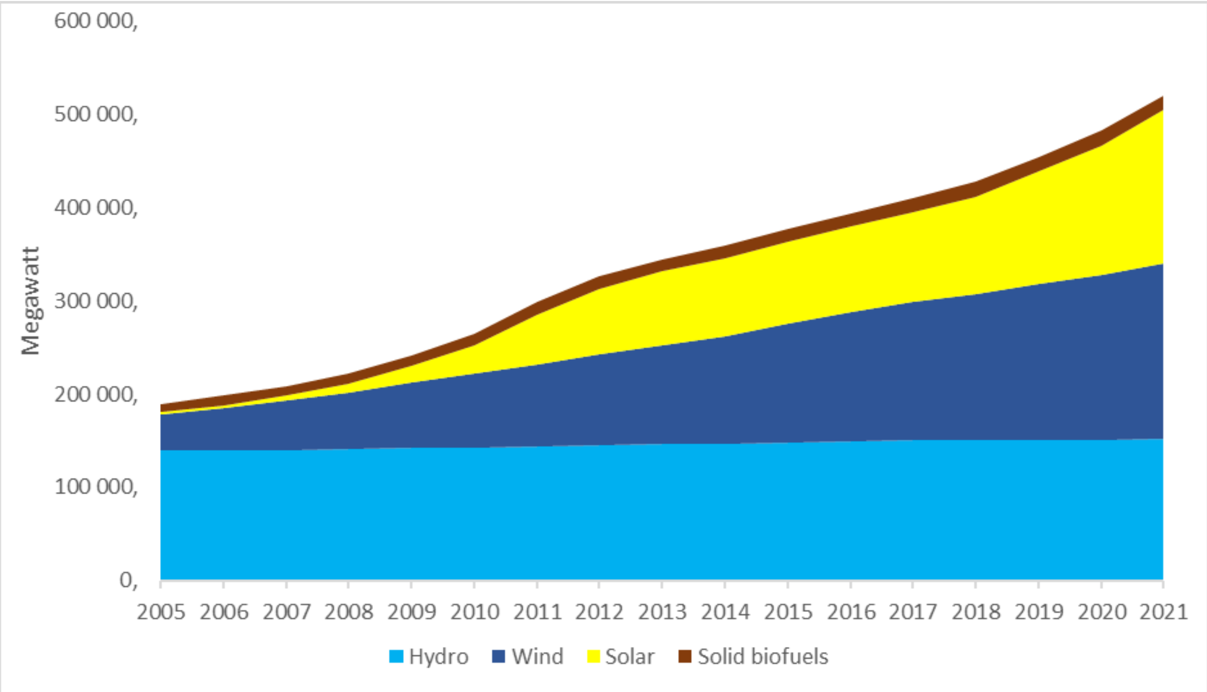
societies can have better energy access and benefit from stable electricity prices (see *Groba & Breitschopf, 2013*). In context of different threats and challenges, the EU consider RE sources as central element in their energy policies.

One can see a correlation between adaptation of EU favourable legislative field and a speed rate of RE development. Since establishing some legislative directives in the EU, clean energy technologies have been expanding quickly during last two decades (see Appendix A.2). Special attention should be drawn to wind and solar energy sources, which saw exponential growth thanks to the policy measures implemented by the EU member states. Section 1.4 of this chapter presents a deeper analysis of main EU directives which defined RE market of member states during last two decades.

EU measures to promote renewables have predominantly focused and substantially contributed to the sector of electricity, which has seen an unprecedented growth during the last two decades (see Appendix A.1). To compare with year 2005, a share of RE sources in total energy mix has more than doubled in 2021 and accounted for around 37.5% (see Figure 1.3). As for heating and-cooling and transport, there has been steady growth during the last two decades with shares of renewables equalling approximately 9% and 22% respectively in 2021. This implies that energy transformation in the two mentioned areas has not been as successful as in the case of electricity. Many agree that ultimate energy transition can be fulfilled only when renewables dominate in all sectors (*von Hirschhausen et al., 2018*). There is a need for special measures to promote renewables in the sectors of transport and heating and cooling, which could be as effective as in the case of electricity. In order to break the total dominance of oil, gas, and coal in those two sectors, there should be legislative, innovation and technology changes. However, one of the most noticeable bottlenecks in those branches is the issue of energy storage (*Shivakumar et al., 2019*). Once a new innovative and affordable mechanism of storing energy is found, there will be a strong impetus for the rapid deployment of renewables in all mentioned sectors.

Some types of RE technologies like hydropower have quite a long history and together with wood were dominant sources before industrial revolution. Also, biomass and geothermal energy are not new names on the market. Like in case of fossil fuels, the mentioned RE technologies were developing actively and used in the countries with abundant energy resources. During the last two decades, two rather new RE technologies have become popular - wind and solar energy. Even though hydro energy still dominates the European RE market in terms of new capacities installed, it looks very possible that wind and solar technology will soon become leaders in terms of total energy supply. Both technologies have seen an unprecedented development during the last two decades in the EU, with their amount of net capacity to double each within several years. As of 2021, wind energy stood for 188 GW of new capacities (see Figure 1.4), making it a leader among other types of RE sources. Second and third are solar and hydropower with a capacity of 164 GW and 152 GW respectively during that year. One should pay attention to the exponential growth of the former technology during the first decade of the 21st century, which accounted for a large increase in newly installed capacities.

Figure 1.4. Net maximum power capacity by RE technology in EU-27 for years 2005-2021



Source: Based on data from *Eurostat*.

So, RE sources have been growing rapidly during last decades, while wind and solar energy technologies are catalyser of such development. Despite some solid bottlenecks, like issue of intermittency or energy storage, prospects of these two clean energy technologies look very promising, as many countries (including EU member states) take additional measures to promote them. Their role increases in light of diminishing technology cost and carbon-free nature. Urgency in context of growing energy demand, price instability or climate change are among other factors which could further boost deployment of wind and solar energy sources, while also enhance their social acceptance. One cannot forget about the significance of energy security components, as countries can solve problems of high energy import dependence and situations where energy is used as a ‘weapon’, by intensive expansion of the RE market. By investing in clean energy technologies such as wind and solar, countries could also benefit from the creation of new jobs, contributing at the same time to the development of their economies.

1.2. Theoretical aspects of energy transition

1.2.1. Definition of energy transition

According to a report by World Economic Forum (*WEF, 2019*), energy transition or transformation is one of the major challenges in the upcoming decades. With a recent popularity of topics like RE sources, climate change mitigation and air pollution, one can highlight a phenomenon of energy transition (*Fouquet & Pearson, 2012*). History knows a few changes in global energy systems, as the largest one addressed a shift from one fossil fuel to another. As for the transformation happening now in energy systems, it can be marked as special, because it considers multiple important aspects like society preferences and environment. Furthermore, ‘modern’ energy transition is based on carbon-free solutions in which one of the leading roles is assigned to RE sources. As this chapter provides insights into a history and current status of energy transformation in researched countries, its ultimate purpose is to shed light on the rationale and perspectives of this phenomenon.

By taking the simplest approach of defining energy transition most scholars (e.g., *Fouquet & Pearson, 2012*) associate it with a post-industrial revolution which encompasses a move away from conventional fossil fuels to clean energy technologies. However, it is a wider category which, besides energy, can also be viewed from other perspectives such as management or logistics. Studies on energy economics often use the following terms: ‘low-energy transition’, ‘sustainability transition’, ‘energy transition’ or ‘energy transformation’. Despite some similarity in interpretation, these categories are not the same. For example, *Cherp et al.* (*2018, p.176*) explains the difference as “low-carbon transitions may occur outside of the energy sector (e.g., in urban planning, industry, agriculture and forestry)”, while “sustainability transitions may also include changes in food systems, distribution of wealth, human rights, governance and conflicts”. Some scholars use a similar definition for ‘low-carbon energy transition’ (e.g., *Fouquet & Pearson, 2012*) by pointing out a modern post-industrial era, in which alternative renewable technologies dominate and constitute a new economic order.

Widely used terms among scholars are ‘energy transition’ and less common ‘energy transformation’. They could be regarded as synonyms, but they can also differentiate depending on the taken approach in a study. Both definitions can imply a significant change in an energy mix during a certain period. On one hand, it can mean a complete move away from conventional fuels to RE sources. On the other hand, such processes include some shifts between conventional fossil fuels only. However, implementation of a new energy package (e.g., EU 'Green Deal'), which anticipates ambitious energy and ecological change, has brought a new trend into the literature discourse. Nowadays, more studies use a concept of 'energy transition', which means a new-carbon free economy with a complete replacement of fossil fuels by RE sources.

Based on the interdisciplinary aspect of energy transition, there is a problem of comparing literature works which are scattered among different fields (*Lu & Nemet, 2020*; *Cherp et al., 2018; Doh et al., 2021*). As mentioned earlier, there is no commonly accepted definition of 'energy transition' due to its interdisciplinary, complex, and multidimensional nature (*Fouquet & Pearson, 2012; Loorbach et al., 2008; Arababadi et al., 2021*). At least, a consensus among scholars exists, as energy transition is defined through a change in energy system, in which a shift to a new technology or prime mover (e.g., a car or a TV set) takes place (*Sovacool, 2016*). A similar definition is provided by *Arababadi et al. (2021, p.2)* who defines energy transition as "the changes in the composition of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system".

However, many scholars acknowledge that it is a wider category than just a transformation in terms of energy source or infrastructure. According to *Araújo (2014, p.1)* energy transition is a change or shift in "constellation of energy inputs and outputs involving suppliers, distributors, and end users along with institutions of regulation, conversion and trade". Such transition also overlaps with a shift happening in areas like management, learning, regulation, materials (*Huh et al., 2019*). A study by *Cherp et al. (2018, p.187)* notes that behind a definition of national energy transitions stand "changes in three co-evolving systems: stand changes in three co-evolving systems: energy flows and markets, energy technologies, and energy-related policies, each in the focus of a specific scholarly field framing three perspectives on energy transitions: techno-economic, socio-technical, and political, each associated with its own disciplinary roots, systemic focus, variables and theories".

To better understand the concept of 'energy transition', one should resort to its history (*Grubler, 2012; Fouquet & Pearson, 2012*). Insights from the past are very important when it comes to interpretation of current situations on the energy market and making projections of the future trends. Energy transition has quite a long history with milestones, which define it. While modern energy transition is often associated with a carbon-free system based on clean renewable technologies, past transitions were mostly relevant to conventional fossil fuels.

As hydropower and wood were the main sources of energy before the industrial revolution, the share of coal in the total energy supply started to increase exponentially during the second part of the 19th and beginning of the 20th centuries (*Sovacool, 2016*). Scholars usually associate this period with a first energy transition, during which coal became the main source of energy, giving a strong impetus to economies, based on an extensive scalable production of different goods (*Ibidem*). Next, two major energy transitions took place during the last 150 years (*Yergin, 1991*). A large transformation came with a high demand for energy and a search for new, more effective technologies, that led to a gradual shift from coal to oil and nuclear energy. This shift is regarded as one of the longest in the history, with its peak between the middle and the end of the last century (*Doh et al., 2021; Yergin, 1991*). A failure of current energy systems in context of economic, social, and environmental domains made a transformation to new more efficient and cleaner technologies inevitable (*Grubler, 2012*), while the biggest catalyser to current energy transition is air pollution and climate change (*Fouquet & Pearson, 2012*).

One of the main pretexts to energy transformation, which is taking place now, are global manifestations against ecological issues during a period of 1970-1990 (*Yergin, 1991*). Furthermore, the emergence of clean technologies like wind and solar energy is also regarded as a beginning of a new era, directed at a shift away from fossil fuels. So, only a few decades ago, energy transition has been given a new meaning and goal, with clean energy technologies lying in the centre of this process.

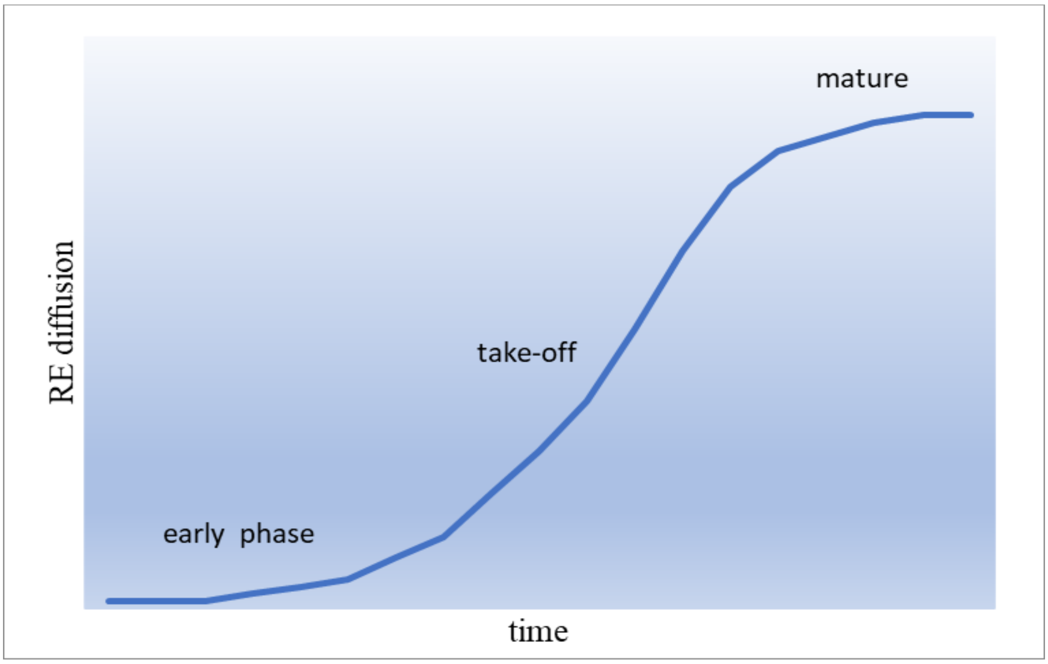
Every previous energy transition ended with changes in consumption preferences (*Fouquet & Pearson, 2012*). As new energy patterns emerged, a global demand for energy has always grown. Furthermore, each complete energy transition has resulted in a shift from cheaper energy sources to a more expensive technology (Ibidem). There is a risk of a rapid, chaotic, and 'impatient' energy transition (*Grubler, 2012*) as a strong push from one energy source to another can fail, pointing out that new modern technologies take quite a long time to reach economies of scale. Especially important are minimization of social costs for society, while policymakers face difficult decisions to keep up to a pace of current changes in energy systems. The 'modern' energy transition is the unprecedented one, as its goal is a low-carbon or totally carbon-free economy, in which conventional fossil fuels are replaced by renewables (*Yergin, 1991*).

1.2.2. Theories of energy transition

Due to the abundance of interdisciplinary studies, approaches, and a lack of consensus on definition of energy transition, it is also challenging to categorize its theories (*Arababadi et al., 2021*). Despite differences in a rationale behind energy transitions, there is clear evidence that most concepts address an inevitable shift from fossil fuels to unlimited RE sources. Given the purpose of this dissertation, diffusion theory of renewable energy sources was strongly relied upon. However, some postulates from other theories were also considered while writing this thesis (e.g., socio-technological concept).

Diffusion theory models became popular during the 1960s (*Rao & Kishore, 2010*) and since then have been widely used in explaining processes inside different domains of science, like economics, management, or marketing. In context of renewables, there are different stages of development (diffusion), as technologies take a form of S-curve (see Figure 1.5) during the whole period (*Rogers, 2010; Rao & Kishore, 2010*). While earlier studies on diffusion predominantly address changes in social aspects (e.g.*, Rogers, 2010*), later works paid strong attention to innovation in technology processes (e.g., *van der Kam et al., 2018*). *Rogers (2010)* explains diffusion through adoption of innovation by certain social groups during a predefined time. The author divides this process into several periods: when first innovators appear, then early adopters, majority, and late majority. There are also other categorisations of diffusion process related to clean energy; as an example, formative and expansion phases were presented in a study by *Piłatowska & Geise, 2021*. *Rao & Kishore (2010)* acknowledge that diffusion is a complex category which should be perceived from multiple aspects such as socio-economic, technological, or institutional domains.

Figure 1.5. Diffusion concept (S-curve) of RE technologies



Source: Adopted from Rao & Kishore, 2010.

As for renewables, their diffusion is premised on a myriad of drivers and barriers (*van der Kam et al., 2018*), while components of environment and energy security are the ones with the highest relevance (see *van der Kam et al., 2018; Balcerzak et al., 2023*). Given a threat posed by conventional fossil fuels in the context of air pollution, climate change and import dependency, a transition to clean and unlimited resources, like wind or solar energy lies in a paradigm of diffusion theory. Also, energy policy plays and important role, as most renewables, being in their early or take-off stage, require strong financial injections. Because a matured market of fossil fuels has a comparative advantage, it becomes justifiable that governments apply policy instruments (e.g., feed-in tariffs) and other measures to boost deployment of renewables. Against this background, a policy should be adjusted to stages of RE diffusion until a complete withdrawal of support measures when markets get saturated.

A socio-technological concept is based on the fact that energy transition is taking place as a part of a shift from a command centralized energy system to a more liberalized and innovative economy built on clean energy sources (*Huh et al., 2019*). Taking on a technological approach, a report by World Economic Forum (*WEF, 2019*) defines energy transition as a replacement of older, less efficient conventional fossil fuels by modern, more productive, and innovative energy technologies. From a social perspective, common efforts and response to the collective challenges are key to the successful energy transition (*Ibidem*). In this context, it is a complex process, which is based on a compromise between society and government. For example, the initial stage of RE promotion is strictly connected with a higher burden for taxpayers bearing extra costs reflected in higher electricity bills. Also, energy transition must include the component of energy security, which lies in stable electricity prices and equal access to it.

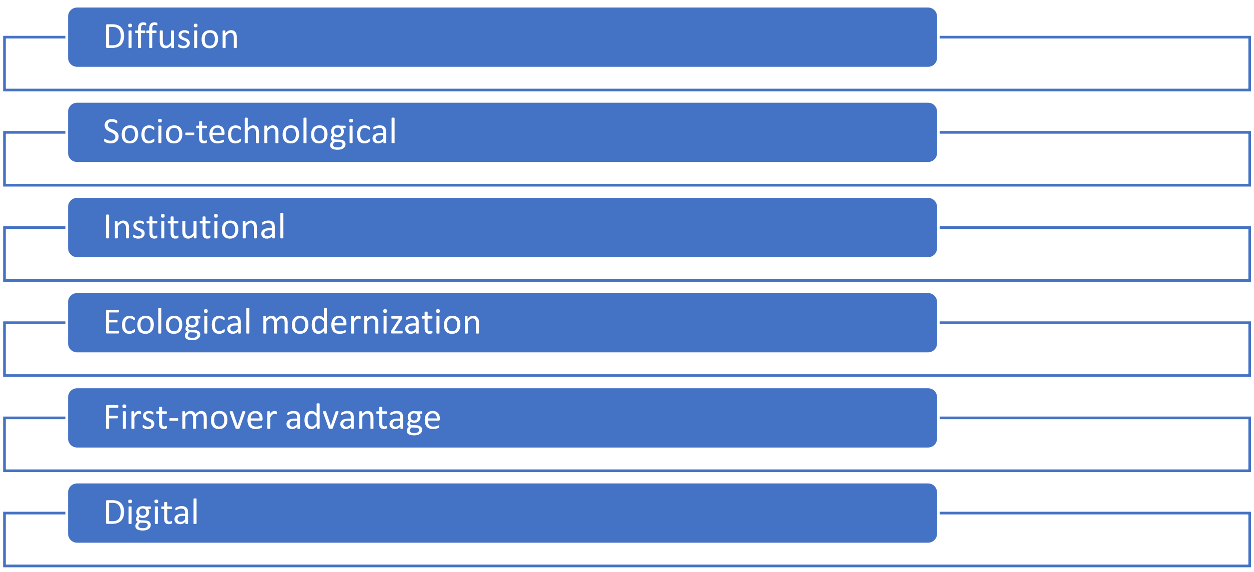
Similar postulates as in the case of socio-technological theory, can be found in the institutional concept of energy transition. According to the institutional concept, two opposite systems, capitalism, and socialism, have different patterns regarding energy sector. Furthermore, one can find an interconnection between practices in political and tax systems of some countries and a level of public intervention to promote energy transition (*Doh et al., 2021*).

The importance of ecological modernization concept was outlined by *Gibbs (2000)*, with a final goal of reaching a trade-off within economic and ecological processes. *Mol et al. (2001)* claims that concern of public opinion about the matter of environment, climate change and air pollution became mainstream and has been very important in a later push in development of RE sources. According to the theory, ecology plays a very crucial role, as energy transition takes place in different domains, such as economic, social, and public sectors.

A first-mover advantage theory is also worth attention, as it helps to understand the prospects and challenges of energy transition (*Doh et al., 2021*). According to the theory, on one hand pioneer countries usually take a huge financial burden at the early stage of energy transition, when costs of the new energy source are high and cannot compete with older, more matured technologies. However, these countries can take advantage from know-how and experience, which helps decrease costs of RE technologies in later phases of diffusion. *Grubler (2012)* and *Sovacool (2016)* acknowledge, that despite the fact that early movers might sustain higher expenditures on new technologies, they might succeed in energy transition only in the long run before it becomes attractive for investors. To achieve this goal, adjusted transformation should take place in political, regulatory and, social and economic areas. However, factors like financial crises or turbulences on energy markets can end up in a failed energy transition and wasted resources (*Doh et al., 2021*).

Energy transition can be also analysed from a perspective of a digital theory (*Huh et al., 2019*). The concept is based on changes, which have been brought by technologies such as computers, phones, and internet. One of the most recent trendy systems is blockchain, which also has a potential to revolutionize not only modern economies, but energy systems as well (*IEA, 2022*).

Figure 1.6. Theories of energy transition



Source: Own compilation

As a result, the literature selects out multiple theories of energy transition (see also Figure 1.6). One of the most popular and frequently addressed by scholars is a concept of diffusion. This theory is applied in many domains and branches, while RE technologies are no exception. It is based on multiple stages of innovation adoption during a certain period. For the purpose of this dissertation, an assumption is taken from the study by *van der Kam et al. (2018)* and *Ragwitz et al. (2015)*, dividing the process of diffusion of RE sources into three general phases: early, take-off and mature (see Figure 1.5). This concept is based on several pillars as the most important are climate-friendly and unlimited renewables and bad implications from use of fossil fuels and support policy measures. As this study strongly builds on the theory of diffusion, other concepts (socio-technological, ecological, institutional, first-mover advantage and digital), which to some extent overlap with diffusion theory have also been taken as a basis for writing this thesis.

1.2.3. Premises, threats, and drivers of energy transition

Apart from historical insights, other components are important such as resource endowment, domestic energy preferences and government policies, which set a direction of energy transition (*Fouquet & Pearson, 2012*). Furthermore, catalysers for energy transition are not only law and institutional factors, but also are in other areas like finance and society (*Grubler, 2012*). As for drivers of energy transition, *Doh et al. (2021)* names a scarcity, energy intensity, a negative public opinion towards conventional energy sources as well as a high demand for clean technologies. Strict attention is paid to alignment of policymakers (*Grubler, 2012*), who need to learn from the lessons of previous good and bad practices of conducting energy policies (*Papież et al., 2018*).

Energy transition trends have been also reflected in performance of business and financial markets. Social responsibility and acceptance, climate change concerns and a strong public support to RE sources tend to affect shareholders' strategies, in which capital gradually shifts away from conventional fossil fuels (*Doh et al., 2021*). One of the biggest opponents of a transformation to clean energy sources were big energy companies (*Ibidem*). Having a large share of fossil fuels in their portfolios, big energy companies are not motivated to change their input energy structure, represented by a constant source of large revenues. Furthermore, such businesses formed a strong lobby against renewables for many years, which halted energy transition. Nevertheless, during the last years, businesses have increased shares of RE sources in their portfolios. Such a trend is in line with the fact that companies also see economic opportunities as costs of some clean technologies constantly go down. Another rationale is that companies care about their own reputation while 'going green' is also gradually becoming a mainstream in the private sector.

One can also select other important drivers of sustainable energy systems such as geopolitical situations, life standards or demographic changes. More efficient technologies, decentralization of policies, and optimization of financial resources are other important factors to facilitate successful energy transition (*IRENA/IEA/REN21, 2018*), while economic growth, technological innovation, and policy amendments are a key to low-carbon energy transition (*Cherp et al., 2018*).

Hence, a transformation in energy systems has never been smooth, and so is the energy transition, which is happening now. Despite good prospects of development, the ongoing energy transition, based on shift from fossil fuels to RE sources is a very complex phenomenon, posing different threats and challenges (*Fouquet & Pearson, 2012*; *Huh et al., 2019 Doh et al., 2021;*). There are many factors which could contribute to a successful change to a new carbon-free system. Especially important are energy policy, private sector, social acceptance, resource endowment, and support mechanisms. According to publication by *IRENA/IEA/REN21 (2018)* the core to energy transition lies in the energy sector itself, as it is responsible for 2/3 of total GHG emissions in the world. As there is a consensus that unprecedented development and enormous potential of further development of wind and solar energy sources lies in the centre of the ongoing energy transition, some scholars acknowledge it is not just a process taking place in energy systems, but also a compromise on different levels: public, society, economy, and technology (*Rao & Kishore, 2010*; *Doh et al., 2021*).

1.3. Theoretical aspects and types of RE policy instruments

As some types of RE sources are only at their initial stage of development and face a strong competition from fossil fuels, many countries have already implemented different measures of economic, financial, and technical support. *Groba & Breitschopf (2013)* marks market failures (e.g., unpriced social costs of emissions) and barriers (e.g., energy price uncertainties) as main factors to justify public intervention and regulation of renewable energy markets. Furthermore, promotion of RE sources is one of the main postulates of various energy transition theories, as, for example, according to diffusion concept such measures are vital in enhancing energy transformation (*van der Kam et al., 2018*). One can outline other reasons behind the necessity in subsidizing renewables: improvement of ecological situation, reduction of GHG, diminishing energy dependency, meeting RE targets etc. Promotion of clean energy technologies takes place usually through implementation of public support measures which are usually called policy schemes or instruments.

One can find different terms regarding RE support measures known in literature as 'policies or support policies', 'policy instruments or incentives', 'support schemes or mechanisms' etc. Even though they are very close in interpretation, scholars use different approaches in their classification[7]. According to Directive 2009/28/EC (*EC, 2009*) policy support can be interpreted as "any instrument, scheme or mechanism applied by a Member State or a group of Member States, that promotes the use of energy from renewable sources by reducing the cost of that energy, increasing the price at which it can be sold, or increasing, by means of a renewable energy obligation or otherwise, the volume of such energy purchased restricted to, investment aid, tax exemptions or reductions, tax refunds, renewable energy obligation support schemes including those using green certificates, and direct price support schemes including feed-in tariffs and premium payments".

Besides the fact that no consensus in literature on categorizations of policy instruments exists, there are some common approaches for their differentiation. Multiple categorizations were applied by scholars to select out support policies (e.g., monetary, and non-monetary; market-based and not-market based; direct and indirect etc.) (*IRENA, 2012; IRENA 2014b*).

One of the most popular categorizations of policy schemes is restricted to a criterion of subject scope (*Groba & Breitschopf, 2013; Banja et al., 2017*): price-based (feed-in system) and quantity-based (auctions, quota obligations). *Groba & Breitschopf (2013)* in their literature review divides a few groups of support instruments. By using a general approach, they single out market-pull and technology-push policies. According to a criterion based on a support for a certain RE source, initiatives can be technology-oriented or technology-neutral. Targets, regulatory policies (e.g., FIT, quota obligations), fiscal incentives and public financing (e.g., public loans, grants, tax exemptions) constitute another popular categorisation of RE policy instruments (see *REN21, 2021*).

As different approaches are used by scholars to segregate main schemes to support development of renewables, there is a need for further research of this aspect. Based on evidence from above-mentioned studies, the categorization of RE policy instruments and their definitions have been provided (see Table 1.1). The most popular support mechanisms to promote renewables among EU member states are feed-in policies (feed-in-tariff (FIT), feed-in-premium (FIP) and net metering), quota-based (tradable renewable energy certificates or obligations),

[7] More information about the classification of RE support is described later in this subsection.

tenders (auctions), fiscal and public incentives (tax incentives, investment grants) and emission caps (e.g., ETS).

Table 1.1. Categories and types of RE policy instruments

Category	Policy instrument	Definition
Quota-based policies	RE targets	a formal commitment to reach a predefined share of generated (or installed) RE (certain clean energy technology) during a given period. It is usually regulated and set on national level
	RE quotas (e.g., Renewable Portfolio Standards (RPS) in the USA)	an obligation set by a national government for energy producers to generate installed a fixed amount (percentage) of energy from RE sources. Tradable renewable energy certificates are the most popular type of quota-based instrument in EU
	Auctions	a standardized process in which a certain amount of RE is sold through a competitive mechanism of bids
Price-based policies	Feed-in tariff	usually a long-term contract, which gives an energy producer a guaranteed price per unit of renewable energy
	Feed-in-premium	a bonus (premium) over a market price, which energy producer receives for a unit of renewable energy
	Net billing and net metering	a contract in which an extra RE energy generated by the client can be offset with used energy supplied by a utility company during a given period. In the case of net metering, the offset amount of energy is settled within a retailed price. In case of net billing, an excess energy generated by the client is offset at a lower price
Public and Fiscal instruments	Tax incentives	different tax measures such as exemptions, credits, reductions for RE investment or production projects
	Public finance	subsidies, loans, grants, public investment, and procurement.
Regulatory instruments	Codes and standards	a special administratively set requirements for RE projects
	National targets and objectives	a formal commitment or guideline to reach a predefined share of generated (installed) RE (certain clean energy technology) during a given period. It is usually regulated and set on national level
Carbon regulations	Carbon tax	a directly set price for GHG emissions in the form of tax rate
	Emissions cap and carbon trading (a cap-and-trade system)	an official limit to produce a certain amount of GHG in form of emissions allowances, which can be also received and traded by companies (e.g., EU Emissions Trading System (EU ETS)

Source: Own compilation according to following sources : *IRENA (2014b); Gawel et al. (2017); IRENA/IEA/REN21 (2018); REN21 (2021).*

One of the most recognizable policy schemes to support RE sources is feed-in tariff (FIT). This incentive has become very popular in many countries and contributed heavily to the development of wind and solar energy technologies (*Lu et al., 2020*). According to *Li et al. (2017, p.660*) FIT includes "an obligation on the part of electrical utilities to purchase the electricity produced by renewable energy producers in their service area at a tariff determined by the public authorities and guaranteed for a specified period of time". As per study by *ICAT, (2019, p.4)* "Feed-in tariff policies are price-based instruments that provide a fixed, guaranteed electricity price, or a fixed or fluctuating price premium. Feed-in tariff policies aim to promote RE deployment by offering long-term purchase agreements with power producers at a specified price per kilowatt-hour. Feed-in tariff policies also include feed-in premiums, which provide power producers with a premium on top of the market price of their electricity production." A simpler definition is presented by *Moerenhout et al. (2012, p.2)* – "a subsidy mechanism whereby renewable energy producers are guaranteed a fixed price for a set number of years". Normally, FITs incorporate elements, such as contracts between producer and a utility company, which include guaranteed grid access and cost-based purchase price (*Ibidem*).

Another category of policy schemes is quota-based instruments, usually represented by renewable energy certificates (REC) or renewable portfolio standards (RPS). The USA is the most distinct representative country where this instrument has a huge popularity. A report by *Wishlade et al. (2017)* defines quota-based schemes through an obligation of energy supplier or generator to produce a certain share of RE sources in its total energy mix. According to a report *REN21 (2020, p.258)* RPS is "an obligation placed by a government on a utility company, group of companies or consumers to provide or use a predetermined minimum targeted renewable share of installed capacity, or of electricity or heat generated or sold". One of the most important features of quota mechanism is a target that mandates energy producers to supply a particular amount (or percentage) of renewables (*de Mello Santana, 2016; Carley et al., 2018*). Thanks to targets, countries or regions determine what level of RE must be deployed or in case of technology-specific quota-based policy it is the amount or percentage of the source of renewables to be generated. As classic quota obligations become less popular, more governments started to use tradable quota-based schemes or renewable energy certificates (REC). As per report by *REN21 (2020, p.258)* REC is "a certificate awarded to certify the generation of one unit of renewable energy (typically 1 MWh of electricity but also less commonly of heat)", while "market participants, such as suppliers or generators, participate in receiving or buying a number of certificates to meet the mandatory quotas established for the year" (*IRENA/IEA/REN21, 2018, p.61*).

Tenders or auctions are becoming more popular with countries set to replace other policy instruments with them. A report by *REN21 (2020, p.259)* defines tender as a "procurement mechanism by which renewable energy supply or capacity is competitively solicited from sellers, who offer bids at the lowest price that they would be willing to accept". Compared with regulatory-based and administratively set FITs and FIPs, auctions are considered by some scholars as more efficient, due to a better redistribution of financial funds (see *Winkler et al., 2019*). That is why an interest to this policy instrument has been growing very fast during the last decade, as other schemes have become less popular. During a period of 2011-2021 a number of European countries applying auctions has grown four times and accounts for 131 in 2021 (*REN21, 2022*). EU ambitions to become a carbon-neutral community by 2050 indicate a growing role of tenders, which could be a main policy instrument in upcoming years. Furthermore, the community's 'Green Deal' plan and its realization package 'Fit for 55' aims at cutting carbon emissions by at least 55% in 2030 compared with a base year 2005 (*EC, Development of EU ETS (2005-2020)*) with auction to be an essential policy to reach climate and environmental targets and accelerate energy transition.

Scholars interpret 'emissions cap and carbon trading' (a cap-and-trade system) as a policy instrument, which has a broader aspect than just a regulation of RE deployment, as its goal is to control changes in climate and environment. One of the most known versions of this support scheme is EU Emissions Trading System (ETS), which is considered as a first international cap-and-trade system, functioning from 2005. The instrument is based on emissions allowances, which are allocated and traded between businesses, which produce GHG emissions (power plants, industry factories and aviation sector). Normally each allowance accounts for one ton of carbon dioxide (CO_2), or the equivalent amount of other powerful greenhouse gases, nitrous oxide (N2O) and perfluorocarbons (PFCs) (*EC, Emissions cap and allowances*). Because more individual customers invest in their installations to produce RE, one should point out to a scheme called net metering or net billing. According to *Wishlade et al. (2017, p.26)* "net metering enables consumers who generate energy and feed it into the grid to consume energy from the grid with the consumption calculated net of energy generated (though the precise arrangements vary)".

Due to the fact that renewables have seen a strong reduction in technology cost during the last decade, there is a need for constant improvement and adjustment of policy schemes. Especially important are legislative frameworks set up to regulate this change, as governments gradually turn from more regulatory-based instruments (e.g., FIT) to more market-oriented ones (e.g., auctions). As for the EU, there is a handful of legislative frameworks oriented on final goals to meet overarching RE targets in all sectors (power, transport and heat). The next section highlights the main features of RE regulation in the EU, whereas special attention is paid to community directives and strategies addressing clean energy technologies and transition.

1.4. Regulation of RE in EU

The EU has been a strong proponent of RE sources and sustainable development for the last three decades, which has also been reflected in multiple legislative acts. The first document initiative to regulate and promote RE sources was 'White Paper for a Community Strategy and Action Plan' in 1997, which set a general target of 6% of total energy consumption (*EC, 1997*) in the EU. Since then, authorities have been very active trying to improve a regulatory field, directed at clean energy technologies and energy transition.

Despite early attempts to regulate RE sources in the EU, the first legislative frameworks, which contributed considerably to development of clean energy were adopted in the beginning of 2000s (most known documents regulating RE in EU are summarized in table 1.2). Back to these times, the cost of renewables was very high, making their scale production not viable. Understanding this, EU policymakers engaged into promotion of RE technologies by changing regulatory field in favour of newer forms of financial support. As policy schemes and measures, like feed-in tariff or quotas became popular, their scope was restricted mainly to the support of renewable electricity. A regulation of RE policy instruments in EU member states started with adoption of Directive 2001/77/EC (*EC, 2001*). The act set indicative targets for countries to push development of RE sources and meet the overall community's objective of 21% of renewable electricity consumption in total power mix in 2010.

Especially popular was Directive 2009/28/EC (*EC, 2009*), also known as Renewable Energy Directive (RED I), which set new targets for EU member states, based on the initial deployment status of RE sources and their potential. Unlike Directive 2001/77/EC, new targets have been established for member states in RED I, which were mandatory. Countries were also obliged to implement their own National Renewable Energy Action Plans[8] (NREAPs) to meet targets set by European Commission. Although strategies and objectives for specific countries varied, collective EU target was established at level of 20% of final energy consumption coming from renewables in 2020. According to the policy document, member states were also obliged to improve energy efficiency and limit GHG emissions by 20% during the same period.

The latest Directive (EU) 2018/2001 (RED II) (*EC, 2018*) to regulate RE sources was strongly focused on the commitments to tackle global climate change and speed up energy transition, which were part of the Paris Agreement (*UN, 2023*). The EU authorities set new

[8] According to Directive 2009/28/EC (RED I) each member state sets own renewable energy targets in context of final energy consumption within three different sectors: electricity, transport, and heat and cooling in order to meet general targets of EU

ambitious binding RE targets for member states with a goal of becoming a global forerunner in terms of clean energy technologies and transformation. The directive, known as RED II was later revised in 2021 and included principles and objectives set in 'Green Deal', as the EU is to become a first community to fulfil a complete phase-out of fossil fuels and become carbon-neutral by 2050. 'Green Deal' (*EC, 2023a*) was first presented in 2019 as a strategy with subsequent steps to boost RE deployment and energy transition in member states. It also includes a mid-term goal of reducing GHG by 55% by 2030, compared with a basic year of 1990 (*Wilson, 2021*). The postulates of 'Green Deal' were listed later in a package called 'Fit for 55' (*KPMG, 2021*) adapted by the European Parliament in 2021 (*EC, 2021a*). The package anticipates objectives mentioned in the strategy, which also includes a revised target of 40% of energy consumption from RE sources by 2030 (*Wilson, 2021*).

Table 1.2. Main EU frameworks to regulate promotion of RE sources

Directive	**Name**	**Main Scope**	**Main aspects**
2001/77/EC	Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market	Electricity from RE sources	sets national objectives in terms of power from clean energy technologies and the indicative target of total renewable electricity consumption in power mix, which accounts for 21% by 2010
2009/28/EC (RED I)	Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources	RE Electricity from RE sources	establishes obligatory overall EU targets, which are: 1) a share of 20% of RE in final energy consumption by 2020; 2) 20% reduction in GHG emissions by 2020; 3) 20% improvement in energy efficiency by 2020. Each Member state was assigned own targets to meet above-mentioned EU objectives
2018/2001/EU (RED II)	Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources	RE in electricity, transport and heat	adopts a common guidelines and regulations for support of RE and sets the obligatory minimum 32% target, which is a share of RE in final EU energy consumption by 2030. Each Member state works on own National Renewable Energy and Action Plans (NREAPs) to reach general EU and national targets

Source: Directives 2001/77/EC (*EC, 2001*), 2009/28/EC (RED I) (*EC, 2009*) and 2018/2001/EU (RED II) (*EC, 2018*).

The ambitiousness of EU plans to tackle climate change and foster RE sources has been questioned by recent events. Member states have faced one of the biggest challenges in early 2020s, as COVID-19, high inflation, and the Russian-Ukrainian War are among major threats to their economic development and prosperity. The most turbulent situation has been taking place in the energy market. Russian aggression and manipulation with oil and gas have strongly contributed to skyrocketing energy prices and economic instability in the EU. Also, as already mentioned, many EU governments realized that a threat of import dependency on fossil fuels from autocratic regimes has been historically very high. In the light of this, governments have resorted to unexpected and rash decisions to prevent further escalation of the ongoing energy crisis.

However, it can be noticed that no agreed plan between member states was established to mitigate above-mentioned challenges and threats. The is no strict strategy regarding one of the biggest polluters coal, as some countries (e.g., Poland) continue to strongly rely on this fossil fuel. Furthermore, the German government agreed to prolong a lifespan of some coal-fired power plants (*Reuters, 2022*). In case of nuclear energy, some countries like Germany already withdrew from this type of energy, whose decision was strongly guided by referring to the Chernobyl and Fukushima disasters in 1986 and 2011 respectively. Opposite measures are taken by Poland. Its government plans to build two nuclear plants which is aimed at reducing dependency on imports of oil and gas. Some countries like France, whose lion's share of energy generation stems from nuclear plants, show signs of even a stronger commitment to this type of energy.

As some member states have already chosen their own steps to tackle the energy crisis, measures have also been taken on the EU level. Despite managing to reduce gas imports from Russia to just 14% in September 2022 (*EC, 2022c*) and pledging to end energy dependency from the country-aggressor in 2027 (Regulation (EU) 2022/1369 (*EC, 2022a*)), the EU is still working on legislative acts aimed at stabilizing energy prices and stronger consumer protection as well as further support of RE sources. One of the main measures to tackle market volatility and potential economic turbulences was a fair redistribution of revenues between energy providers and consumers (Regulation (EU) 2022/1854) (*EC, 2022b*). Based on the new challenges at the beginning of 2020s and objectives stemming from 'Green Deal', the EU implemented a Regulation (EU) 2021/240 (*EC, 2021b*) with the purpose of improving administrative and institutional aspects of national economic, social and energy policies. As an addition to this document Regulation (EU) 2021/241 (*EC, 2021c*) included recovery plans and financial packages for member states to avoid further turbulences and tackle crises on different markets, including the energy sector. In the light of Russian aggression, some amendments to 'Green Deal' and mentioned Regulation (EU) 2021/241 were made, which included Recovery and Resilience Facility. This framework consists of a REPowerEU plan (*EC, 2022d*), whose goal is to allocate financial resources directed to modernize energy system and infrastructure in the EU. Measures regarding energy efficiency and diversification were also taken to curb dependency on imported fossil fuels.

One should point out the ambitiousness of some countries and regions in terms of ecological prosperity and development of renewables, as some of them already implemented official strategies, in which no fossil fuels exist in the upcoming decades. Among them is also the EU. Already mentioned, the ‘Green Deal’ encompasses carbon-free economy with RE sources to dominate the energy mix by 2050. However, to achieve this goal, European authorities also labelled nuclear and gas as sustainable sources in 2022 (*European Parliament News, 2022*). From one side such a decision can be considered as a strong reaction to the ongoing turbulence on energy markets, as they look to be comprehensible from a political or economic point of view. From the other side, it could have destructive implications for renewables. Critics also claim that labelling nuclear energy and gas practically as RE source implies that their lobby can benefit from large public and private financial funds (*DW, 2022*). Even more, it remains questionable if both mentioned conventional technologies could help the EU to achieve its sustainability goals. For many years natural gas belonged to a category of fossil fuels. Despite being more ecologically friendly compared with coal or oil, natural gas still causes damage to the environment. Furthermore, this type of energy source can be even more harmful during its extraction and transportation. As for nuclear energy one should be at least worried about a threat in context of a radioactive emission or nuclear explosion.

To sum up, the European Union prioritizes a concept of sustainable energy in its policy, which anticipates a rapid deployment of RE sources. The roots of the modern EU legislative frameworks to regulate clean energy technologies go back to 2001, when a Directive 2001/77/EC was adopted. Even though its scope was only restricted to regulate RE electricity market, it was later taken by policymakers as a basis for future legislative documents. Also, Directive 2009/28/EC is considered as a one of strongest impetus to the deployment of RE sources. The document regulated policy schemes in member states, which play a very important role in meeting obligatory targets for renewables (*Shivakumar et al., 2019*). The speed of RE development has been on an unprecedented rate in the 2010s, that also had an effect on the recent regulatory changes. Building on the obligations set in the Paris Agreement, in 2019 EU member states have agreed to ‘Green Deal’ - a strategy which sets an ambitious target to cut GHG by 55% in 2030, as the EU plans to become a carbon-free community by 2050 (*Montanarella & Panagos, 2021*). Later in 2021 followed an adaption of ‘Fit for 55’ - EU's package of steps, which show how member states are going to realize their ‘Green Deal’ objectives. Despite the fact that the community aims to reach some goals of this sustainable development plan by also labelling nuclear energy as a clean energy source, the prospects of technologies like wind and solar energy remain optimistic.

1.5. Energy transition in Poland and Germany

This section addresses the past and current development of energy transition in Poland and Germany. The focus here is on the historical facts which have contributed to changes in energy systems of the analysed countries. Furthermore, aspects, which could potentially have a significant influence on energy transition and wind and solar energy development in Poland and Germany, are presented.

To begin with, both countries are member states of the EU, to some extent sharing similar economic, social, and political aspects. Germany and Poland are getting compared more often with each other due to the fact of their proximity, territorial size, or close trade relations. However, there is also much disparity as far as energy policy is concerned. Germany has become a strong proponent of RE sources, and accelerated its energy transformation back in the 1990s, right after German reunification. As for Poland, the role of renewables remained marginal for a long time before a recent push in development of technologies like wind and solar energy. New clean energy sources have been overshadowed by a dominant environment-friendly coal, which lies in the centrepiece of Polish energy system. However, a strong growth of wind and solar energy in recent years presents optimistic opportunities for energy transition in this country.

1.5.1. Germany

Germany is one of the leaders in deploying RE sources. Furthermore, it is a number one country among EU member states in terms of uptake of wind and solar energy sources. According to a database *IRENA, Country Rankings* the country ranked 3rd by total wind and solar energy capacity installed and generated just behind the USA and China in 2020. Germany became known for its ‘Energiewende’ - an extensive energy and environmental policy, in which a special role has been assigned to renewables.

Many scholars agree that Germany was one of the first countries to embark on a new ambitious energy policy based on wind and solar energy sources (*Pelegry et al., 2016*). The country is considered as a first mover in context of revolutionary policy changes in times when the cost of some RE technologies was still very high (*Hedberg, 2017; Quitzow et al., 2016*).

The role of German ‘Energiewende' is immense as it is a unique and unprecedented policy in core of which lies postulates of ‘modern’ (sustainable) energy transition. This scalable project arouses international interest, as its main principles were later adopted by other countries as a foundation of their policies (*Quitzow et al., 2016*).

One can find an abundant amount of literature concerning the term ‘Energiewende’. Some studies summarize it by considering only its technological context: a transition from conventional fossil fuels to new clean energy sources (e.g., *Pelegry et al., 2016*). As some scholars believe that ‘Energiewende’ was developed to address only GHG reduction (*Morris & Pehnt, 2014*) and climate change (*Weimann, 2013*), others point to its broader scope. In this context, ‘Energiewende’ also addresses aspects of employment, energy import dependence or sustainable development (*Agora Energiewende, 2019* and *Pelegry et al., 2016*). A general definition of the term ‘Energiewende’ has been provided by a polish economist A. Kwiatkowska-Drożdż (*OSW, 2013*), who interprets it through a national long-term and strategic policy project, which entails a smooth transition from conventional energy to renewables. According to *von Hirschhausen et al. (2018)* ‘Energiewende’ is quite a long period of energy system transformation, which started from the first environmental movements in 1970 in Germany.

There are many studies which underline the immense role played by ‘Energiewende’ not only on the domestic front but also in the global arena. Positive socio-economic and environmental implications, a decision to phase out nuclear energy by 2022, and accelerated deployment of RE sources are the main factors behind the success of ‘Energiewende’ (*Sonnenschein et al., 2014*).

One of the main discussion points of German ‘Energiewende’ (e.g., *Hedberg, 2017; Sonnenschein et al., 2014*) lies in fact that energy transition has been observed predominantly in the electricity sector. Critics argue that new changes must be adapted in German energy policy which include more ambitious targets also for transport and heat sectors. At the same time, neglecting both mentioned sectors with a focus only on the electricity market made a comprehensive ‘Energiewende’ hard to occur (*Sonnenschein et al., 2014*). Nevertheless, some scholars (e.g., *von Hirschhausen et al., 2018*) point out the fact that ‘Energiewende’, which started from the electricity sector has already laid a foundation for transformation in transport and heat.

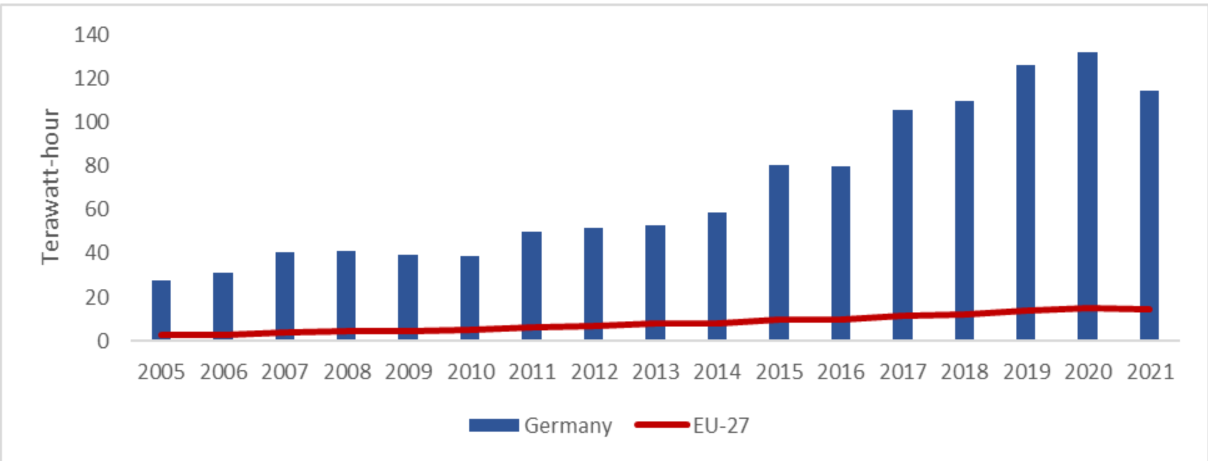
One of the biggest challenges Germany faces in the coming years is filling the gap which is going to be left because of the phase-out of nuclear energy and coal fuels. Despite the promising prospect of RE expansion, there is still a pending threat of energy shortage in the light of simultaneous increase of energy consumption (*Jurca, 2014*). The other elements related to Germany RE policy are energy storage and efficiency. New technologies and innovative solutions could decide how strong an energy revolution will be in the coming decades or even years. Another challenge of German 'Energiewende' refers to a change in the RE public support system which includes participation of corporate companies and grid modernization. The diminishing role of small and middle size businesses as well as a stronger dependency on fossil fuels in the light of increased import of gas and oil are other factors which could hamper the development of RE sources in Germany. Despite some critics, Germany was one of the first countries to unveil a scalable development of RE sources catalysed by a unique energy policy called 'Energiewende'.

Wind and solar energy are in the centrepiece of German energy transition. A generous financial support and low cost of technology have been crucial for the wind and solar energy scalable development in the country. At first, many sceptics had doubts about initial activities of German policymakers in the 1990s when role of renewables on global energy market was marginal. Wind and solar energy technologies have seen an unexpected growth as new 'Energiewende' policy made Germany one of the global leaders. Both energy sources accounted for around 28.5% in the total electricity mix in 2021 (*Our World in Data, 2020*). As for other two sectors: transport and heat, their share was much lower. Nevertheless, German policymakers stayed optimistic and expect a strong interest from investors in all sectors of economy in the coming years.

Some experts assign wind energy a leading role in the coming decades (see *Baran, 2015*). Initial policy measures to support RE sources are traced back to the 1990s and addressed mainly 'cheaper' biomass (*Ibidem*). Later in the 1990s, implementation of a new FIT instrument had driven at that time more costly wind and solar energy technologies on a large scale. Germany was a pioneer in terms of investing in these two intermittent energy sources. An amendment of a RE law in 2000 (Erneubaren-Energie-Gesetz - EEG) and the adoption of FIT has accelerated the speed of wind energy development in Germany. The new policy was crucial in attracting interest from individuals, communities, municipalities, and small business (*Nkomo, 2018*). At the beginning of 2010, Germany was one of the global forerunners by wind capacity installed and electricity generated. Closer to the end of the decade, the dynamics of the wind energy deployment slowed down, while countries like China and the USA dominated this global energy market. Germany possesses enormous potential of wind energy sources, also due to favourable weather conditions.

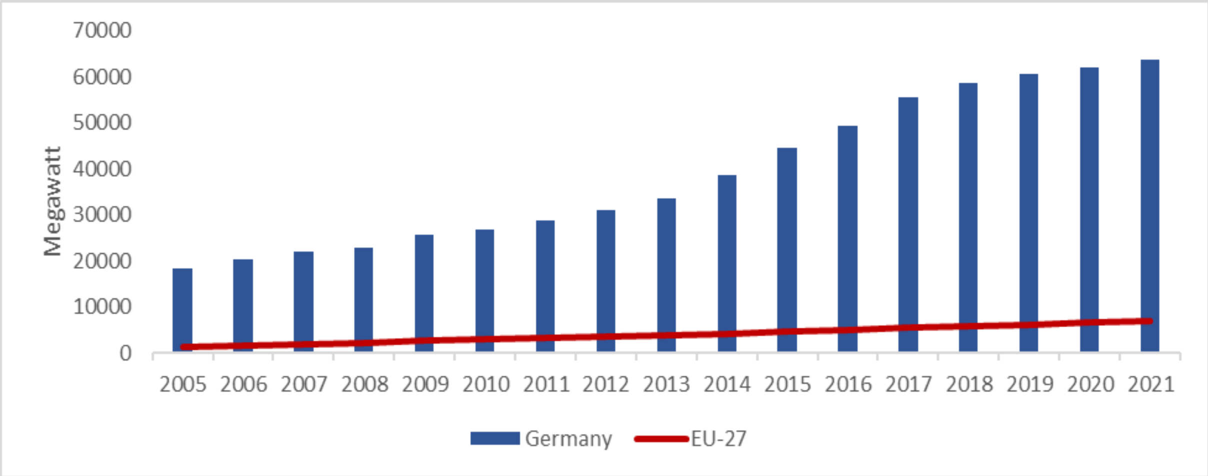
According to *IRENA (2016)* the projected German wind energy production in 2030 stands at 214 TWh. As per 2021 wind turbines in this member state generated 113.8 TWh (*BMWK, 2022*). However, one should consider obstacles which could also hamper expansion of wind energy. For example, an average proximity of wind farms to communities, which stands at 500 m, is one of the sharpest requirements of regulatory frameworks in German lands (*Longa et al., 2018*). According to some scholars, the main reason behind slower development of wind energy market lies in recent changes in the legal field. Also, administrative procedures and resistance of communities towards large wind farms have had a negative effect. As per Figures 1.7 and 1.8, wind power recorded a rapid development beginning from 1990. Despite some law and administrative obstacles, this clean energy market has been prospering very fast, especially during the period of FIT in 2000-2016. The trend did not change after incorporation of tenders as the main policy instrument in 2016. Ever since, wind energy has developed very fast under more market-based auction policy. One should mention also about the importance of a new renewable technology like offshore wind energy. Offshore wind energy has seen a rapid growth not only in Germany, but across other member states. According to some reports (*Wilson, 2020*) offshore wind technology still has almost all its potential untapped and can be a crucial in achieving future German 'Energiewende' targets.

Figure 1.7. Wind electricity production in Germany for years 2005-2021



Source: Based on data from *Eurostat*.

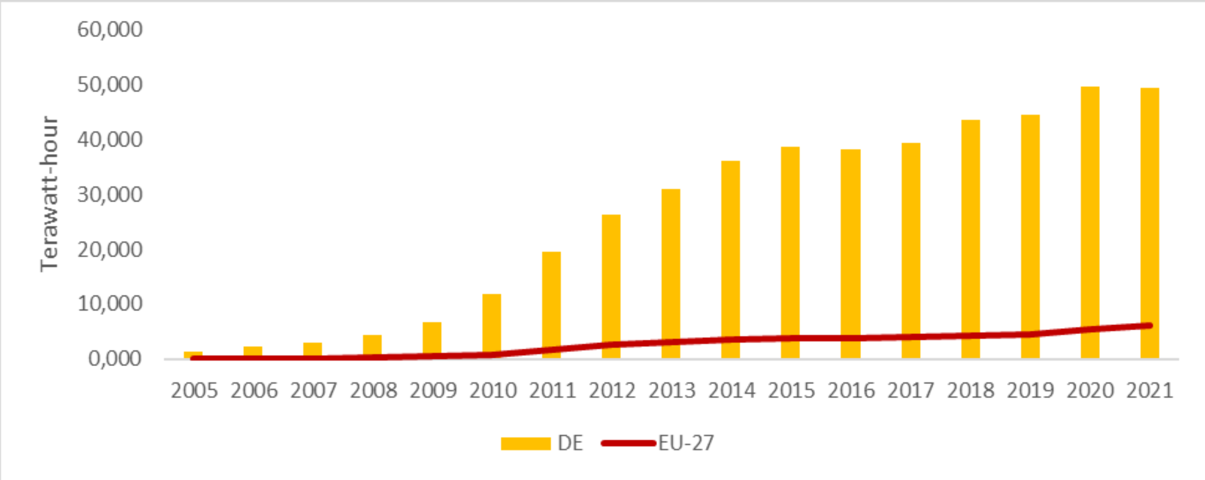
Figure 1.8. Wind electricity net capacity installed in Germany for years 2005-2021



Source: Based on data from *Eurostat*.

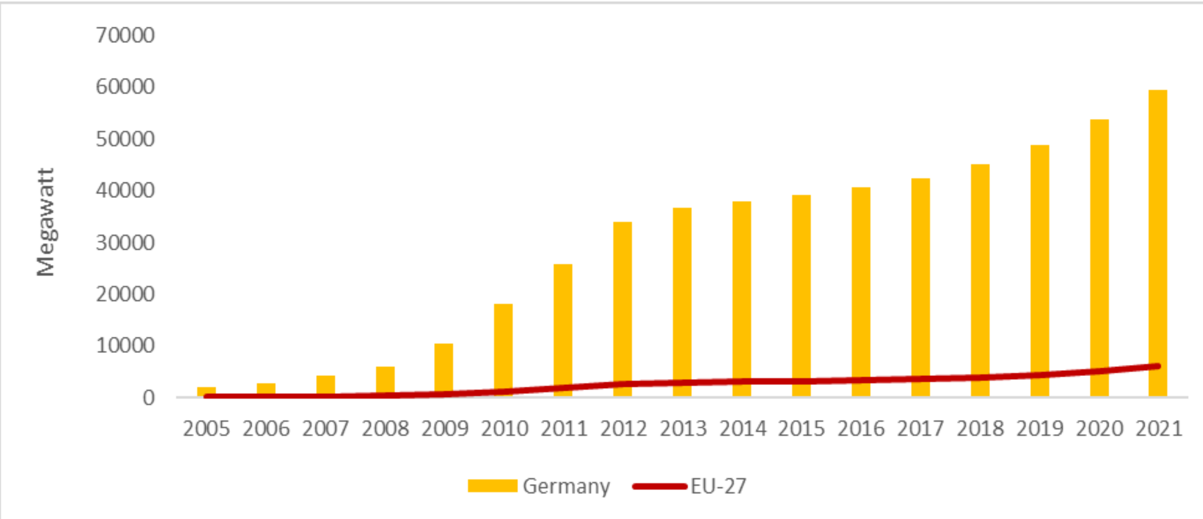
Solar energy is another backbone of German 'Energiewende'. In a similar way to wind energy, Germany is also a pioneer when it comes to solar energy, as the country actively supported this type of RE source when the cost of technology was still high back in the late 90s and first decade of the 21st century. Since then, Germany has seen a strong and continuing growth and, despite a slowdown in recent years, the country has one of the largest solar energy markets in the world. Germany has a good potential for expansion of solar energy despite having a lower degree of isolation in comparison with some Southern European countries (*Bódis et al., 2019*). Its potential in terms of solar electricity generation accounts for 70 TWh in 2030 (*IRENA, 2016*), compared with already generated 50 TWh in 2021 (*BMWK, 2022*). In contrast to big wind farms, solar energy projects in Germany have been characterized as less extensive, making them attractive among smaller businesses and communities. With the help of an aggressive energy policy (*Pelegry et al., 2016*) and, despite not having the most favourable weather conditions, (*Bódis et al., 2019*), the government managed to remain as one of the leading positions globally in deploying solar energy. A relatively low cost of the technology (*IRENA, Global LCOE and Auction values*) has also given an additional boost to the development of solar PV market. The biggest progress in the solar energy development in Germany was seen in the period of 2005-2015 (see Figures 1.9 and 1.10), when FIT policy was dominant. After implementation of the auction instrument in 2016, the pace of solar power generation stalled. In the meantime, many scholars remain positive about future perspectives of this clean energy market in Germany (e.g., *Bódis et al., 2019*).

Figure 1.9. Solar electricity production in Germany for years 2005-2021



Source: Based on data from *Eurostat*.

Figure 1.10. Solar electricity net capacity installed in Germany for years 2005-2021



Source: Based on data from *Eurostat*.

1.5.2. Poland

Due to the fact that the Polish economy has seen an impressive nearly 10-fold growth beginning from 1990, its energy sector has been one of the major factors contributing to the prosperity of the country during last three decades. The Polish economy has been strongly dependent on heavy fossil fuels going back to the communist era. To compare with other EU member states, particularly Germany, which embarked on an unprecedented RE policy called ‘Energiewende’, Poland still relies heavily on the indigenous coal and lignite (*Żuk & Szulecki, 2020*) as main energy sources even though its share in energy mix has decreased from 86.6% to 70.8% during the period of 2010-2021.

According to *Ancygier & Sulecki (2014)* Poland's electricity in the 1990s was almost 100% coal based. In a similar way to most EU leading countries at this time, the Polish share of renewables in total energy mix was marginal. As mentioned, Germany managed to decrease its dominance of fossil fuels dramatically and increase its share of RE sources in electricity generation from 3.4% in 1990 to 45.3% in 2020 (*BMWK, 2021*). Furthermore, no more nuclear energy will be produced in Germany, as the next phase-out is faced by coal in 2038 (*Szczerbowski, 2018*), while renewables (mostly solar and wind energy) are prioritized to replace them. A totally different situation is seen in Poland, where no strong change in energy policy shift has been noticed. Additionally, in a prevailing position of coal and lignite sources, the country plans to build a new nuclear plant as a measure to curb its energy independence (*European Parliament News, 2022*).

There is a late consensus among academics and policymakers that energy policy, where fossil fuels are seen as an undisputable and dominant force, can lead to dramatic consequences. It has been scientifically proven that fossil fuels exert a negative impact on climate change and air quality. According to a report by *World Bank (2018),* Poland is among 20 countries with the highest rate of CO_2 emissions. The growing problem is smog, which existed for many years, but only recently became a matter of a tense discussion in the media and political field. To make the things worse, 36 out of 50 of the most polluted cities in Europe are located in Poland (*WEF, 2018*). Apparently, there is a strong consensus in the literature that Poland can benefit more if it accelerates its development of RE sources, while, at the same time, it should diminish its role of coal and lignite. However, Poland is still far behind other EU states in terms of speed of energy transition, while a matter of constant supply of cheap energy stands over the issues of air pollution and climate change (*Ibidem*). Nevertheless, the EU's rigorous policy and new local legal frameworks could give a strong impetus in combating air pollution problems in Poland. Also, expansion of renewables should also contribute to solving this issue.

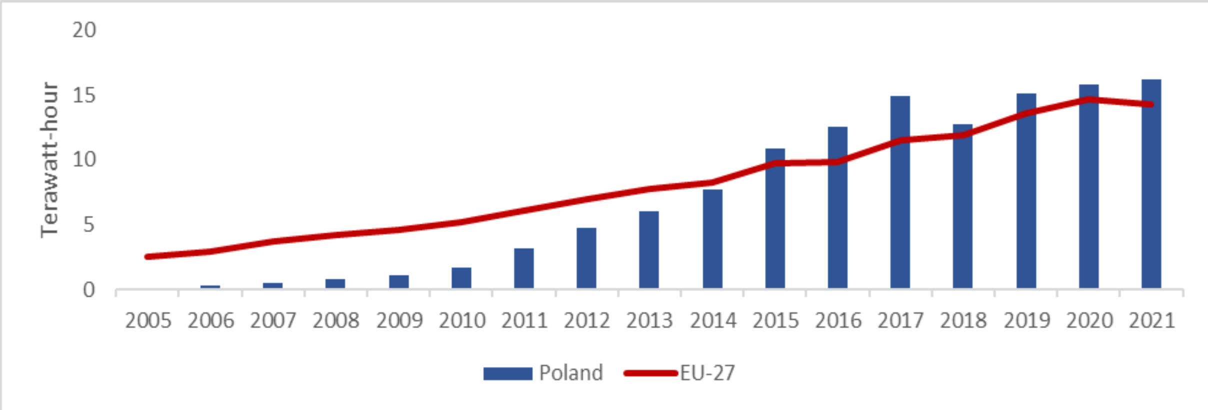
Despite the fact that the Polish economy still promotes its heavy energy sector, there are some merits that the country achieved. During the last few decades, the country managed to decrease energy intensity substantially. As per report by *IEA (2017)*, no other country performed better than Poland in terms of this indicator. 60% of Polish coal energy was constructed more than three decades ago (*IEA, 2016*). Nevertheless, it can boast of capital modernization which improved the level of cost-effectiveness of all energy sectors. Some scholars consider the low cost of conventional energy as the reason why the social acceptance level with regard to coal industry has increased. However, declining prices and higher costs of coal mining can become a challenge for the country in the long term (*Szulecki, 2017*). This industry has been unprofitable during the last few years in Poland and, as a result, has created additional burdens to taxpayers. Moreover, coal mining, which accounts for thousands of employees in Poland, is considered a major political and social influence, thus posing a threat to the development of renewables.

As renewables are just at their outset in Poland, wind and solar technologies still have a little share in the overall country's energy mix. One of the main reasons for such slow deployment is that clean energy has been beyond the priorities of Polish energy policy for a long time. However, the growing maturity of wind technology and recent spike in solar energy (see Figures 1.11 and 1.12) gives hope for a positive future dynamic.

Wind energy has quite a long history in Poland. Even though a first wind farm was built in 1991, expansion of this technology started only two decades ago. Poland possesses huge wind energy resources, especially in the Northwestern region (*PSEW, 2020*). Different reports predict a very strong development of this clean energy technology in the coming years (*IOŚ-PIB, 2018*). As per *Flanders Investment and Trade (2019)* wind energy has the biggest potential among other renewables and can reach 27% in total energy production by 2050. It was actively subsidized during a period of 2005-2016, becoming the fastest developing RE technology in Poland during that time. Such a strong growth could be contributed by quota certificates, which were dominant during that phase. After adoption of new RES (Renewable Energy Sources) Act in 2015 (*IEA, 2020*), new policy instruments were introduced (e.g., net metering, tenders) for wind energy, which later replaced quotas. As a result, there was a decline in a further diffusion of this technology in Poland after 2017. This could be also explained by restrictions stemming from the above-mentioned legislative document regarding limits in new sites for building wind turbines (*Papież et al., 2019; Iskandarova et al., 2021*).

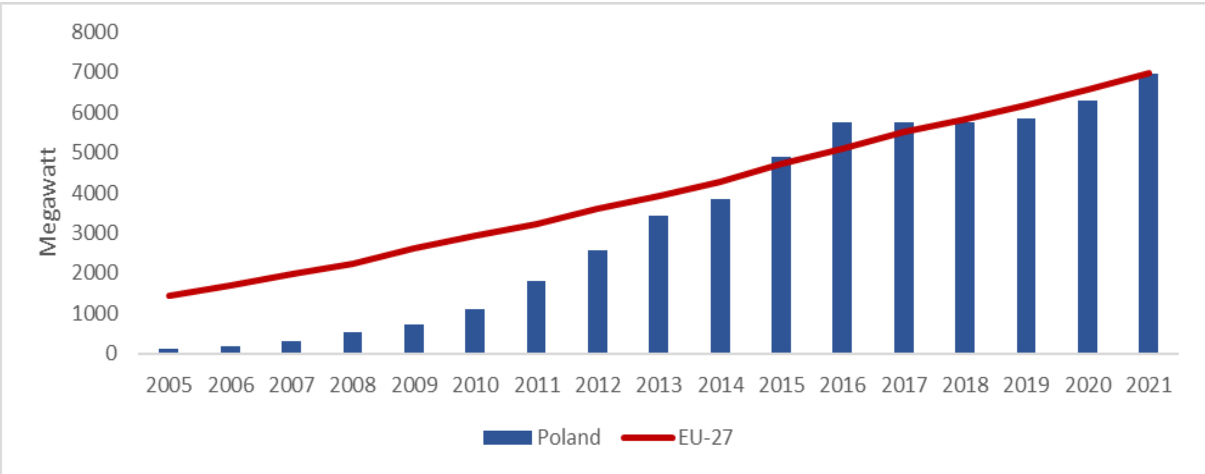
One of the newest RE sources in Poland is wind offshore energy. According to the National Energy and Climate Plan (NECP) (*Ministry of Climate and Environment of Poland*) only by 2025 the country plans to support installation of 1 GW of wind offshore capacity in the area of the Baltic Sea (*PSEW, 2019*). Favourable weather and geographical conditions and decreasing technology costs could be pivotal in further diffusion of this type of energy in Poland. Even though the cost of onshore wind technologies is relatively lower, Poland can learn for example from the experience of other countries, such as Germany or Denmark, which can boast of scalable offshore wind energy projects (*World Bank, 2018*).

Figure 1.11. Wind electricity production in Poland for years 2005-2021



Source*:* Based on data from *Eurostat.*

Figure 1.12. Wind electricity net capacity installed in Poland for years 2005-2021

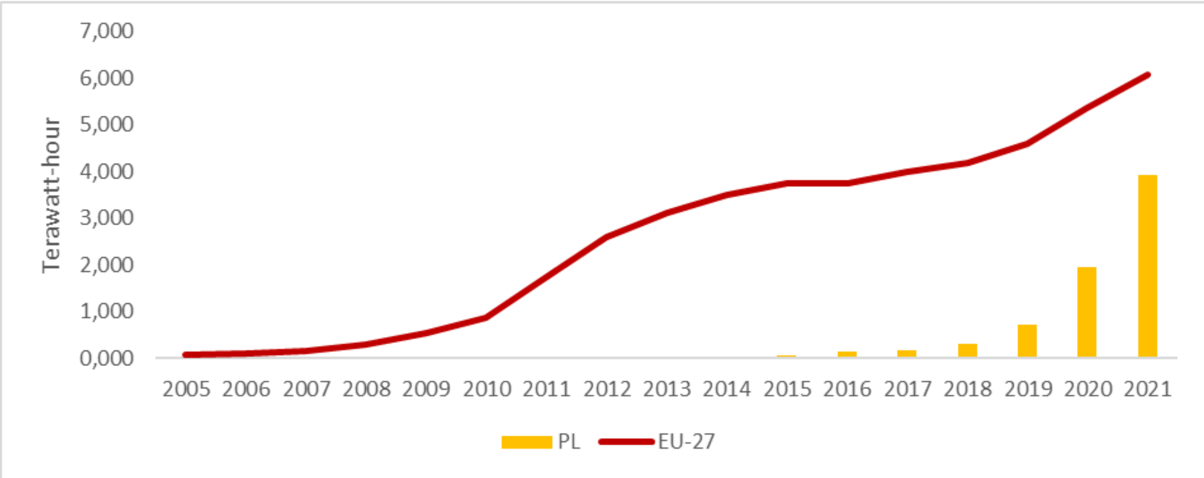


Source: Based on data from *Eurostat*.

Solar energy has the one of the largest potentials for growth among all RE technologies in Poland. According to reports by *IRENA (2015)* and *Flanders Investment and Trade (2019)* the average insolation in Poland is approximately the same throughout the whole territory. During the period of green certificates from 2005 to 2016, Polish RE energy policy has mainly focused on the promotion of co-firing biomass hydropower and wind energy. Until recently, solar power technologies experienced a very slow development due to their high cost and unfavourable legal frameworks (*Paska & Surma, 2014*; *Szulecki, 2017; PSEW, 2019*).

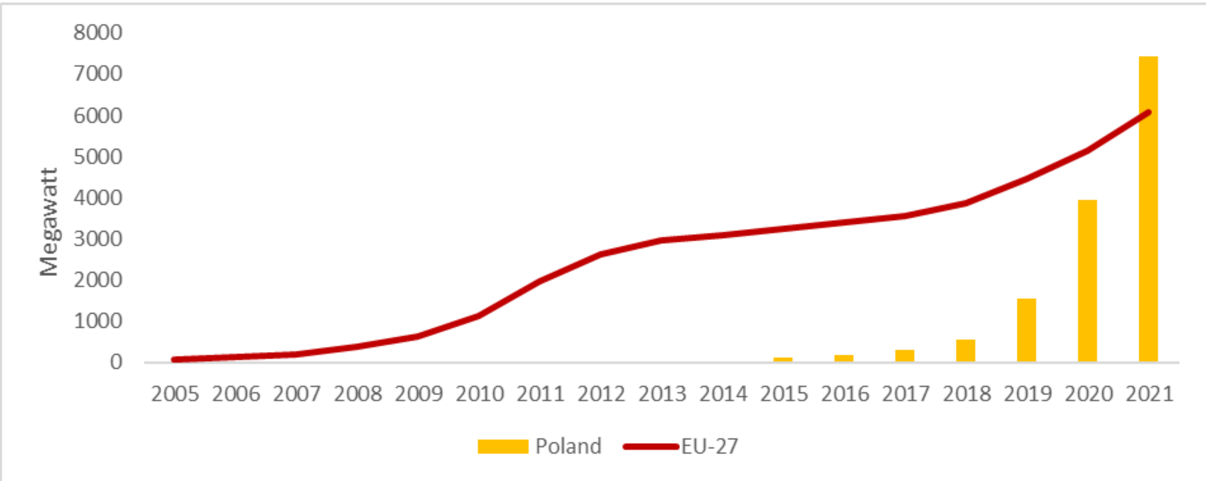
However, a recent rise in solar PV capacity and generation (see Figures 1.13 and 1.14) could be explained by impetus, stemming from a change to more favourable legislative initiatives. The new regulatory framework - RES Act adopted in 2015, which came in force in 2016 (see *IEA, 2020*) has been responsible for an increased amount of rooftop installation whereas private households benefited strongly from recent support to PV projects (*Igliński et al., 2022*). As marked by some scholars, such impetus came from new policies, like tenders (*Iskandarova et al., 2021; Igliński et al., 2022*). Also, a special program called 'My Electricity' (see *Ministry of Climate and Environment of Poland, 2019*) is considered to be a strong driver of solar energy in Poland recently. Despite this progress, Poland is still trailing the developed countries where shares of solar energy sectors are relatively much higher. A drop in the cost of solar technology and changing laws in favour of renewables can be crucial for the future positive dynamics of the solar energy market in Poland.

Figure 1.13. Solar electricity production in Poland for years 2005-2021



Source*:* Based on data from *Eurostat.*

Figure 1.14. Solar electricity net capacity installed in Poland for years 2005-2021



Source*:* Based on data from *Eurostat.*

Late changes in regulatory and political environment, which came only few years ago, reflect a neglecting position of Poland towards solar energy. However, to justify this decision, one can point to a lower financial capability of Polish budgets or relatively high technology costs of solar energy (e.g., in comparison with coal) during the period of quota certificates. From the other side, some researchers (e.g., *Iskandarova et al., 2021*) predict even stronger uptakes in solar energy in the coming years thanks to the mentioned positive changes.

To sum up, the global role of wind and solar energy sources is hard to overestimate in the ongoing energy transition. Their uptake has grown substantially in many countries during the last two decades, also contributing to diminishing dominance of conventional fossil fuels. Despite some drawbacks, renewables like wind and solar energy can only gain on importance with aspects like environment and energy security to be on the top of economic and political agenda nowadays. In the light of different threats and crises, prospects of continuing progress of the two mentioned intermittent energy technologies look even more promising. Also, positive features like low pollution, dynamically decreasing technology cost, stabilizing electricity prices or filling gap of growing global energy demand constitute the rationale for further expansion of RE market, which is one of the main and integral part of the ongoing energy transition.

The previous transformations in energy systems concerned a replacement of one fossil fuel with the other. Therefore, the 'modern' energy transition is considered as an unprecedented phenomenon, in which a shift from conventional energy sources to renewables takes place. This study strongly relies on diffusion theory of energy transition, in terms of which development of RE technologies is divided into three main periods: early, take-off and maturity phases. Furthermore, this concept strongly relies on the principle of justification of policy subsidizing, whereas corresponding support measures should be applied on each stage of RE diffusion. Premises of other concepts of energy transition (e.g., socio-technological, ecological modernization and first-mover advantage theories) are also taken into account according to their relevance while writing this thesis.

Being one of pioneers in the branch of wind and solar energy, EU also stays on the front of the modern energy transition. The community has been adopting and amending various legislative acts in order to boost deployment of renewables. As a prominent example of this, is the adoption of 'Green Deal' strategy and 'Fit-for 55' plan to make EU a carbon-free community within next three decades.

One of the main measures to support wind and solar energy sources is assigned to policies or policy instruments. Support mechanisms such as feed-in system, quotas or tenders have been responsible for an unprecedented development of RE sources in many countries. However, critics frequently question the expediency and usefulness of such measures. In order to contribute to this debate, empirical research on performance of policies supporting wind and solar energy has been performed in this study, as its scope is limited to selected EU member states with a special focus on Poland and Germany.

Energy system of Poland and Germany are very different, especially in terms of promoting RE sources. As Poland's energy policy is predominantly focused on fossil fuels like coal, Germany has conducted aggressive 'Energiewende' to boost development of RE sources during last decades. The both countries also conducted different schemes to support renewables (FIT in Germany and quota certificates in Poland), before gradually shifting to tenders recently. Despite slow dynamics on RE market in Poland, strong progress in the context of solar energy has been recorded recently. Also, strong development of wind energy technologies has been halted due to some rigorous changes in legislative field. Concerning Germany, also areas of transport, heat and cooling should be the subject of continuous development, as the sector of electricity is already strongly dominated by wind and solar energy sources. In order to complete a comprehensive energy transition, acceleration of RE deployment must be undertaken in all sectors of the economy.

In order to accentuate the role of wind and solar energy, a discourse from literature on this topic has been highlighted in Chapter 2. Also, a comprehensive review of relevant studies has been conducted regarding performance of RE policies in this chapter. This is in line with the main research purpose of this study to assess effectiveness and efficiency of wind and solar energy policies in Germany and Poland on background of other EU member states. While conducting the literature review, a special focus has been placed on performance of main instruments (such as FIT, quotas and tenders) to support wind and solar energy sources.

2. LITERATURE REVIEW ON ROLE AND PERFORMANCE OF RE POLICY

2.1. Role of wind and solar energy policy

In the following chapter of this dissertation, a comprehensive literature review has been conducted to discuss the main characteristics, trends, research evidence and limitations of RE (with a strong focus on wind and solar energy) policy performance. Due to the abundance of studies on this topic, the most relevant and cited studies have been selected. This chapter aims to categorize the most popular literature streams and patterns. Such analysis helped to identify some major insights and gaps in the literature, as well as avenues for further research.

Also, the important goal of the literature review was to find a robust empirical and methodological framework which could be best tailored to the analysis. While importance of monitoring and assessment of policy performance has been highlighted, a special attention is drawn to literature discourse on popular RE support instruments. Furthermore, categories of policy convergence and design have also been highlighted in this chapter. The strategy of research conducted in this dissertation is presented in Figure 2.1, with literature review to be the initial step. Also, this chapter covers the selection process of main criteria for assessment of wind and solar energy policies.

As already mentioned in Chapter 1, energy policy, which includes different components such as legal frameworks, energy security measures, policy instruments, targets etc., contributed considerably to changes which took place in energy markets during the last two decades. Special attention should also be paid to policy instruments which have been a driving force in the development of wind and solar energy. Furthermore, scholars acknowledge their scalable effects in terms of socio-economic, political, and environmental dimensions. For the purpose of this dissertation, energy policy is defined through a certain support instrument (e.g., FIT, auction) or their combination, aimed at the promotion of wind and solar energy technologies.

There is a consensus in literature that energy policy is crucial for the development of the RE market, while renewables still face a fierce competition from conventional energy sources (*Zhao et al., 2013; Ahmadov & van der Borg, 2019*). On one side, countries like Germany, which saw antinuclear manifestations already back in the 1980s, invested vast financial resources as a form of public support to accelerate energy transition. On the other side, critics often question public support to renewables, as a long public involvement might send bad signals for the private sector at the same time distracting investors (*Fouquet & Pearson, 2012*). Nevertheless, a decreasing technology cost of wind and solar energy already gives a prospect of overcoming this challenge in the very near future. Additionally, there might be a previously mentioned problem, which is the longevity and dominance of fossil fuels. Like previous transitions, a move away to clean technologies also demands time. For example, it can be important for private investors and public authorities to track which technologies are more efficient during all stages of diffusion[9].

Figure 2.1. Strategy and main steps in conducting research presented in this thesis

Source: Own compilation

[9] See Section 1.2.2 (Chapter 1) for more information about stages of diffusion of RE sources.

One can find more than enough evidence from theoretical and empirical research, that RE support measures play an important role in driving RE development (*Sun & Nie, 2015; Ciarreta et al., 2017; Choi et al., 2018; Kabel & Bassim, 2019*). Thus, policymakers have a challenging task of choosing the appropriate type of RE policy (or a combination of policies) called also support instruments or schemes. No universal approach exists for designing the right support mechanism, as there are many factors that could have a direct impact on choices of policymakers, such as budget size, environmental targets, and other country-specific aspects (*Romanov et al., 2018; García-Álvarez et al., 2017; Donastorg et al., 2017*). Despite discussion on the selection of best tailored RE support instruments and some critics of such policies, literature highlights the consensus that they have contributed significantly to the accelerated growth of renewables, whereas their main beneficiaries are wind and solar energy technologies (*Li et al., 2017; Anguelov & Dooley, 2018; Shivakumar et al., 2019*).

There is an extensive literature devoted to the topic of RE policy. The analysis of studies relies basically on the recent theoretical and empirical papers which refer to the performance of wind and solar energy policies (e.g., *Romanov et al., 2018; Choi et al., 2018; Kabel & Bassim, 2019*). Furthermore, the following review also encompasses a number of reports and policy documents (*e.g., REN21, 2019; IRENA, 2019*). By analysing the prior research studies, an attempt to segregate several literature streams was made and a chosen approach and methodology which would fit best to our research analysis is described in the next chapters.

Most of the selected research works on the role and performance of RE policies takes a macro approach with a focus on a country level (*e.g., Kocsis & Hof, 2016; Ciarreta et al., 2017; Shivakumar et al., 2019; Özdemir et al., 2019*). There are some studies where regions or local provinces are examined (*e.g., Zhao et al., 2016; Winter & Schlesewsky, 2019; Zhou & Solomon 2020*). As a growing body of literature addresses a scope of one particular country (*e.g., Polzin et al., 2015; Kocsis & Hof, 2016; Ciarreta et al., 2017; Choi et al., 2018; Carley et al., 2018*), some of the studies conduct a cross-country comparison analysis (*e.g., Aguirre & Ibikunle, 2014; Pyrgou et al., 2016; Baldwin et al., 2016; Shivakumar et al., 2019*) to assess how strong the policies stimulate clean energy technologies.

Even though the literature shows that most of the studies on RE policy are focused on the EU, (*e.g., García-Álvarez, 2017; del Río et al., 2017; Ahmadov & van der Borg., 2019; Özdemir et al., 2019)* and the USA *(e.g., Shrimali et al., 2015; Carley et al., 2018; Anguelov & Dooley, 2018; Zhou & Solomon, 2020*), works that concentrated on other countries was also analysed. More recent studies on this topic indicate that scholars have redirected their focus to developing regions, like China, India, South Korea, Turkey, etc. (*Murat Sirin & Ege, 2012;*

Surana & Anadion, 2015; Zhao et al., 2016; Choi et al., 2018). The rationale behind such trends can be explained through a higher interest from investors and the expansion of the RE market in the mentioned countries, as well as the ease of access to the data available.

While the scope of the dissertation is wind and solar energy, studies were selected addressing mainly these two RE technologies. However, a literature on the role and performance of RE sources (as a whole) has also been included, as many authors normally associate renewables with wind and solar energy. Both RE technologies aroused strong interest from scholars due to their high pace of development and gradual reduction of technology costs in many countries (*IRENA, 2019; REN21, 2020*).

In terms of types of technology selection, this literature review highlights a few groups of studies. First, one has a focus on just one RE source - wind or solar energy (*e.g., Zhao et al., 2016; Dijkgraaf et al., 2018; García-Álvarez et al., 2017*), second, sets of studies encompass both mentioned technologies (e.g., *Li et al., 2017; Shivakumar et al., 2019; Anguelov & Dooley, 2018*). Other parts of literature research addressed several RE technologies, including wind and solar energy (*e.g., Ragwitz et al., 2015; Choi et al., 2018*). Another array of empirical works was also classified, where RE technologies are presented as one unit (*e.g., Ciarreta et al., 2017; Zhou & Solomon, 2020*). However, in general, if studies on RE technologies are to be grouped, scholars are mainly focused on wind and solar energy sources.

In order to draw any conclusions about RE policy, it is important to conduct its evaluation first. There is an extensive literature on the topic of RE policy assessment. The relevant studies use various methodology, geographical scope, time periods and other data. The general evidence shows that a growing body of literature addresses wind and solar energy within an electricity market. In the next sections a comprehensive literature review was conducted regarding the performance of the mentioned clean energy policies. The objective of this analysis is to identify the main patterns, gaps, and avenues for future research. An important goal of this chapter is to select a suitable base supporting the main research of this thesis, with a strong focus on the performance evaluation of wind and solar energy policies in the analysed countries. In this case, a literature review could be the most suitable approach.

Therefore, a growing body of literature on renewables (e.g., *Baldwin et al., 2016; Kabel & Bassim, 2019, Romano et al., 2017; Kilinc-Ata, 2016*) provides strong evidence that RE policy plays an important role in the successful promotion of renewables. Still, the biggest debate on the topic of RE policy is related to the category of policy instruments and their performance. While some governments implement just one RE policy, some have two or more instruments at the same time. That is why there is an extensive literature which tries to measure separate impacts the particular policy scheme has on development of a certain RE technology or renewables in general (*Romanov et al., 2018; Polzin et al., 2019*).

Also, the clear evidence is that the most studies concentrate on wind and solar energy as both technologies became very interesting for the scholars due to their wide expansion in many countries (*REN21, 2019*). Such dominance of wind and solar energy can be one of the reasons why the scope of this empirical study is limited to both mentioned technologies. However, the empirical approach and methodology used in the dissertation (see Chapters 3 and 4) can also be applied in the case of other RE sources (e.g., bio- and hydro energy). This might be considered as a suggestion for future research.

Before presenting a methodological and empirical framework of the research, it is of high importance to recognize the dominant streams and literature discourse on performance of RE policy instruments. The theoretical framework covering definitions, characteristics, theories, and classification of RE policies has been discussed in Chapter 1. In terms of this topic, the most intensive and continuous debate has focused on the comparison between different support schemes (policy instruments) such as feed-in tariffs (FIT), renewable portfolio standards (RPS - most popular quota-based instrument), tenders, and other policies (e.g., *del Río et al., 2017; Choi et al., 2018; Matthäus, 2020*). In the next sections an in-depth analysis of the literature regarding RE policy performance with a strong focus on the most popular policy instruments to support wind and solar energy sources is presented.

2.2. Monitoring and assessment of RE policy performance

Many studies assign the RE policy a significant role, especially in a context of energy transition, environment, and climate change (*Ragwitz et al., 2015; Shivakumar et al., 2019; Polzin et al., 2019*). *Lu et al. (2020)* outlines the following components of a well-designed policy:

- policy design
- policy implementation
- policy monitoring
- policy assessment
- policy feedback
- policy amendment

One of its most important elements lies in a constant monitoring or assessment of performance which can also be a key factor for policy improvement. It should be also noted that continuous tracking (monitoring) and evaluation (assessment) of RE policy was one of the initial steps made by governments right after adopting the first policies and instruments supporting renewables, when shares of renewables were still very low (*Ragwitz et al., 2015*).

Like in many other activities, the effects of RE policy can be measured with the help of a special audit, normally referred in the literature to as 'monitoring' or 'assessment'. The scope of such aspects in the dissertation is limited mainly to the performance of wind and solar energy policies in the overall RE policy performance. It is also important to select the most suitable criteria for policy assessment (it is described in next section).

Polzin et al. (2019) note that policy schemes to promote renewables should be a subject of constant assessment at least because it encompasses a significant financial support which must be surveyed in a continuous and diligent manner. According to *Abotah (2014),* the focus should be an emphasis on the continuation of RE policy monitoring as it might help find out what is still needed to be done (e.g., verification if the targets can be met). Such actions provide policymakers with information, which can be considered while adapting new RE support policy. Furthermore, *Puig & Morgan (2013)* point out that evaluating performance of policies supporting renewables in a regular manner is crucial for policymakers to gradually improve the design of those policies. Careful and permanent monitoring can contribute to a more effective policy, with lower economic costs and a better investment climate.

In the meantime, such assessment could be a very useful instrument when it comes from one side to identify a policy's negative effects in a timely manner, and spotting options for optimization of such support programs. Evaluation of support policies is very important as the external environment may be changeable with time. Monitoring and assessment of RE policy measures could also help adjust to the changes in national and international developments and pay significant attention to eliminating non-economic barriers as a main priority. According to a report by *IEA (2011)*, a continuous assessment could also provide outlines to future policy evolution. *Shivakumar et al. (2019),* in their empirical study indicated that such monitoring can be a good starting point for making future projections and discovering trends that in turn help identify drivers and barriers related to the implementation of RE policy. In addition, *Puig & Morgan (2013)* suggest that assessment of RE policies could also provide guidance for policymakers in other countries seeking to get a better use of renewables and improve measures related to supporting such technologies.

To conclude, it must be noted that continuous monitoring and assessment of RE policy is of high importance. It can give policymakers answers if the policy can reach its targets or has already completed them and can also lead to improvement in policy design. Monitoring of RE policy might also be useful for further research addressing projection of trends or revealing drivers or barriers related to RE policy.

2.3. Rationale behind selection of assessment criteria

Implementation and monitoring of energy policies is often related with measuring their success. The literature outlines the following criteria to evaluate performance of RE policy (*IRENA, 2014a; Ragwitz & Steinhilber, 2013; Lu et al., 2020; Ortiz & Leal, 2020*): effectiveness, efficacy, efficiency, equity, environmental and economic effects, social acceptability, and political feasibility, institutional or legal feasibility and replicability (see Table 2.1).

Table 2.1. Main criteria to assess RE policies

Criterion	**Meaning**	**Key aspects related with RE policies**
Effectiveness	a degree to which the target has been achieved	it usually indicates how policy triggers RE generation or installation growth during a certain period. The following popular benchmarks are used for measuring policy impact with help of effectiveness: target or objective, techno-economic potential
Efficacy	a comparison between what is achieved and what was the target or goal	efficacy is very similar to another criterion ‘effectiveness’. The difference is that no degree of reaching a RE target can be measured within efficacy
Efficiency	an ability or suitability of a measure to achieve a given objective at the lowest expense	literature outlines two types of the criterion: static and dynamic efficiency. The former is focused on minimizing all possible cost related to policy, while the latter also addresses effects from learning, technological progress and GHG emissions reduction in the long run
Equity	a fair distribution of policy impacts between economic actors	all renewable policies have a strong impact on government, taxpayers, utility companies, businesses etc. A discussion of its fair distribution is one of the most important tasks of policymakers
Environmental and economic effects	policy implications in sectors of economy and ecology	RE policy can have a strong reflection on areas such as economic growth, international trade, employment inflation etc. Also, it can have an environmental effect in the form of GHG emissions reductions
Social acceptability and political feasibility	social acceptability means how positively it is perceived by the public, while political feasibility focuses on the attractiveness and support from the policymakers’ side	both social acceptability and political feasibility of measuring RE policy are closely related to other above-mentioned criteria through social norms and political structures.

(see continuation of the table on the next page)

(continued)

Institutional feasibility	how competent policymakers are to implement and amend legal acts	it depends on economic realities and political feasibility. For, example, developed countries have usually more stable and well-structured institutions, which can 'legally' implement, amend or withdraw polices
Replicability	how close a policy can be copied and realized in other countries or jurisdictions	difference in economic development, traditions or social preference, resource potentials could bring the same results when just recreating RE policy in another jurisdiction. The analysis of such factors and insights from good and bad practices is often undertaken by policymakers

Source: according to *IRENA (2012); IRENA (2014a); Ragwitz & Steinhilber (2013); Mir-Artigues & del Río (2016); Lu et al. (2020); Ortiz & Leal (2020).*

Many scholars emphasize that using a criterion of 'effectiveness' in terms of policy, supporting renewables is of high importance (*e.g., Romano et al., 2017; Polzin et al., 2019*). However, measuring effectiveness itself cannot be the main goal of empirical research (*Choi et al., 2018*). In this study, apart from using 'effectiveness' a benchmark of 'efficiency' as an additional framework was applied to provide more robust research on policies to support wind and solar energy in Poland and Germany as a background of other EU member states. The author of this thesis selected two above-mentioned criteria in this dissertation, as they are most popular among scholars, when it comes to measuring performance of RE policies. Furthermore, these two criteria fit best into the research of this thesis due to their ease in interpretation and quantitative assessment. Given the popularity of the benchmarks 'effectiveness' and 'efficiency' in the literature on RE economics, it is not only important to understand their meaning but also differentiate them.

It has been also discussed about the rationale behind the selection of effectiveness as a reference metric (*Ragwitz et al., 2015; Shivakumar et al., 2019; Polzin et al., 2019*), while many studies highlight it as one of the most suitable criterion for evaluation and monitoring of RE policies (*Klessmann, 2012; IRENA, 2014a; Resch, 2016*). Also, its 'flexible' and 'not complex' nature is positively acknowledged by scholars (*Ortiz & Leal, 2020*). Against this background, there is a need to better understand what effectiveness in terms of policy to support renewables is.

In general, effectiveness implies a degree to which a certain target has been achieved. In terms of energy, it can be measured as growth in capacity installed or electricity generated during a predefined period of time (*IRENAa, 2014*; *Ragwitz et al., 2015*). In a similar way, effectiveness metric has often been used by scholars addressing RE development as most discussion in literature is devoted to effectiveness through the prism of growth in deployment of renewables in the total energy portfolio (*IRENA, 2014a; Ragwitz et al., 2015; Shivakumar et al., 2019*).

This study strongly adheres to a definition of effectiveness presented in a policy report by (*IRENA, 2014a, p.14)* as "the extent to which intended objectives are met. For instance the actual increase in the amount of renewable electricity generated or share of renewable energy in total energy supply within a specified time period". Some scholars use targets as a reference benchmark to measure performance of mechanisms to support renewables (*Ibidem*). The effectiveness of RE policy is high if a value of its installed capacity or generation is equal to or exceeds the set objective (*Winkler et al., 2018*).

However, measuring effectiveness of RE policy with help of targets doesn't consider a very important factor which is the ambitiousness of the national RE policy (*Ibidem*). For this purpose, the most recent studies in their analyses of RE policy effectiveness use realizable potential as a benchmark value instead of targets. Such an approach is also taken in this work, whereas an indicator-based method has been selected to assess effectiveness of researched countries in terms of wind and solar energy policies (see Chapter 3).

Overall, policy effectiveness can be also defined in terms of different metrics. Apart from installed capacity or energy (electricity) generation, there are other reference values with the help of which effectiveness can be measured: e.g., consumption, jobs created, energy assessed. The chosen metrics depend on the features of the policy design, instruments, or targets (*Ragwitz et al., 2015*).

In line with a handful of studies (*Mir-Artigues & del Río, 2016*; *Ragwitz et al., 2015; Winkler et al., 2018; Ortiz & Leal, 2020*), two main concepts of measuring successfulness of RE policies are differentiated. They are based on 'effectiveness' and 'efficiency'. However, one should also point out a less common but strongly related term, which is 'efficacy' (*Verbruggen & Lauber, 2012*). There is a marginal difference between 'effectiveness' and 'efficacy'. The latter is defined as "a comparison between what is achieved and what was the target or goal" (*Ortiz & Leal, 2020, p.2*). Unlike 'effectiveness' 'efficacy' strictly focuses on whether a certain target is achieved without indication of its degree[10]. Such a 'harsh approach' in assessing performance (*Ibidem*) could also mean why this concept is not popular in literature of energy economics.

Another important criterion in measuring performance of RE policy is based on the concept of 'efficiency' (*Verbruggen & Lauber, 2012; Mir-Artigues & Río, 2016; Winkler et*

[10] e.g., if a country reached a yearly 9% of RE growth comparing with a targeted value of 10%, it still means the policy has no success. The same result is when the actual RE growth is only 1%.

al., 2018; Ortiz & Leal, 2020). A study by *Winkler et al. (2018)* states that efficiency describes the ability or suitability of a measure to achieve a given objective at the lowest expense and is generally the most important evaluation criterion, followed by effectiveness. Usually, governments pay much attention to efficiency of RE policy by implementing the most optimal budget to support renewables. Policymakers tend to choose a support scheme, the cost of which is minimized (*del Río et al., 2017*) with the best benefits.

According to *Winkler et al. (2018)* and *Fidanoski et al. (2021),* efficiency means simply that a predefined result is received at the lowest possible cost. *Ortiz & Leal (2020, p.2-3)* provide a similar definition of efficiency: "resources (e.g., funding to invest), which typically are limited, are being well used". While the term 'effectiveness' goes in most cases with objectives as a reference benchmark, the concept of 'efficiency' is more complex as it can encompass different components (dimensions) which can be used for its measuring (*Ibidem*).

Some studies (e.g., *IRENA, 2014a; Mir-Artigues & Río, 2016; Winkler et al., 2018*) point out to the categorization of the two concepts: static and dynamic efficiency. As for a concept of 'efficiency' the report (*IRENA, 2014a, p.20*) defines it as "the ratio of outcomes to inputs, for example, renewable energy targets realized for economic resources spent, mostly measured at one point of time (static efficiency) and called cost-effectiveness. Dynamic efficiency adds a future time dimension by including how much innovation is triggered to improve the ratio of outcomes to inputs". Besides minimizing the cost of support levels, a fair distribution of financial burden is another important aspect which can be included into a concept of static efficiency (*Winkler et al., 2018*). On the other side, elements like technological progress, innovation and learning are crucial on each stage of RE development (diffusion) and determine dynamic efficiency of policy scheme (*Mir-Artigues & Río, 2016*).

The approach of measuring efficiency in a static background is very popular in the literature of energy economics (*Verbruggen & Lauber, 2012*). The simplest interpretation of static efficiency can be described through an amount of energy generated or capacity installed presented in a currency equivalent (e.g., USD/MWh) (*IRENA, 2014a*). Using a reference value of energy generation can be more attractive, as it shows how profitable the 'investment' has been, after deducting capital and other costs, which also include financial allowance from a support scheme (*Ibidem*). There is a debate in the literature, which 'costs' are relevant to RE policy support. While one group of scholars use an approach to assess static efficiency through optimization of generation cost (e.g., *Winkler et al., 2018*), the other is focused on consumer cost (*del Río & Cerdá, 2014; de Mello Santana, 2015*).

In contrast to a cost-effectiveness, which takes a short-term approach, dynamic efficiency also addresses a problem of climate change and GHG emissions in the long run (*Verbruggen & Lauber*, *2012*; *Mir-Artigues & del Río, 2016*; *Winkler et al.*, *2018*). Factors of innovation, competition, diversity and learning effects can lead to a decrease in technology cost of renewables and acceleration of their development (*Mir-Artigues & del Río, 2016; Winkler et al., 2018*). While measuring static efficiency, it is also important to understand all the processes related with RE and its policy. That could help select out all possible kinds of costs, which also include hidden expenses, transactions, and administrative costs (*Verbruggen & Lauber*, *2012*).

Given the purpose and methods applied in this dissertation, an approach of measuring efficiency, which is closely related to Data Envelopment Analysis (DEA) and regression methods, has been selected (see Chapter 3). Such concepts have some features from above-mentioned static and dynamic efficiency and have become recently popular in the literature (e.g., *Sağlam, 2017; Toma et al., 2017; Mezősi et al., 2018; Papież et al., 2019*) on RE policy performance. As the term 'efficiency' is often expressed in the context of a combination of inputs and outputs, their ratio is nothing else as 'productivity'. However, efficiency is more of an exact concept as it can be defined through a relative distance between different subsets of inputs and outputs (*Toma et al., 2017*). *Moutinho et al. (2017)* define efficiency or technical efficiency as best possible production possibilities represented by a certain set of output and input variables as most efficient DMU[11] (Decision Making Unit) is technically situated on optimal frontier. This thesis also adheres to the approach based on a DEA method, which fits well into a comparative analysis of researched countries. Furthermore, one should consider that such an approach measures only relative values of efficiency. A detailed coverage on assessing performance in terms of DEA efficiency is presented in Chapter 3, while results and their meaning are presented and interpreted in the last two chapters. Also, an additional assessment of external factors affecting this efficiency with the help of regression models is applied.

According to a book by United Nations (*UN*, *2019*), there are many examples of approaches for measuring performance of the renewable policy but, to remain feasible, they need to comply with the principles of transparency and data source reliance. One should point out to the fact that some methods of RE policy effectiveness and efficiency have been highlighted in different policy reports, briefs, and projects, usually promoted by governments' reputable international energy organizations (e.g., IRENA, IEA). This is important as many

[11] Decision Making Units (DMUs) are defined as homogenous systems[11] (see *Park & Kim, 2018*) or peer objects (see *Mardani et al., 2016*), which convert input resources into outputs.

scholars have continued their research based on data and recommendations included in these studies and policy documents.

Many scholars attempted to measure RE policy performance by applying more than just one criterion (*Ciarreta et al., 2017; Özdemir et al., 2019*). One should indicate research which used both benchmarks of assessment of policy effectiveness and efficiency (e.g., *Ragwitz et al., 2015; Winkler et al., 2018*). Combining with other criteria could also deliver more reliable and robust outcomes of research on assessing policy performance (e.g., *Ragwitz et al., 2015; Shivakumar et al., 2019*). In theory, a trade-off between both concepts can be the best option especially when policy decisions have already triggered RE supply, while also important is a goal of generating energy with the lowest cost (*Özdemir et al., 2019*). In a similar way, *Matthäus (2020)* concludes that an exact balance between effectiveness and efficiency can be crucial for a country's RE policy to succeed. Such combinations of the two criteria gives a more detailed explanation regarding success in optimizing technology costs and the encouraging development of renewables (*Ibidem*). The application of the research framework, in which a tandem of criteria effectiveness and efficiency have been applied, is positively highlighted in the literature.

So, while conducting a selection process of methodology and empirical parts of this dissertation, a combination of these two benchmarks was applied. First, an initial part of empirical research (indicator-based evaluation) is undertaken, which is based on the estimation of wind and solar policy effectiveness in Germany and Poland on the background of other EU countries. The main methodological framework, based on indicators to measure effectiveness of RE policy that has been applied in this dissertation, was predominantly used in different reports and projects usually sponsored by reputable international organizations (e.g., IRENA, IEA). Then, the second part of the research relied on the quantitative approach whose objective is to identify how efficient the mentioned polices are and why. The analysis is based on the DEA and regression models, considered as ones of the most suitable in measuring policy efficiency. The synergy of both approaches to assess wind and solar policy effectiveness and efficiency in Poland and Germany can contribute to the literature by delivering a reliable, state-of-art, and comprehensive research outcome with regard to the given case study.

Therefore, there is a consensus in the literature that a combination of effectiveness and efficiency benchmarks could sketch a broader picture about performance of RE policies (see *Ragwitz et al., 2006; Polzin et al., 2015; Romano et al., 2017; Choi et al., 2018*). Furthermore, with the help of both criteria, one can receive a valuable answer on the question: is the policy successful or not? (*del Río & Cerdá, 2014*) However, not every energy policy scheme that is considered to be effective is efficient at the same time. Policymakers pay attention to both criteria as governments with a goal of maximizing the supply of renewables or pushing the deployment of a certain RE technology, (e.g., wind energy) tend to choose a framework which is most effective. Since the experiences of many countries show that some RE technologies such as wind or solar energy matured enough at some point, there is a need for new policy goals and measures that are aimed at bringing down technology costs and support of renewables (or a certain type of RE source). In this case governments prefer an RE policy which turns out to be most efficient. Against this background these two criteria (effectiveness and efficiency) were employed as an exploration of performance of wind and solar energy policies in the researched countries.

2.4. Review of previous studies on RE policy performance

As already mentioned, when it comes to the literature on the problem, it can be pointed out that scholars mostly conduct an empirical comparison analysis to test which policy instrument is better (*Ciarreta et al., 2017; Ramírez et al., 2017; Romanov et al., 2018*). Also, the lion's share of literature discussion is focused on the two policies: FIT and quotas. However, a recent trend shows that other mechanisms have become popular such as tenders (*Baldwin et al., 2016; García-Álvarez et al., 2017; Li et al., 2017*). As for other policy instruments (e.g., tax incentives or economic subsidies)[12], they are not often addressed in the academic literature. A detailed description of most relevant studies on the topic of RE policy performance is presented in Appendix B.

A general finding shows that most studies which refer to performance of feed-in tariffs (FIT) relate to the EU or some member state where this instrument is dominant (*Pyrgou et al., 2016; García-Álvarez et al., 2017; Ahmadov & van der Borg, 2019*). In turn, there is another scheme with a similar popularity among scholars called quota (e.g., renewable portfolio standards, green certificates). In this case, much literature covering this type of policy focuses mainly on the USA (*Shrimali et al., 2015; Carley et al. 2018; Zhou & Solomon, 2020*). However, assessment of quota-based instruments, normally having a different name, such as tradable green certificates (TGCs) (*Ciarreta et al., 2017*), is also common in studies within countries where this policy has been implemented (e.g., UK, India, Spain, or China).

[12] Classification of RE policy instruments are presented in the first chapter of this dissertation.

With consideration to the fact which policy instrument is better, literature can be divided into a few streams depending on a number and type of policies and RE technology researched. The literature overview finds the following patterns regarding the amount of RE policy instruments: some of the studies focus on performance of one policy scheme (*Pyrgou et al., 2016; Upton & Snyder, 2017*), while others compare two (*García-Álvarez et al. 2017; Choi et al., 2018*) or more instruments (*Kilinc-Ata, 2016; Özdemir et al., 2019*). Most of these studies use various methods, which can be one of the reasons for different results on policy performance. The analysis shows that evidence in the academic literature concerning which support instrument contributes most to the development of different RE technologies is divided.

Such as in the case with RE policy performance, support mechanisms are examined with a focus on a specific clean technology (e.g., wind energy), two, more or RE technologies in general. Empirical results show that a policy to support different types of clean energy sources provides various results on RE performance (*García-Álvarez et al., 2017; Donastorg et al., 2017*). Such a discrepancy in insights from the performance of various types of renewables may depend on many aspects, such as the fact that certain RE sources could be on different phase of technology diffusion (see *Romano et al., 2017; García-Álvarez et al., 2017; Romanov et al., 2018*). As already mentioned, each policy could have a different impact on renewables. Moreover, even the same policy instrument adopted in two countries with similar aspects of economic or social development can have totally opposite implications related to the RE market. Such a phenomenon can be explained by e.g., discrepancies in socio-economic or political conditions among various countries (*Kilinc-Ata, 2016; Polzin et al., 2019*). Especially the level of financial support or regulatory requirements could be crucial in making decisions related to the development of the clean energy technologies (*Romanov et al., 2018*).

There are many reasons why certain RE policy instruments are often addressed in the literature. While many studies emphasize the popularity of FIT and quota-based schemes as they have been implemented by most countries in the world (*Sun & Nie, 2015; Baldwin et al., 2016; Xin-gang et al., 2017*), their contribution to the development of the RE market has also been significant (*Li et al., 2017; García-Álvarez et al., 2017; Ambec & Crampes, 2019; Polzin et al., 2019; REN21, 2019*). Furthermore, some scholars point out that both mentioned policies are also among leaders in driving investment in renewables (*Dusonchet & Telaretti, 2015, Polzin et al., 2019*). A comparison analysis of both instruments' performance is viable after understanding the main differences between them (*Li et al., 2017*). As mentioned in Chapter 1, FIT is focused on the price and profit guarantee for energy producers while quota-based mechanisms normally aim at delivering a certain targeted amount/percentage in supply from renewables while at the same time preferring technologies with the lowest costs. That is why many authors claim that FIT would be better in the case of supporting immature technologies (*Polzin et al., 2019*) which are just at the starting point of government support (*Li et al., 2017*). Thus, quotas could play an important role on the RE market by optimizing technology costs (*Upton & Snyder, 2017*).

To summarize, based on patterns coming from literature review, it can be noted that debate on policy instruments is one of the most popular streams in the branch of RE economics. There are many studies concluding that policies in general have positively influenced the RE market. One can also indicate that a comparison analysis between two or more instruments is very popular among scholars. Another clear evidence is that most of these studies address predominantly wind and solar energy sources, at the same time exploring which out of the two policies is better, FIT or quotas. A policy scheme which recently gained attractiveness among governments and academics is tender. Less popular in academic works are tax incentives, grants, or economic subsidies. Furthermore, even the same policy tools such as FIT could have totally different implications in various countries. This stems from the presence of different factors that can affect the performance of that policy (e.g., size of financial support or social acceptance of renewables in the country) or policy design (see Section 2.5). Many studies emphasize the need for further research on this problem to obtain stronger and reliable results.

2.4.1. FIT

A great deal of literature on the topic of RE policy instruments has highlighted the importance of FIT in stimulating deployment of renewables (*Romano et al., 2017, Choi 2018*)**.** As already mentioned, many of these works focus on the EU market due to the fact that FIT has been dominant there for quite a long time (*Kabel & Bassim, 2019*). In general, this instrument is considered to be very popular as more governments implement it in order to speed up an expansion of the RE market (*Pyrgou et al., 2016; Romano et al., 2017; Choi et al., 2018*). Many earlier research papers set together FIT with quota-based instruments in a comparative analysis (e.g., *Zhao et al., 2013*) that constituted the biggest debate on the topic. More recent analysis compares FIT with tenders, as the latter became very popular during the last few years often replacing FIT or complementing it (e.g., *Matthäus, 2020*). While there seems to be strong evidence that FIT is very effective (*Kahia et al., 2014; Pyrgou et al., 2016; Ciarreta et al., 2017; Kabel & Bassim, 2019*), it has been widely debated on its efficiency, as critics usually point out to high financial costs of this policy instrument (e.g., *Pyrgou et al., 2016*).

Although the literature addressing FIT compared with other RE instruments is extensive, a small number of studies focus just on this policy alone without comparing it with other instrument(-s). Usually, these studies target wind or solar energy technologies. For example, *Sangroya & Nayak (2015)* examine the effectiveness of FIT in stimulating the development of wind energy market in India. The study uses an econometric regression model and employs a panel dataset during the years of 2001-2011. The authors concluded that FIT and a strong demand for energy are two main rationales behind a rapid deployment of wind energy capacity in the case study country. Similar research is presented by *Zhao et al. (2016),* which applies the same methodology during a lifespan of 2001-2013. The findings of the study show that FIT was very effective in increasing wind power capacity in the analysed country. *Pyrgou et al. (2016)* used a dynamic model to investigate under which circumstances the system of FIT in Spain, Cyprus, Germany, and Denmark could collapse. This study covered a time span from 2009 to 2014 and concluded that FIT has led to a strong growth of the RE market. However, the policy turned out to be not efficient in the selected countries due to generous financing, providing investors with high profits and increasing electricity prices. *Dijkgraaf et al. (2018)* conducted an analysis addressing the impact of FIT on the solar energy market. The study employs a panel dataset of 30 OECD (Organisation for Economic Co-operation and Development) countries in a period from 1990 to 2011. The authors found that FIT was effective and contributed substantially to the growth in the share of solar (PV) in the total electricity portfolio of the researched countries. Furthermore, they concluded that previous literature didn't reveal its full potential, as there was missing evidence on the effects of support instruments and its components (policy design).

Despite positive feedback, some critics point out a high generosity of FIT incentives and the fact that this type of mechanism might be too expensive for both government and society (*Ciarreta et al., 2014; Nordensvärd & Urban, 2015; Pyrgou et al., 2016; de Mello Santana, 2016*). This tool could be a large burden for countries, entailing detrimental implications on the RE market (*Dijkgraaf et al., 2018*). For example, the rate of FIT was so high in Spain that governments stopped financing RE projects in 2012 that led to a substantial decline in the RE market (*del Río & Cerdá, 2014; Pyrgou et al., 2016*). Different views on performance of this tool can be found with a reference to Germany, where FIT has been a leading policy during the last two decades (e.g., *Romano et al., 2017; Dijkgraaf et al., 2018*). On one hand, Germany experienced an unprecedented market growth of renewables such as wind and solar technologies during that period, pointing out to an enormous success of FIT. On the other hand, critics often point out the increasing financial cost of its implementation. For example, generous tariffs of this policy can lead to energy extra profits for RE generators, encouraging them to produce large amounts of energy (*Pyrgou et al., 2016*). This can provoke not only a distortion on energy markets or high electricity costs but also a tension on transmission lines *(Ibidem).* There are also some scholars that found no evidence in the relationship between FIT and growth in RE supply (*Smith & Urpelainen, 2013; Aguirre & Ibikunle, 2014*).

In summary, many countries implemented FIT making it the most popular policy instrument in the world. The literature review provides strong evidence that FIT is an effective tool to support RE sources, which also plays an exclusively important role in stimulating deployment of wind and solar technologies. Although FIT is an effective instrument which substantially contributes to RE deployment in many countries, such positive effect can be not acknowledged, if there is a gap in assessment of other factors influencing the realization of the policy. At the same time, some studies note negative impact of FIT or no evidence at all. They conclude that FIT can be also detrimental for the RE market, pointing to its low efficiency. Some countries, such as Spain, that employs a generous FIT policy, had to face sizable problems creating a bubble on the market of renewables. More research is necessary in terms of its particular element, which determines the impact of the whole policy on RE development. It would be interesting to examine the success of FIT or other policy instruments on different stages of RE technology diffusion. Another interesting question for future research could be: which countries are the best for such policies?

2.4.2. Quotas

Renewable portfolio standards (RPS) or similar quota-based policies (or quotas) have seen a strong interest from scholars (*Shrimali et al., 2015; Upton & Snyder, 2017; Carley et al., 2018; Anguelov & Dooley, 2018; Zhou & Solomon, 2020*). There is a sizable stream of studies which strong focus on the USA, where RPS is considered the main policy instrument to support renewables (*Wiser et al., 2017; Upton & Snyder, 2017, Zhou & Solomon, 2020*). Also, as already mentioned, it is often compared with FIT, as there is a strong discussion on which RE instrument is better (*Fischlein & Smith, 2013*).

Some studies (e.g., *Shrimali et al., 2015; Wiser et al., 2017; Zhou & Solomon, 2020*) highlight the important role of quota-based instruments in terms of effectiveness. It has also been empirically tested by *Wiser et al. (2017),* who examined performance of RPS in the context of environmental and economic dimensions in different states of the USA. They combine a cost-benefit analysis[13] (CBA) with a scenario approach to measure impacts of RPS. The authors concluded that RPS was exclusively effective in deploying solar and wind energy.

Polzin et al. (2015) qualify RPS as an effective policy instrument which is superior to other policies. The study uses a regression analysis of some OECD representative countries in a period from 2000 through 2011. The authors concluded that RPS can contribute to the development of renewables and, together with FIT, (also considered to be effective) they can build an optimal combination of policy mix. However, a lack of analysis on designing an optimal combination could turn out to be a major gap, so more comprehensive empirical evaluations are necessary in this area.

Baldwin et al. (2016) measured the degree to which certain RE policy instruments contributed to RE market growth. The research uses a regression analysis including a panel data set of 164 countries in a period of 1990 to 2010. The general finding is that support policies are the main drivers of RE development. The authors highlighted the importance of RPS and concluded that, apart from FIT, no other policy can have a stronger and more positive influence on the RE production. Similar conclusions are provided by *Bento et al. (2018)* as they claim RPS to be an effective policy tool and a strong catalyser in the generation of RE sources.

Despite some strong empirical evidence from literature on the importance and success of quotas, some studies on RE policy performance point out that research regarding RPS lacks a systematic approach (see *Shrimali et al., 2015, Zhou & Solomon, 2020*). For example, *Zhou & Solomon (2020)* underlined the importance of conducting more research in the area of policy design elements of RPS instead of just focusing on measuring the effects of this instrument. The authors found weak evidence that RPS is effective in pushing production of renewable energy sources in the electricity sector. There is more empirical research, which shows unreliable results on performance of quota-based schemes (*Upton & Snyder, 2017*) or state that RPS is not successful (*Delmas & Montes-Sancho, 2011; Kilinc-Ata, 2016; García-Álvarez et al., 2017*). Also, there are studies, which show different impact of quotas while comparing them with other instruments especially FIT[14].

A separate stream in literature is devoted to RPS as they could encompass different targets depending on a country or a region. Closely related to RPS is the term of 'stringency', defined as an increase in a targeted percentage of energy produced, or change in deadline, so

[13] Cost-benefit analysis (CBA) is a popular method of assessing efficiency and is applied in different branches such as economy health, education. It is based on measuring profits and losses from investment in terms of a certain project or policy (see *Choi et al., 2018*).
[14] A comparative analysis of studies on RPS and FIT is conducted in the next subsections.

that the same amount of energy is generated within a shorter period of time (*Lawson, 2020*). Against this background, studies started to assess which portfolio standards are more successful in deploying renewables: with higher or lower targets. The question of stringency has become a widely discussed topic, especially in the USA, where various states apply different targets of RPS (*Zhou & Solomon, 2020*).

Shrimali et al. (2015) also addressed the issue of stringency of RPS, granting that each state in the US employs a different RPS policy. The authors used a panel regression analysis to investigate how a degree of RPS in each US state correlates with deployment of RE capacity during a period of 1991–2010. According to the study, prior empirical literature on this topic lacked a quality evaluation framework as a growing body of works didn't account for a factor of heterogeneity. The main finding revealed that states with a more stringent RPS policy led to a higher RE capacity. The authors also indicated that assuming that RPS in each state is the same policy might yield misleading results. That also means that a more stringent policy can have negative effects on RE growth too. Another work from the literature stream belongs to *Zhou & Solomon (2020).* They conducted an economic regression approach which applied a panel dataset for the 1998-2017 period and investigated the impact of the stringency of RPS on the deployment of RE sources (installed capacity) in 28 states of the USA. The study indicated that stringent RPS in states with high potential RE resources is more effective in increasing capacity of renewables (*Ibidem*).

Opposite evidence in terms of RPS stringency has been presented by *Anguelov & Dooley (2018)*, who employed a panel dataset during a period between 2004 and 2014 with a scope of the USA. They underlined the importance of RPS as an effective tool in deploying renewables. Interestingly, the authors concluded that states with less stringent RPS are more successful. A level of RE consumption there is higher compared to states with a more stringent policy. The reason for this lies in efficiency as states prefer cheaper biofuels or hydro resources to wind and solar energy.

To conclude, similar to the case with FIT, quota-based instruments have been empirically examined in many studies. In general, it is not easy to draw a conclusion whether quota mechanisms are successful to promote renewables, as scholars use different research approaches that can lead to high discrepancies in results. Especially popular in literature is RPS, which has been a dominant instrument in the USA, where it also contributed substantially to the growth of the RE market. As RPS could have different targets in various countries or regions, scholars often examine their effect on performance, which is called stringency. There is an emerging consensus in the literature that more stringent RPS policies perform better.

However, some studies point to different results, claiming that countries with more stringent targets can reduce the pace of RE development. Some studies emphasize the importance of policy design as more in-depth analysis of RPS can provide a wider picture of the effectiveness or the efficiency of the mentioned quota-based policy instruments (*Shrimali et al., 2015; Zhou & Solomon, 2020*). Many studies assume that RPS is similar across different countries and regions, which can be misleading. As most of the studies address RPS, focusing only on the USA, there is a need for more research in other geographical areas where this policy instrument has been adapted. More general insights from literature review about quota-based instruments are provided in a comparative analysis with FIT that is presented in the next section.

2.4.3. Comparative analysis of FIT and quotas

As described earlier in this section, there are many studies which assess performance of FIT or quotas (RPS) separately. However, one of the largest debates on RE policy is devoted to the question which of these two types of instruments is better? A recent trend shows that scholars started to concentrate on comparing the two mentioned instruments using different geographical scopes, criteria, methods or RE technologies.

One stream of this topic (*Zhao et al., 2013; Baldwin et al., 2016*) highlights strong evidence that both FIT and RPS lead to a broader development and diversity of RE sources. At the same time, the current debate about comparative performance of both policy instruments is very polarized. On one hand, empirical literature provides evidence of FIT superiority over RPS (*Verbruggen & Lauber, 2012; Kilinc-Ata, 2016; García-Álvarez et al., 2017*). On the other hand, there is another segment in literature, where RPS is considered to be a more successful policy or there is no clear evidence stating which framework is better (e.g., *de Mello Santana, 2016; Li et al., 2017*). Furthermore, there are also studies which compare these schemes with other instruments such as tenders or tax incentives (e.g., *Winkler et al., 2018; Özdemir et al., 2019; Matthäus, 2020*).

More recent streams in literature compare FIT and RPS (quotas) in the context of different aspects like technology-orientation and technology-neutrality (e.g., *de Mello Santana, 2016; Matthäus, 2020*), leading to different policy implications. Also, the main criteria for measuring the performance of these policies are effectiveness and efficiency (*del Río & Cerdá, 2014; Winkler et al., 2018*). It should also be noted that there is a range of comprehensive research studies which account for factors directly affecting RE certain policy instruments. There are some empirical studies which conclude that both instruments are effective, without highlighting which one is better. *Baldwin et al. (2016)* asserted that FIT and RPS are the two most popular policies in the world which normally support a certain type of RE (technology - oriented). Both tools can remain effective in the long term as long as governments and the private sector maintain their strong commitment to renewables. While analysing which tool (quotas or FIT) is better, many scholars investigated their performance by considering income status of the country or level of resource endowment in certain regions (*Baldwin et al., 2016, Romano et al., 2017*).

An earlier study by *Verbruggen & Lauber (2012)* conducted a literature review where FIT and tradable green certificates (TGCs) are compared. The authors highlighted the importance of the two instruments at the beginning phase of RE promotion. Both policies are presented as a solution for fast and scalable deployment of renewables. Their results point out that both FIT and TGCs show high performance results, however FIT is considered to be more effective. Unlike this study, *Li et al. (2017)*, which conducted a panel data model and employed EU member states during a period from 1996 to 2013, concluded that only FIT can be successful at the initial stage of RE technology development whereas opposite results were obtained in the case of RPS.

García-Álvarez et al. (2017) applied a regression model with a panel data set from 2000 to 2014 and the focus of the study was restricted to EU member states. The authors evaluated policy implications of FIT and RPS on wind onshore capacity in the electricity segment. The findings of the study highlight the superiority of FIT in deploying capacity of the given RE technology. The empirical study also showed that there is no evidence that RPS exerts a positive impact on wind energy development. Totally different results were presented by *de Mello Santana (2016)*, who assessed FIT and RPS (quota) in terms of static efficiency or cost-effectiveness. The author employed a levelized life cycle cost[15] (LCC) method often used in empirical studies with CBA approach. The findings show that RPS policy is more efficient compared with FIT. The study also suggests policymakers adopt tenders, which together with quota-based instruments, constitute an optimal policy mix.

There is an emerging consensus in the literature that FIT is more effective in driving renewables. This is in line with theoretical approaches that RPS policy is based on predefined targets, in which governments aim at deploying a certain amount of renewables at the lowest cost. Unlike FIT, the goal of RPS is not maximizing the generation of RE supply that can have limits on effectiveness. However, empirical studies, where criterion of efficiency is considered, could provide a different picture.

[15] Levelized life cycle cost (LCC) – is a method, based on measuring certain project by comparing its discounted value of gains and costs during a period of exploitation (see de Mello Santana, 2016).

Governments pay much attention to efficiency with attempts to measure the cost of a certain RE policy normally financed by taxpayers. Policymakers tend to choose the support scheme, the cost of which is minimized (*del Río et al., 2017*). A growing body of literature that focuses on efficiency of FIT and RPS (quota) yields contradicting findings, making it hard to draw an unambiguous conclusion on which policy is better. Most of the research on efficiency is based on the econometric approach with indicator-based and cost benefit analysis.

Choi et al. (2018) conducted an empirical analysis comparing FIT and RPS tools in different periods in South Korea. The authors applied cost-benefit analysis (CBA) to find out which RE instrument is more efficient from government and producer perspectives. Their study yielded mixed results: from the government side, RPS is more efficient for solar energy, while FIT is better in the case of promoting other renewables including wind energy. Diametrically opposite findings are provided from the perspective of energy producers. *Choi et al. (2018)* concluded that in light of abundance of empirical studies about RE policy performance, there is a lack of comprehensive research yielding robust results. They also found out that assessing different policy instruments within a cross-country analysis can lead to inaccurate results as there are many country-specific factors which need to be considered. The authors also acknowledged that their empirical research is worth special attention as two different RE tools (RPS and FIT) have been evaluated within the same country (cased study of South Korea).

So, not every policy instrument that is considered to be effective is at the same time efficient. Policymakers pay attention to both criteria as governments with a goal of maximizing supply of renewables or pushing deployment of a certain RE technology (e.g., wind energy) tend to choose a policy which is most effective. Since experiences of many countries show that some RE technologies like wind or solar energy became more matured, there is a need for new policy goals aiming at bringing down cost of renewables (or a certain type of RE source). In this case, governments prefer an instrument which turns out to be most efficient.

Recently, there is a tendency when more academic studies apply a two-criteria analysis to measure performance of RPS and FIT with the help of both effectiveness and efficiency. *Sun & Nie (2015)* employed an equilibrium model[16] to assess the performance of two most popular RE policy instruments. They concluded that even though FIT is more effective in deploying renewable capacity, RPS is more efficient from the perspective of consumers.

[16] According to *Özdemir et al. (2019, p. 2)* equilibrium model "determines the net costs that must then be recovered from subsidies by accounting for the value of power at different times and places, which results from the simultaneous interaction of supply and demand throughout the network".

Ciarreta et al. (2017) relied on the simulation model approach with a case study of Spain and conducted a comparison analysis of Tradable Green Certificates (TGCs) and FIT in period from 2008 to 2013. Despite the fact that the authors provided strong evidence that FIT is an effective tool, the cost of this policy proved to be relatively high. In turn, TGC is found out to be a relatively more efficient policy instrument.

A study by *Özdemir et al. (2019)* employed a market equilibrium model with an established scenario framework to compare RE generation- and capacity-oriented policy instruments in EU member states. The authors assumed that RPS and FIT can belong to any of the two above-mentioned groups of policies. They also stated that each of the instruments delivers similar results on effectiveness. In the long run, policies RPS and FIT can yield better effectiveness and efficiency scores in terms of capacity uptake due to learning-by doing. Conversely, generation-oriented schemes are more efficient in the short run.

To summarize, there is a consensus among scholars that FIT, and quotas (usually RPS), are the two most important and popular RE policy instruments. There is also an extensive literature on the comparison of the two policies in terms of policy performance. One of the most common criteria used in the literature on performance of FIT and RPS (quota) is effectiveness and efficiency. Many works on this topic rely on econometric multi-criteria analysis or case studies.

One can draw a conclusion that FIT is more effective than quotas. However, in studies where efficiency is used, results stating which policy is better are more controversial. Empirical studies, in which both efficiency and effectiveness are applied to compare performance of the policies, provide more comprehensive and robust results. However, based on these works, it is not easy to determine which one is evidently more successful. Even though RPS theoretically is aimed at selecting out technologies with lower energy costs, some empirical studies claim that FIT is more efficient than RPS. The abundant literature on a comparison between FIT and RPS employs a different geographical scope, assumptions, methods, and time periods. This can lead also to discrepancies in the empirical findings.

In general, literature on the topic of yields contradictory results, making it difficult to conclude which out of the two mentioned instruments is more successful. A lack of studies building on a previous similar methodological framework is the main gap regarding the literature stream on performance of FIT and quotas. There is also a need for more works which address different factors that can have an impact on RE policy performance. Also, FIT and quotas is frequently highlighted in works, in which a comparative analysis is conducted in the context of multiple policy instruments (see next subsection).

2.4.4. Tenders and other RE policy instruments

Tenders or auctions also draw attention from academics after they recently became very popular among policymakers. As most literature addresses FIT and quotas (RPS) due to their strong contribution to promoting renewables and bringing down the cost of RE technologies, auctions used to be considered as a policy with many drawbacks. Since technologies like wind and solar energy have become more mature in some countries and their deployment pace has seen new records, governments have taken new measures in order to increase performance and better monitor support policies (*Kitzing et al., 2019*). Recently, auctions returned in the sphere of interest of scholars forming a new stream of literature about RE policy performance. There is a growing body of studies which note an important role of this policy instrument in driving renewables (*del Río & Cerdá, 2014; de Mello Sentana, 2016; Kilinc-Ata, 2016; Matthäus, 2020*).

De Mello Sentana (2016) and *Dijkgraaf et al. (2018)* indicated that tenders are effective in mitigating an investor's risk, while supporting extensive RE projects. This support mechanism is also considered to be efficient in encouraging a competition between investors, while addressing projects and technologies with the lowest costs (*del Río & Cerdá, 2014; Kilinc-Ata, 2016*). Auctions unlike FITs have a cap on the renewables supply and can lead to positive effects of the RE policy especially in terms of efficiency (*Kitzing et al., 2019; Winkler et al., 2018*). That is why an important feature of tenders is that governments are able to control RE production or capacity.

Proponents of auctions also consider auction as a very flexible policy instrument which can be easily tailored to the changing conditions of a market and government energy policy (*Kitzing et al., 2019*). Critics often point out that tenders can impair competition preferring a certain RE technology by not contributing to an optimal energy mix (*del Río & Cerdá, 2014*). They also question the stability of this type of policy instrument due to a situation when there is a low number of bids from investors (*Kylili & Fokaides, 2015; Matthäus, 2020*). Furthermore, auctions are criticized for high bureaucracy and unfair treatment of actors, for example, supporting big investors with higher financial resources rather than communities or smaller companies (*Dijkgraaf et al., 2018*). This can also impede social acceptance for this type of instrument (*Fell, 2017*).

Despite some critics towards the performance of tenders, European Commission recommends it as an important tool which can gradually replace other policies like FIT (*EC, 2013*). A rationale behind such a step is that tenders can promote competition very effectively with minimum financial support levels (*Ibidem*). A more in-depth discussion on tender's performance can provide better insights for policymakers. It is important to highlight the importance of differentiating technology-oriented and technology-neutral auctions as both of them entail different implications in the development of the RE market.

Many studies highlight the importance of carefully designed and aligned auctions (*del Río & Cerdá, 2014; Winkler et al., 2018*). For example, *Winkler et al. (2018)* concluded that auctions can prove to be effective if production of renewables is close to the set goal. A mismatch between a planned and actual deployment can be a major reason behind the ineffectiveness of auctions. The author notes that successful auctions have to promote the projects which can be realized with the lowest cost.

An econometric analysis by *Ahmadov & van der Borg (2019)* is in line with previous empirical studies (e.g., *Jenner et al., 2013*), and notes that FIT compared to tenders is more effective as it leads to a higher level of RE generation. One should emphasize an already mentioned study by *Winkler et al. (2018),* in which performance of tenders is assessed on the background of other policy instruments in the selected EU countries during a time span of 2005-2016. The authors also investigated the difference in performance of government policies where auctions have been adapted and countries with different policies like FIT or RPS. The study employed a mix of various methods. First of all, the research conducted a cross-country analysis, measuring effectiveness and efficiency of tender and non-tender policies. In addition, the authors identified factors which can have significant impact on the mentioned policies. The findings provided no evidence if tenders are successful or not due to contradictory results. However, the authors agreed that tenders can be both effective and efficient if the policy is designed carefully and other factors such as land availability and resource endowment are also considered.

An interesting empirical analysis by *Kilinc-Ata (2016)* attempted to compare the effectiveness of different RE policy instruments (FIT, RPS, tenders and tax policies) between states of the USA and countries of EU. The authors of the study used a panel dataset with a time span of 1990-2008. The findings suggest that the level of effectiveness in deploying renewables among the countries depends mainly on the type of RE policy instrument. It was concluded that quota-based policies such as RPS are found to be not effective. Also, the authors agreed that other policies like FITs, tenders, and tax incentives positively affect the deployment of renewables.

By employing a levelized lifecycle costs analysis (LCA), *de Mello Santana (2016)* compared the efficiency of tenders against RPS (quota) and FIT instruments. The study also examined the difference in efficiency of various support instruments. The author concluded that tenders, together with RPS, are the two best policy tools in terms of efficiency. According to the author, FIT can yield large profits for producers of renewables that are at the same time financed indirectly by energy consumers.

The literature review reveals that the majority of empirical studies employ a comparison analysis of tenders with other policy instruments such as quotas or FIT (e.g., *Kilinc-Ata, 2016; Winkler et al., 2018*). By conducting such analysis with other policies, scholars try to find out the rationale behind tender's superiority or prove its positive effect on the RE market. This is especially true as many governments plan a gradual replacement of policy schemes with tenders' role to gain significance in recent years. Similar to cases measuring performance of FIT and RPS, studies on auction deliver equivocal results what normally depend on the scope, time span, methods, and other features of research. More recently, the research is focused strictly on some particular element of tender's policy design, claiming that such analysis would bring more robust and precise results (e.g., *Matthäus, 2020*).

The intensive discussion in literature is devoted to the policy implications stemming from categories of technology-oriented (with goal to support a particular RE technology) and technology-neutral auctions (supports renewables in general by normally selecting the most cost-effective projects) (*Polzin et al., 2019*). The choice between the two mentioned types of support mechanisms often depends on the policy goals of the country. The same classification could be found in the case of FIT and RPS (quota) (e.g., *de Mello Santana*). However, most of the studies covering technology-oriented and technology-neutral policies are focused on tenders.

De Mello Santana (2016) concluded that technology-neutral auctions anticipate a strong competition between projects where more mature RE technology with lower generation cost is preferred. This means that certain RE technologies could be deprived of any policy support. An interesting conclusion was drawn in an empirical analysis by *Matthäus (2020)*, as no evidence was found that a choice between a technology-oriented and a technology-neutral instrument could lead to a different level of effectiveness in the RE policies. However, the author acknowledged that if a government aims to achieve a desired efficiency level, then technology-neutral instruments are preferred. *Polzin et al. (2019)* underlined, that similar to the case with efficiency and effectiveness, policymakers also tend to look for a trade-off between technology-neutrality and technology-orientation. This balance is of high importance especially while optimizing domestic RE policy (e.g., when governments already achieved a certain amount of

RE supply, technology diversity or environmental goals, then a shift to a more cost-effective (efficient) policy becomes necessary) (*Romano et al., 2017*).

Policymakers have to think carefully before adopting one of the two mentioned categories of policies. The rationale behind choosing one of them normally depends on how it is going to be tailored to policy goals and market environment (*Kitzing et al., 2019*). The literature provides evidence that governments choose technology-oriented instruments if the main objective is to promote the particular RE technology, while paying less attention to its efficiency. In this situation, such policy tools can be more successful to promote immature RE sources or diversify a portfolio mix of renewables (*del Río & Cerdá, 2014; Kitzing et al., 2019*). When a supply of renewables has to be supported with the lowest cost incurred, then the use of technology-neutral schemes should be recommended (*de Mello Santana, 2016; Polzin et al., 2019*).

There are not many studies addressing the other RE policy instruments, as scholars usually show interest in the three earlier (FIT, quotas and tenders) reviewed in this chapter. Scarce research on other support mechanisms such as tax incentives or subsidies often addresses a comparison analysis with more popular policies like FIT. For example, results of the already mentioned study by *Li et al. (2017)* show that FIT and RPS were both successful in deploying solar (PV) power, and the effect of FIT was even stronger. At the same time, the authors concluded that tax incentives are also successful in promoting solar power.

Ramírez et al. (2017) conducted a comprehensive econometric model by using profitability analysis where policies FIT, and net metering have been compared in selected EU countries in terms of efficiency. The authors employed a model with different scenarios of instrument combinations with regard to the solar PV energy market. Obtained evidence shows that both instruments while interacting with each other can contribute substantially to deployments of renewables.

Romanov et al. (2018) employed a regression model with a dataset of 106 countries during the period of 1997-2014 to assess the effectiveness of various RE polices. The empirical study revealed that out of many RE policy instruments, tax incentives and strategic planning proved to be the most effective in deploying wind energy production, and that in the long run, they benefit from a positive impact of 'learning by doing'. Within these policies, governments could be more flexible to changes in RE policy instruments in countries with especially dynamic developments in the socio-economic domain.

It can be concluded that tenders attracted many critics and proponents at the same time. Opinions among scholars are differentiated, especially when its benefits and disadvantages are compared. Recent studies on tender performance emphasize that this type of policy is bureaucratic and supports mainly the large projects of wealthy investors. Proponents of auctions claim that they are cost-effective and flexible in changing policy design, as they foster competition between RE technologies. Another benefit is that unlike FIT, tenders have a cap on the RE supply that can ascertain the targeted amount of renewables to be deployed in the market. While conducting analyses of studies measuring effectiveness and efficiency of tenders, one can mark a strongly visible pattern that most of them compare this instrument with policies like FIT or RPS. No general conclusion can be drawn whether auctions are successful policies. As more countries consider complementing or switching from one instrument to another, many scholars start to examine it in a combination with other instruments. However, there is an emerging consensus in the literature that well-designed and aligned tenders could prove to be very effective and efficient. Further research needs to be conducted in this area to find out if auctions are compatible with other policy instruments.

Also, one should accentuate a literature stream, which focuses on discussions regarding technology-oriented and technology-neutral policies. Such classification is typical for tenders and less common in the literature regarding FIT and RPS. There is a consensus in the literature that both technology-oriented and technology-neutral instruments differentiate substantially in terms of effectiveness and efficiency. It depends heavily on the policy goals and level of maturity of RE technologies. If governments aim to maximize the supply of a particular type of renewables, they tend to choose a more effective technology-oriented policy. When a certain RE technology is mature enough or policymakers reach a predefined amount of RE supply, then a technology-neutral instrument is chosen.

Relatively little can be found about other policy instruments like tax incentives, subsidies, and other less popular support mechanisms. Like in the case of tenders, the mentioned policy instruments are normally compared with RPS or FIT. Considering a low number of studies, no general evidence can be drawn on the performance of such policy frameworks.

2.5. Importance of policy convergence and design

Many countries have already implemented different policy tools to support renewables. Most of them employ two or more policies (e.g., Germany). It is important to measure the general effect of a combination of RE policy instruments on the deployment of renewables. Many scholars examine the performance of interplay between some RE policy instruments, which is one of the newest streams of research on the topic of RE economics (*Polzin et al.*, *2015; Ambec & Crampes, 2019; Ahmadov & van der Borg, 2019*). A literature review points out that a convergence of different policies could increase effectiveness and efficiency (*Romanov et al., 2018; Özdemir et al., 2019*). However, there is also a discussion that using only one policy could lead to much better results (*Romano et al., 2017*). A combination of instruments within one country or region can result in a lower performance of the combined efforts, as some of the policies may prove to be incompatible. In general, there is no prescription for choosing a successful set of policy schemes, at least because the same policy instruments could be different in terms of policy design elements (*Romanov et al., 2018*). There are also other country-specific, socio-economic, or political factors which can determine if such interaction would be productive (*Özdemir et al., 2019*).

Some studies (e.g., *Özdemir et al., 2019*) indicate that a right combination of the policy instruments could be a key in lowering costs of a specific RE technology. Research by *Ambec & Crampes (2019)* applied an economic model to investigate policy implications of various schemes to promote solar and wind energy. The authors of the study conducted an analysis aimed at selecting out the best combination of RE policy instruments and optimal policy design. They concluded that both FIT and RPS are more effective together with other policies, which can keep tariff prices or a targeted quantity of RE technology within a desired level.

Another mentioned study by *Ramírez et al. (2017)* showed that most of the selected countries could benefit from an interplay of FIT and net metering, but under conditions that other elements of the combined policy design are optimized. The authors also concluded that the best policy mix for support of renewables can be achieved in countries where RPS and tenders are the two main instruments. There is also an opinion that having at least two policy instruments can be useful for developing countries (*Donastorg et al., 2017*). *Ahmadov & van der Borg (2019*) conducted a-few-dimensions research by using a statistical analysis and regression model to assess the performance of various RE policies in selected EU member states. They considered environmental taxes to be the optimal tool to support renewables. Furthermore, a better effect is yielded if this instrument is combined with one of the following policies: FIT, RPS or tender. However, they also conclude that a careless approach to policy design can bring negative implications.

As many studies insist on the importance of the compatibility of policies, other factors may also play an important role. *Romano et al. (2017)* concluded that it is necessary to choose a set of policy instruments which will be optimal in the context of energy and environmental goals. Furthermore, *de Mello Santana (2016)* suggested that policymakers should opt for a policy portfolio with technology-neutral and technology-oriented instruments. Such combinations are important in optimizing RE policy, where a balance (a trade-off) between efficient and effective impact on renewables can be found in the short run and in the long term.

However, there are also studies which point out that having more than just one policy instrument can be harmful for RE development (*Kalkuhl et al., 2013; Zhao et al., 2013*). An assessment by *Kalkuhl et al. (2013)* indicates that instruments like FIT or RPS (quotas), when functioning separately rather than together with carbon pricing policy, are more effective in driving RE deployment. Some scholars acknowledge that incompatibility of some RE policy instruments could entail a reduction in capacity or consumption. A research done by *Zhao et al. (2013)* showed that some RE schemes cannot be compatible and may bring about negative implications on the RE market. Also, *Mundaca & Richter (2015)* stated the fact that most jurisdictions dispose of more than just one RE instrument and acknowledged that there is a need for further research on the interaction or convergence of different policy schemes.

There are also studies assessing the performance of FIT and RPS which address high- and low-income status effects. The aspects regarding developed and developing countries and their income status are important in how a certain policy can influence the development of the RE market (*Smith & Urpelainen, 2013; Baldwin et al., 2016; Romano et al., 2017*). A growing body of literature on this special topic indicates a direct relationship between availability of financial resources and a performance of RE policy (*Zhao et al., 2013; Smith & Urpelainen, 2013; Sangroya & Nayak, 2015; Baldwin et al., 2016; Romano et al., 2017*). General findings suggest that developed countries are more successful in deploying renewables, whereas poor states do not possess enough financial resources that can impede the development of RE sources. However, governments can choose the most appropriate policy instrument, relying on the budget size they have.

The factor of income status is also relevant to the study, as in the next chapter, a comprehensive analysis of factors influencing wind and solar energy policy in Poland and Germany has been conducted. Since the two countries belong to different groups by socio-economic development, it would not be difficult to conclude how this factor affected RE policies in both mentioned countries on a background of other EU member states.

There is a strong debate in the literature about which RE policy is better. Many authors acknowledge the dominant role of FITs and RPS, while some of them consider tenders, subsidies, and other less popular policies as the most suitable to foster deployment of renewables. However, countries which have the same dominant support instrument, could differ strongly in terms of policy performance. For example, FITs commonly used in Germany and Spain during last two decades, show totally different outcomes in terms of effectiveness of FIT (*del Río & Cerdá, 2014; Pyrgou et al., 2016*). Why does this happen when the same RE policy instrument can be suitable in one country and unsuccessful in another?

The answers to this question could be many, such as a discrepancy between countries in terms of social acceptance of renewables or the development of domestic energy infrastructure. There are many other political and socio-economic factors influencing the functioning of a support policy on the RE market. As noted by *Polzin et al. (2019),* the answer could lie in the fact that even though the same RE policy instrument is used, its elements might differ significantly depending on the country. A system of these elements is nothing else but the policy design.

A careful approach to the selection and implementation of policy design by governments should be as important as choosing the right RE policy instrument or a combination of them (*Mir-Artigues & del Río, 2016, de Mello Santana, 2016; del Río et al., 2017; García-Álvarez, 2017*). Some studies consider that a policy design plays an important role in encouraging RE sources and its elements need to be examined very carefully (*Matthäus, 2020; Ahmadov & van der Borg, 2019*). So, it is of high importance to understand how those elements can influence RE deployment (*Shrimali et al., 2015; Abrell et al., 2017*).

One can draw a conclusion that a topic on a convergence of some RE policy instruments is very up-to-date as more scholars attempt to solve this research problem. Although some studies suggest positive relationships between a convergence of policy tools and RE deployment, others have found no impact or point out to the fact that some of them cannot be compatible. Since many countries employ more than one support scheme, it is of high importance to examine how these, or other policies, can function together.

Also, a policy design plays a key role in improving RE policy performance. Many authors find that particular elements of FIT, RPS, tenders and other instruments are as important as the whole policy. Some components of the same support instrument can differentiate, as for example, predefined targets of RPS. It also is mentioned by scholars that the changes in elements of policy design can have detrimental effects. That is why policymakers are recommended not to resort to dramatic measures of switching from one scheme to another. Better options could be to find out some potential of change in the policy design of a particular support instrument like RPS or tender. Even though this topic attracted much interest from scholars recently, some gaps still exist due to a lack of studies. Literature addressing different policies also notes the need for further research on policy design (*Shrimali et al., 2015; Baldwin et al., 2016; Polzin et al., 2019*).

2.6. Literature gaps and general conclusion

There is strong evidence in the literature that RE policy is very important in promoting the development of renewables. An extensive discourse addresses the aspect of policy performance and comparison between policy instruments. One must admit that even the same schemes as FIT or tenders could have different policy implications in various countries. With consideration to these and other issues, a comprehensive analysis of multiple studies on the topic was conducted, focusing on their approaches, assumptions, results, and other important data.

This chapter attempted to categorize the main patterns and methods for measuring performance of the RE policy. An analysis of studies on different support schemes is very important as it gives an opportunity to see the broader picture on the topic of RE policy. The literature review aims also to find out the most common literature streams on performance of policies, supporting renewables. Another objective of this chapter was a search for gaps in relevant literature and future research possibilities.

When referring to performance of RE policy, a growing body of studies addresses criteria of effectiveness and efficiency while focusing mainly on wind and solar energy. Regarding policy instruments, most of the literature streams provide no clear evidence which one is better. For example, there is an emerging consensus in the literature that FIT turned out to be effective in driving RE development. In the context of efficiency, scholars provided polarized results. As for other support mechanisms (quotas and tenders) no equivocal evidence could be outlined.

In general, the existing literature lacked a systematic approach and comprehensive analysis, especially in research on impact factors, interaction between polices, and less popular instruments such as tax incentives. By applying multiple methodological approaches, a handful of studies chose a new empirical framework without building on the previous research. It was discovered that only a small number of studies provided more comprehensive research, as they accounted also for other factors (e.g., social acceptance or resource endowment). In order to clarify these mixed results, new research is necessary.

It is also important to categorize policies as technology-oriented and technology-neutral. The general evidence from the literature review shows that policymakers choose between these two types, and that heavily depends on the policy goals that the governments pursue. Further studies can focus on the aspects of policy design or convergence, which are rather new streams in the literature.

There were additional studies reviewed which emphasized the importance of further research regarding factors which directly impact the policy supporting clean energy sources (*Lutz et al., 2017; Upton & Snyder, 2017; Dijkgraaf et al., 2018; Polzin et al., 2019*). Unlike most of the reviewed literature, an effort was made to concentrate on a renewable policy in general while also referring to a particular policy instrument. Furthermore, an assumption was made that the dominant (main) policy instrument is responsible for the whole impact on the deployment of renewables. For example, it is FIT and tender in the case of Germany. It is in line with some studies, which point to difficulties in cross-country analysis of policy instruments, especially when several different schemes are compared within more than one state (*Mundaca & Richter, 2015; Choi et al., 2018*).

The effectiveness of RE policies of the EU member states were systematically assessed from around mid-2000's until 2015. Not much empirical assessment has been carried out after 2015. Due to the lack of this systematic research on the given problems during the last few years, the importance of previous evaluations are very valuable and therefore improve on the analytical framework which can also be applied in the further studies.

Despite abundance of studies closely related with efficiency, scholars indicate importance of new research in the domain of performance of clean energy technologies due to dynamic nature of RE market and need for constant improvements in support measures (*Mir-Artigues & Río, 2016; Winkler et al., 2018; Ortiz & Leal, 2020*). Besides that, there are many studies which emphasize the importance of further research regarding factors which directly impact the policy supporting clean energy sources (*Lutz et al., 2017; Upton & Snyder, 2017; Dijkgraaf et al., 2018; Polzin et al., 2019*). The existing literature is mostly restricted in its scope as it focuses on the performance of a particular RE policy instrument without controlling for other factors such as the cost of technology or the energy security aspect. With consideration of this issue, this research overcomes this limitation as an attempt is made to fill the gap by carrying out research in terms of how effective and efficient wind and solar energy policies are.

As a growing body of scholars are focused on a cross-country comparison of one or more certain policy instruments, such an approach can have some limitations too. Critics often point out the problem of heterogeneity (e.g., *Verbruggen & Lauber, 2012*; *Fell & Linn, 2013*). The same policy mechanisms (e.g., auction) can differ in terms of organization, structure, and implementation in various countries. A reason for this can be a difference in sociopolitical, economic and policymaking areas. Also, a lack of common framework regarding definition and interpretation of RE sources can play a significant role. Some scholars admit that a more generic approach to research with an application of criteria like effectiveness and efficiency can prove to be feasible to avoid the above-mentioned caveats (see *Verbruggen & Lauber, 2012*).

Unlike the fact that the prior research predominantly addresses performance of a particular policy instrument (e.g., FIT), this research takes on a more holistic approach in measuring effectiveness and efficiency of wind and solar energy policies in EU member states (in particular, Poland and Germany). One of the largest limitations indicated in the literature was a utilization of a methodological framework consisting of only one criterion. Also, a lack of structured and regular studies building on previous research is missing. Furthermore, a growing body of literature that focuses on different RE policies yields contradictory findings, making it difficult to select clear and robust evidence. It is also important to adjust and create new empirical frameworks to assess policy performance due to a dynamic nature of RE sector and recent challenges to the energy market overall. These and other facts strongly point out a need for further research on the topic, especially considering a growing role of renewables and their contribution to an unprecedented and sustainable energy transition.

While research in this dissertation is different from the studies reviewed above, some important insights were found from each of the identified literature streams. These were taken into consideration while conducting this research. By carrying out a literature review, a set of several empirical studies has been selected, on which the research is built. Some research works have already been mentioned in this literature review (e.g., *Ragwitz et al., 2015; Shivakumar et al., 2019*). The detailed analysis of the relevant studies on which the empirical analysis relies is presented in the next chapter.

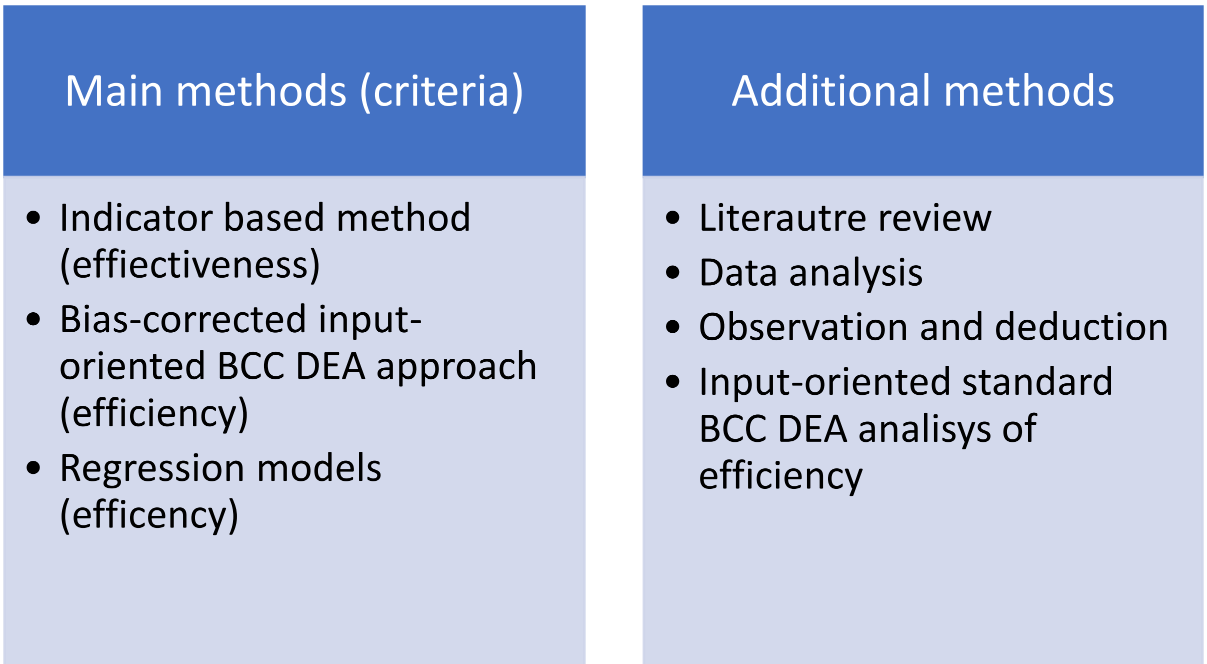
The exploration of the academic works on RE performance helped to outline the discourse on the main aspects of the topic, as the literature gaps and caveats have been identified. While many scholars emphasize the need for more research in the field of RE policy, the dissertation with a goal of measuring effectiveness and efficiency of wind and solar energy policy in Germany and Poland (on the background of other EU member states) can contribute to the literature with very valuable, comprehensive, and up-to-date insights. This may be the first research work on RE policy performance whose geographical scope is restricted mainly to the two mentioned EU countries.

By conducting this literature review, the main goal of this chapter has been achieved as the most appropriate empirical and methodological frameworks have been selected. In line with extending literature on the topic, concepts of effectiveness and efficiency have been chosen for this study. Also, with help of methods such as indicator-based approach, DEA analysis and regression models, important results and valuable evidence were obtained. The application and more detailed description of these frameworks are described in the next chapters of this dissertation.

3. METHODOLOGICAL ASPECTS OF MEASURING RE POLICY PERFORMANCE

The previous chapter encompasses a profound review of relevant literature, with a final goal to highlight the discussion on the given problematic and find out the most suitable methodological concept to carry out research in this dissertation. Given the main objective of this study, the best-tailored methods have been selected to conduct a comparative analysis on policy effectiveness and efficiency in the sector of solar and wind energy in Germany and Poland on the background of EU countries. First, policy effectiveness for the given countries was measured with the help of an indicator-based approach. Besides that, an additional analysis was conducted to reveal how different policy instruments contributed to the wind and solar energy development. Second, performance of the mentioned policies was evaluated in terms of efficiency based on DEA methodology. Also, external factors were addressed to better interpret results on efficiency, which is an additional research based on regression models. The main and auxiliary methods applied in this study are shown in Figure 3.1.

Figure 3.1 Main and additional methods used in the research



Source: Own compilation

Before describing the methods, there is a need to shed light on the discourse on performance of RE policy, with a special focus on the quantitative assessment of effectiveness and efficiency based on indicator-based and DEA techniques. Against this background, an analysis of related (peer) studies was conducted that employed similar approaches to measure policy performance. Based on the reviewed studies, a framework was formulated, which incorporates adaptation and modification of the methodology from the relevant literature. The chapter also presents the data chosen for the applied methods, and special attention is paid to the rationale behind the selection of variables such as realizable potential or electricity generation. Furthermore, the importance of addressing multiple dimensions (e.g., energy security or employment) is highlighted. The empirical application of the mentioned methodology is presented in the next chapter with regard to wind and solar energy policies across selected EU countries (with a special focus on Poland and Germany).

3.1. Analysis of the related peer studies on measuring performance of RE policy

As mentioned earlier in the dissertation, the general literature review presented in the previous chapter helped to categorize strands of studies which address the selected problem. Such analysis laid a foundation to find out methodological and empirical frameworks best tailored to the current research. To better understand the importance and reliability of such analysis, an in-depth review of these related studies was carried out and are presented in the following section. Later in this chapter, a detailed description of the methodological framework and data selection process is provided.

One of the most important but also challenging parts of any research is a selection of the most suitable methodological framework. Assessment of policies supporting renewables in the context of performance is no exception. In order to fulfil this task, a rigorous and overacting literature review needs to be undertaken. This part of the chapter presents an overview of the most relevant studies on which the empirical and methodological framework of this research is built.

The scope of the dissertation is also restricted mainly to the electricity market, which is the main driver of the RE deployment and greenhouse gas emission reductions. As mentioned in Chapter 1, other RE sectors like heat and transport still have a small share in the total energy mix in the researched countries. However, they could also play a vital role in the upcoming years. Since the two mentioned sectors of RE are not highlighted yet as of particular importance, this dissertation concentrates predominantly on the electricity market.

3.1.1. Effectiveness

An abundant number of methods and approaches exist as far as measuring policy performance is concerned. Considering studies reviewed in the previous chapter, it can be concluded that most of the research on effectiveness and efficiency of different RE policies applies a quantitative approach. In consideration with the literature review, one can select the following approaches to assess policies to support renewables: ex-post econometric models (e.g., *Zhao et al., 2016; García-Álvarez et al., 2017*) and multi-criteria analysis (e.g., *Winkler et al., 2018; Winter & Schlesewsky, 2019*). Also, common are case studies (e.g., *Puig & Morgan, 2013; Ciarreta et al., 2017*) or literature review (e.g., *Kabel & Bossim, 2019; Polzin et al., 2019*). Among quantitative methods, scholars usually employ regression models (*e.g., Sangroya & Nayak, 2015; Polzin et al., 2015; Kilinc-Ata, 2016; Zhao et al., 2016; García-Álvarez et al., 2017*). Also, other common methods in this area of research need to be mentioned such as equilibrium models (*Sun & Nie, 2015; Abrell et al., 2018; Özdemir et al., 2019*) and DEA analysis (*Meleddu & Pulina, 2017; Toma et al., 2017; Brzezicki & Prędki, 2018; Mezősi et al., 2018; Papież et al., 2019*).

A less popular literature stream in the context of methodology relies on the indicator-based approach. This method is considered very useful and not complicated as it has been positively reflected in a handful of studies (e.g., *Ragwitz et al., 2015; Shivakumar et al., 2019*). Before presenting a framework regarding assessment of policy effectiveness, a review of literature using a similar body of works (peer-related studies) has been undertaken. This step aims at revealing important insights, such as the benefits and disadvantages of the mentioned approach. Furthermore, the analysis of the peer-related studies also attempts to define the main features of the methodological framework.

The approach of policy effectiveness assessment, on which this dissertation is built, has its origin in a policy document presented by European Commission in 2005 (*EC, 2005*) and later in 2008 (*EC, 2008*). Other studies within FORRES (*Ragwitz et al., 2005*) and OPTRES project (*Ragwitz et al., 2007*) empirically examined policy performance of different RE technologies in selected EU member states. So, the above-mentioned studies were first to present a theoretical and empirical evaluation of RE policies with the help of the indicator-based analysis. This body of work provides a comparative empirical analysis of support policies across EU and OECD countries by employing various indicators (see Table 3.1).

Table 3.1. Indicators to measure effectiveness of RE energy policy

Indicator	Definition	Study where a given indicator was applied
Installed capacity	A maximum volume of energy (electricity) that a country, power station, etc. can generate (in MW)	*IRENA (2014a)*
Energy (electricity) generation	a volume of energy (electricity) produced in a given period (in MWh)	*IRENA (2014a)*
Policy Effectiveness Indicator	A ratio of certain RE technology generation in a given year to its realisable potential estimation in a target year (e.g., 2030)	*IRENA (2014a), Ragwitz et al. (2015); Puig & Morgan (2013) ; Klessmann (2012)*
Policy Impact Indicator	An existing progress of OECD countries to meet RE generation in future target or scenario (e.g., WEO 450 scenario 2030, NREAP target in 2030)	*IEA (2011); EEA (2014)*
Deployment Status indicator	Measures maturity of national RE markets. It consists of following benchmarks: % of RE generation in energy consumption and Policy Effectiveness Indicator and installed capacity.	*IRENA (2014a); Ragwitz et al. (2015)*

Source: Own adaptation based on sources highlighted in the table.

Since then, the given framework has become popular and been reflected in further research studies. It also became a part of a regular monitoring and assessment of RE support policies across EU countries. The framework was later used and modified in several other papers, reports, and policy documents that also speak for reliability and popularity of the given evaluation. Later studies (*Steinhilber et al., 2012*; *Klessmann, 2012; Puig & Morgan, 2013*), which used this approach didn't provide substantial updates to the mentioned indicator-based analysis. Nevertheless, due to the changing conditions of the RE market, there has been a need for further policy assessment and monitoring.

Klessmann (2012) conducted a multicriteria analysis of support schemes of various RE technologies across EU member states, in which an indicator-based approach measuring policy effectiveness and efficiency is applied. While choosing the 2003-2009 period, the author also monitored the success of researched countries in a way to achieve RE targets in 2020. An important contribution of the study is an exploration of barriers and drivers which affect deployment of renewables. General findings of the work indicate that countries which used FIT are most effective. However, the author also notes that an existence of some barriers such as rigorous administrative requirements or low degree of social acceptance tend to have a strong, but negative impact on deployment of renewables.

Some of the relevant studies also include new criteria for measuring RE policy performance, among which besides effectiveness, is efficiency. A report by *IRENA (2012)* extends the previous research on policy performance of RE sources and broadens the list of benchmarks to equity, political feasibility, and replicability. The continuation of the mentioned study was followed by *IRENA (2014a)*, which considers the approach of using multiple criteria as a useful toolkit to monitor policy performance across different countries. Even though the two IRENA-sponsored reports don't provide an empirical application, such a body of works conducts a detailed analysis of the indicator-based methodology with a strong focus on its benefits and limitations. Insights from those studies have been considered while developing a methodological framework of this dissertation. For example, for the purpose of conducting strong and reliable research, it is important to include countries that have similar geopolitical and economic aspects (a suitable example is EU member states).

Building on RE-Shaping project (*Steinhilber et al., 2012*), a later project called Dia-Core (*Ragwitz et al., 2015*) continued evaluation and monitoring of RE policy across EU member states using the similar group of indicators. By following a previous body of work, *Ragwitz et al. (2015)* highlights a comparison of policy effectiveness and efficiency of different policy instruments across selected EU countries during the 2010-2013 period. The study also introduced a composite indicator (Diffusion Indicator) on the basis of a regression model and market surveys. However, due to the complexity of the metric, it did not find any application in further empirical studies. Nevertheless, various insights have been taken from the study. One of them is that countries with more mature RE markets are usually more successful in promoting certain clean energy technologies. It was also revealed that member states in which quota policies are dominant are especially effective in deploying wind energy.

Nowadays, most governments employ more than just one support policy tool. A special feature of the peer-related works (see *Steinhilber et al., 2012; Klessmann, 2012; Ragwitz et al., 2015*) is an assumption that a dominant RE instrument(-s) accounts for the whole impact on RE deployment. For example, feed-in tariffs and premiums (FIT) had been the main policy mechanism in Germany during a long period until recently, while other tools like tax incentives were also present (however they are considered not to be dominant). Since it is a very complex task to quantify a separate impact of a respective policy instrument, this dissertation also adheres to the assumption of the previously mentioned body of work. In this case, assessment of policy performance concerns a dominating support scheme, or a combination of a few main support instruments implemented in a selected country.

The dissertation also refers to some extent to a book by *Mir-Artigues & del Río (2016)*, as it analyses similar approaches to find the most common criteria to measure RE policies. Also shown are studies that address the issue of measuring policy effectiveness and could be divided into two groups, whereas both criteria are calculated either against policy targets or techno-economic potential. Furthermore, *Mir-Artigues & del Río (2016)* emphasize the importance of using an indicator-based framework based on techno-economic potential, as such an approach provides a better interpretation of policy performance. The conclusion drawn points out a high importance of assessing support policy in a holistic manner. This thesis is in line with such a statement as a more in-depth analysis of the aspects of RE policy (e.g., status of wind and solar development, presence of support instrument, their performance, and effects) yields stronger results. Against this background, it is also agreed that a few-tier research[17] addressing different dimensions and elements of RE policy can bring the highest-quality assessment.

The most recent work this dissertation is built on in terms of policy effectiveness is an empirical study (*Shivakumar et al., 2019*), which takes an interesting approach by measuring the past and future trends of RE deployment in selected EU member states. This study includes ex-post and ex-ante analysis aiming at identifying factors which accelerate or impede the deployment of renewables. The author strongly relied on the above-mentioned body of work, and applied a modified indicator for measuring policy effectiveness simply called 'Deployment Indicator'. For identification of past trends, a simple indicator - net installed capacity in electricity sector is also employed in the study. It should be pointed out that that only indicator-based approach and identification of factors impacting RE deployment do not constitute a robust research framework. That is why they performed additional meta-analysis of popular scenarios to evaluate how close some selected EU countries are in meeting their RE targets in 2020. This study also reveals that the presence of some policy instruments (e.g., FIT) as well as various factors like social acceptance tend to strongly affect policy effectiveness. As also marked in the study, the global economic crisis in 2007-2008 and the Fukushima nuclear disaster had a negative impact on deployment of renewables across EU member states.

There is also another strand of literature (*EC, 2007; IEA, 2011; EEA, 2014*), addressing a similar toolkit of performance indicators. Its main difference to the framework presented in the projects mentioned above (*Steinhilber et al., 2012*; *Klessmann, 2012; Ragwitz et al., 2015*) is that policy effectiveness is measured against reference values such as RE targets and scenarios. On the basis of the already mentioned Policy Effectiveness Indicator (PEI) (*IEA, 2011*) created a Policy Impact Indicator (PII), which measures existing progress of OECD countries in meeting RE generation in WEO 450 scenario 2030. Also, *EEA (2014)* follows this body of works by applying PII to assess policy effectiveness in selected EU countries in years 2006–2011. However, instead of 'scenario' category, the authors used targeted amount of a

[17] In this case, it is measuring RE policies with help of effectiveness and efficiency benchmarks.

certain RE technology in years 2020 and 2030 (which is set in countries' NREAPs) as a reference benchmark. That approach is not suitable for this thesis, as it has some limitations. On one hand, a lack of data and transparency in methodology is pertaining to research with scenario and pathway analysis. On the other hand, an approach which uses national RE targets doesn't account for a factor of ambitiousness of different countries. That's why, while measuring policy effectiveness, the author of the thesis opts for an indicator-based approach where techno-economic potential as a reference benchmark is applied that aims at overcoming those limitations.

It can be concluded that, even though a great deal of literature has discussed the issue of RE policy effectiveness, not many studies provide inclusive and comprehensive outcomes. There are also not many peer studies which assess policy performance in a reliable, systematic, and continuous manner. Based on these principles, PEI was selected as part of the methodological framework to measure policy effectiveness, which has been described in detail in the Section 3.2.

Many scholars emphasize that measuring effectiveness of certain policies supporting renewables is of high importance (e.g., *Romano et al., 2017; Polzin et al., 2019*). However, measuring effectiveness alone cannot be the main the goal of empirical research (*Choi et al., 2018*). The profound review of studies[18] shows that effectiveness and efficiency are two main criteria used by scholars in measuring performance of wind and solar energy support policies. As already mentioned, most literature concentrates on the quantitative methods to measure effectiveness of RE policy. Also, as acknowledged by some scholars (e.g., *Ragwitz et al., 2015; Shivakumar et al., 2019*) combining it with other criterion can deliver more valuable outcomes of the research. By following a number of studies (e.g., *Ragwitz et al. 2015; Winkler et al., 2018*) this research also employs an effectiveness-efficiency interplay to measure performance of RE policy. The synergy of the both approaches could contribute to the literature by delivering a reliable, state-of-the-art, comprehensive research. The next section provides a detailed analysis of studies which applies the DEA method to measure policy efficiency.

3.1.2. Efficiency

A literature review conducted in the previous chapter revealed that most studies are restricted in scope as their focus lies on economic performance of a particular RE policy instrument or policy in general. Also, the methodological framework, based on an indicator-

[18] A comprehensive literature review on effectiveness and efficiency is performed in chapter 2.

based approach, provides important but also limited insights into how RE policy performs. With consideration of this issue, this dissertation overcomes this limitation, as an attempt is made to fill the gap by also carrying out research which, besides policy effectiveness, also includes a criterion of efficiency.

As already mentioned in Section 2.3 of previous chapter the definition of efficiency is adhered to which can be relevant to measuring performance in different aspects (dimensions). Based on the purpose of this work, efficiency or technical efficiency is defined as the best possible production amount (output) of certain components (DMUs) received from a given subset of inputs. Actually, the novelty of such an approach is that it goes outside mainstream economic or energy dimensions. By measuring policy efficiency with the help of the DEA approach, another goal of this dissertation is reflected which also controls for other aspects such as environment, energy security or employment. By using this method, efficiency scores can be estimated across researched countries as one can also provide explanations for the results obtained.

Therefore, the novelty of this research lies in measuring the efficiency of wind and solar energy policy in context of multiple dimensions and variables used in the DEA model. It is perhaps the first empirical study to use a set of input variables among, which are subsidized amount (cost of policy) and installed capacity of wind and solar energy technologies. Moreover, an unusual output variable is taken in the form of direct and indirect jobs (dimension of employment) in wind and solar power sectors. A detailed description of relevant variables and data sets has been conducted in Section 3.4 of this chapter.

There is an extended literature on the DEA approach to measure economic efficiency of RE sources in general (*Woo et al., 2015; Moutinho et al., 2018; Fidanoski et al., 2021*; *Kara et al., 2021*) or in the context of individual technologies (*Sueyoshi & Goto, 2014; Li et al., 2017; Mezősi et al., 2018; Papież et al., 2019*). However, only a small but increasing number of studies employ this method to assess policy performance (efficiency) of certain clean energy sources. Most of these works[19] have been published during last few years that reflect not only a growing role of RE development, but also policy measures supporting them.

As a classic DEA energy efficiency approach uses a simple input-output relationship in the context of production (*Charnes et al., 1978*), later studies usually included aspects such as energy and environment, which even established a separate literature stream, called eco-efficiency (e.g., *Woo et al., 2015; Moutinho et al., 2018; Czyżewski et al., 2020*). Recent

[19] All these studies have been analysed below in the section.

literature on this method has been dominated by studies which use multiple aspects (dimensions) (e.g., *Papież et al., 2019; Kara et al., 2021*). For example, besides economic and environmental parameters, they also measure efficiency of renewables through energy security or technology dimensions.

Table 3.2. Summary of relevant studies using DEA approach in RE policy

Author (s), year and reference	**Method**	**Scope (researched period)**	**Technology scope**	**Variables**	
				Inputs	***Outputs***
Papież et al. (2019)	Bias-corrected DEA, regression	EU (2015)	Wind	Capacity installed, average power density	Power generation, economic, energy security, environmental indicators
Mezősi et al. (2018)	Output-oriented CCR model, indicator-based analysis	Selected EU countries (2015)	Wind and solar	Cost-effectiveness indicator, LCOE	Share of wind, solar and RE
Sueyoshi & Goto (2014)	Input-oriented BCC DEA	Germany and United States	Solar	Insolation, PV modules, land area	Annual power generation, Installed capacity
Meleddu & Pulina (2017)	BCC DEA, regression	21 Italian provinces (2003-2010)	Solar, RE	R&D expenses, other expenses, radiation protection expenses, electric power consumption	PV power, renewable energy)
Park & Kim (2018)	Panel DEA approach and MI (Malmquist Index)	South Korea (2009-2013)	RE	Investment in dissemination (policy support subsidies) and technology (R&D)	A number of companies and jobs, volume of power production
Chachuli et al. (2021)	Output-oriented CCR model	Malaysia (2012-2017)	RE	Publications, graduates with minimum master's degree, patents, and electricity prices	Installed capacity

Notes: BCC - Banker-Charnes-Cooper, CCR - Charnes-Cooper-Rhodes, R&D - research and development.

Source: Own adaptation based on sources highlighted in the table.

Even though assessing efficiency of clean energy technologies with help of DEA analysis is popular among scholars, not many studies use this methodology to assess RE support policies (*Sueyoshi & Goto, 2014; Meleddu & Pulina, 2017; Mezősi et al., 2018; Park & Kim, 2018; Papież et al., 2019; Chachuli et al., 2021*). All relevant empirical works on this topic are summarized in Table 3.2. Reference is made to a study by *Mezősi et al. (2018),* which applies a panel DEA analysis in measuring wind and solar power policy in selected EU countries. The authors employed a 2000–2015 dataset to assess how efficient wind and solar electricity policies are from an economic point of view. The study applies a cost efficiency indicator as an input variable, which is calculated based on a country's financial capabilities. Besides measuring economic efficiency, the authors also employed a technology aspect presented by the resource endowment of a given RE technology in selected countries. This parameter is already incorporated as another input variable presented by LCOE (levelized cost of electricity). A share of wind, solar and total renewable electricity are among output metrics. It is interesting to note that the study covers different research areas. For example, a cross-country comparative analysis is carried out based on the criterion of a 'first mover' status in the context of supporting RE technologies. Other research addresses the impact of financial budgets of selected countries on RE uptake. As a result, both factors tend to have a strong positive impact on deploying wind and solar energy sources. Other general insights indicate that the decreasing cost of capital and interest rates positively affects the diffusion of mentioned technologies.

Due to some research similarity, another study by *Papież et al. (2019),* was followed which evaluates the efficiency of investment in wind power in 2015 across multiple EU countries. The study takes on a two-tier approach, which consists of a bias-corrected DEA analysis by *Simar & Wilson (2007)* and a truncated bootstrapped regression model. The authors used a technology aspect as an input variable in the DEA model: capacity installed, and average power density (both refer to wind energy). The research expands behind standard economic efficiency, as it also employs environmental and energy security dimensions with corresponding indicators as output variables. For better interpretation of the results, a regression model is set up to also evaluate the effects of different wind energy policies, energy mix, and wind power utilization on efficiency of this clean energy technology. Strong evidence could be drawn from the study, as the authors provided a detailed cross-country analysis of efficiency levels within the already mentioned dimensions. In general, wind power deployment brought benefits in terms of environmental aspect, while also improving energy security of researched EU countries. However, as for RE support instruments, no clear evidence is obtained. For example, positive association is noticed in the case of FIT policies, while a negative result on wind power investment is extracted for quotas.

By formulating a methodological framework based on a DEA framework, some valuable insights were also taken from other academic works on RE policy performance (efficiency). One of them is a case study by *Sueyoshi & Goto (2014)*, which employs the mentioned method to investigate efficiency of solar power stations in Germany and the USA. Another goal of this study is to present a comparative analysis of national policies to support solar electricity across mentioned countries. The authors used next input data: insolation, average annual sunshine, solar modules, and land area. Among outputs installed capacity and generation from solar power are employed. The results indicate that German solar power stations are more successful in terms of efficiency, while the USA would be more effective if the country implements FIT by an example of the mentioned EU state. However, the authors also have some restraints, as the German system of FIT is characterized by a strong financial burden lying on taxpayers.

Meleddu & Pulina (2017) explores efficiency of a public spending in 21 Italian provinces during a 2003-2010 period. The study employs a panel DEA and bias-corrected DEA approach (*Simar & Wilson, 2007*) by using various public expenses (e.g., research and development -R&D) as inputs and renewable and solar power generation - as outputs. Additional research was performed to find out how factors like real gross domestic product (GDP), population density and qualifications in technical degrees influence performance of renewables in the selected country. The results show that Southern regions are more efficient as far as public expenditures in RE is concerned. Other important evidence indicates that GDP and high-quality technical skills of employees have a strong impact on the efficiency of the RE sector.

Park & Kim (2018) used a panel DEA approach and Malmquist Index[20] (MI) technique to measure performance of national RE policies during the period of 2009 and 2013 in South Korea. The main goal of the study was to compare transition effects taking place as a result of a replacement of FIT scheme (which ended in 2012) by a new RPS policy. As for the DEA model, it includes the following input parameters: investment in dissemination (policy support subsidies) and technology (R&D) of various RE sources (wind, photovoltaic, solar heat, geothermal, bioenergy and fuel cells). The outputs are a number of companies and jobs, as well as a volume of power production. The authors concluded, that in general, a shift from FIT to RPS led to a lower efficiency of the new policy instrument (which is RPS). The same conclusion was drawn for solar and wind power. However, RPS brought about a positive effect after the transition period, as a result of a better utilization of the technology aspect (R&D).

Chachuli et al. (2021) investigated the efficiency of R&D policy instruments in Malaysia using a dataset of 2012-2017. The empirical work employs a DEA approach and measures the potential effect of the FIT instrument on various RE sources. Among input variables are publications, graduates with minimum master's degree, patents, and electricity prices, while as output, installed capacity is presented. As a result, R&D policy is the most inefficient in case of wind energy, while hydro energy gets the best performance score. Other

[20] Malmquist Index (MI) is a special dynamic linear programming method based on input-output relationship technique, which allows to compare efficiency changes within different periods.

evidence suggests that FIT can boost development of the RE market in the analysed country while having a strong positive impact on R&D.

Hence, the comprehensive review of the literature presented in the previous chapter and in-depth analysis of relevant studies in this section helped to select out research patterns, methodology specifics and variables, which can be tailored to measure effectiveness and efficiency of wind and solar energy support policies. In line with the mentioned literature analysis, a two-tier methodology was selected to assess performance of mentioned policies: an indicator-based framework (effectiveness) and DEA analysis along with regression (efficiency).

A literature review of the peer-related studies on measuring effectiveness and efficiency of RE policy also shows that many attempts have been made to create and constantly improve the indicator-based and DEA methods that would consider differences between countries in terms of a heterogeneity of various components (e.g., techno-economic potentials or financial capabilities). Given the fact that the mentioned frameworks used in the reviewed studies show importance and robustness of such analysis, they also form a comprehensive research in the context of policy assessment especially important in the light of dynamic field of policy regulation and the RE market.

3.2. Indicator-based approach of policy effectiveness

As the author builds on a body of works from the previous section, an extended and improved version of the indicator-based and DEA approaches has been presented and applied in this dissertation to assess the effectiveness and efficiency of wind and solar energy policy across selected EU countries with a strong focus on Poland and Germany. While presenting the framework in this section, the focus is placed on characteristics, benefits, and limitations of the mentioned methods. As already emphasized, a combination of both approaches for the purpose of a more comprehensive and robust research has been selected.

The literature review conducted in Chapter 2 shows that scholars usually use a cross-country approach in measuring policy performance. A comparative analysis between countries is more successful when they have some common geographic, political, social or economic background (*IRENA, 2014a; Shivakumar et al., 2019*). Popular among scholars is research which includes groups of countries like OECD or EU member states. Such cross-country analysis is especially suitable for the indicator-based approach which is described in this section.

In order to provide a cross-country comparison, European Commission (*EC, 2005*) created its own approach to measure performance of policy support called 'Policy Effectiveness Indicator' (PEI). As some earlier studies, like *Ragwitz et al. (2005)* measured policy effectiveness against a country's target regarding particular RE technology during a given year, later works (*Ragwitz et al., 2007; EC, 2008*) employed a category of realizable potential as a reference benchmark instead. Since then, this indicator was updated moderately and integrated into the framework of further EU-funded projects like RE-Shaping (*Steinhilber et al., 2012*), Dia-Core (*Ragwitz et al., 2015*) and one UN-sponsored project (*Puig & Morgan, 2013*). This body of work defines PEI as a relation of a yearly growth in the production of a certain RE technology to its remaining techno-economic (realizable) potential. A year by which this potential is measured in later studies has been updated from 2020 to 2030 due to the fact of approaching of new time horizon (see *Ragwitz et al., 2015*).

Building on the previous body of works (e.g., *Ragwitz et al., 2015; Shivakumar et al., 2019*), some changes in an approach to the category of 'potential' were also made. As observed by *IRENA (2014a)*, values of PEI can vary substantially across different countries based on the stage of RE technology development (diffusion). For example, an effectiveness rate increases when technology costs start to decline substantially and, later when the market gets saturated, the value of the PEI can decrease sharply. To correct results for bias, cumulative values of PEI outcomes have been estimated, while the analysis, which considers different stages of technology diffusion, has also been performed in the dissertation. The results on PEI across selected EU countries are presented in Chapter 4.

In a resent empirical work by *Shivakumar et al. (2019)* a modified metric has been developed and called 'Deployment Indicator'. The technique of the indicator is very similar to the PEI approach covered in the previous body of works. The main difference lies in the reference value, which in the case of the newer study, has a techno-economic potential by 2050. The authors of the work extracted data on the potential for EU countries from a report EU Reference Scenario 2013 (*EC, 2014*). In line with *Shivakumar et al. (2019)*, a 2050-time span for the techno-economic potential was also chosen for this study. Against this background, the selected period would fit better into the ongoing analysis, as the year 2030 is approaching.

In line with other studies (e.g., *Ragwitz et al., 2015*), it is agreed that the rationale behind choosing PEI lies in the fact that it measures policy effectiveness across heterogenous states with different size of territory, economy, starting level of RE market, as well as policy priorities and ambitions. In addition, its scope is a group of countries which can be compared in terms of their homogeneity (e.g., EU member states or OECD countries). Furthermore, the indicator has been continuously employed by scholars and reflected in multiple projects and reports related with EU and international organizations. Actually, reliability and continuity of research in the area of the indicator-based framework serves as another reason for its application in the current study. Therefore, the updated formula applied in this dissertation for Policy Effectiveness Indicator (PEI) is described as follows:

$$PEI_n^i = \frac{Q_n^i - Q_{n-1}^i}{TEP_{n-1}} \qquad (3.1)$$

where: PEI_n^i – Policy Effectiveness Indicator for a selected RE technology in year *n;* Q_n^i - renewable electricity of a selected RE technology (here wind or solar electricity) in year *n*; TEP_n - Additional techno-economic potential[21] (of electricity generation) in year n until 2050.

The general advantage of the PEI is that by incorporating a reference value 'additional techno-economic potential', it provides unbiased information on the effectiveness of a certain support policy (*Ragwitz et al., 2015; Mir-Artigues & del Río, 2016*). It is beyond the scope of the dissertation to analyse the different modelling approaches to calculate potentials of RE sources. However, the main categories and definitions of potentials are presented in Table 3.3.

Table 3.3. Types of potentials of RE sources

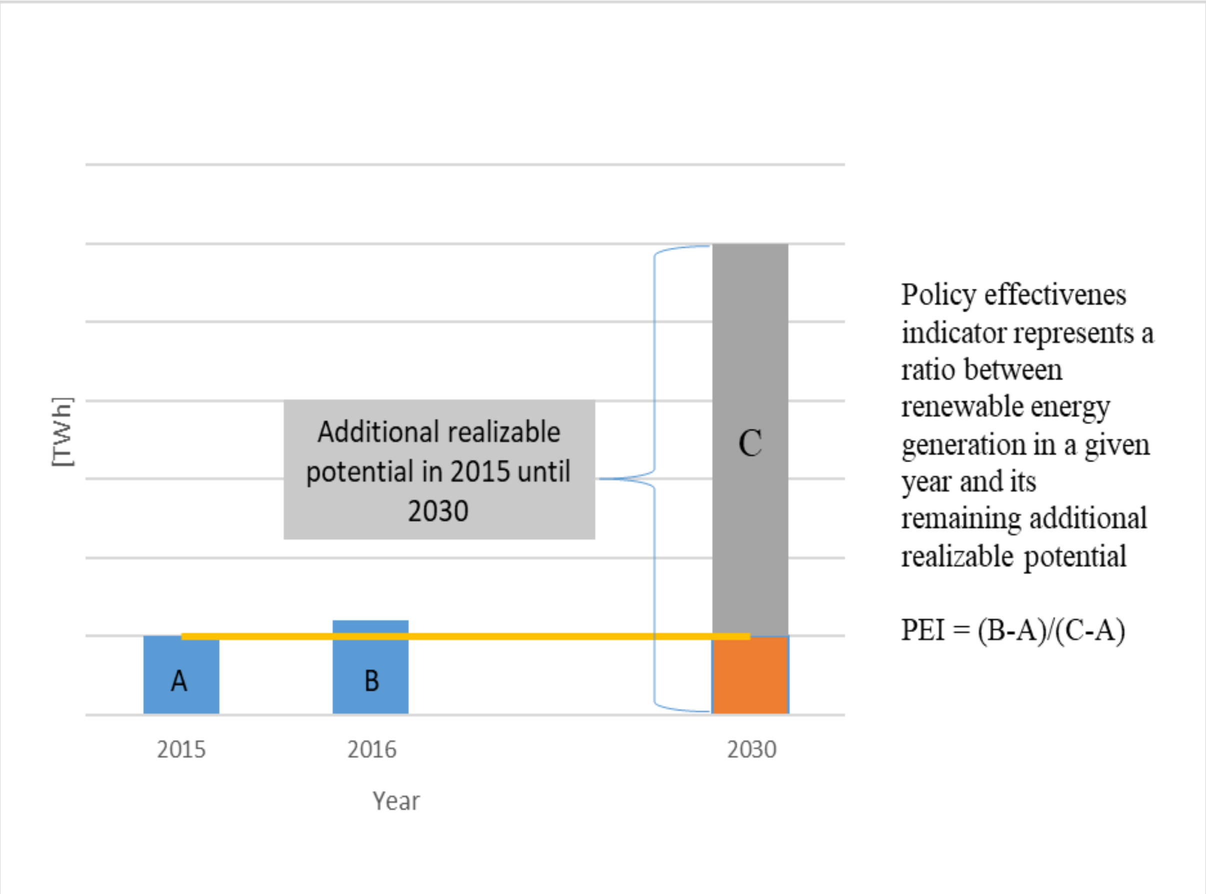
Types of potential	**Definition**
Theoretical	the physical amount of maximum available resource of a certain energy technology at a given location.
Technical	a part of theoretical potential which accounts for a possible extraction of a given energy source under certain conditions (e.g., available land for wind turbines or R&D status in a country)
Realizable (techno-economic)	the part of a technical potential which is achievable if all existing policy barriers can be overcome, and all driving forces are active. The realisable potential is time-dependent, i.e., it must relate to a certain year. In the long run, the realizable potential tends towards the technical potential as non-economic barriers are gradually overcome.
Economic	the part of the realizable potential that can be produced profitably without the need for government support, i.e., the amount of renewables production with a cost of production that is competitive with existing conventional non-renewable technologies.

Source: According to *Puig & Morgan (2013); Ragwitz & Steinhilber (2014); Resch et al. (2016).*

[21] *Ibidem*

In reality, measuring techno-economic (realizable) potential faces a large number of difficulties. Such assessment is based on a compound calculation of different technical and economic aspects of the energy market. Very often, in order to estimate potential levels, a complex modelling of technological and innovation learning, investor behaviour, prices and other categories are conducted. Furthermore, for assessing a realizable potential, projected levels of deployments and different technical constraints have to be considered. According to *Puig & Morgan (2013, p.16)* a realizable potential is estimated "based on a long-term view of the technical potential, adjusted to take account of unavoidable medium-term constraints". The estimates on realizable potential for each renewable energy technology rely strongly on a resource endowment in a certain country and expected development of an RE technology. An example of measuring PEI, in which realizable potential is employed, is described in Figure 3.2.

Figure 3.2. An example for calculating the Policy Effectiveness Indicator



Source: Adopted from *Ragwitz et al. (2015).*

Another important feature of such indicator-based method concerns assessment of the RE policy as a total rather than a particular policy instrument (e.g., a tender). This means that even though a country has multiple support schemes at its disposal, the whole effect from promoting renewables is being granted only to the main (dominant) policy instrument (-s). Such a holistic approach is rarely common in the literature of energy economics, as most of the studies address a single policy instrument or some elements of policy design (e.g., rate of FIT). As already noted in previous sections, the body of empirical works (*Steinhilber et al., 2012; Puig & Morgan, 2013; Ragwitz et al., 2015; Shivakumar et al., 2019*) is followed in the ongoing research as this study addresses the performance of the dominant policy instrument (-s) across analysed countries.

Despite the attractiveness of PEI, it also has some limitations. As noted by *Puig & Morgan (2013)*, the indicator does not account for an aspect of innovation progress which develops differently in various countries. Another restriction of the PEI is that estimation of a realizable potential is provided by a separate and neutral entity, indicating the subjective evaluation. The data on the potential can also lead to a sensitivity of the indicator: the higher value of potential means the lower policy effectiveness and vice versa (*Klessmannn, 2012*). However, as for the data on the potential, it has been continuously monitored and updated in popular databases like *Green-X* project and later in *EU Reference Scenario (2020)* database that indicates a strong reliability of the data.

As mentioned above, PEI doesn't account for some important factors. Despite these limitations, it is concluded that they are not significant. Furthermore, there is a consensus in literature (*Mir-Artigues & del Río, 2016; Shivakumar et al., 2019*), that measuring policy effectiveness with help of the PEI can be a very useful approach. Also, the research that includes such an effectiveness-based approach is very often complemented with other criterion like efficiency (*Steinhilber et al., 2012; IRENA, 2014a; Ragwitz et al., 2015; Winkler et al., 2018*). Such a combination aims at enriching research by providing more insights for policymakers, whereas effectiveness and efficiency are closely related and when assessed together, provide a broader picture of policy performance.

To conclude, an indicator-based approach to measure effectiveness of RE policies of the EU member states was systematically employed by scholars in a period between mid-2000s and 2015. Only one empirical assessment has been carried out during the last few years (*Shivakumar et al., 2019*). By taking into consideration the importance of previous evaluations and a lack of research on the given problematic in recent years, the framework has been improved upon which can also be applied in further studies.

PEI is a well-tailored tool to conduct a comparative analysis of policy effectiveness across different countries. Continuous utilization by scholars, easiness in estimation and availability of data are among the major advantages of this method. Also, use of a realizable techno-economic potential as a reference benchmark increases the value of the approach. Against this background, PEI has been employed as the first part of the ongoing research to evaluate effectiveness of wind and solar energy policies of selected EU member states.

Despite being frequently used and positively highlighted by some scholars, it has some limitations. Worth mentioning is also the fact that the use of the PEI to measure the degree of policy success doesn't answer the question of why it is effective or not. Furthermore, countries with stronger financial capabilities usually deploy renewables faster. This means that measuring effectiveness alone doesn't answer an important question if their policies promote renewables in the most optimal (efficient) way. Against this background, the literature (*Ragwitz et al., 2015; Mir-Artigues & del Rio, 2016; Shivakumar et al., 2019*) agrees that such an approach should be combined with other assessment criterion like efficiency.

The second part of the research, which employs the DEA method, aims to solve the mentioned limitations as it provides insights into ranking of EU states with most and least efficient wind and solar energy policies. Furthermore, an efficiency framework is applied which also integrates the DEA method with regression analysis. Such a combination aims to help find out why some countries are successful or not in deploying researched clean energy technologies. Similar to effectiveness, the second part of the study based on efficiency relates strongly to Poland and Germany, as a comparative analysis of support policies against other EU member states was conducted.

3.3. DEA method of policy efficiency

The speed of RE market development and growing significance of technologies like wind and solar energy has also influenced the research approach and methodology employed by scholars to measure their performance. While earlier strands of literature usually addressed market growth or technology cost estimation (e.g., *Puig & Morgan, 2013; Ragwitz et al., 2015*), more recent studies evaluate performance of RE sources also in terms of other dimensions of RE sources, like social aspect (e.g., *Mezősi et al., 2018*; *Park & Kim 2018*; *Kara et al., 2019*). In this context, the DEA framework serves as a very suitable tool to empirically assess energy performance (efficiency) from different perspectives.

A consensus coming from the reviewed literature was considered, which includes a recommendation of using a more comprehensive methodological and empirical framework. That is why instead of taking simple metrics for measuring performance, a more sophisticated approach was employed in this thesis with a purpose to assess policy efficiency with the help of DEA methodology. Scholars often use DEA method to measure performance of different energy sources from an economic perspective while also controlling for environmental parameters (e.g., *Woo et al., 2015; Moutinho et al., 2018*). As the former addresses cost and profits coming from investment in RE, the latter usually concerns the fact of how various projects based on clean energy technologies contribute to the reduction of CO_2 emissions.

A recent trend shows that studies which employ DEA analysis usually encompass more dimensions to assess RE technologies, whereas their assessment doesn't end up in finding evidence only from economic or environmental dimensions. The DEA approach employed in this research was also extended by going outside the framework of evaluating RE support policies from a perspective of development (energy generated or capacity installed). It is in line with recent empirical studies (*Mezősi et al., 2018; Park & Kim., 2018; Kara et al., 2019; Papież et al., 2019*), which also control for other important categories such as environmental, social, and energy security components.

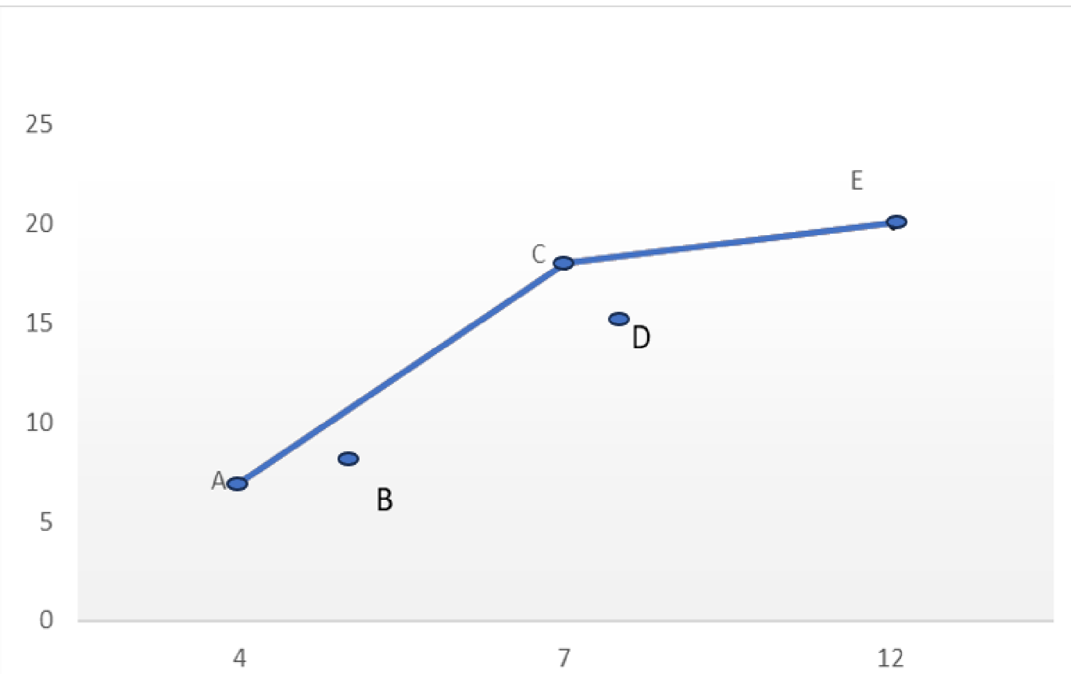
In a broader aspect, a development and promotion of RE sources leads to positive effects on ecology, contributes to a growth in high-qualified employment, helps countries diversify energy resources, and diminishes dependence on energy imports. Given global challenges like climate change and air pollution, environmental dimension is very often discussed and empirically utilized in literature of energy efficiency. Other category economists assign a significant role, which is a creation of new jobs, serves as an important barometer of countries' economic activity. Last but not least important is the energy security component. Given the current status of many countries in terms of energy dependence on autocratic regimes, the value of this category cannot be overestimated. All these mentioned dimensions have been employed in the ongoing research, in which DEA method is applied.

As for a DEA approach, it takes its roots back to 1978 (*Charnes et al., 1978*), becoming a popular framework to measure efficiency in different areas. Since then, the method was often employed in a field of economy, environment, medicine, agriculture etc. DEA framework stems from microeconomics theory of production with simple input-output ratio. It is a type of a non-parametric frontier methodology which includes optimal production-possibility frontier serving as a proxy for other parameters (*Papież et al., 2019*). Unlike parametric approaches, this model doesn't frame a specific input-output relationship (*Toma et al., 2017*), whereas it estimates relative efficiency of so-called decision-making units (DMUs), defined as homogenous systems[22] (*Park & Kim, 2018*) or peer objects (*Mardani et al., 2016*), which convert input resources into outputs. Wind and solar energy policies across the researched countries are considered as DMUs in this dissertation.

There are no specific guidelines in choosing a number or weights of inputs and outputs in DEA analysis (*Moutinho et al., 2017*). Furthermore, the incomplexity of this method and no necessity to set up assumptions means that it became very popular among scholars (*Toma et al., 2017*; *Chachuli et al., 2021*). Another important point of this method is that DMUs with lower scores can take guidance from the most efficient units in order to increase their performance (*Toma et al., 2017; Simar & Wilson, 2007*). DEA is especially suitable for analysis with a small amount of DMUs during a short term period (*Park & Kim, 2018*).

A simple illustration of DEA efficiency is presented in Figure 3.3. Points A, C and E are the best production possibilities, delivering most outputs from given inputs and are technically laid on an optimal frontier. Their values get maximum values (each equalling 1) and constitute most efficient combinations. All other points (e.g., B and D) are placed below the frontier (with their values lower than 1) and are considered not to be efficient.

Figure 3.3. Illustration of standard DEA efficiency based on example



Source: Own adaptation.

[22] DMUs in this study are RE support policies.

In general, the DEA model can be input or output – oriented. The former includes a proportional decrease in inputs leaving outputs unchanged. The latter focuses on maximization of proportional increases in outputs, while inputs remain constant (*Papież et al., 2019*). The literature also selects two popular methods of DEA framework: Charnes-Cooper-Rhodes (CCR) (*Charnes et al., 1978*) and Banker-Charnes-Cooper (BCC) (*Banker et al., 1984*). The difference between both models lies basically in a category of returns to scale (RTS), which is static under CCR and variable under BCC. *Banker et al. (1984)* improves on a framework by *Charnes et al. (1978)* on two main points. First, the BCC model allows for the identification of reasons behind low efficiency levels. Second, benchmarking efficiency under this model controls for scale effect and measures pure technical efficiency (PTE). This implies that one additional unit of input doesn't lead to a proportional production of one additional unit in output (as in the case with CCR or constant returns to scale).

An input-oriented BCC DEA model is employed in order to find out how successful countries are in realization of their wind and solar energy policies X (presented in this research through input parameters like the amount of financial support and installed capacity) in different output components Y (power generation, employment, environmental and energy security indicators)[23]. The input-oriented BCC DEA framework applied in this thesis is as follows:

$$\theta^* \rightarrow min,$$

Subject to:

$$\sum_{i=1}^{n} x_{ij}\,\lambda_j \leq \theta x_{i0},\ i = 1,2,\ldots,m, \qquad (3.2)$$

$$\sum_{i=1}^{n} y_{rj}\,\lambda_j \leq y_{i0},\ \ r = 1,2,\ldots,s,$$

$$\lambda_j \geq 0,\ \sum_{i=1}^{n} \lambda_j = 1$$

where θ - a DEA efficiency score; *n* - an amount of DMUs; *m* - an amount of inputs, *s* - an amount of outputs; x_{ij}- a sum of ith input parameter, which is converted into jth output; y_{rj}- a sum of rth output, which is generated from jth DMU; The model controls for a variable return to scale (VRS) effect, as it is characterized by a convexity constraint ($\sum_{j=1}^{n} \lambda_j = 1$) (see *Papież et al., 2019*).

[23] More information about selected DEA input and output variables is provided in Section 3.4.2.

Efficiency scores or relative efficiency (θ) presented in DEA models are calculated as a ratio of total weighted inputs to their outputs. Their values may vary between 0 and 1 (*Mardani et al., 2016; Moutinho et al., 2017*). The DMUs, which take the score lower than 1 means that the use of the inputs is not efficient (*Moutinho et al., 2017*). Countries with the best possible policies get a score of 1, which is graphically located on the optimal frontier. Given the purpose of this dissertation, a comparative analysis in terms of efficiency across analysed countries implies that DMUs (here wind and solar energy policies) are compared and ranked from least to most efficient (see *Mezősi et al., 2018* and *Papież et al., 2019*).

Some scholars (e.g., *Mezősi et al., 2018*) acknowledge the fact that policy efficiency should be assessed from different perspectives, as the DEA framework can deal with problems of the multidimensionality. In a similar way to an indicator-based approach, the DEA method proved to be useful while carrying out a comparative efficiency analysis of clean energy sources across different countries which belong to one group with similar economy characteristics (e.g., EU or OECD) (*Moutinho et al., 2017; Mezősi et al., 2018*). Furthermore, the method is well compatible with the power sector, which presents homogenous metrics of electricity production (*Mezősi et al., 2018*). In general, some scholars (e.g., *Moutinho et al., 2017*) point out that such a framework is especially suitable for a comparative analysis, where various parameters within different dimensions are employed. Despite the fact that DEA is considered to be quite flexible approach, there is one theoretical principle often cited by scholars (see *Wu et al., 2016*), which says that the triple sum of input and output variables cannot be larger than the amount of observations (DMUs): $n > 3 (m + s)$.

The goal of this research based on the DEA approach is to conduct a comparative analysis of efficiency levels of wind and solar energy policies across selected EU states. The framework provides valuable insights by not only presenting a cascading list of best and worst performers (*Sueyoshi & Goto, 2014*), but also sketches the length of a certain policy to the frontier, which is the most efficient (*Mezősi et al., 2018*). Despite being frequently used and positively noted by scholars, the DEA model also has some limitations. One should note that the method contains estimations on efficiency scores which are relative (not absolute). As marked by *Toma et al. (2017)* DEA doesn't control uncertainty, as it omits important parameters like stochastic error, confidence intervals, or tests statistics. The method is very sensitive to input and output values, as some little discrepancy in data could lead to misleading results (*Sağlam, 2017*). It is important to note that the model cannot accept zeros. However, scholars usually replace them with very small entries in order to solve this problem (*Ibidem*).

Considering these caveats, a bias-corrected DEA method based on *Simar & Wilson (2007)* procedure is employed in this study. Preliminary research with help of standard DEA has been also conducted in this study with the main goal of comparing results with bias-corrected estimations. The both methods belong to category of an input-oriented BCC DEA model described in Equation 3.2.

Some scholars (e.g., *Toma et al., 2017*) indicate that a traditional analysis, which only includes standard DEA efficiency estimations, could yield inconsistent and weak results. For the purpose of overcoming this caveat, a DEA approach by *Simon & Wilson (2007)* was partially employed, which controls for bias and uncertainty. The methodology framework within this approach to assess policy efficiency consists of two steps. The first one is based on the bias-corrected DEA method and homogenous bootstrap algorithm. A large advantage of bootstrapping is that it helps check the accuracy of the results by correcting DEA efficiency estimations (*Toma et al., 2017*; *Papież et al., 2019*). Additionally, the parametric bootstrap develops confidence intervals for regression variables and variance of the error term distribution (*Toma et al., 2017*). Such an approach incorporates a suitable estimator of the actual unspecified sampling distribution (*Ibidem*). A second step of this procedure includes a truncated bootstrapped regression which employs alternative variables to test robustness and effect relationships of efficiency results.

This study on policy efficiency strongly relies on bias-corrected DEA analysis, which is the first step of procedure described by *Simon & Wilson (2007).* A bit modified approach is taken when the second step of this algorithm is concerned as a standard instead of truncated regression model is employed. Next section highlights methodological aspects of applying regression approach in the ongoing research.

3.4. Regression approach to measure external factors on policy efficiency

As mentioned, the main difference to the approach applied in this study and a procedure introduced by *Simar & Wilson (2007)* is that a standard regression model is employed instead of truncated one. Since the aim of this research is to employ bias-corrected efficiency scores into regression analysis, there is no need to revert to an additional procedure of bootstrapping. Against this background, a standard regression approach is used in order to evaluate the impact some selected external factors could have on policy efficiency.

While there is an emerging consensus that national RE policies strongly contributed to the development of renewables, they have also played leading roles in the energy transition process (*Ragwitz et al., 2015*; *Li et al., 2017; Shivakumar et al., 2019*). A category, which is in a strong focus of scholars and decision makers, relates to policy instruments (*Li et al., 2017; Shivakumar et al., 2019; Anguelov & Dooley, 2019*). As already highlighted in the Chapter 2 of the thesis, resource endowment also plays an important role in deploying renewables. Especially, wind and solar energy potentials serve as solid factors which determine the progress of countries in terms of these clean energy technologies. In this context, a regression model is employed to evaluate the effects of the main policy instruments and RE resource endowment on the efficiency of wind and solar energy policies across EU member states. Two primary equations of regression are introduced for wind and solar energy policies:

$$\theta\_W_{it} = FIT_{iw} + QUOTA_{iw} + TNDR_{iw} + TAX\_INV_{iw} + \ W\_speed_i \qquad (3.3)$$

$$\theta\_S_{it} = FIT_{is} + QUOTA_{is} + TNDR_{is} + TAX\_INV_{is} + \ PV\_potential_i \qquad (3.4)$$

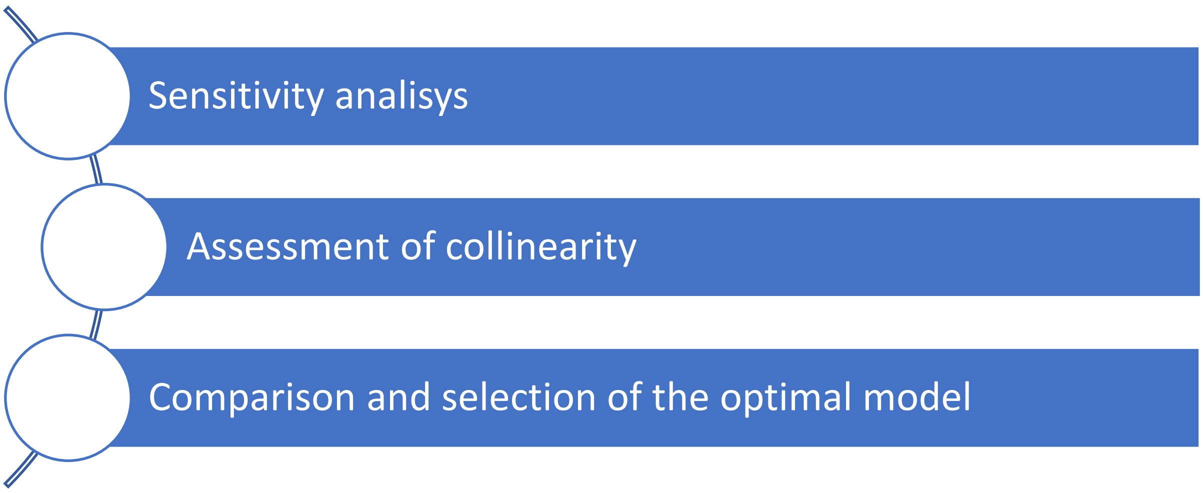
where: dependent variables θ_W and θ_S stand for efficiency scores of wind and solar energy policies, *i* represents a selected EU country, *t* - a year, *s* and *w* – stand for solar and wind energy respectively; the following are explanatory variables: *FIT* refers to feed-in tariffs and premiums, *QUOTA* - quota-based instruments, *TNDR* - tender, *TAX_INV* – tax incentives and investments, *PV_potential* - average solar power theoretical potential, *W_speed* – mean wind speed.

Studies are followed, including those of *Aguirre & Ibikunle (2014)*, *Polzin et al. (2015)*, *Liu et al. (2019)* and *Papież et al. (2019),* that measure the effect of certain RE support schemes with help of econometric regression. Building on *Papież et al. (2019)* an approach is used similar to the truncated bootstrapped regression model published by *Simar & Wilson (2007)*. Unlike the above-mentioned studies which incorporated a general categorization of RE support policies[24], the classification of wind and solar energy policies chosen is restricted to the most dominant ones across EU countries (FIT, quota-based instruments, tenders, tax incentives and investment grants), which have been summarized in the next section.

[24] For example, *Papież et al. (2019)* select out three categories of policy instruments: economic, regulatory and policy support instruments.

Hence, this study also aims to obtain the most significant results regarding the role played by external factors in wind and solar energy policies of EU countries. In this context, it is also important to choose the appropriate regression model to obtain the best possible results. Due to some difficulties and limitations in creating regression models, scholars (e.g., *Sağlam, 2017; Papież et al., 2019*) point out various important steps to improve on this approach (see Figure 3.4). As one of them is based on sensitivity analysis, the other assesses collinearity among predictors using variance inflation factors (VIF), while the third step aims to select an optimal model - characterized by parsimonious parameterization yet effective in describing the studied phenomenon. The final regression is chosen from a pool of models encompassing all possible predictor combinations, and the optimal model is identified through adjusted R-squared. These three techniques are explained in detail and applied in the next chapter in Section 4.4.

Figure 3.4. Additional steps to optimize regression models



Source: Own compilation.

In summary, a bias-corrected DEA method together with regression models is considered to be an important tool in delivering strong and unbiased findings. For the sake of a better explanation of DEA results, additional research is performed, which includes measuring the effect of some external factors on bias-corrected DEA efficiency scores. Based on the scope and objective of this research, resource endowment and main RE support schemes of EU countries are employed as control variables affecting efficiency scores. All variables for regression models are described in the following sections of this chapter.

3.5. Data collection

A strong focus in this study is placed on data availability, collection and reliability. Given the purpose of the research and selected methods (an indicator-based approach, DEA and regression), a special task has been done to collect best-tailored and up-to-date data sets. Regarding the indicator-based method to assess policy effectiveness, sources of *Eurostat* (European Statistical Office) and *EU Reference Scenario* (*EC, 2021d*) have been used in this research. As for DEA approach to measure policy efficiency, data from the following databases was extracted: *Eurostat; EDGAR* (The Emissions Database for Global Atmospheric Research, European Commission); *EurObserv'ER* (monitoring project of RE development in the EU) and "*Study on energy costs, taxes and the impact of government interventions on investments*" (*EC, 2020*). In order to assess impact factors of policy efficiency with help of regression model, data from the following sources have been acquired: the study by *Ragwitz et al. (2015)*; *REN21* (reports from an international policy network); *RES-LEGAL* (database on RE policies in EU member states); *CEER* (Council of European Energy Regulators); *ESMAP* (Energy Sector Management Assistance Program - World Bank database) and already mentioned *EurObserv'ER*. A detailed explanation regarding variables and corresponding databases is provided in the next subsections.

3.5.1. Indicator-based approach

The most common benchmarks to measure renewable energy policy performance presented by metrics of installed capacity and generation (*Mir-Artigues & del Río, 2016; García-Álvarez et al., 2017*) have also been applied as raw data in this study (see Section 4.1 of Chapter 4). The former shows a potential maximum energy (electricity) output that can be gained at a certain point of time for a particular RE technology across different countries or regions (*Polzin et al., 2015*). The latter accounts for a volume of energy (electricity) produced (*IRENA, 2014a*). While being usually estimated in absolute quantities (e.g., MW or MWh) during a certain period of time (e.g., year), they could be also presented in relative values (as a change in %) (*IRENA, 2014a; Mir-Artigues & del Río, 2016*). Simple metrics have a number of positive sides, the most important of which is an easiness in obtaining data. Besides that, interpretation of these indicators is not complicated and does not require a specific knowledge and analytics.

While conducting a cross-country analysis, a suitable reference benchmark for calculating a Policy Effectiveness Indicator (PEI) has been defined based on the literature review. As mentioned earlier, PEI includes two independent variables. One of them is electricity generation of wind and solar energy sources measured in Terawatt hours (TWh). The data on wind and solar power generation for the researched period in this study is taken from the *Eurostat* database.

A techno-economic potential (electricity generation in TWh) in 2050 was chosen as a reference quantity in a PEI approach. A similar method used by *Shivakumar et al. (2019)* is taken in this study while measuring policy effectiveness. *Shivakumar et al. (2019)* extracted data on techno-economic potential from the EU Reference Scenario report, using a version of the report from 2014 (*EC, 2014*). The availability of a newer version of a data set gives a unique opportunity to calculate effectiveness with the help of PEI. In the case of data on techno-economic potential, it is derived from the EU Reference Scenario (*EC, 2021d*[25]).

3.5.2. DEA framework

A two-tier DEA approach is adopted in this study to assess performance of RE support policies. As already mentioned, the first part of DEA analysis addresses multiple efficiency dimensions of wind and solar power policies across different EU member states including Germany and Poland. While energy and economic and environmental dimensions were selected based on a literature review of related studies in which the DEA approach is used, an energy security component is also included which is rarely employed in similar analysis. The rationale behind adding this aspect lies in arising global threats on the political, energy and economic arenas during the last few years[26]. All dimensions in the first part of DEA analysis correspond with chosen input and output variables which are described later in this section and summarized in Table 3.4. In general, two subsets of input are employed (cost of policy support and installed capacity) and four of output (power production, direct and indirect jobs, environmental and energy security indicators).

The cost of policy support of wind and solar energy is chosen as input which is expressed as a financial resource subsidized by various policy instruments (FIT, tenders and other) in selected EU countries. It is perhaps the first empirical study to use this kind of data which is

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[25] Many studies on scenarios and development pathways used the EU Reference Scenario 2020 *(EC, 2021d)* database as a benchmark in projection of renewable energy trends. The methodological framework for the Reference Scenario encompasses a set of interrelated models which rely on different technical and economic aspects. The model from this source set takes also into account data on the historical development of RE sources in EU member states and also on the national RE sources targets that are reflected in their National Renewable Energy Action Plans (NREAPs).

[26] Russian invasion in Ukraine in 2022 and high energy import dependency of many countries in recent years constitute a global threat to economic and energy security.

derived from an EC-related database (*EC, 2020*). This is in line with an approach found in works by *Park & Kim (2018)* and *Meleddu & Pulina (2017).* Both empirical studies use supported amounts of RE sources in Korea and Italy respectively as input parameters. In a similar way to the ongoing research, *Mezősi et al. (2018)* employs a supported amount of wind and solar power as inputs to measure efficiency of policy schemes in selected EU member states whose data is obtained from *Council of European Energy Regulators* (*CEER)* reports. Despite the reliability of this database, which provides quantitative statistics on RE policy instruments in EU Member states, its biggest limitation in the context of this study is that much of the data regarding the supported amount of RE sources is missing for certain countries, among which is Poland. As this country is at the centre of this research, the database *EC (2020)*, which presents full statistics required to collect data on cost of policy support of wind and solar energy across Poland, Germany and other EU countries, was chosen.

Table 3.4. DEA inputs and output variables for measuring policy efficiency of wind and solar energy policies in EU-27

Dimension (aspect)	**Variable**	**Name**	**Definition**	**Unit**	**Scope**	**Data accessibility period**	**Database**
Economic (policy)	Input 1.1. *SUP_W*	Cost of policy support, wind energy	Supported amount of a certain technology in a given country (controlled for inflation)	MLN EURO	Energy	2008-2018	*EC (2020)*
	Input 1.2. *SUP_S*	Cost of policy support, solar energy					
Technical (energy)	Input 2.1. *CAP_W*	Wind Cumulative Installed Capacity	Cumulative installed capacity of a certain technology in a given country	MW	Electricity	2000-2020	*Eurostat*
	Input 2.2. *CAP_S*	Solar PV Cumulative Installed Capacity					
	Output 1.1. PR_W	Solar power production	Generation of a certain technology in a given country	TWh	Electricity	2000-2020	*Eurostat*
	Output 1.2. PR_S	Wind power production					

(see continuation of the table on the next page)

(continued)

Environmental	Output 2.1. *ENV_W* Output 2.2. *ENV_S*	Environmental indicator (wind and solar energy)	CO_2 emissions avoided by replacing conventional energy with wind and solar electricity	Mt CO_2	Emissions, electricity	2000-2020	*Eurostat*
Energy Security	Output 3.1. *SEC_W* Output 3.2. *SEC_S*	Energy security indicator (wind and solar energy	The extent to which energy security of a given country's energy security would improve if conventional energy were replaced by wind and solar electricity	Mtoe	Electricity	2000-2020	*Eurostat*
Socio-economic	Output 4.1. *JOB_W* Output 4.2. *JOB_S*	Direct and indirect jobs in wind and solar power market	Direct and indirect jobs related to a certain technology (wind or solar power) in a given country	Number of jobs	Jobs	2009-2020	*EurObservER*

Source: Own adaptation based on sources highlighted in the table.

Installed capacity of a certain RE technology (wind and solar power) is a useful metric, especially as far as comparison of RE market development with other energy sectors is concerned. This benchmark has been frequently employed by scholars as an input variable together with an electricity generation. Along with data on cost of policy support, a cumulative installed capacity during the researched period was applied as the second input variable in the DEA framework. The data on installed capacity is derived from *Eurostat* database. The values of this metric are presented in MW.

As installed capacity doesn't control for operational performance (*IRENA, 2014a*), analysts often use power generation as an output variable. Wind and solar electricity production was employed as the first and main output parameter (measured in terawatt-hours (TWh), whose data is also taken from *Eurostat*). While a share of RE technologies is rarely chosen by scholars, power generation serves as a basic benchmark for assessing efficiency.

The next subset of outputs is a number of direct and indirect jobs in the wind and solar power market. The literature on the DEA approach reveals that this variable was usually treated as an input. A very rare case when this economic category was chosen as an output could be found in a study by *Park & Kim (2018)*. Scholars frequently use GDP (e.g., *Woo et al., 2015*) as a basic output parameter to measure efficiency of RE sources from an economic perspective. However, a category of employment was chosen to show how efficient wind and solar energy policies are in creating new jobs. The data on employment is derived from *EurObserv'ER* database.

Given the importance and mainstream in literature (*Sueyoshi & Goto, 2014; Woo et al., 2015; Moutinho et al., 2017; Papież et al., 2019*), environmental dimension is also highlighted in DEA analysis. A corresponding indicator was chosen which was presented by *Papież et al. (2019)*, and measures avoided CO_2 emission due to a replacement of fossil fuels by wind and solar power. This indicator is presented as following:

$$ENV = \frac{CO2 \cdot PR_i}{tPR} \qquad (3.5)$$

where: ENV - environmental indicator; CO_2 – total CO_2[27] emission from electricity industry; PRi – gross power generation from a certain RE technology, tPR – gross power production.

Besides the environmental aspect, an energy security indicator was also employed which is the fourth and last output parameter. Not many studies control for energy security dimensions (*Ibidem*). However, this parameter was chosen in this DEA model based on its growing significance. The formula for the energy security indicator is calculated as follows:

$$SEC = \frac{IMPORT \cdot PR_i}{tPR} \qquad (3.6)$$

where: SEC - energy security indicator; $IMPORT$[28] – total import of fossil fuels; PRi – gross power generation from certain RE technology, tPR – gross power production.

3.5.3. Regression models

As already mentioned in Section 3.4 based on available data, two groups of external factors were selected which look to affect the efficiency of wind and solar energy policies: main

[27] Data on CO_2 emissions is derived from EDGAR - Emissions Database for Global Atmospheric Research (*EDGAR*).
[28] Data on *IMPORT* is derived from *Eurostat.*

policy instruments and resource endowment. As already referenced in this chapter, the main policy mechanisms in EU countries are presented as follows:

- FIT
- Quota-based instruments
- Tenders (or auctions)
- Tax incentives and investment grants

Table 3.5. Description of factors in regression models

Category	Variable	Abbr.	Definition
RE policy instruments	Feed-in system	*FIT*	Usually forms two types: 1) Feed-in tariff (FIT) - a long-term contract, which gives an energy producer a guaranteed price per unit of renewable energy 2) Feed-in premium (FIP) - a bonus (premium) over a market price, which energy producer receives for a unit of renewable energy
	Quota-based policies	*QUOTA*	An obligation set by a national government for energy producers to generate and install a fixed amount (percentage) of energy from RE sources. Tradable renewable energy certificates are the most popular type of quota-based instruments in EU
	Tenders	*TNDR*	A standardized process in which a certain amount of RE is sold through a competitive mechanism of bids
	Tax incentives/ Investment grants	*TAX_INV*	Tax incentives - different tax measures such as exemptions, credits, reductions for RE investment or production projects. Investment grants - direct subsidies made by a government to a business for investment purpose
Resource endowment	Mean wind speed	*W_speed*	Measures wind resource in a certain area/country
	Average solar power theoretical potential	*PV_potential*	Also referred to as theoretical PV potential - a long-term amount of solar resource available on a horizontal surface on Earth, measured in kWh/m2/day.

Source: Own compilation.

As for the main policy instruments, they have been selected according to their dominance in EU countries. The described policy instruments and periods of their presence in analysed EU member states are presented in Figure 4.7 (in Chapter 4). Factors regarding wind and solar energy resources include mean wind speed and average solar power theoretical potential respectively.

The groups and variables of these impact factors are summarized in Table 3.5. They serve as control variables in the regression model approach. Data on the main support mechanisms in EU countries is obtained from multiple sources: a study by *Ragwitz et al. (2015)*, reports from an international policy network *REN21*, database on RE policies in EU member states *RES-LEGAL*, monitoring project of RE development in the EU *EurObserv'ER* and *CEER* database. As for resource endowment factors, data for mean wind speed is extracted from the *Global Wind Atlas*, while values for average solar power theoretical potential are derived from World Bank database (*ESMAP*).

So, this chapter provides a detailed description of methods, databases, data sets and variables, which are applied empirically in the following chapter. Together they constitute a methodological concept, on the basis of which corresponding results were obtained and evidence summarized. The empirical research conducted in the next chapter consists of two consecutive parts. First one is built on the indicator-based analysis and includes application of PEI to measure effectiveness of wind and solar energy policies in Germany and Poland (with other selected EU member states in the background) during a period of 2005-2021. The computation of results within the indicator-based method has been conducted on *Excel*. The second part of the research concerns assessing efficiency of the selected EU countries and is divided into two stages. First one includes application of DEA method to measure policy efficiency of the mentioned technologies in the analysed countries. The period of the research has been selected year 2018. The second stage also concerns assessing efficiency of wind and solar energy policies in the mentioned countries, with a goal to reveal why some policies of member states perform worse or better. This approach is based on regression model and includes a research period of 2005-2018. Both DEA and regression analyses have been computed on the platform of statistical programming called '*R*'.

4. PERFORMANCE ASSESSMENT OF WIND AND SOLAR ENERGY POLICY IN POLAND AND GERMANY ON THE BACKGROUND OF EU COUNTRIES

4.1. Analysis of relevant data on wind and solar energy policies in EU member states

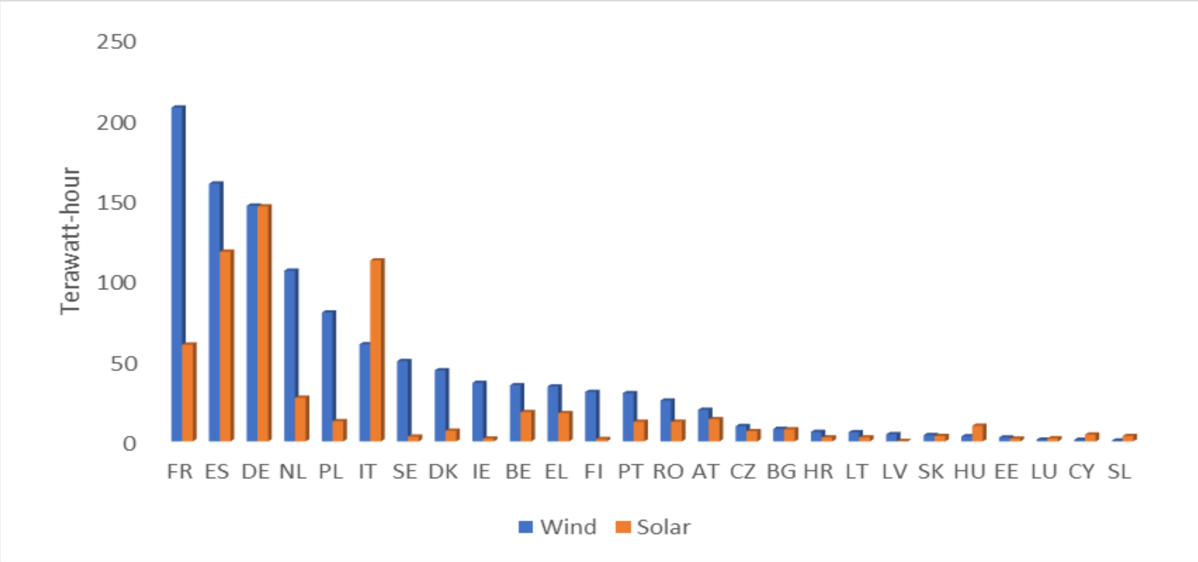
This chapter provides results and analysis for policy effectiveness and efficiency of wind and solar energy technologies in Germany and Poland on the background of other selected EU countries. For this purpose, a profound quantitative analysis was undertaken, which includes an application of indicator-based (effectiveness), bias-corrected DEA and regression approaches (these methods are described in Chapter 3). As mentioned earlier, the research is limited only to wind and solar energy technologies. The scope of the dissertation was also mainly restricted to the electricity sector. While the research refers to two countries, Germany and Poland, other selected EU member states have been employed into the analysis to make it more transparent and the results more comparable.

Before conducting research regarding policy performance, a detailed analysis of wind and solar energy markets across EU members states (EU-27) and their development during the researched period of 2005-2021 is provided. First of all, a techno-economic potential in 2050 is evaluated to reveal countries with best and worst prospects in the context of wind and solar energy. Additionally, this comparative analysis relies on simple benchmarks of electricity generation and net installed capacity to trace back the market development of the mentioned energy technologies. Data on techno-economic potential in 2050 and electricity generation are employed in the next section for measuring policy effectiveness.

Furthermore, an analysis of policy instruments (during the 2005-2021 period), as well as endowment of wind and solar energy resources in the above-mentioned countries was performed. Given the availability of the most recent databases, a comparison between these countries was conducted in 2018 in terms of the cost of policy support, jobs created, energy security, and environment. In this section, these indicators were used in the context of comparative analysis of raw data. As for other sections of this chapter, they were utilized as input data for the framework of indicator-based, DEA and regression approaches.

Based on data from Figure 4.1 and Appendix D, Germany and Poland are in the top five ranking with the highest techno-economic potential in 2050 to generate wind electricity (equalling 146,4 TWh and 80 TWh respectively). The two countries could benefit from vast territory and have also a possibility to deploy offshore turbines. As for other member states, open access to the sea and vast resources also brings France, Spain, Netherlands, Italy, Sweden, and Denmark into favourable positions to deploy this type of RE technology. Regarding solar energy, Germany, with a potential to produce 145,9 TWh in 2050 outperforms other countries with much richer solar resources (e.g., Italy or Spain). As for Poland, its techno-economic potential in this technology is relatively much smaller and accounts for only 12,6 TWh.

Figure 4.1 Techno-economic potential of wind and solar electricity generation in 2050



Source: Own compilation according to *EU Reference Scenario (2020)* database.

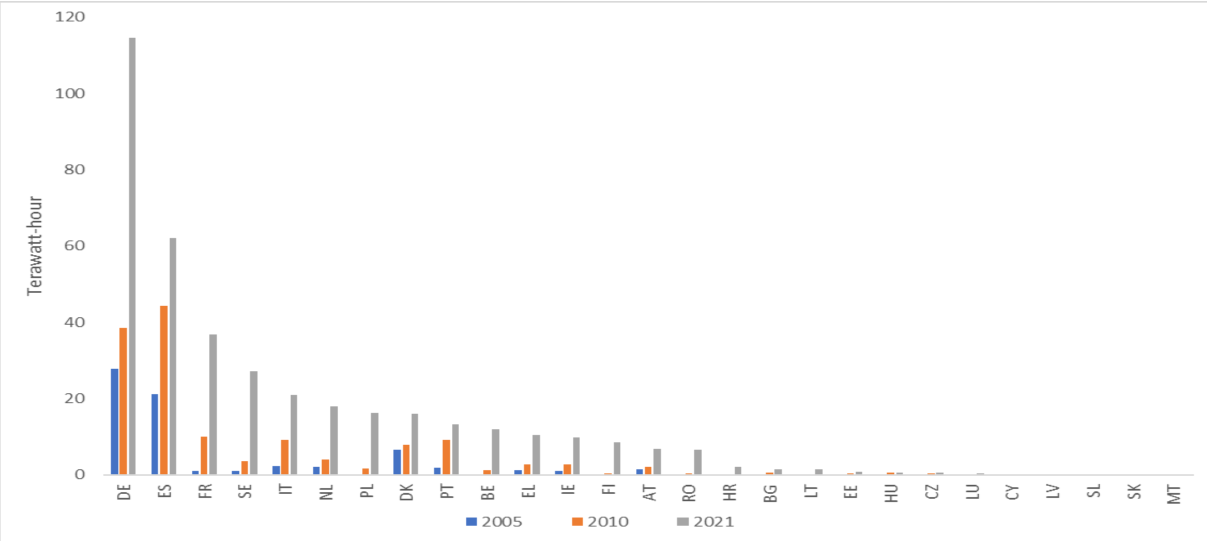
Figures 4.2-4.5 indicate how wind and solar power markets developed during the 2005-2021 period in the EU. These charts present electricity generation and net capacity installed in terms of mentioned clean technologies. The year 2010 is also included to see how countries promoted these two energy sources in the early phase (when technology cost was high[29]). Overall, an idea to include years of 2005, 2010 and 2021 into the analysis was to reveal which countries could be considered as 'early movers' or 'late adapters', which is in line with diffusion theory of energy transition[30]. Raw data on wind and solar power production during the period of 2004-2021 is presented in Appendix D.1 and D.2 respectively.

It can be observed from Figures 4.2 and 4.3, that Germany leads in terms of wind power generated and net capacity installed through the whole researched period. Among other countries, which promoted wind energy in earlier periods, when technology cost was high, were Spain, Denmark, Portugal, France, and Italy. As for Denmark and Portugal, their pace of

[29] See Figure 1.1 (Chapter 1).
[30] Detailed information regarding diffusion theory is provided in Subsection 1.2.2. (Chapter 1).

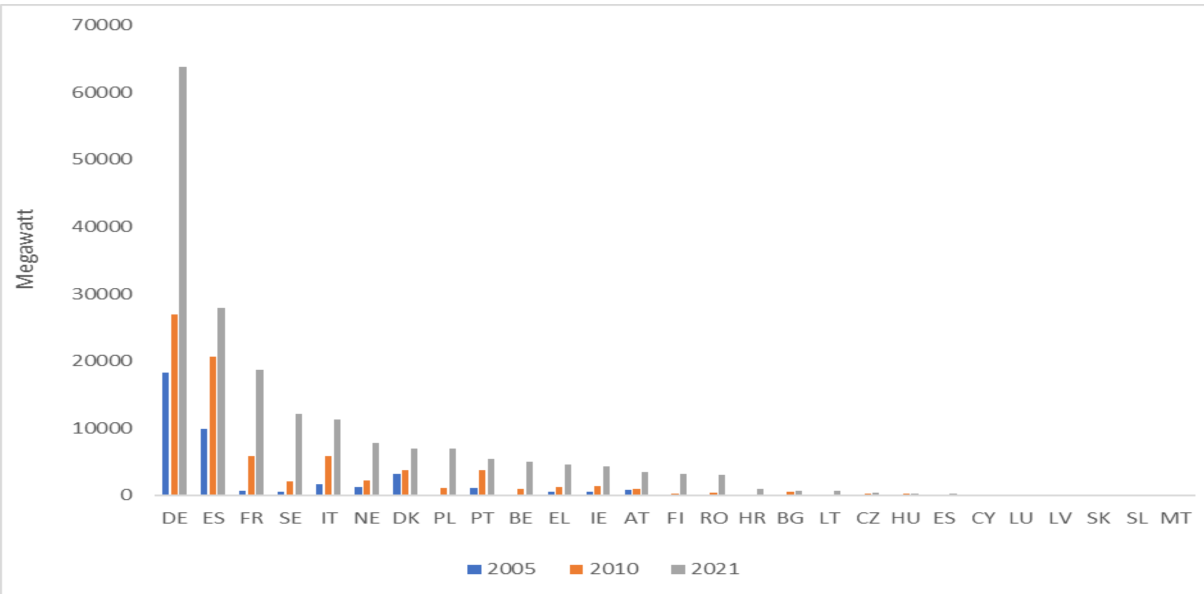
development dropped in the last period. Most countries started to promote the wind energy sector after 2010, as the cost of this technology continued to decline substantially. Also, Poland is among these countries, as it later outperformed ‘early movers‘ Netherlands and Denmark in terms of wind power production in 2021. Apart from Poland, other countries which only started to invest considerably into wind energy during the latest period were France, Belgium, Finland, and Romania.

Figure 4.2. Wind electricity production in EU member states for years 2005, 2010 and 2021



Source: Own compilation according to *Eurostat.*

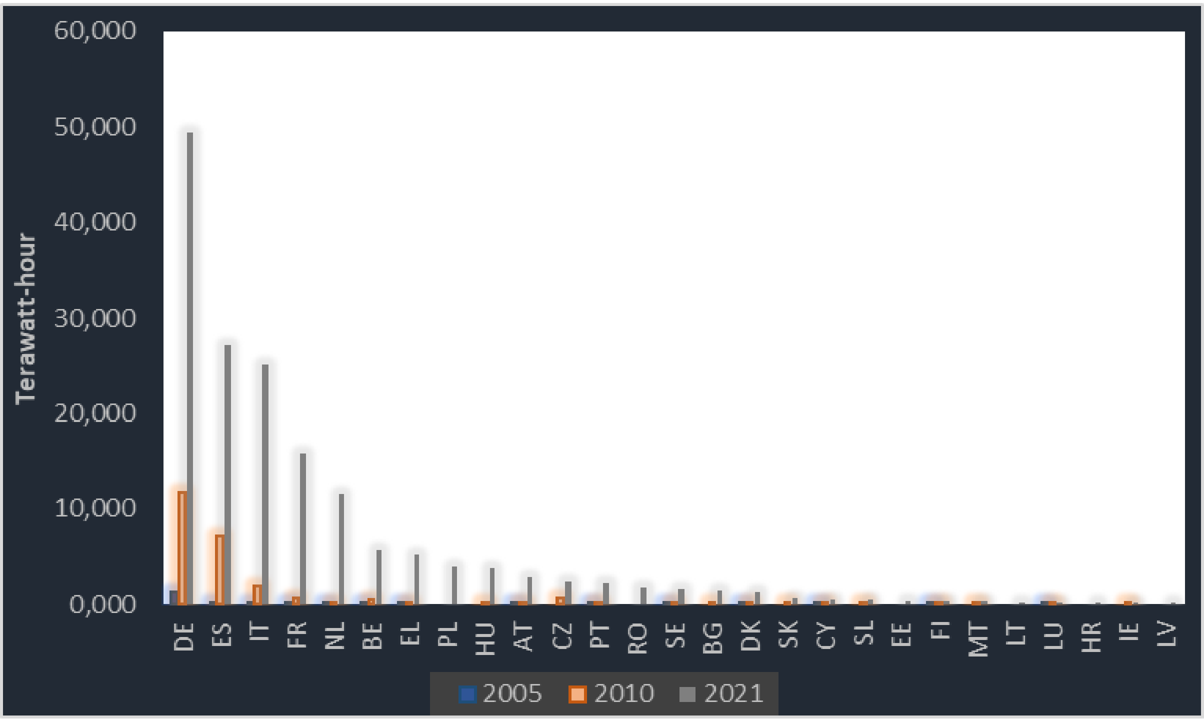
Figure 4.3. Wind electricity net capacity installed in EU member states for years 2005, 2010 and 2021



Source: Own compilation according to *Eurostat.*

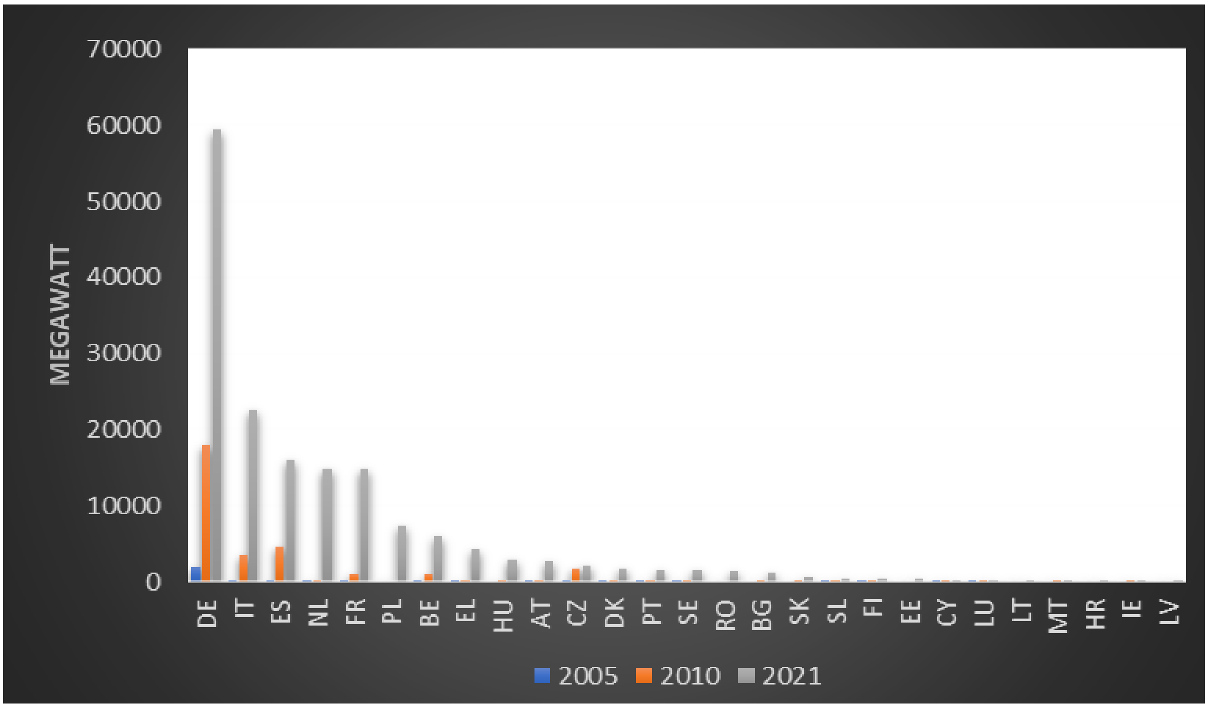
As one can notice in Figures 4.4 and 4.5, EU member states have seen marginal progress in terms of solar energy development in the early period. Less mature solar energy markets started to grow in 2010 in light of a strong reduction trend of technology cost. By considering years 2005 and 2010, Germany, Spain, Italy, Belgium, and Czech Republic could be marked as 'early movers'. Their strong growth also continued up until 2021, while countries like France, Netherlands, Greece, Poland, and Hungary were among the ones with the strongest uptake in terms of solar power production and net capacity installed during the same year. In general, unlike wind energy, solar energy is a new technology as most countries have seen strong growth only during the latest period. With the exception of a few countries (e.g., Germany and Spain), this market is at the beginning phase of development as its trend indicates a strong and continuous growth.

Figure 4.4. Solar electricity production in EU member states for years 2005, 2010 and 2021



Source: Own compilation according to *Eurostat.*

Figure 4.5. Solar electricity net capacity installed in EU member states for years 2005, 2010 and 2021



Source: Own compilation according to *Eurostat.*

As the above data on techno-economic potential and power production of wind and solar technologies will be used for measuring policy effectiveness, the assessment of raw data, which concerns policy efficiency, was also provided. For the purpose of research on policy efficiency variables were divided, which were applied in DEA and regression models. As already mentioned, for DEA, two subsets of input (cost of policy support and installed capacity) and four groups of output (power production, direct and indirect jobs, environmental and energy security indicators) parameters were employed. A detailed explanation of them is found in Table 3.4 of Chapter 3. The analysis of dominant policy instruments (FIT, quotas, tenders, tax and investment) and resource endowment (average wind speed and solar power potential) in researched countries was also performed, as these variables are later taken in a regression approach.

Descriptive statistics of input and output variables applied in DEA analysis for year 2018 are presented in Table 4.1, while their values across researched EU countries are reported in Appendices E.1 and E.2. Estimations on installed capacity and production of wind and solar energy across EU countries were already described in the context of policy effectiveness earlier in this section. Also, the illustration of values on employment, energy security and environmental indicators across EU member states in 2018 are presented in Appendices F.1, F.2 and F.3 respectively. As expected, Germany led in all three parameters. Interesting to note is that Poland is among the top three countries with the best environmental effect from wind energy. In terms of creating new jobs in the wind energy sector, the leaders among EU member states are Denmark, Spain, The Netherlands, and France. Most employees in the solar energy sector are registered in France, The Netherlands, and Hungary. Countries such as Spain, Netherlands, Italy, and Denmark performed best in terms of gains received from replacing fossil fuels with wind and solar energy (environmental aspect). They also benefited most from lowering import dependence by developing the mentioned cleaned energy technologies (energy security aspect). All these observations refer to the year 2018.

Table 4.1. Descriptive statistics of the DEA variables across EU member states (data on wind and solar energy in 2018)

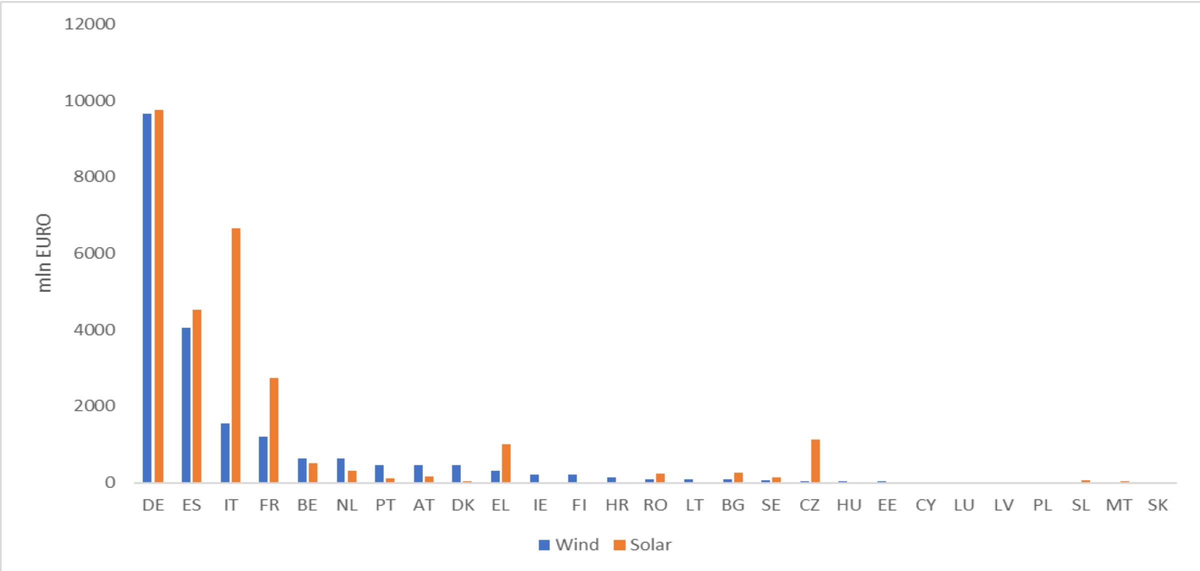
Wind energy variable		*Unit*	*Mean*	*Min*	*Max*	*SD*	*Median*
Input	*SUP_W*	MLN Euro	1004,38	1,68	9652,93	2235,27	259,02
	CAP_W	MW	70158,35	977,07	534334	128307,75	25307,62
Output	*PR_W*	TWh	15,38	0,22	109,95	25,34	8,05
	JOB_W	Number of jobs	11935	100	106200	24315	3750
	ENV_W	coefficient	5,32	0,03	49,20	10,93	1,73
	SEC_W	coefficient	7,14	0,11	39,24	9,74	4,52
Solar energy variable		*Unit*	*Mean*	*Min*	*Max*	*SD*	*Median*
Input	*SUP_S*	MLN Euro	1371,30	0,46	9743,58	2639,52	145,40
	CAP_S	MW	35301,25	53,91	347886	81300,29	6067,70
Output	*PR_S*	TWh	5,60	0,02	45,78	11,03	1,18
	JOB_S	Number of jobs	5280	100	41900	9767	1750
	ENV_S	coefficient	2,03	0,01	20,49	4,71	0,31
	SEC_S	coefficient	2,69	0,01	16,34	4,40	0,43

Note: *SUP* - cost of policy support, *CAP* - cumulative installed capacity, *PR* - power production, *JOB* - direct and indirect jobs, *ENV* - energy environmental indicator, *SEC* - energy security indicator, *W* - wind energy, *S* - solar energy.

Source: Own calculations.

In terms of expenditures on policies supporting wind and solar energy sources, Germany is also here as an undisputed leader, spending around 9652,9 and 9743,6 million Euros respectively in 2018 (see Figure 4.6). As for other countries with the highest financial capabilities to promote wind and solar energy during the same year, they are Italy, Spain, and France. One should also mark Greece and Czech Republic as big spenders in terms of solar energy. As for Poland, its financial support of wind and solar energy sources in 2018 was relatively marginal (around 1,7 and 5 million Euro respectively). In general, one can notice a pattern which shows that countries which are the largest in terms of economy size (e.g., Germany, France, Italy, and Spain) spend the most on these RE technologies. Also, as for member states from Central and Eastern Europe (except for the Czech Republic's expenditures in solar energy), the digits of this indicator look to be relatively marginal for both wind and solar energy.

Figure 4.6. Policy expenditures on wind and solar energy sources by EU member states in 2018



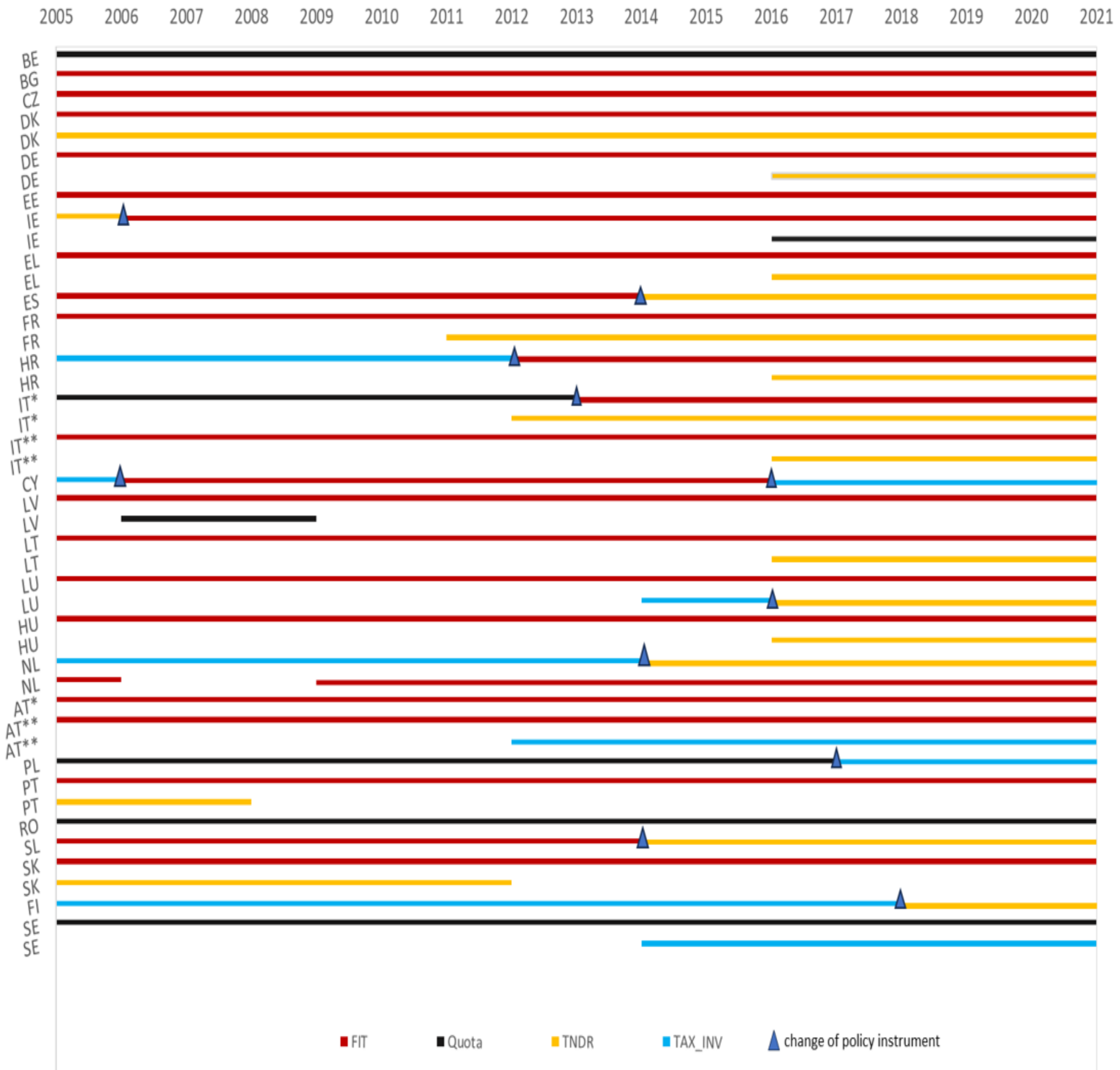
Source: Own compilation according to *Eurostat.*

As already accepted in this study, policy instruments and resource base of wind and solar energy were selected as the two subsets of an external factors, affecting efficiency. Figure 4.7 traces back the development of the main support schemes promoting wind and solar energy across EU countries during the years 2005-2021. During that period countries used different support mechanisms, like FIT, quotas, tenders, tax incentives and investment grants. The most dominant policy instrument across Europe is FIT, being operational in 19 countries as of 2021[31]. Less popular are quotas and tax/investment policies, as each of them are present in only four countries. In general, no significant change is observed during a 2005-2021 period as far as a number of the three mentioned (active) policy instruments is concerned. One can outline tender as a new popular support mechanism as of 2016, when many countries started a transition to more market-based measures. A number of EU countries where tender is considered as a main instrument increased from 4 in 2005 to 14 in 2021. In the next sections of this chapter, an effect these policy instruments could have on policy effectiveness and efficiency of wind and solar

[31] This number didn't change, as the same amount of countries (19) had FIT mechanism in force in 2005.

energy policies across EU members states, with the main focus on Poland and Germany, is explored.

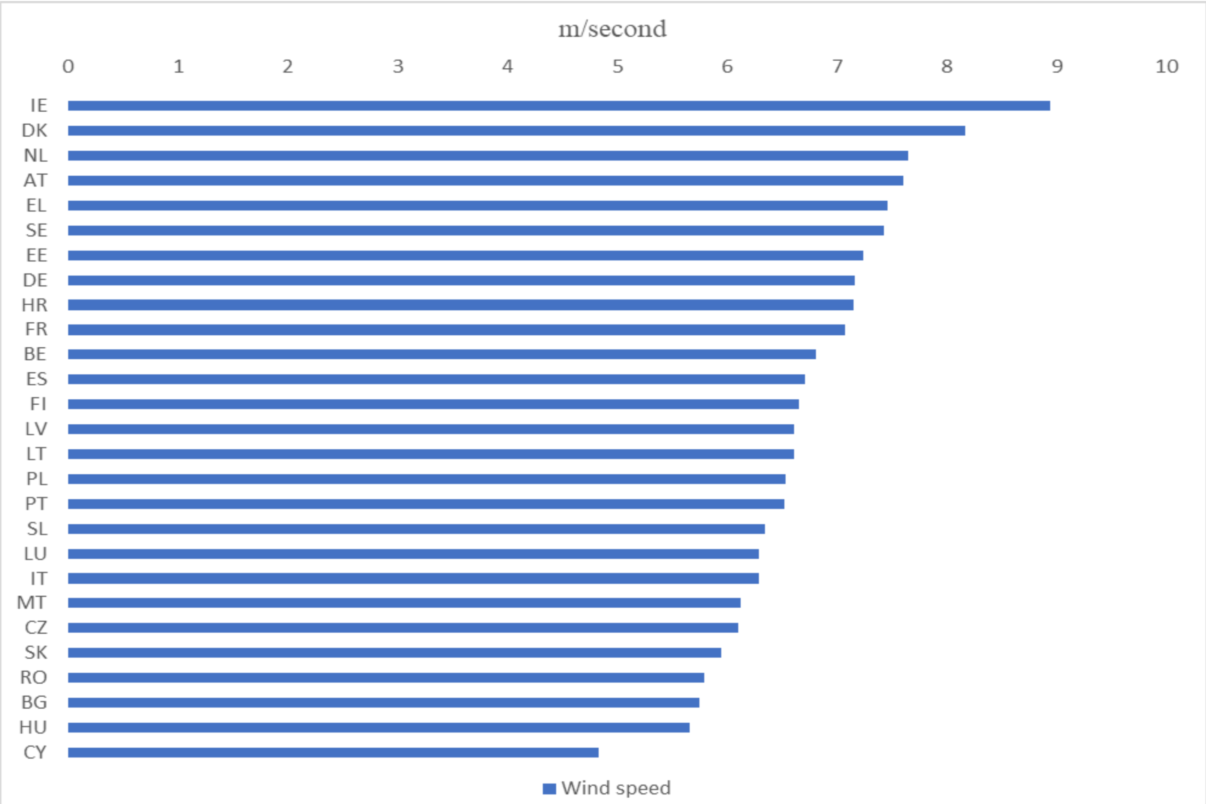
Figure 4.7. Main wind and solar energy policy instruments in EU member states during period of 2005 - 2021



Source: Own compilation according to *Ragwitz et al., 2015*; *CEER database; RES-LEGAL; REN21, 2021* and *EurObserv'ER*.

Another selected subset of external factors which could have a strong impact on policy efficiency is resource endowment. A comparative ranking of EU member states in terms of wind and solar energy resources is depicted in Figure 4.8 and 4.9. Ireland, Denmark, Netherlands, and Austria are among the countries with the highest average wind speed, while Romania, Bulgaria, Hungary, and Cyprus are at the bottom of the ranking. One can point out to a pattern that most countries from the geographical North have richer wind energy resources compared with those from the South. However, no strong difference in values between these regions could be observed. Furthermore, no strict correlation could be found between average wind speed and production of this technology in the selected EU countries. For example, Spain which is in the middle of the ranking (average wind speed) is the second-best country in terms of power production (see Figure 4.9). A similar case can also be noticed for Poland as the country with a below average wind resources, saw its market strongly developing in recent years. In order to explore the impact of wind and solar energy, research on policy efficiency based on a regression model approach was conducted in Section 4.4 of this chapter.

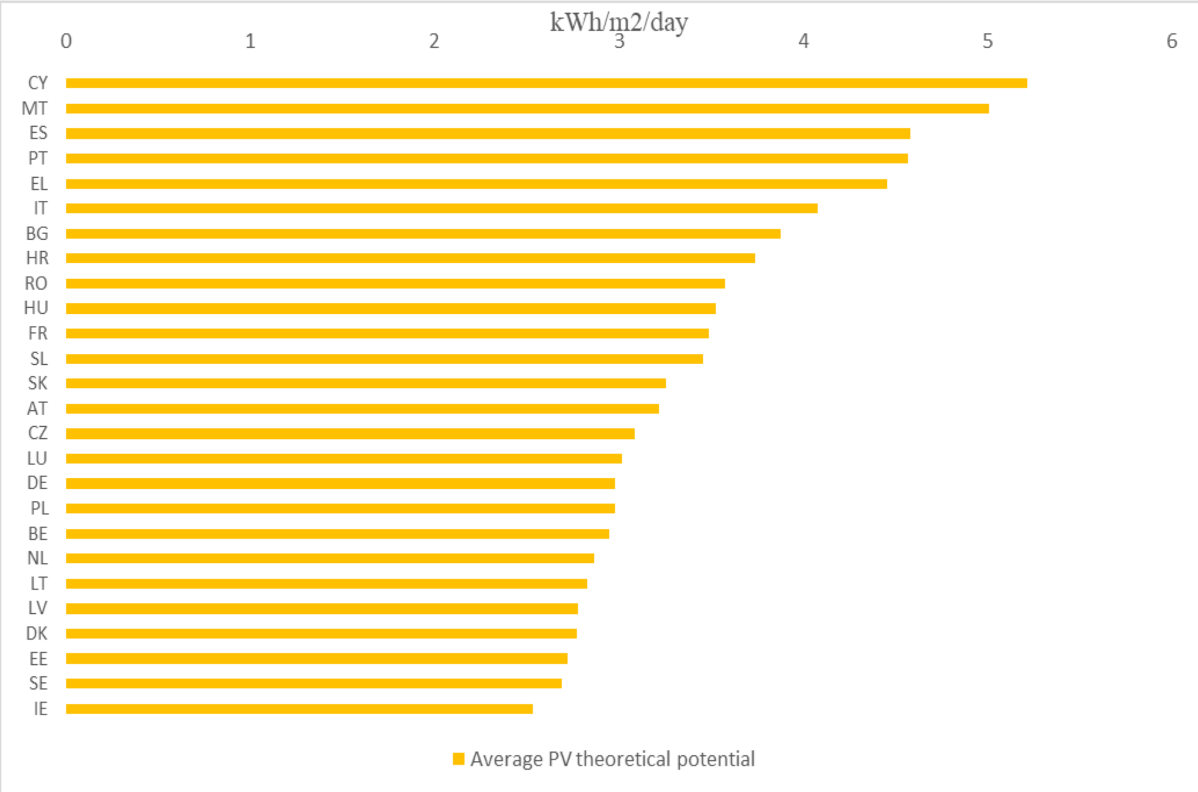
Figure 4.8. Average wind speed across EU member states (in m/s)



Source: According to *Global Wind Atlas.*

Predictably, an opposite picture could be seen in the case of solar energy resources, as Southern countries can boast of considerably higher average irradiance (Figure 4.9). Cyprus, Malta, Spain Portugal, and Italy are among leaders in terms of solar power theoretical potential, while Latvia, Lithuania, Denmark, Estonia, Sweden, and Ireland are among the least sunny countries. One could mark a strong gap between countries with the highest and lowest solar power potential. However, it is interesting to note that countries like Germany and Poland, being less endowed with solar resources, tend to be among leaders in the context of investing in this type of clean energy. This can be due to the fact that in light of the latest positive trends (e.g., reduction in technology cost and favourable regulatory environment), some countries extensively developed their solar energy market, indicating a strong effectiveness (see Section 4.2). However, the picture could be totally different when revealing how efficient these countries use their resources (Section 4.3).

Figure 4.9. Average solar power theoretical potential across EU member states (in kWh/m2/day**)**



Source: According to *ESMAP*, *2020.*

So, the analysis of raw data on wind and solar energy development performed in this section indicates a handful of interesting patterns. Despite different progress, EU member states have been developing very fast during last two decades in terms of mentioned RE technologies, as their theoretical (resource endowment) and techno-economic potential remains far from untapped. Also, a strong growth has been recorded in terms of employment, while aspects of energy security and environment gain on importance. One can note that countries in EU used different policy instruments to support wind and solar energy sources throughout different periods. This is in line with the fact, that EU assigned these clean energy technology a leading role in current energy transition with ambitious plans to become a carbon-free community within the next two decades.

4.2. Estimations of indicator-based approach

With help of policy effectiveness indicator (PEI), a first part of a cross-country research on performance of wind and solar energy policies across selected countries was undertaken. The second part of the framework addresses policy efficiency and is based on DEA and regression methods. The combination of these two approaches (policy effectiveness and efficiency assessment) should present a more comprehensive research with robust findings.

The indicator-based approach sheds light on policy effectiveness of Germany and Poland and other selected EU countries and covers a researched period of 2005-2021. General information, literature review, and methodological framework of this approach were described in Chapter 3. In line with other literature studies (e.g., *Ragwitz et al., 2015; Shivakumar et al., 2019*), policy effectiveness indicator (PEI) is employed into the framework of monitoring and assessment of policy performance. Besides that, it is assumed that such analysis could prove to be very useful due to continuous research in this area, and available and up-to-date data sets.

As the first step of the empirical research concerns policy effectiveness and is based on comparative PEI estimations, an initial plan was to include all EU member states into the study. Due to very low values (e.g., wind electricity generation) in the case of Malta, this country was excluded from the analysis. This part of the research included the following countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. Besides calculating PEI scores, a detailed analysis of how effectiveness changed during researched periods was provided. Furthermore, this analysis extended to reveal possible patterns in context of how some dominant support instruments could impact wind and solar energy policy effectiveness in the selected countries.

Average PEI scores for selected EU countries were estimated based on values of wind and solar electricity production and their correspondent realizable potential in 2050. In order to investigate dynamics of wind and solar energy technologies across the researched countries, the analysis covering average PEI scores was split into three periods (2005-2010, 2011-2015 and 2016-2021). This aimed at providing valuable insights as additional assessment of how policy instruments could affect effectiveness within different periods was performed. Furthermore, such approach improves on an analysis which is simply based on a year-by-year comparison. By performing the ongoing study which compares average PEI estimations within the three subsequent periods, this research not only controlled for seasonal weather discrepancies, but also avoided bias, which can stem from the fact that countries which actively promoted renewables in the early periods inclined to be more effective overall.

Table 4.2. Average PEIs (%) of wind and solar energy during 2005-2010, 2011-2015 and 2016-2021 periods

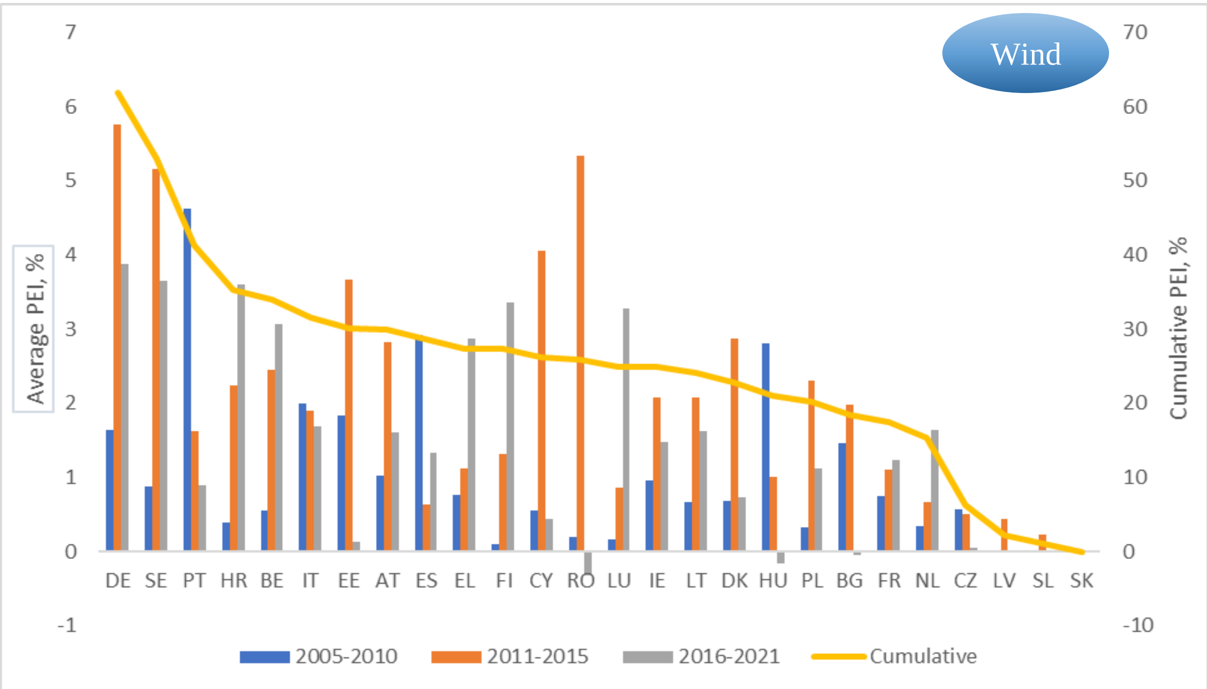
	Wind energy				**Solar energy**			
Country / Period	2005-2010	2011-2015	2016-2021	Cumulative value*	2005-2010	2011-2015	2016-2021	Cumulative value*
BE	0,55	2,46	3,07	34,00	0,51	2,74	2,35	30,87
BG	1,46	1,98	-0,04	18,41	0,03	3,65	0,19	19,57
CZ	0,57	0,50	0,05	6,24	1,61	5,17	0,14	36,34
DK	0,69	2,87	0,73	22,81	0,01	1,81	1,78	19,81
DE	1,64	5,75	3,87	61,82	1,28	3,70	1,21	33,44
EE	1,83	3,67	0,13	30,08	0	0	3,39	20,35
IE	0,96	2,07	1,47	24,95	0,01	0,04	0,85	5,31
EL	0,76	1,12	2,86	27,32	0,15	4,26	1,28	29,91
ES	2,92	0,63	1,33	28,66	3,97	0,86	1,80	38,95
FR	0,75	1,11	1,24	17,46	2,58	3,82	4,27	60,23
HR	0,40	2,25	3,61	35,24	0,95	5,37	8,63	84,32
IT	1,99	1,90	1,68	31,54	0,28	3,74	0,31	22,26
CY	0,56	4,05	0,44	26,20	0,02	0,57	1,35	11,07
LV	0,01	0,44	-0,02	2,15	0	0	0,45	2,71
LT	0,66	2,08	1,63	24,14	0	0,58	0,79	7,63
LU	0,17	0,87	3,28	24,98	0,10	0,50	1,88	14,35
HU	2,81	1,02	-0,15	21,03	0,91	0,33	-0,05	6,77
NL	0,35	0,67	1,64	15,32	0,01	0,78	6,38	42,27
AT	1,03	2,83	1,61	30	0,09	1,23	2,24	20,09
PL	0,32	2,30	1,12	20,14	0	0,09	5,14	31,32
PT	4,62	1,62	0,90	41,20	0,29	0,96	1,98	18,38
RO	0,20	5,33	-0,32	25,92	0	3,26	-0,38	14,01
SL	0	0,24	-0,01	1,10	0,06	1,55	0,89	13,44
SK	0	0	0	-0,01	0,08	2,91	0,82	19,94
FI	0,09	1,32	3,35	27,29	0,03	0,09	3,38	20,86
SE	0,88	5,15	3,65	52,98	0,04	0,60	8,05	51,50

Notes: *cumulative values of PEI (%) during the whole 2005-2021 period.

Source: Own calculations.

Without detailed research, one could expect a strong position of Germany in terms of RE deployment. The country was one of the ‘early movers’ and invested heavily in technologies like wind and solar energy during the last two-three decades. Based on PEI results presented in Table 4.2 and Figure 4.10, it can be acknowledged that Germany is the most effective country in terms of wind energy policy based on the whole period of 2005-2021 (with cumulative PEI score equalling 61,82%). Also, Germany was the 7th most effective country during the early period (2005-2010), when technology cost was high, and FIT was the only main policy instrument. The country benefited much from this mechanism during the take-off period (2010-2015) as its average effectiveness of wind energy policy increased significantly from 1,64% to 5,75% (to compare with the previous period). Even though Germany’s average policy effectiveness decreased to 3,87% during the 2016-2021 timespan, this score remains the best among EU member states. One should also note that during the most recent period, tenders gained in significance with a final goal to replace the FIT system, as some countries like Germany planned to gradually withdraw support of wind energy due to the increasing maturity of this market.

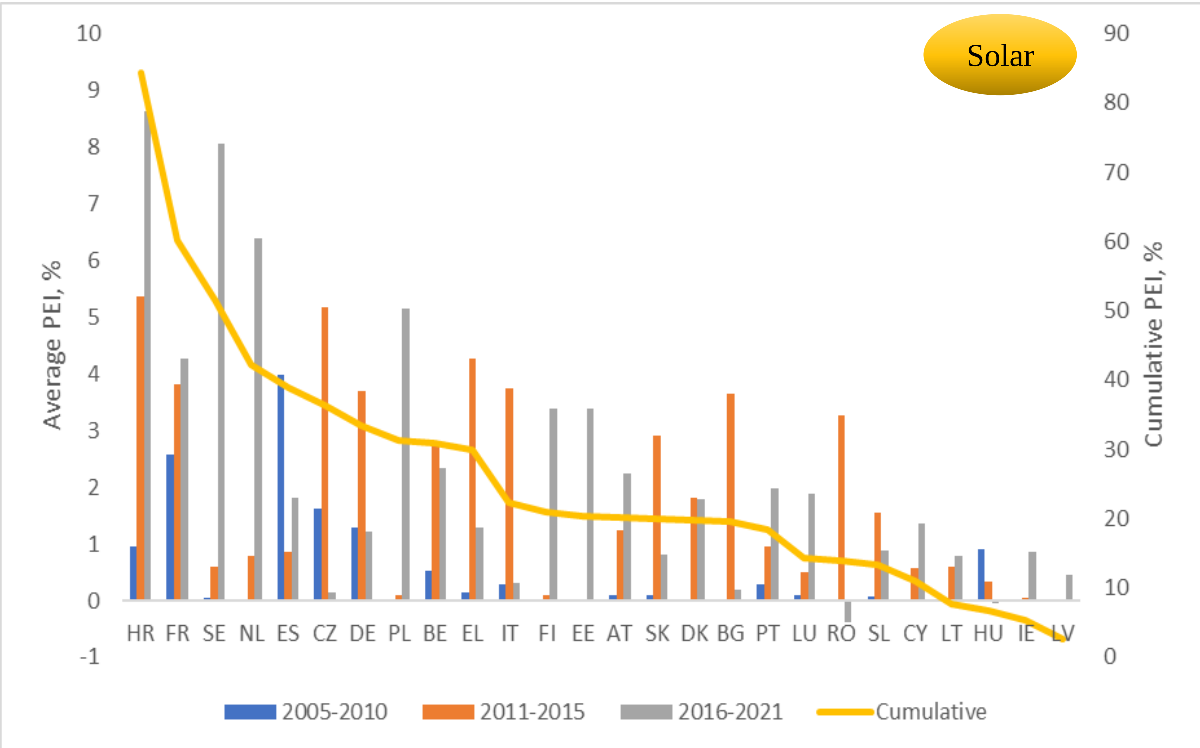
Figure 4.10. Average wind PEI (%) in selected EU countries during 2005-2010, 2011-2015 and 2016-2021 periods



Source: Own calculations.

Despite having a less favourable geographical position, Germany's solar energy has grown into one of the largest markets not only in Europe but also globally. Like in case of wind turbines, this country strongly contributed to solar energy deployment in the early period when technology costs were too high. Similar to wind energy, Germany gradually increased its policy effectiveness (see Figure 4.11) of solar energy during two periods of FIT dominance (2005-2015). Germany was especially successful in promoting this technology during a second period (2011-2015), characterized by a generous FIT program (with average PEI score being 3,7%). The latest period (2016-2021) ended with half of its policy effectiveness (1,21%), as less cost-effective tenders were adopted. As for solar energy, Germany's cumulative PEI score in years 2005-2021 was 33,44%, which is two times lower compared with wind energy during the same period. In terms of this indicator, Germany is behind the following countries: Croatia, France, Sweden, Netherlands, Spain, and Czech Republic.

Figure 4.11. Average solar PEI (%) in selected EU countries during 2005-2010, 2011-2015 and 2016-2021 periods



Source: Own calculations.

Unlike Germany, Poland in general cannot boast of an extensive policy with regard to promotion of renewables during the mentioned periods. By taking insights from the theoretical part and literature review evaluated for this dissertation, one can point out a slow market development in terms of wind and solar energy technologies which is caused by many different factors such as strong competitiveness from fossil fuel energy sources (coal) or a low level of acceptance from society. Based on observed data from Figure 4.10, as expected, Poland was much less effective (with cumulative PEI of 20,14%[32] during the whole analysed period) in deploying wind energy source compared to Germany. However, the country was relatively quite effective (with average PEI equalling 2,3%) during a take-off period (2011-2015) when technology costs started to decrease significantly. Besides a boost from a reduction in technology costs, such growth could be also explained through the existence of quota certificates, which were the main RE support instrument during the first two periods. Even though a shift to tenders after 2015 resulted in a stronger development of this market, PEI of wind energy in Poland decreased to 1,2% during the 2016-2021 period. As previously mentioned in Chapter 1, a recent slow diffusion of wind energy could be caused by restriction measures stemming from changes in the domestic legislation field to regulate RE.

Regarding solar energy, Poland's policy effectiveness was very low during the first two periods from 2005-2015 (see Figure 4.11). This might be due to the fact that the main focus of the country's policy was coal, while the main RE policy instrument during that time was a quota that preferred predominantly cheaper bioenergy and wind technology. Poland started to support solar energy much later than other countries, as the situation changed completely when the country recorded a significant growth in solar power in the last period. As illustrated in Figure 4.11, its average PEI score increased substantially during the 2016-2021 timespan, equalling 5,14%. Thanks to this strong surge, Poland's cumulative value during all periods of 2005-2021 equalled 31,32%, which makes it one of the eight leaders (with slightly worse result compared to Germany) in terms of policy effectiveness of solar energy. Based on the trend of how this type of RE developed in Poland, it can be stated that quotas, which were in force during first two periods, didn't contribute much to the solar energy market development. However, recently this country actively promoted this technology with different support programs and one of them was tender and a special local program called 'My Electricity' (from Polish: Mój Prąd - see *Ministry of Climate and Environment of Poland, 2019*).

One can draw also other valuable insights from the ongoing analysis. Most countries which employed quota-based instruments have been effective in deploying wind energy sources. This concerns especially Belgium, Sweden, Italy, and Romania. The latter was very effective during a take-off period; however, it recorded a sharp decline during the latest phase

[32] In terms of solar energy, Poland recorded a below average PEI score among EU member states during a period of 2005-2021

(2016-2020). Also, Poland benefited strongly from the quota support policy during a take-off period (2011-2015) when technology costs were still relatively high but continually decreased. Besides that, the importance of FIT mechanisms should be acknowledged in promoting wind energy during the early and take off periods (2005-2015). As for other policy instruments, one can note a positive impact of tenders in some countries, especially during the latest period of 2016-2021. Regarding tax incentives and investment grants, no special pattern could be observed.

Unlike wind energy, not many countries invested strongly in solar energy during the beginning period. Also, member states, in which FIT was the main policy instrument (Germany, Bulgaria, Italy, France, Greece or Czech Republic), were very effective in deploying solar energy especially during a take-off period (2011-2015). The analysis shows that some countries (Poland, Netherlands, Denmark) used tenders quite effectively during the latest period of maturity (2016-2021). As one can notice, very different rates of progress in terms of policy effectiveness of solar energy across researched EU countries were made, and no strict patterns can be noted for countries with quotas or tax incentives.

4.3. Assessment of DEA efficiency

The first stage of the analysis of policy efficiency is based on estimations from input-oriented BCC DEA model. The rationale and features of the method have been described in the Chapter 3. For the purpose of a more comprehensive analysis, this approach consists of two separates parts: standard and bias-corrected DEA assessment. First one provides only with preliminary results, as the second one delivers main and stronger results, based on which evidence and conclusions from the research on policy efficiency have been drawn. Furthermore, building on estimations of bias-corrected DEA assessment, the next stage of the analysis is conducted based on regression models (see Section 4.4).

The scope of the study aimed to include all countries from the EU. However, due to the fact that values regarding wind and solar energy production or installed capacity are marginal, some member states were excluded from observation. As a result, the following countries are employed into the DEA analysis: Belgium, Bulgaria, Czech Republic, Denmark, Germany, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Luxemburg, Hungary, Netherlands, Austria, Poland, Portugal, Finland, and Sweden. Since available data on costs of policy support can be extracted only for the 2008-2018 period, performance for the most recent year 2018 was assessed.

First, efficiency estimations were calculated within a standard input-oriented BCC DEA model with variable returns to scale (VRS), which is presented in Equation 3.2 in Chapter 3. The computation of the results is undertaken separately for wind and solar energy policies across the analysed countries. It was conducted with the help of 'R' platform, which is a popular software program in a branch of statistics. The applied standard input-oriented BCC DEA model contains two inputs: cost of policy support and installed capacity, while four outputs include the following variables: power production, direct and indirect jobs, environmental and energy security indicators. More information on input and output variables was collected and analysed in Section 3.4.2 (Chapter 3).

As mentioned previously, the DEA method is very sensitive to any discrepancies in data sets. For the purpose of getting more robust and consistent results, a sensitivity analysis was performed. This step employs five models, which constitute a combination of predefined parameters. The developed five models include or exclude certain outputs from the original DEA model (apart from power production), while inputs - cumulative installed capacity and cost of policy support remain in all models. They are summarized in Table 4.3 and contain sets of various analysed DEA input and output variables. Model M1 includes power production as the only output variable and is taken as a benchmark for other models as they also include this mentioned variable. Models M2, M3 and M4 besides electricity production (energy dimension) incorporate also environmental, energy security and socio-economic component (direct and indirect jobs) respectively. The last model M5 is a complete one, as it includes all predefined inputs and outputs.

Table 4.3. Input and output parameters in five models

DEA variables	**Abbr.**	**M1**	**M2**	**M3**	**M4**	**M5**
		PR	***PR_ENV***	***PR_SEC***	***PR_JOB***	***ALL***
Inputs						
Cumulative Installed Capacity (MW)	*CAP*	X	X	X	X	X
Cost of policy support, (Mln Euro)	*SUP*	X	X	X	X	X
Outputs						
Power production (TWh)	*PR*	X	X	X	X	X
Environmental indicator (Mt CO_2)	*ENV*		X			X
Energy security indicator (Mtoe)	*SEC*			X		X
Direct and indirect jobs in power sector	*JOB*				X	X

Source: Own compilation.

Preliminary results with country ranking in case of all five models for the year 2018 are presented in Appendices G.1 and G.2, which refer to wind and solar energy policy respectively. Given the fact that obtained outcomes on standard DEA efficiency scores are very similar across all above-mentioned five models, only a detailed analysis for model M5_ALL (which includes all selected input and output variables) is provided later in this section. Additionally, illustration of the obtained standard DEA efficiency scores for all five models are presented in Appendices H.1-H.5 (for wind energy) and H.6-H.10 (for solar energy).

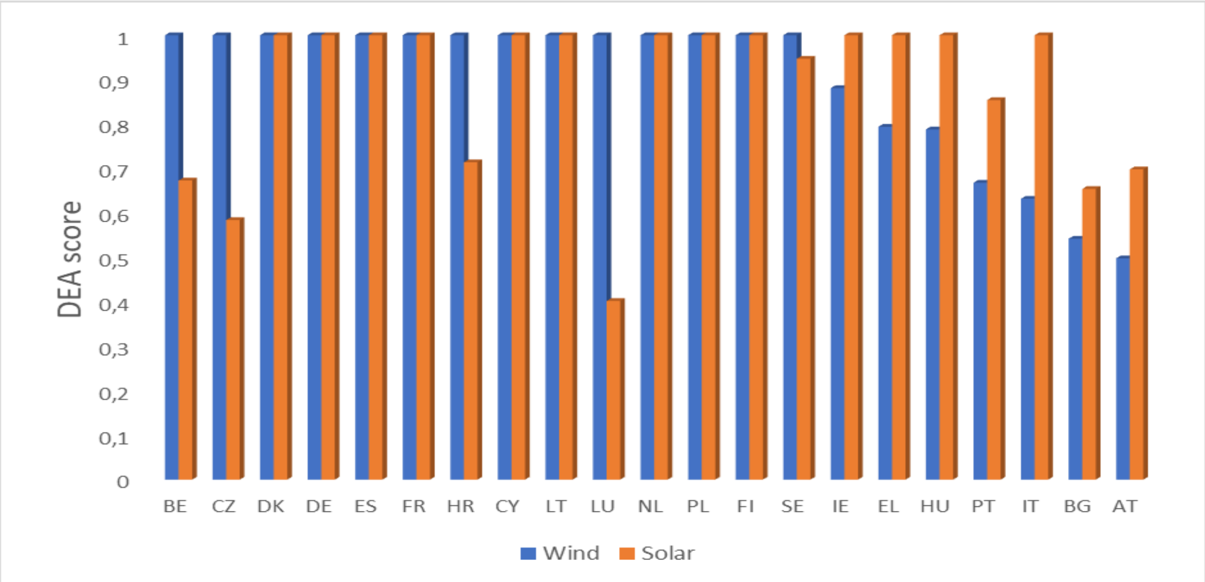
According to the general DEA approach, only whose DMUs with performance score equalling 1 can be considered as efficient. However, additional analysis was performed, assuming that wind or solar energy policies, which are closer to the optimal frontier obtain are categorized as efficient or more efficient. In a similar way, the ones situating far from the optimal frontier, are considered as less efficient or inefficient DMUs. Also, a number of observations (DMUs) in the ongoing research is three times greater than the sum of total inputs and outputs: 21 > 3(2+4), indicating robustness of the accepted DEA model (see *Wu et al., 2016*).

Standard DEA efficiency scores (θ) for model M5 across wind and solar energy policies for selected EU member states in 2018 are highlighted in Figure 4.12. In general, the obtained DEA efficiency scores (coefficients) ranged from 0,498 to 1 and 0,402 to 1 for wind and solar energy policy respectively. Concerning wind energy policy, Germany, Poland, Belgium, Czech Republic, Denmark, Spain, France, Croatia, Cyprus, Lithuania, Luxemburg, Netherlands, Finland, and Sweden are considered to be efficient. These countries with the best possible policies obtained a score of 1, which is graphically located on the optimal frontier. Wind policies of Bulgaria and Austria are the most inefficient as both secured the lowest scores - 0,542 and 0,498 respectively. Among other inefficient countries with scores substantially below 1 are Ireland, Greece, Italy, Hungary, and Portugal.

As for solar energy policies, the following countries can be considered efficient: Germany, Poland, Denmark, Ireland, Greece, Spain, France, Italy Cyprus, Lithuania, Hungary, Netherlands, and Finland. At the other end, Luxemburg and Czech Republic have the most inefficient solar energy polices with scores of 0,402 and 0,584 respectively. Also, Belgium, Bulgaria, Croatia, Austria, Portugal, and Sweden belong to the group of inefficient countries as their efficiency scores lie below the optimal frontier.

All above-mentioned estimations have been calculated based on a standard DEA procedure. The preliminary results obtained from this method are considered as secondary in this research. The aim of the application of such an approach in the ongoing research was to determine which policies are considered to be efficient (by minimizing inputs with a level of output remaining the same: input-oriented BCC DEA model). The results of this model indicated countries with efficient wind and solar energy policies (receiving efficiency score 1), and those that were not efficient (all scores below 1). Furthermore, the goal of employing this approach was to show how the obtained results differed between those which were corrected with bias[33].

Figure 4.12. Standard DEA efficiency scores (for Model 5) of wind and solar energy policies across selected EU member states in 2018



Source: Based on own calculations.

Given the limitation of the standard DEA approach explained in Chapter 3, an improved assessment has been conducted next based on the bias-corrected DEA method (also input oriented BCC model). This approach described in a study by *Simar & Wilson (2007)* corrects efficiency scores for bias. Also, in line with the purpose of this research, a bias-corrected method provides a ranking of countries cascading from the most to the least efficient policies instead of dividing them only to the ones with efficient or non-efficient support mechanisms.

As in the case with the standard model, bias-corrected DEA efficiency scores were estimated for proposed models from sensitivity analysis. This procedure implies establishing different models of assessing efficiency based on a number of input and output variables. In an

[33] Bias-corrected DEA efficiency approach is explained next in this section and is considered to be the main method of DEA in the ongoing research

analogical way to the standard DEA approach, also five models have been developed with relevant parameters (see Table 4.3).

The results on bias-corrected DEA efficiency are also computed on ‘R’ platform with the help of ‘rDEA’ package[34]. Tables 4.4 and 4.5 present bias-corrected DEA efficiency scores for five models in the context of wind and solar energy policy in selected EU countries during 2018. Additionally, the ranking of countries was prepared, highlighting best and worst performers. For the purpose of checking the consistency of the models and a better overview of the results, they are also illustrated in Figures 4.13 and 4.14.

Based on the results obtained, one can conclude that values of bias-corrected DEA efficiency scores are the highest in case of model M5_ALL, which includes all predefined input and output variables. The values for wind energy policy in this model vary between 0,271 and 0,803, while a range in the case of the solar energy policy lies between 0,306 and 0,916. Also, as one can point out, no DMU received the highest efficiency score of 1 as the results were much lower compared to those obtained in the standard DEA model. This can be explained by the technique of bias-correction.

Based on the interpretations from Table 4.4 and Figure 4.13, the results obtained for models in the case of wind energy policies look to be unambiguous. As observed, similar results were received for models M4_PR_JOB and M5_ALL, which are also the highest, while models M1_PR and M2_PR_ENV provided the lowest average efficiency scores. Based on the mean values of researched countries, all models for wind energy policy were consistent with the baseline model, which indicates a strong impact of the analysed dimensions (aspects) on policy efficiency. As per model M1_PR, Finland and Belgium have the highest wind power conversion rate (with efficiency scores of 0,594 and 0,577 respectively), while Cyprus (0,636) and Finland (0,599) reached the top of the rankings in terms of environmental benefits (M2_PR_ENV). Also, Spain (0,669) profited strongly from energy security benefits (M3_PR_SEC). Croatia and France joined the group of best performers as they are most efficient in creating new jobs (M4_PR_JOB) with their results equalling 0,726 and 0,716 respectively. The already mentioned member states such as Spain, Cyprus, Croatia, and France settled themselves at the top of the ranking in the most comprehensive model M5_ALL, which includes all input and output variables. At the other end, countries such as Bulgaria, Greece, Hungary, and Austria are considered to be the most inefficient by considering their overall ranking of five models. Surprisingly, Germany’s policy performance is also considered to be relatively low, while

[34] More information on ‘rDEA’ package can be found in *Simm & Besstremyannaya (2023).*

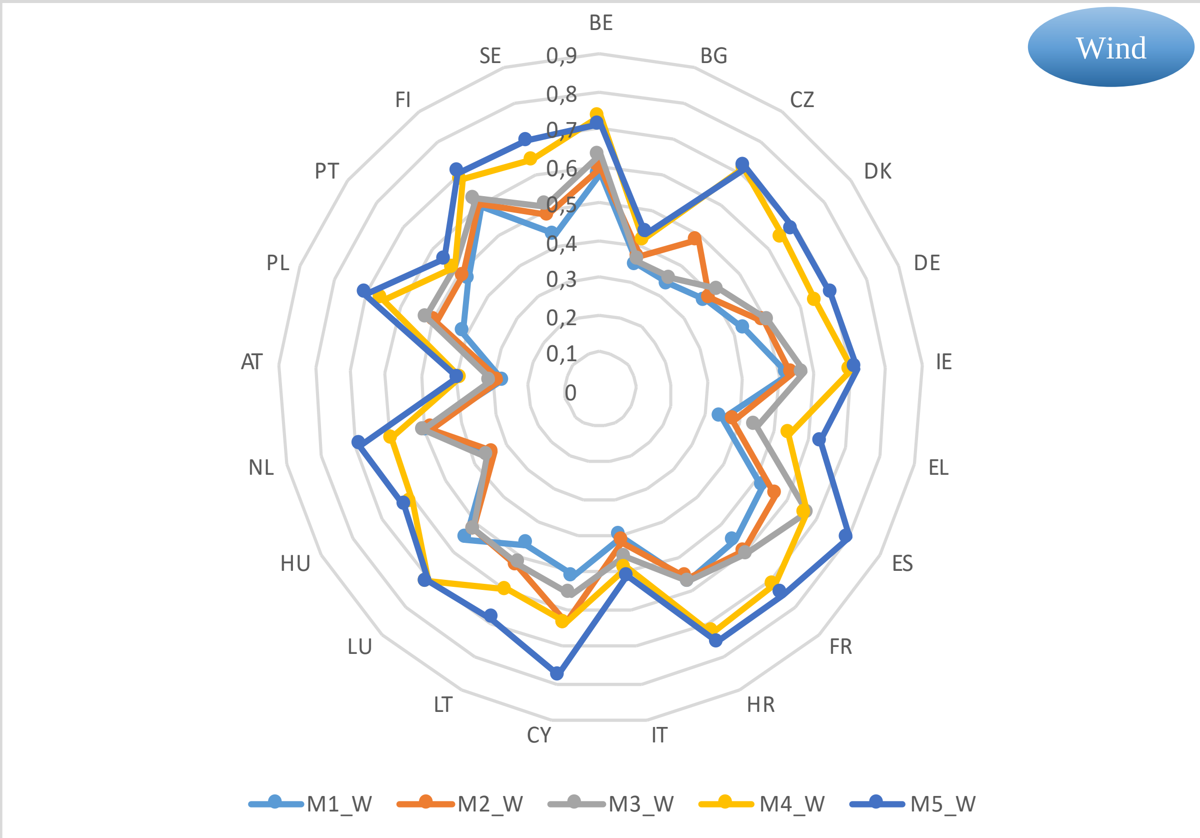
Poland (despite being in the middle of the general ranking) is superior across all models apart from model M1_PR. Factors behind obtained efficiency scores of Poland, Germany and other selected member states are analysed in Section 4.4 in this chapter.

Table 4.4. Bias-corrected DEA efficiency scores (with ranking) of wind energy policy across selected EU member states during 2018. Five models

M1_PR			**M2_PR_ENV**			**M3_PR_SEC**			**M4_PR_JOB**			**M5-ALL**		
Rank	EU ID	Score	Rank	EU ID	Score	Rank	EU ID	Score	Rank	EU ID	Score	Rank	EU ID	Score
1	FI	0,594	1	CY	0,636	1	ES	0,669	1	BE	0,733	1	ES	0,803
2	BE	0,577	2	FI	0,599	2	BE	0,627	2	HR	0,726	2	CY	0,78
3	HR	0,574	3	BE	0,597	3	FI	0,616	3	FR	0,716	3	HR	0,757
4	FR	0,556	4	FR	0,594	4	FR	0,606	4	CZ	0,715	4	FR	0,75
5	LU	0,55	5	ES	0,57	5	HR	0,575	5	LU	0,706	5	CZ	0,721
6	IE	0,525	6	HR	0,565	6	IE	0,57	6	IE	0,704	6	IE	0,719
7	ES	0,524	7	IE	0,54	7	CY	0,559	7	FI	0,682	7	BE	0,71
8	CY	0,509	8	LT	0,53	8	LT	0,522	8	ES	0,664	8	LU	0,71
9	NL	0,498	9	LU	0,517	9	PL	0,521	9	DK	0,654	9	FI	0,704
10	PT	0,468	10	PL	0,494	10	PT	0,519	10	PL	0,652	10	PL	0,702
11	LT	0,467	11	DE	0,491	11	LU	0,515	11	DE	0,649	11	SE	0,697
12	DE	0,439	12	SE	0,488	12	SE	0,515	12	SE	0,643	12	DE	0,696
13	SE	0,432	13	PT	0,487	13	NL	0,506	13	CY	0,636	13	DK	0,689
14	PL	0,412	14	CZ	0,484	14	DE	0,503	14	HU	0,608	14	LT	0,688
15	IT	0,4	15	NL	0,484	15	IT	0,458	15	LT	0,598	15	NL	0,687
16	DK	0,378	16	IT	0,415	16	EL	0,449	16	NL	0,596	16	EL	0,634
17	HU	0,353	17	DK	0,39	17	DK	0,424	17	EL	0,542	17	HU	0,629
18	EL	0,351	18	EL	0,384	18	HU	0,364	18	PT	0,52	18	PT	0,556
19	BG	0,347	19	BG	0,373	19	BG	0,358	19	IT	0,486	19	IT	0,51
20	CZ	0,34	20	HU	0,344	20	CZ	0,356	20	BG	0,419	20	BG	0,436
21	AT	0,271	21	AT	0,282	21	AT	0,305	21	AT	0,389	21	AT	0,397

Source: Own calculations.

Figure 4.13. Comparison of bias-corrected efficiency scores of selected EU member states in 2018 for five models. Wind energy policy



Source: Based on own calculations.

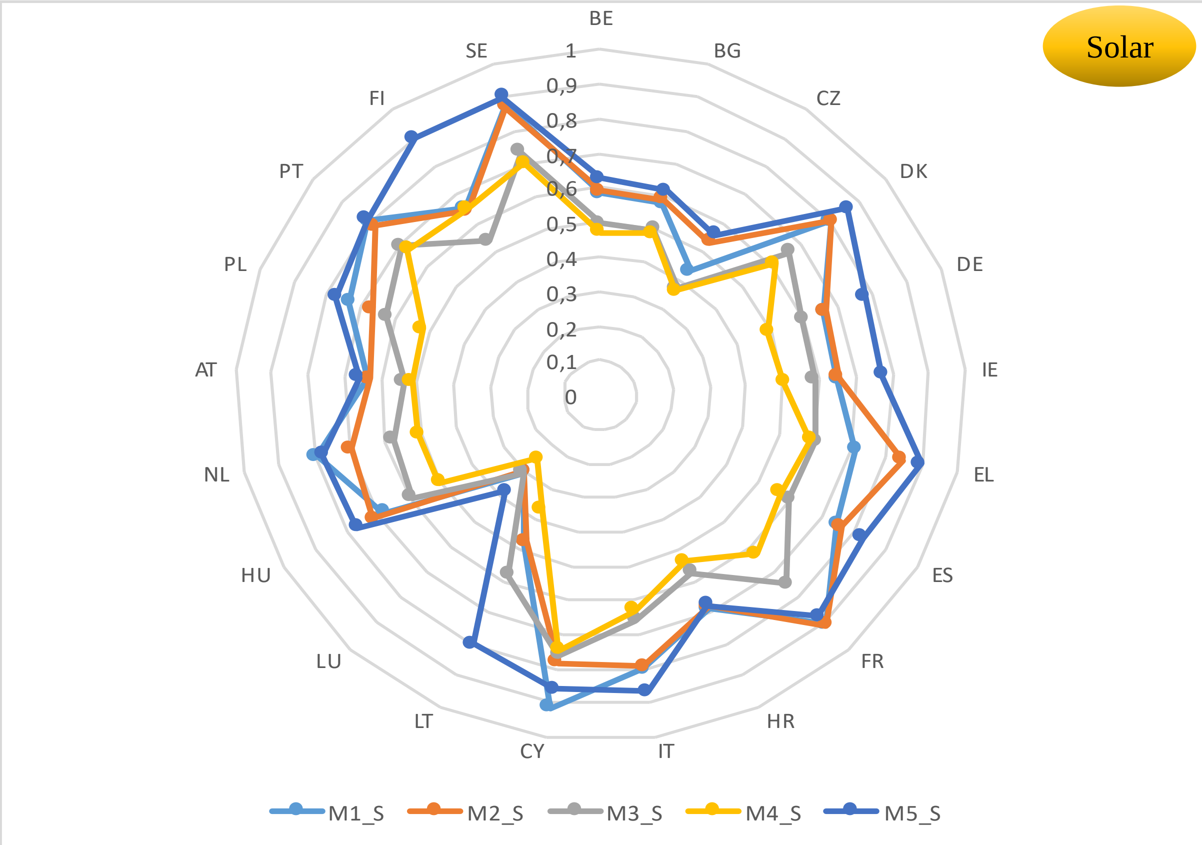
In a similar way to wind energy policy, it is also difficult to define some patterns in terms of efficiency scores for solar energy policies in 2018. As M1_PR, M2_PR_ENV, M5_ALL provided the highest average results, M3_PR_SEC and M4_PR_JOB produced the lowest efficiency scores. Stemming from Table 4.5 and Figure 4.14, it can be acknowledged that all the models generated quite similar results, which means they are consistent between themselves, starting from the baseline model (M1_PR) and finishing with the most comprehensive one (M5_ALL). Based on the results obtained from Cyprus (0,916) and France (0,904), these countries convert their solar power generation in the most efficient ways (as per model M1_PR). As for environmental benefits (M2_PR_ENV), apart from France (0,911), Sweden (0,87), and Greece (0,845) Cyprus and France also presented themselves as the best performers. In terms of energy security gains (M3_PR_SEC), Sweden (0,762) has one of the most optimal policies along with Cyprus (0,762) and France (0,748). Also, Portugal (0,671) joins the group of efficient countries, while being a significant contributor in terms of benefits from employment (M4_PR_JOB) in the solar power market. In terms of total gains received from all dimensions (energy, environmental, energy security and employment aspects – all constituting model M5_ALL), countries like Sweden, Greece, Finland and France look to be very efficient. At the other end, Austria, Belgium, Bulgaria, Czech Republic, Lithuania, and Luxemburg obtained the lowest efficiency scores within all five models. Surprisingly, Poland and Germany delivered average and below average results respectively as far as solar energy policy is concerned.

Table 4.5. Bias-corrected DEA efficiency scores (with ranking) of solar energy policy across selected EU member states during 2018. Five models

M1_PR			**M2_PR_ENV**			**M3_PR_SEC**			**M4_PR_JOB**			**M5-ALL**		
Rank	EU ID	Score	Rank	EU ID	Score	Rank	EU ID	Score	Rank	EU ID	Score	Rank	EU ID	Score
1	CY	0,916	1	FR	0,911	1	CY	0,762	1	CY	0,747	1	SE	0,902
2	FR	0,904	2	SE	0,87	2	SE	0,762	2	SE	0,702	2	EL	0,897
3	SE	0,875	3	EL	0,845	3	FR	0,748	3	PT	0,671	3	FI	0,897
4	PT	0,809	4	DK	0,808	4	PT	0,693	4	FI	0,647	4	FR	0,876
5	DK	0,804	5	IT	0,796	5	DK	0,66	5	IT	0,63	5	IT	0,867
6	IT	0,8	6	PT	0,785	6	IT	0,658	6	FR	0,628	6	DK	0,865
7	NL	0,797	7	CY	0,783	7	PL	0,625	7	DK	0,612	7	CY	0,859
8	ES	0,748	8	ES	0,76	8	EL	0,606	8	EL	0,591	8	ES	0,829
9	PL	0,737	9	HU	0,717	9	ES	0,599	9	ES	0,568	9	PT	0,815
10	EL	0,717	10	NL	0,7	10	DE	0,596	10	HR	0,535	10	LT	0,801
11	HR	0,687	11	HR	0,68	11	HU	0,593	11	PL	0,522	11	DE	0,776
12	HU	0,683	12	PL	0,669	12	IE	0,586	12	AT	0,515	12	NL	0,776
13	DE	0,657	13	DE	0,66	13	NL	0,58	13	HU	0,508	13	PL	0,776
14	FI	0,654	14	IE	0,652	14	LT	0,578	14	NL	0,508	14	IE	0,773
15	IE	0,65	15	FI	0,646	15	HR	0,572	15	IE	0,506	15	HU	0,766
16	AT	0,635	16	AT	0,632	16	FI	0,538	16	DE	0,493	16	HR	0,676
17	BE	0,583	17	BE	0,592	17	AT	0,536	17	BG	0,487	17	AT	0,662
18	BG	0,58	18	BG	0,589	18	BG	0,5	18	BE	0,469	18	BE	0,626
19	LT	0,473	19	CZ	0,534	19	BE	0,496	19	LT	0,371	19	BG	0,617
20	CZ	0,433	20	LT	0,471	20	CZ	0,374	20	CZ	0,364	20	CZ	0,559
21	LU	0,306	21	LU	0,304	21	LU	0,308	21	LU	0,253	21	LU	0,381

Source: Own calculations.

Figure 4.14. Comparison of bias-corrected efficiency scores of selected EU member states in 2018 for five models. Solar energy policy



Source: Based on own calculations.

To sum up, as for standard procedure, most EU countries, including Poland and Germany, lie on the frontier of optimal efficiency and deliver maximum results. This stems from the direct quantitative approach of the method. For example, some countries, which have relatively very small expenditures on policy support, might also generate low power production. However, these countries might be at the same time very efficient from the point of utilizing its resources. For this and other reasons, bias-corrected analysis takes some important aspects into account and, as a result, provides more robust results. The bias-corrected or bootstrapped technique of calculating wind and solar energy DEA efficiency scores can be considered as a reliant method and is taken as the main method of measuring policy efficiency. As already mentioned, Tables 4.4 and 4.5 along with Figures 4.13 and 4.14 provide a profound comparative estimation of biased-corrected results for five models described from Table 4.3. While models on wind energy policy show quite consistent results, more discrepancies are observed in the case of solar energy policy. Interesting to note is that in the case of both clean energy technologies, Poland and Germany can be found in the middle of the ranking with quite low efficiency scores. Furthermore, Germany’s policy in context of wind and solar energy which is one of the most effective (see Section 4.2), tends to be inefficient based on outcomes from the bias-corrected DEA method. In order to explain these results, an additional analysis was performed, which aimed to show how impactful some external factors could be on the efficiency of wind and solar energy policies across the researched countries.

4.4. Results of regression models.

The second stage of the framework on efficiency incorporates an analysis of external factors which could potentially affect the performance of wind and solar energy policies. Scholars often apply a regression approach as an additional tool to interpret policy efficiency. Especially truncated or censored regressions are positively acknowledged in literature (see *Sağlam, 2017, Papież et al.,2019*), as they control for bias. Based on the fact that this step of research already employs estimations of bias-corrected DEA in dependent variables, a standard linear regression should be a well-tailored tool for measuring effects external factors have on wind and solar energy policy efficiency across selected EU member states.

The first stage of the analysis on policy efficiency based on the DEA framework helped make conclusions how wind and solar policies of the analysed countries are ranked. The second stage of this research presented in this section employs regression method, which gains on importance as it helps to answer a question why certain policies are efficient or not. Furthermore, such an approach presents itself as an additional agenda to find out if some aspects are significant in driving or curbing efficiency of the mentioned policies. Also, since the aim of the current research is to find out general policy effects, regression models look to be a suitable approach for a group of EU member states, including Germany and Poland.

As presented in Chapter 3, this part of the analysis is based on two main regression Equations 3.3 and 3.4, which relate to wind and solar energy respectively. Next, an optimization of these regression models is presented, which consists of three consecutive steps. First is a sensitivity analysis and the other two are called assessment of collinearity (variance inflation factor) as well as model comparison and selection process. This three-tier approach (see Figure 3.4 in Chapter 3) aims at compiling a strong and reliable regression framework which can estimate external effect factors in the most optimal way. Each step of the algorithm to compile the most suitable and reliable regression models is explained below in this section.

In terms of sensitivity analysis, which is the first step of the optimization process, regression models are applied, in which results from five models of bias-corrected DEA are presented as dependent variables. Technology resources and main policy instruments have been selected as two separate groups of external explanatory parameters to investigate their effect on already obtained bias-corrected DEA efficiency scores. So, the analysis includes two groups of external determinants, as the first one is presented by resource endowment - wind speed and solar power theoretical potential parameters. The second set of factors consists of main EU policy instruments, which are feed-in tariffs and premium, quota-based mechanisms, tenders, tax incentives and investment grants. Detailed description of the main policy instruments and resource endowment variables are presented in Table 3.5 (Chapter 3).

The computation of regressions is conducted separately for both mentioned clean energy policies across analysed EU member states and is performed for five models (M1-M5) analogical to whose from DEA analysis (see Table 4.3). Also, in a similar way to a bias-corrected DEA framework, this analysis attempts to include the same set of EU member states. However, due to a lack of data on average solar power technical potential, Finland is excluded. So, this part of research is represented by 20 EU member states and covers a period of 2005-2018.

As mentioned, dependent variable in the regression equations is represented by bias-corrected DEA efficiency scores (θ) obtained for the year 2018 and varies from 0 to 1. Regarding explanatory (predictor) variables, mean wind speed (W_speed) and average solar power theoretical potential ($PV\_potential$) are taken as a constant. A different approach is applied for quantifying other selected explanatory variables, which had been the EU main policy instruments to support wind and solar energy during the 2005-2018 period. Given the purpose of this research, dominant support mechanisms are abstracted to four categories (parameters) which are feed-in tariffs and premiums (*FIT*), tenders (*TNDR*), quota-based schemes (*QUOTA*), tax incentives and investment grants (*TAX_INV*). Based on their presence in countries researched, they are proportionally calculated in range from 0 to 1. For example, when a certain support scheme was in force during years 2005-2012, it takes a value of 0,5 (as it covers half of the entire period). Such a technique could be suitable in quantifying the effects of main wind and solar energy policies during the indicated period. Calculated values based on availability of certain support mechanisms across EU member states are described in Appendix I.

In order to create robust regression models, scholars often explore a level of correlation between selected variables. As a traditional tool to measure multicollinearity[35] between predictor parameters in regression is the application of variance inflation factor (VIF). The

[35] Multicollinearity – a theory which implies that predictor variables in a regression model are correlated.

rationale behind applying this technique is that results of various multiple linear regression models can be very sensitive even to slight changes in data or variables. This tool also implies that the stronger the relationship between variables is, the more difficult it is to explain coefficient estimates of a selected regression. The basic and a simple rule of VIF is that if any of its values is greater than 5, then the correlation between independent variables is too strong, meaning that a selected regression model is dubious. This technique has been applied in the current part of regression analysis and is considered as the second step of optimization process.

Table 4.6. Results on variance inflation factor between independent (predictor) variables

Wind energy	FIT_w	$QUOTA_w$	$TNDR_w$	TAX_INV_w	W_speed
	9,224	9,381	1,293	1,506	1,382
Solar energy	FIT_s	$QUOTA_s$	$TNDR_s$	TAX_INV_s	$PV\_potential$
	9,516	12,098	1,459	1,402	1,917

Note: *FIT* - Feed-in tariff, *QUOTA* - quota-based instrument, *TNDR* - tenders, *TAX_INV* - tax incentives and investment grants, *W_speed* - mean wind speed, *PV_potential* - average solar power theoretical potential, *w* - wind energy, *s* – solar energy.

Source: Own calculations.

Obtained results on the variance inflation factor (VIF)[36] for compiled in this study main regression models (Equations 3.3 and 3.4) are presented in Table 4.6. As one can notice, for both wind and solar energy, there are two values[37], which are greater than 5. Based on this evidence, it can be concluded that both above-mentioned primary regressions are not suitable and require further modification. Against this background, an additional technique is used in this research, aimed at adjusting these regression equations, so that they are robust and reliable. In this context, the next step of optimization of a regression approach is performed based on model selection process.

As there could be some restraint concerning the robustness of multiple linear regression models, often a technique of comparison and selection of the optimal model is used with the aim to outline new regressions with the best relationship between predictor (explanatory) and dependent variables. For the purpose of extracting more precise and significant evidence of how selected external factors contribute to efficiency levels of wind and solar energy policies in the analysed countries, an additional tool is applied called adjusted R-squared (*adjr*) technique[38]. This analysis is the third step of optimization process in the context of regression models, which

[36] VIF results have been calculated on platform 'R'.

[37] Here the two values relate to FIT and quotas respectively.

[38] Unlike using simple R-squared method, author opts for adjusted R-squared technique, which controls for bias, when a number of variables increases in regression.

has been also performed on 'R' platform with help of 'MAAS' package (see *Ripley et al., 2023*). The approach is based on selecting the best possible combination of variables for already accepted multiple linear regressions (in this case these are primary Equations 3.3 and 3.4 from Chapter 3). In other words, it aims to build new models in which explanatory variables predict dependent parameters best (*Statology, 2022*). The formula for computing the adjusted R-squared (*Ibidem*) is presented as follows:

$$adjr = 1 - \frac{(1-R^2)*(n-1)}{\mathrm{n-k-1}} \qquad (4.1)$$

Where: *adjr* - adjusted R-squared; *n* is a number of observations; and *k* is a number of predictor (explanatory) variables.

New regression models could be considered as useful when a value of adjusted R-squared (*adjr*) is the largest of all the models compared. The illustration of this algorithm is performed via 'Leaps' package[39]. Appendix J highlights the process of optimal selection of variables for the five models which delivers the most significant results. A black fill and higher value of *adjr* means that a certain predictor variable fits best into the new regression. All models are illustrated separately for wind and solar energy.

Table 4.7. Obtained optimal regression equations for five models

Model	Wind energy policy	Solar energy policy
M1 PR	$\theta\_W_{it} = TAX\_INV_w$	$\theta\_S_{it} = FIT_s + QUOTA_s + TNDR_s + TAX\_INV_s + PV\_potential$
M2 PR_ENV	$\theta\_W_{it} = FIT_w + QUOTA_w$	$\theta\_S_{it} = FIT_s + QUOTA_s + TNDR_s + TAX\_INV_s + PV\_potential$
M3 PR_SEC	$\theta\_W_{it} = FIT_w$	$\theta\_S_{it} = QUOTA_s + TNDR_s + PV\_potential$
M4 PR_JOB	$\theta\_W_{it} = FIT_w$	$\theta\_S_{it} = FIT_s + QUOTA_s + TNDR_s + TAX\_INV_s + PV\_potential$
M5 ALL	$\theta\_W_{it} = FIT_w + QUOTA_w$	$\theta\_S_{it} = QUOTA_s + TNDR_s + PV\_potential$

Note: θ – bias-corrected DEA efficiency score of *W* - wind energy and *S* - solar energy, *FIT* - Feed-in tariff, *QUOTA* - quota-based instruments, *TNDR* – tenders, *TAX_INV* – tax incentives and investment grants, *PV_potential* – average solar power theoretical potential, *w* – wind energy, *s* – solar energy, *i* represents a selected EU country, *t* - a year,

Source: Own compilation.

[39] More information about 'Leaps' package can be found in *Lumley & Miller (2022).*

Based on the above-mentioned model selection technique, new stronger regression equations were obtained for wind and solar energy policies and are presented in Table 4.7. Similar to the case with primary regression Equations 3.3 and 3.4, dependent parameters remained unchanged for both energy technologies. As far as the predictor variables for wind energy policy are concerned, three groups of regression models can be selected out based on primary Equation 3.3. The first set consists of the model M1_PR which includes only tax and investment (TAX_INV_w) variables. The second group is represented by models M3_PR_SEC and M4_PR_JOB, which incorporates the only feed-in system (FIT_w) parameter. And the third group (M2_PR_ENV; M5_ALL) - contains both explanatory variables: feed in system (FIT_w) and quota-based instruments ($QUOTA_w$). For solar energy policies, two groups of regression models were developed. The first one (M1_PR; M2_PR_ENV; M4_PR_JOB) includes all parameters from the primary regression Equation 3.4. The second set (M3_PR_SEC and M5_ALL) contains three variables: quota-based instruments ($QUOTA_s$), tenders ($TNDR_s$) and solar power potential *(PV_potential)*.

The results (coefficients) of the five regression models for wind energy policy are presented in Table 4.8. Additionally, p-values[40] are highlighted in brackets. All models, except for M1_PR and M4_PR_JOB provide significant results for feed-in tariffs and premiums (FIT_w). The evidence is unexpected as models M2_PR_ENV, M3_PR_SEC and M5_ALL indicate that the mentioned support instrument tends to have a negative impact on efficiency of wind energy policy. This means that small benefits are expected to be acquired in terms of environmental, energy security and employment. Such a situation can be explained by the fact that countries might overinvest in this clean energy technology with general costs to be exponential. Also, some scholars (e.g., *Papież et al., 2018; Mezősi et al., 2018*) noted that FIT could have a marginal impact in light of rigorous regulatory requirements and diminishing number of sites for building new wind turbines in many EU countries. Another reason could be that the maturity of the wind energy market, which implies that government intervention (e.g., financial support via FIT mechanism) into this sector is no longer required or is marginal. As there is a consensus in the literature (e.g., *Baldwin et al., 2016; Kilinc-Ata, 2016; García-Álvarez et al., 2017; Papież et al., 2018*) regarding a positive impact of feed-in tariffs on efficiency in terms of wind energy, there are still some scholars that empirically confirm its discouraging effect (*Pyrgou et al., 2016; Romano et al., 2017; Ciarreta et al., 2017*). However,

[40] P-value measures the level of probability if the result is obtained by chance. Normally, results are considered to be statistically significant if p-value is lower than 0,05. For the purpose of this research p-value, coefficients with p-values < 0,1 are also considered as significant.

the obtained results can be also at least consistent in the case of Germany, where FIT has been a main support mechanism for decades. In this context, the explanation of below average (bias-corrected DEA) efficiency scores for this country in terms of wind energy policy looks to be reasonable.

As for the remaining policy instruments, one can point out a negative effect of quota instruments ($QUOTA_w$) on wind energy policy. However, the only results obtained for models M2_PR_ENV and M5_ALL were not significant. Accordingly, no conclusion can be made in the case of quotas, which was in the centre of Poland's energy policy supporting renewables during the period of 2005-2016. Also, a lack of results can be noted for tenders ($TNDR_w$), while in the case of tax and investment mechanisms (TAX_INV_w), model M1_PR indicated a positive association with the performance of wind energy. However, this result is not significant as its p-value exceeds 0,1 threshold. Surprisingly, no evidence can be obtained as far as the effect of wind speed (W_speed) is concerned. Theoretically, this factor could be very important and should be positively correlated with efficiency. However, as mentioned in Section 4.1, values of wind speed are not so strongly differentiated across selected EU member states. In this context, its effect could not be significant or marginal. Other reasons for the lack of results on the impact of wind speed could stem from the fact that other external factors might have a strong effect. For example, discouraging regulatory measures (implementation of new legal frameworks in Poland and Germany regarding limited sites where new turbines can be built[41]) could be crucial in how the wind energy market in a certain country develops.

Table 4.8. Outcomes of five regression models. Wind energy policy

	M1	**M2**	**M3**	**M4**	**M5**
	PR	***PR_ENV***	***PR_SEC***	***PR_JOB***	***ALL***
FIT_w	n/a	-0,236 (0,085·)	-0,104 (0,08·)	-0,066 (0,302)	-0,27 (0,091·)
$QUOTA_w$	n/a	-0,181 (0,1961)	n/a	n/a	-0,243 (0,145)
$TNDR_w$	n/a	n/a	n/a	n/a	n/a
TAX_INV_w	0,175 (0,103)	n/a	n/a	n/a	n/a
W_speed	n/a	n/a	n/a	n/a	n/a
Const	0,4297 (1,5e-13***)	0,695 (2,62e-5***)	0,575 (4,02e-10***)	0,667 (1,56e-10***)	0,916 (7,45e-8***)

Note:*10% significance code, ** 5% significance code, *** 1% significance code.

[41] More information on regulation of RE sources in EU, Germany and Poland is found in sections 1.4 and 1.5 (Chapter 1).

FIT - Feed-in tariff, *QUOTA* - quota-based instrument, *TNDR* – tenders, *TAX_INV* – tax incentives and investment grants, *PV_potential* – average solar power theoretical potential, *W_speed* – wind speed, *w* – wind energy.

Source: own compilation.

More unequivocal results are extracted for solar energy policy, presented in Table 4.9, where p-values are also highlighted in brackets. In this case, all main policy instruments have a strong and positive correlation with solar energy policy efficiency. As also noticed, quotas ($QUOTA_s$) and tenders ($TNDR_s$) tend to have a significant positive effect on the performance of solar energy policy, which is observed in all models. The results look especially consistent in the case of Poland, where quotas and tenders have played a major role in supporting RE sources. As for Germany, it can be also noted that it benefited from feed-in system (FIT_s) and tenders ($TNDR_s$) as far as solar energy policy is concerned. Based on the obtained results, (FIT_s) and tax/investments (TAX_INV_s) actually exert quite a significant effect on policy performance of solar energy. The former policy tool indicates robust evidence observed in models M2_PR_ENV and M4_PR_JOB, while the latter - in models M1_PR and M4_PR_JOB. The analysed countries where these two instruments are regarded as main policy tools are expected to receive major gains in terms of solar energy generation, environment, and employment. In general, the results are in line with other empirical studies, which indicated a significant and positive impact of feed-in tariffs (*Baldwin et al., 2016; Li et al., 2017*), quota-based mechanisms (*Wiser et al., 2017; Choi et al., 2018*), tenders (*Kilinc-Ata, 2016; Winkler et al., 2018*), tax and investments (*Li et al., 2017; Ahmadov & van der Borg, 2019)* on solar energy. As for resource endowment of solar energy (*PV_potential*), all models show a very strong and positive relationship with the efficiency of solar energy policy. A recent positive trend in terms of regulatory and legal frameworks, lower market maturity, reduction in technology cost of solar energy, and growing prices for fossil fuels can be other factors, which, together with resource supply and policy instruments, could cause a positive synergy effect on the solar energy market development across analysed EU member states.

Table 4.9. Outcomes of five regression models. Solar energy policy

	M1	**M2**	**M3**	**M4**	**M5**
	PR	***PR_ENV***	***PR_SEC***	***PR_JOB***	***ALL***
FIT_s	0,307 (0,198)	0,366 (0,111)	n/a	0,308 (0,064·)	n/a
$QUOTA_s$	0,6140 (0,04*)	0,634(0,027*)	0,159 (0,063·)	0,54588 (0,01**)	0,161 (0,109)

(see continuation of the table on the next page)

(continued)

$TNDR_s$	0,435 (0,004**)	0,412(0,005**)	0,203 (0,062·)	0,272 (0,008*)	0,272 (0,039*)
TAX_INV_s	0,331 (0,036*)	0,228 (0,113)	n/a	0,24195 (0,025*)	n/a
$PV\_potential$	0,178(0,003**)	0,169(0,003**)	0,085(0,02*)	0,1611(0,001***)	0,086(0,052·)
Const	-0,394 (0,307)	-0,398(0,276)	0,231 (0,103)	-0,439 (0,102)	0,38 (0,029*)

Note: * 10% significance code, ** 5% significance code, *** 1% significance code.

FIT - Feed-in tariff, *QUOTA* - quota-based instrument, *TNDR* – tenders, *TAX_INV* – tax incentives and investment grants, *PV_potential* – average solar power theoretical potential, *s* – solar energy.

Source: Own calculations.

To sum up, the general findings reveal that effects of some selected external factors are significant overall. However, they are completely different in the case of wind and solar policy. Support mechanisms like FIT look to exert a negative influence on the efficiency of wind energy policy. Regarding quota-based instruments tend to negatively affect efficiency of wind energy policy. As for tax incentives and investment, it could have a positive effect in terms of the mentioned technology. However, the results for both quotas and tax and investments in this case are not statistically significant. No evidence was obtained in the case of wind speed factor. On the other side and as expected, all the main policy instruments (FIT, quotas, tenders, tax incentives and investment grants) are significantly and positively associated with the efficiency of solar energy policy. When considering results from all five models, one should mark tenders as the most efficient tool in improving solar energy policy. Similar results were obtained for a factor of solar power theoretical potential, which tends to contribute very strongly to a development in the solar energy market. Given a lack of data, this research is only restricted to two sets of explanatory variables (dominant policy instruments and resource endowment). Despite this fact, some important and robust findings were obtained, in which their effect on the efficiency of wind and solar energy policies were presented. More details regarding general evidence and conclusions regarding obtained results are highlighted in the Chapter 5.

5. DISCUSSION, CONTRIBUTION, LIMITATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1. Discussion and summary

This chapter intends to sum up the main results of the present work, as the most valuable insights have been highlighted. Based on the purpose set and results obtained in this dissertation, the author also presents how this work contributes to literature and policymakers. Additionally, limitations and avenues of further research have been described.

By strongly relying on theoretical and methodological aspects of the selected problematic, a comprehensive empirical part was conducted, which was divided into two separate research analyses to address policy performance (effectiveness and efficiency). As both analyses were performed separately for wind and solar energy, a strong focus was placed on Germany and Poland. Also, other EU countries were included in this study during the researched periods.

Before conducting research on policy effectiveness and efficiency, a general data analysis regarding wind and solar energy status in EU member states was presented, covering a period of 2005-2021. By presenting the data on generated electricity and installed capacity it can be stated that unlike wind, solar energy sector is rather new market in Europe, as most countries started to develop this technology only during the latest period. While Germany belongs to a small group of 'early movers', Poland recorded a rapid increase in uptake of this technology during the last few years. Regarding wind energy, EU countries also contributed strongly to diffusion of this energy technology during analysed period, while Poland and Germany have one of the biggest techno-economic potential in it. Despite steady progress of wind energy sector, many EU countries could fear about its prospects due to recent unfavourable changes in legislative field (e.g., recent restrictive administrative procedures in Poland and Germany can be a major issue, indicating a lack of sites, where new wind farms can be built).

The phenomenon of 'Energiewende' and expanding policy of FIT and tenders made Germany the biggest public spender in terms of wind and solar energy as per year 2018. Concerning Poland, its spending on the two clean technologies look relatively low also comparing with other EU countries during the same period, as one of its biggest challenges lies in the strong dependence on conventional fuels like coal resources. Also, based on obtained data Germany is considered one of the leading states in how strongly wind and solar energy contributed to environment, energy security and employment, while Poland can boast of significant environmental gains coming from wind energy diffusion. Regarding the analysis of main policy instruments in EU member states during years 2005-2021, the most popular are FIT, while more and more countries have started to concentrate on tenders recently. Also, a comparison in terms of wind and solar energy resources (potential) has been provided. Based on it and as expected, a general evidence was formulated, in which countries from north tend to have more favourable conditions for deploying wind energy, while southern states are better endowed with solar irradiance.

In the first part of the main research, a Policy Effectiveness Indicator (PEI) was employed to compare estimations on effectiveness in the selected EU member states during the predefined periods of 2005-2010, 2011-2015 and 2016-2021. This is in line with the diffusion theory, which categorizes three main timeframes of RE diffusion (early, take-off, and maturity phases). In addition, some empirical studies employed a similar technique, which implies a comparison of performance benchmarks within different periods (e.g., *Mezősi et al., 2018*). Additionally, while measuring policy effectiveness of selected countries, a similar approach used by *Shivakumar et al. (2019)* has been applied in this research. It is based on the availability of a main policy instrument (-s) during the analysed period in a certain country. According to this technique, this study explores how certain support mechanisms (FIT, quotas, tenders, tax incentives and investment grants) could potentially affect effectiveness of wind and solar energy policies during the selected periods.

In summary, Germany is the most effective country (with cumulative PEI score equalling 61,82%) in terms of wind energy policy during the whole researched period of 2005-2021. When referring to the three diffusion phases selected in this analysis, it can be acknowledged that this country is among the ‘early movers’ having strongly invested in this clean energy technology during its early years. Germany was also the most effective country during periods of 2011-2015 and 2016-2021 characterized with a strong financial support by FIT during the take-off phase and by tenders during the maturity period respectively. Regarding Poland, it receives a below average effectiveness score during the whole timespan (with a cumulative PEI of 20,14%) despite the fact that its wind energy policy gained strongly from quota certificates in years 2005-2015. Furthermore, Poland’s performance dropped during the latest period as quotas were replaced with tenders as the new main support instrument. It can be concluded that Germany conducted the most effective wind energy policy, while Poland’s belongs to a group of countries with low effectiveness, which is also in line with hypothesis H1 of this research.

As far as solar energy policy is considered, Germany is the 7th highest performing member state when the whole researched period is measured. Germany is also among countries with the highest PEI score during the first two periods (2005-2010 and 2011-2015), characterized by a strong push from a FIT scheme. Such a strong development during the early and take-off phases makes this country one of few pioneers of this technology in times when the cost of solar energy was very high. In years 2016-2021, when tenders became the dominant support instrument, Germany's policy effectiveness decreased substantially. As for Poland, its solar policy became only effective during the recent phase, as tenders contributed significantly to this progress (4th best score). In earlier and take-off periods (2005-2010 and 2011-2015 respectively) only a marginal output of this technology was recorded, which has to do with possible low support from a main policy instrument - quota certificates. In general, Germany is superior in terms of effectiveness of solar energy policy. However, Poland has performed much better during the latest period. This is partially consistent with hypothesis H1.

Other valuable insights could be taken from this research on effectiveness of wind and solar energy policies. First of all, countries with quota-based mechanisms were very effective in supporting wind energy during the whole period. Such evidence is also consistent with other studies (e.g., *Ragwitz et al., 2015*). As is the case with Germany, other EU member states have also seen a strong push by FIT in the first two periods and in the latest phase by tenders. These results are in line with *Ragwitz et al. (2015)* and *Shivacumar et al. (2019)*. The general evidence on wind energy policy is consistent with hypothesis H2 by indicating a strong support from FIT and quota. As for solar energy, no certain pattern could be defined in case of quotas, tax incentives and investment grants. However, one can observe a considerable contribution of FIT to policy effectiveness during a take-off phase (2011-2015). Also, the recent period (2016-2021) is characterized by a strong positive effect of tenders on the development of the solar energy market. The results are in line with *Shivacumar et al. (2019).* This is also partially consistent with hypothesis H2, as not only FIT, but also tenders contributed strongly to the development of solar energy.

The second part of the empirical study addresses the efficiency of wind and solar energy policies across EU countries (with a strong focus on Poland and Germany). Such analysis was conducted by strongly building on *Simar & Wilson (2007)* approach, which employs two stages of research based on DEA and regression methods. The former approach (DEA) is highly rated among scholars as it can employ different dimensions. As for this study, it addresses energy, environmental, energy security, and socio-economic aspects. The DEA model, applied in this research, includes two input variables (cost of policy support and installed capacity) and four output variables (power production, direct and indirect jobs, environmental, and energy security indicators).

A first stage of the research on efficiency was concerned with the calculation of bias-corrected DEA estimations for year 2018 (as most recent data is available for this year) in analysed countries. Such an approach is well-suited for a special group of countries (such as EU member states) and helps create a ranking with the most and least efficient countries. Since a standard DEA method has some limitations, the bias-corrected procedure to measure policy efficiency of wind and solar energy in analysed countries has been applied, being a reliable and most suitable approach to measure policy efficiency in this research.

Additionally, a sensitivity analysis has been performed, selecting out five models (M1-M5), which included a different set of output variables as inputs remained the same for each model. Based on the results from the five models within the bias-corrected DEA method, in general, Poland looks to be more efficient compared to Germany in terms of wind energy policy. The latter is only superior in the context of gains from wind power generations (model M1). In terms of benefits from environmental, energy security, and employment, Poland's wind energy policy tends to be more efficient. This means that hypothesis H1 is refuted here as Poland (ranked 10th) gets a better bias-corrected DEA score (0,702) in terms of the general result (model M5), while Germany (0,696) is placed at the bottom of the policy efficiency ranking (12th). Surprisingly, Poland is also more efficient than Germany in terms of solar energy even though their general DEA scores are similar (with both recording 0,776), ranked 11th and 12th respectively. Among five models, Poland receives a lower score only in the case of benefits from the environmental component (model M2). In general, when comparing results with other EU member states, both analysed countries recorded average or below-average policy efficiency scores, as their wind and solar energy policies look to be relatively inefficient. However, when exploring only these two countries, Poland is slightly more efficient when all benefits from all analysed components (dimensions) are considered. This is also contrary to the already mentioned hypothesis H1, considering Germany to have a more efficient solar energy policy.

Given the purpose of this dissertation, a second tier (stage) of the analysis on efficiency based on regression method was applied to investigate the effects of external factors on wind and solar energy policy. By employing variables such as main policy instruments (also applied in research on policy effectiveness) and resource endowment (wind speed and solar power theoretical potential) their effects on obtained DEA efficiency scores were extrapolated. As regression models to quantify the mentioned impact factors across analysed EU countries were applied, the period of 2005-2018 had been selected. A similar approach of measuring policy efficiency by using DEA and regression methods is reflected in the literature (e.g., *Papież et al., 2019*).

In order to find out why certain policies are efficient or not, optimization of regression models was performed. Such a procedure consists of three steps. First one is based on sensitivity analysis, which in a similar way to DEA techniques, employs the same five models for regression approach. This approach aims to avoid a situation in which some slight change in predictor variables could lead to major changes in results. The second and third step addresses compilation of the best possible regression equations based on assessment of collinearity (variance inflation factor - VIF) and model selection technique called adjusted R-squared. These steps are taken to obtain regression models in which a number of predictor variables is optimized as well as best correlation between them and dependent variables is obtained.

The results of regression approach on policy efficiency in the case of wind energy show that countries with FIT tend to have a negative (and significant) impact in models with environmental (M2), energy security (M3) and employment aspects (M4), while no evidence is provided in the case of power generation (M1). As for quota-based instruments, they could also have a negative relationship in terms of environmental (M2) and general efficiency (M5) benefits. However, all these results are not significant. The evidence obtained is partially consistent with *Zhao et al. (2013)* and *Papież et al. (2019)*, as some policy instruments (e.g., quotas) tend to have a negative impact on efficiency of wind energy. Also, no results have been received in case of tenders while tax incentives and investment grants were efficient in generating wind electricity (M1) - however as in case with quotas these outcomes are not statistically significant. Surprisingly, no evidence was obtained regarding wind speed implications. It can be concluded that FIT tends to have a negative effect on the efficiency of wind energy policies, at least in the case when benefits from employment and environment are taken into account. For other policy instruments (quotas, tenders, tax investments and grants) and resource endowment (wind speed), no statistically significant evidence or no results at all have been extracted. Due to some gaps in results on effect factors regarding wind energy policy, no conclusion can be made for hypotheses H2 and H3 here.

More insights can be taken from the results in the case of impact factors on the efficiency of solar energy policy. Especially efficient are tenders with very significant results across all five models. Also, quotas tend to be strongly efficient, especially in terms of energy generation (M1) environmental (M2) and employment (M4) benefits. As for FIT, the only significant but positive score is obtained in the case of gains received from the employment aspect (M4). Also, the evidence is in line with some studies (e.g., *Li et al., 2017*), which empirically indicate a strong impact of policy instruments on solar energy market and its performance. Given the fact that in general, countries with tenders as the main policy instrument tend to perform best in terms of efficiency of solar energy policy, it can be stated that hypothesis H2[42] is refuted. Regarding the influence of resource endowment, the results reveal that a very positive and significant role in terms of solar energy policy efficiency is played by solar power theoretical potential Furthermore, this result is consistent with hypothesis H3, claiming that resource endowment (here solar power theoretical potential) has a strong and positive correlation with policy efficiency of solar energy policies. So, all selected dominant support instruments and also solar power theoretical potential are considered as strong external factors of solar energy efficiency. When considering statistically significant results, it can be stated that especially quotas, tenders and solar power potential have a strong and positive effect in all efficiency aspects: power generation, environmental, energy security and employment components.

5.2. Original contribution

The present work strongly builds on the assumption that assessing the role and performance of RE policies is up-to-date and gains in significance, especially in the light of different challenges[43]. Furthermore, such an approach aims at proving valuable insights which can influence decisions of policymakers regarding a better planning and implementation of support policies of RE energy in different countries. The overarching purpose of this thesis is to contribute to the literature of energy economics by performing a comparative assessment of effectiveness and efficiency of wind and solar energy policies in selected countries.

The contribution of this doctoral thesis addresses the theoretical domain, as all key points are summarized, which stand for the significance of energy transition and the role of wind and solar energy technologies in this process. Additionally, the author of this study enriches the literature in the field of RE policy and advances the knowledge regarding the types of support instruments.

Also, an extensive contribution is made as far as the in-depth literature review in the field of RE policy performance is concerned. The value of such analysis grows as a comparison

[42] Hypothesis 2 claims that countries with FIT (feed-in tariff) and quota-based instruments deliver better results than the ones with tenders.
[43] As already mentioned in chapter 1, such challenges are global warming, energy security, price fluctuations and growing energy demand.

of the most relevant and cited studies in the researched area is performed to discover main patterns, methods, gaps, and limitations. Thanks to a detailed assessment of literature and, in accordance with set research objectives, the methodological concept was selected, which fit optimally into the research. Furthermore, the analysed time span was extended to collect the most relevant data in order to obtain more robust results.

The doctoral dissertation contributes to the methodology knowledge, as it builds on a framework, which is a combination of indicator-based, DEA and regression approaches. The methods which have been used in previous research have been also improved upon in several ways. First, the most relevant and up-to-date data sets have been used and employed into the selected frameworks. Second, limitations of the methods applied in previous studies have been considered, as the aim is to provide a research base by achieving synergy from a combination of the two criteria (effectiveness and efficiency). Also, for a better comparative analysis, the researched period was divided into several phases (in case of indicator-based approach). Third, by employing the DEA method policy, effects from multiple dimensions have been quantified. As most of the previous studies addressed policy performance from an economic perspective, there is a need for a broader analysis. Against this background, in addition to energy and environmental economics, value to the literature on socio-economic (employment) and energy security dimensions has been added. Also, a deeper research on policy efficiency has been conducted, where regression approach was additionally applied to discover impact factors behind strong and low efficiency of certain policies.

The cross-country analysis of wind and solar energy policy effectiveness and efficiency also represents a significant contribution to scholars. The empirical findings could be taken as a basis or compared in further research, as the importance of measuring support policies increases due to a dynamic nature of RE market and policy. Besides valuable insights stemming from the results of the empirical research, the main points were also discussed, which could lead to improvement in policy performance not only in the case study countries (Poland and Germany), but also in other countries and jurisdictions.

One can point out to a general contribution of the present work which is addressed to society. Besides presenting wind and solar energy sources in good light, the aim was to attract attention to the adjacent domains such as sustainable development, air pollution, global warming, or energy security. The interest of society in these mentioned categories grows with every day, as energy transition comes closer to its final phase.

5.3. Conclusion

Renewable energy sources have seen an unprecedented growth during the last few decades. The significance of their role is only growing in the global energy arena, whereas clean energy is given a leading role to deal with worldwide threats such as global warming, energy security, price fluctuations and growing energy demand. Furthermore, mankind is facing a challenge in the light of energy transition, as the world is entering a new era premised on a carbon-free system. Actually, wind and solar energy remain as innovators in this historic energy transformation, while conventional fossil fuels continue to lose in being significant.

Despite some drawbacks of these two RE technologies, among which critics usually indicate intermittence in supply and limited storage capabilities, wind and solar energy sources can dominate the global market in the next decades due to some advantages such as diminishing technology costs and of being a carbon-free nature. Other important aspects address the fact that renewables like wind and solar energy technologies already dominate the power sector in many countries. However, the transport, heat and cooling sectors are still strongly reliant on conventional fossil fuels. There is an emerging consensus in the literature that energy transition is going to happen only when all sectors are subjected to a carbon-free sustainable development. Some years ago, a shift from fossil fuels to renewables looked to be far from realizable. The recent development, however, presents clear and promising prospects for energy transition, whose final phase looks to be over within the next few decades. There is already some strong evidence that indicate that some countries are on their closing stage of the energy transition process. For example, EU member states have adopted multiple legislative acts (e.g., 'Green Deal') with the main goal to accelerate energy transition in all branches. Such measures could be a turning point in creating the new completely carbon-free community in the near future.

One of the most important roles in promoting renewables like wind and solar energy technologies is occupied by energy policy. Due to a relatively high technology cost and a long domination of conventional fossil fuels, many countries implemented different financial and other support measures to boost the development of renewables. There is a strong debate in the literature related to the performance of such policies. Despite some critics, a consensus among scholars exists indicating their immense contribution in the unprecedented growth of the clean energy market, the lion's share of which accounts for wind and solar energy technologies. Given the purpose of this research, RE policies are identified with policy instruments. In order to measure the effectiveness and efficiency of wind and solar energy policies in the selected countries, the following policy instruments have been summarized as most dominant in the EU during the last two decades: FIT, quotas, tenders, tax initiatives and investment grants. These four mechanisms have been the subject of detailed research in this study on the role and performance of wind and solar energy.

As the scope of this present work is to a large extent restricted to Germany and Poland, other countries were also included in the analysis to obtain a body of more comprehensive research. This is perhaps the first study which employs two case study countries, Germany, and Poland, as part of a comparative assessment of wind and solar energy policies. Both countries have had different histories as far as the development of RE sources are concerned. As for Germany, it is regarded as a pioneer in promoting renewables while having one of the largest wind and solar energy markets. Conversely, Poland's energy policy has been mainly restricted to coal, with RE playing a secondary role. However, Poland recently managed to expand its RE energy market considerably as prospects of further development look even more promising. In this thesis, an overarching research was delivered covering the effectiveness and efficiency of wind and solar energy policies in Germany and Poland, comparing also with other EU member states. The research in terms of policy performance could draw additional interest, since countries used different support measures (e.g., FIT in Germany) during the researched period.

A literature review conducted in this study revealed some important patterns in identifying the problematic, indicated research gaps and helped develop the author's own methodological concept. The in-depth review of the relevant studies on RE policy performance showed that a scope is usually restricted to a comparison of popular support instruments like FIT, quota instrument or tenders. Other patterns suggest that criteria of effectiveness and efficiency have been positively highlighted by scholars to measure such performance. As most of the studies addressed RE sources in general, less attention is drawn to wind or solar energy technologies as a separate object of research. Scholars often acknowledge the importance of addressing multiple dimensions in research to obtain stronger results on RE policy performance.

In general, there is an emerging consensus in the literature pointing out strong need for more research in assessing policy performance of clean energy technologies. This stems from a dynamic nature of the RE market, the importance of monitoring of policy performance and the lack of a continuous and comprehensive body of work in that area. On one hand, a general assessment of policy effectiveness as being a component of economic dimension was selected. On the other hand, a more comprehensive analysis regarding efficiency was carried out which expanded behind the traditional economic approach as other important components (energy security, environment, and employment) were also employed into the research. Furthermore, an additional analysis was performed by measuring the impact of external factors of resource endowment and main policy instruments on policy efficiency.

Based on a detailed literature review, a methodological concept was formulated, which was best tailored to the objectives and scope of this study. Against this background, an indicator-based and DEA were utilized for measuring effectiveness and efficiency respectively. Furthermore, a regression approach has been applied in order to identify why certain policy instruments were efficient or not. A combination of the mentioned methods provided a detailed study on the performance of wind and solar energy policies in different EU member states, among which are Germany and Poland. Such a methodological approach is rigorous, as the best suitable data sets and variables to conduct robust and high-quality research were employed.

Given the results and interpretation of the current research, it can be concluded that Germany conducts the most effective wind energy policy, while Poland belongs to a group of countries with low effectiveness. Germany also is superior in terms of effectiveness of solar energy policy; however, Poland has performed much better during latest period of maturity (2016-2021). Countries with quota-based mechanisms were very effective in supporting wind energy during the whole researched period. Also, FIT as a main policy instrument, contributed strongly during the early (2005-2010) and take-off (2011-2015) periods, while tenders were effective in countries during the latest maturity phase (2016-2021). As for solar energy, FIT and tenders were especially effective in the take-off and maturity periods respectively.

In terms of efficiency, Poland tends to be more efficient compared with Germany, when all five models of bias-corrected DEA are considered. This evidence is recorded for both wind and solar energy policy. Germany looks to be more efficient only in terms of gains from environmental components in a case of solar energy policy. Considering comparative analysis on the background of other EU member states, it could be noted that Germany and Poland obtained below-average results in terms of policy efficiency for both wind and solar energy policies.

By taking general evidence from regression models, FIT tends to have a negative effect on efficiency of wind energy policies, at least in the case when benefits from employment and environment are considered. As far as solar energy is concerned, all policy instruments are considered to be positive and statistically strong external factors. No results were obtained in the case of wind speed, while solar power theoretical potential has a considerable and statistically significant impact on performance improvement (efficiency) of solar energy policy.

In general, strong insights for Poland and Germany could be taken from empirical research of the thesis. As for wind and solar energy, Germany with its unprecedented policy

‘Energiewende’ is regarded to be a pioneer in the branch of renewables. It is one of the most effective EU member states during the researched period 2005-2021. This country benefited much from FIT, which was in force as a dominant support scheme until 2016. Germany has also been quite effective after the main policy shifted to tenders in the same year. However, based on results from bias-corrected DEA analysis for year 2018, Germany can be regarded as low-efficient in terms of both wind and solar energy policies. The main reason could be a too generous and expensive FIT system, which led to limited benefits from employment, environment, and energy security for wind and solar energy.

As for Poland, in order to formulate a general conclusion, evidence from wind and solar energy policies needs to be separated. Regarding wind energy, despite a strong push during early periods, Poland had conducted a relatively low-effective policy when a researched period 2005-2021 is considered. A shift to tenders from quota-based certificates in 2016 didn’t contribute much to the expansion of wind energy. As for solar energy, mixed evidence was provided. Based on marginal production of solar energy during the first two periods (2005-2010 and 2011-2015), policy effectiveness was close to zero. However, by taking results from the more recent period (2016-2021), its overall effectiveness is among the highest in the EU, as Poland managed to increase its own solar energy output manifold recently thanks to positive policy incentives. One of them includes tenders and smaller projects such as ‘My electricity’. In terms of efficiency, Poland performs better than Germany in the context of wind and solar energy policy. However, Poland’s scores are also considered average or below-average, when comparing with other EU member states. It has also been proved, that quota-based certificates, while being the main policy instrument until recently, had an average impact on wind energy while its support for solar energy was marginal. Nevertheless, Poland has good prospects especially in the solar energy branch as it was also empirically proved in this study that tenders and solar irradiance tend to have a significant and strong positive impact on efficiency of the mentioned technology.

5.4. Limitations and further research

Despite the high importance of this dissertation and its strong contribution to theoretical and empirical literature, there are also some limitations. First, the analysis was restricted predominantly to the electricity sector, which is characterized by a rapid shift to renewables such as wind and solar technologies in the EU. Given the fact that these two mentioned RE sources have contributed to the large extent to the power market, other sectors are only addressed in this study according to their relevance. However, based on evidence from the literature, in order to facilitate a complete shift to a carbon-free system, energy transition should also take place in transport, heat and cooling branches. The research can be extended beyond the power sector, while other RE sources like bio- or geothermal energy may also be employed. Additionally, the scope of a similar analysis could include countries outside the EU community or take a cross-regional dimension.

Other limitations of the work may lie in the approach of assessing performance of support policies. Due to the complexity of the approach to quantify the policy instrument alone, an assumption was made that only main support frameworks are responsible for all implications. However, usually one country could have many support measures at its disposal to boost its deployment of RE sources (e.g., R&D or ETS system). A lack of data for analysed countries and low amounts of some variables are another example of boundaries to this research that were encountered in attempts to conduct a comparative cross-country analysis of EU member states in the context of wind and solar energy policy performance. A strong challenge was met while quantifying some datasets related to the effects of external factors, as only resource endowment and main RE policy instruments were selected for regression methods.

To assess policy effectiveness, a simple indicator-based analysis was selected. This approach included a reference benchmark of techno-economic potential. One could point to some bias as values of this variable are derived from a certain database estimated on a separate model and assumptions. A similar direction of future research in this area can employ more indicators or present a more comprehensive study of factors which boosted or impeded effectiveness.

Based on availability and reliability of data, one can extend the analysis by adding other criteria suggested by *Mir-Artigues & del Río (2016).* By also employing criteria like legal feasibility, one can present a more extensive study of cross-country policy performance. Such an approach looks to be overarching, however challenging in light of low availability of data and problems with selection of appropriate approaches and methods. Against this background, this study addresses only effectiveness and efficiency, which constitutes not only a comprehensive research, but also includes strong, up-to date and comparable input datasets. Also interesting could be a direction of assessment which includes a similar methodological concept and compares policy instruments within one country in different periods. This research reveals that even the same policy instruments promoting wind and solar energy sources can perform differently across countries. That is why there is a strong need for an in-depth analysis of support mechanisms to maintain constant improvement of policy support on each stage of technology diffusion.

As revealed in Chapter 3, some caveats come from methods and approaches related to measuring policy efficiency. Scholars usually point out to the fact that assessment within the DEA method has some important but restrictive points which merit attention. For example, by conducting a cross-country analysis, one can obtain results which are relative but not absolute. A subjective approach in the selection of variables as well as the sensitivity of input data are regarded as other limitations of this method. By choosing other paths for further research (also overcoming the mentioned restrictions), one could apply a more complex approach (e.g., Malmquist technique), as it can provide DEA results which can be comparable within different periods.

Other shortcomings of this study could be a subjective approach towards the selection of factors which affect performance of wind and solar energy technologies. Similar caveats can be summarized when it comes to regression method, while choosing the appropriate variables. As different predefined endogenous variables were used (e.g., cost of policy support or mean wind speed) in this research to estimate policy efficiency, further research could employ other factors from already selected dimensions, such as economic (GDP) or a socio-economic (a number of qualified employees) aspect. Despite these and other shortcomings, this dissertation could present itself as an up-to-date and profound study, which opens interesting paths for further research and improvements with regard to economics and policy of RE energy.

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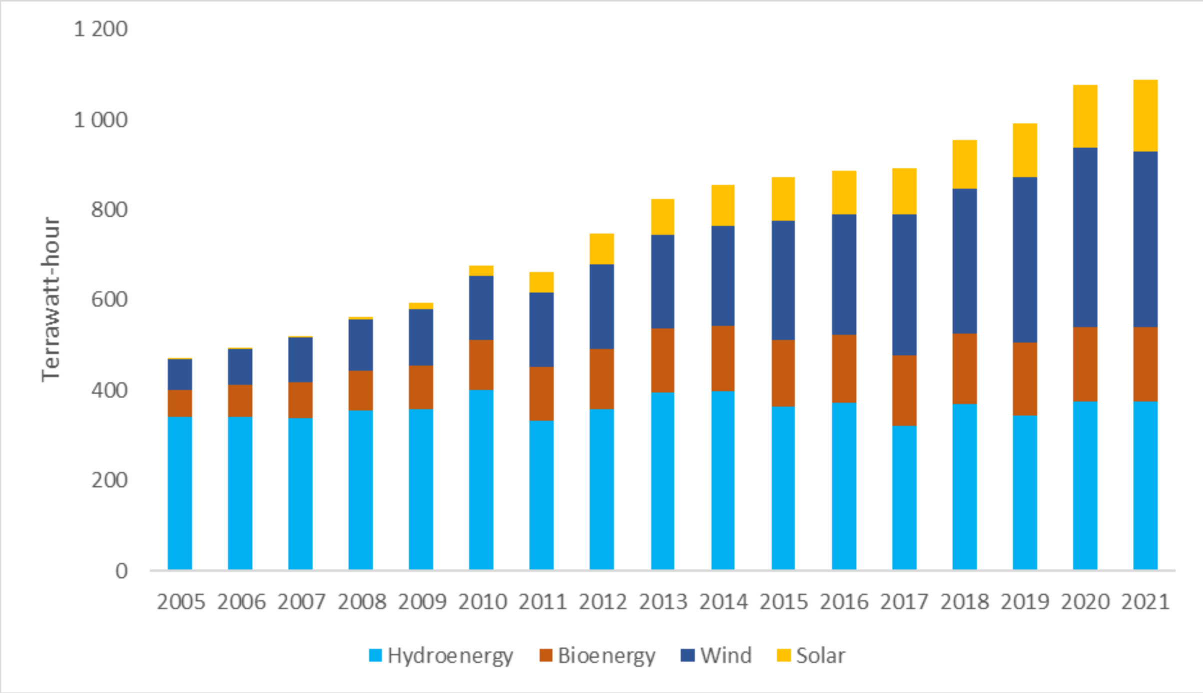
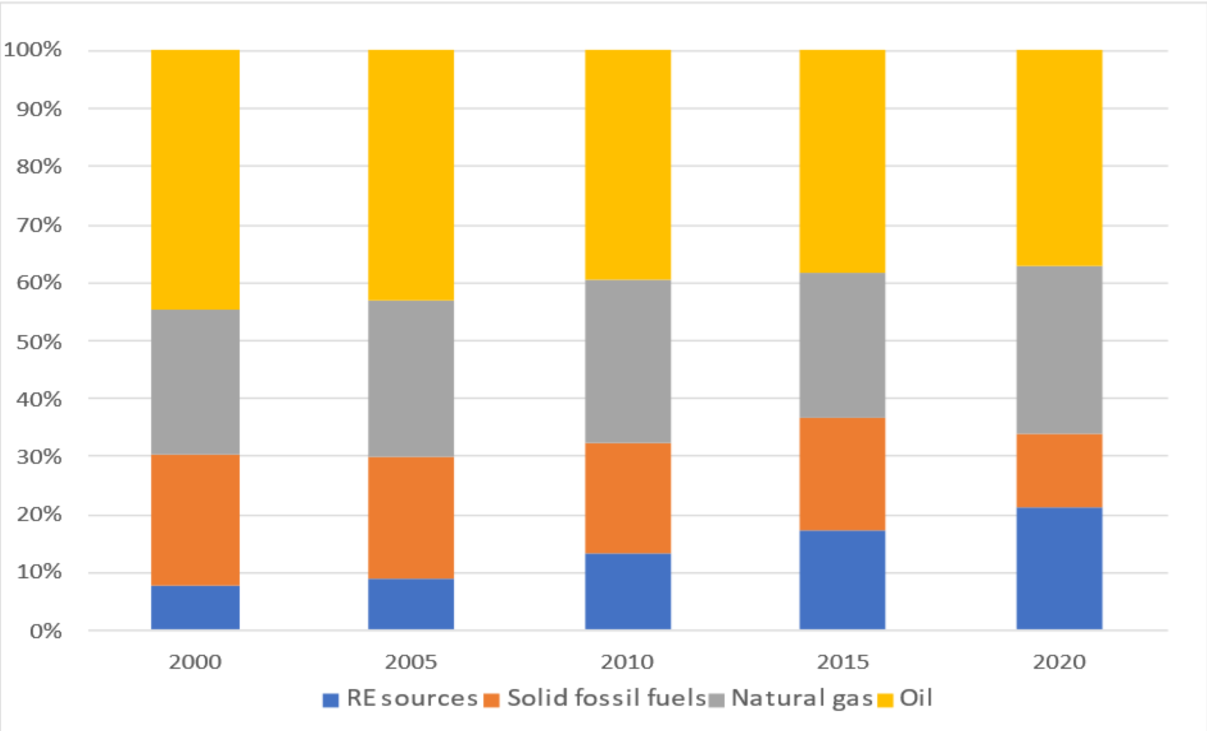
APPENDICES

Appendix A.1. Gross electricity production from RE sources (TWh) during a period of 2005-2021 in EU-27



Source: Based on *Eurostat.*

Appendix A.2. Total energy supply (by type of energy) in EU-27 during a period of 2000-2020



Source: Based on *Eurostat.*

Appendix B. Overview of studies on RE policy performance

Author (-s), year and reference	Methodological approach	Geographical scope	Researched period	Technology scope	Addressed RE policy
Abrell et al. (2017)	Case study, equilibrium model	Germany and Spain	Not specified	RE sources in general, wind and solar energy sources	RE policy in general
Aguirre & Ibikunle (2014)	regression models	OECD, EU and BRICS countries	1990–2010	Multiple RE policy instruments	Multiple RE policy instruments
Ahmadov & van der Borg (2019)	Case study, statistical analysis, a regression model	Netherlands and Belgium	1997-2015	RE sources in general	Multiple RE policy instruments
Azhgaliyeva et al. (2018)	a regression model	106 countries	1997-2014	Wind energy	Multiple RE policy instruments
Baldwin et al. 2016)	a regression model	164 countries	1990-2010	RE sources in general	Multiple RE policy instruments
Carley et al. (2018)	a regression model, interview	USA states	1992-2014	Multiple types of RE sources	RPS
Choi et al. (2018)	cost-benefit analysis (CBA)	South Korea	2002-2016	Multiple types of RE sources	FIT and quota RPS
Ciarreta et al. (2014)	Merit Order Effect Modelling	Spain	2008–2012	Multiple types of RE sources	FIT
Ciarreta et al. (2017)	simulation model	Spain and Germany	2008-2013	RE sources in general	FIT, Quota-based certificates
de Mello Santana (2016)	a levelized life cycle costs (LCC) method	not specified	not specified	RE sources in general	FIT, quota RPS, tenders
Delmas & Montes-Sancho (2011)	a regression model	USA	1997 to 2006	Multiple types of RE sources	quota RPS
Dijkgraaf et al. (2018)	1990 to 2011	30 OECD countries	1990 to 2011	Solar energy market	FIT
Dusonchet & Telaretti (2015)	Comparative economic analysis	France, Germany, Greece, Italy and Great Britain	Not specified	Solar energy	Multiple RE policy instruments
García-Álvarez et al. (2017)	a regression model	EU member states	2000 to 2014	Wind energy	FIT and quota RPS
Jenner et al. (2013)	Indicator-based approach, a regression model	EU member states	1992-2008	Wind and solar energy	FIT and quota RPS
Kabel & Bassim (2019)	Literature analysis	Not specified	Not specified	RE sources in general	Multiple RE policy instruments
Kalkuhl et al. (2013)	equilibrium model	Not specified	Not specified	RE sources in general	Multiple RE policy instruments

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Author (-s), year and reference	Methodological approach	Geographical scope	Researched period	Technology scope	Addressed RE policy
Kitzing et al. (2019)	Literature analysis	EU member states	2000-2011	RE sources in general	Multiple RE policy instruments
Kilinc-Ata (2016)	1990-2008	USA states and EU member states	1990-2008	RE sources in general	FITs, RPS, tenders and tax policies
Kylili & Fokaides (2015)	Economic analysis	Cyprus	2013	RE sources in general	auctions
Li et al., 2017)	a regression model	EU member states	1996 and 2013	RE sources in general	Multiple RE policy instruments
Matthäus (2020)	a regression model	Not specified	1990-2017	RE sources in general	auctions
Mundaca & Richter (2015)	Indicator-based analysis	USA	Not specified	Multiple RE sources	RE policy in general
Nordensvärd and Urban (2015)	Interview	Germany	Not specified	Wind energy	FIT
Özdemir et al. (2019)	a market equilibrium model	EU member states	Not specified	RE sources in general	FIT and RPS
Polzin et al. (2019)	Literature analysis	Not specified	Not specified	Multiple RE sources	Multiple RE policy instruments
Polzin et al. (2015)	a regression model	Selected OECD countries	2000 till 2011	Multiple RE sources	Multiple RE policy instruments
Pyrgou et al. (2016)	Parametric economic model	Denmark, Germany, Cyprus, and Spain	Not specified	RE sources in general, solar energy	FIT
Ragwitz et al. (2015)	Indicator-based analysis	EU countries	2007- 2014	Multiple RE sources	RE policy in general
Ramírez et al. (2017)	econometric model and profitability analysis	EU countries	2000-2014	RE sources in general, solar energy	Multiple RE policy instruments
Romano et al. (2017)	Statistical description, T-test	56 developed and developing countries	2004–2011	RE sources in general	Multiple RE policy instruments
Sangroya & Nayak (2015)	regression model	India	2001-2011	wind energy	FIT
Shivakumar et al. (2019)	Statistical and indicator-based analysis	Austria, Bulgaria, Finland, Germany, Ireland, Slovenia, and Spain	2005-2013	Multiple RE sources	RE policy in general
Shrimali et al. (2015)	regression model	USA	1991–2010	RE sources in general	RPS
Smith & Urpelainen (2013)	regression model	Not specified	1979–2005.	RE sources in general	FIT
Sun & Nie (2015)	an equilibrium model	Not specified	Not specified	RE sources in general	FIT, RPS, R&D

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Author (-s), year and reference	**Methodological approach**	**Geographical scope**	**Researched period**	**Technology scope**	**Addressed RE policy**
Upton & Snyder (2017)	regression model	49 USA states	1990 to 2013	RE sources in general	RPS
Verbruggen & Lauber (2012)	a literature review	Not specified	Not specified	RE sources in general	FIT and quota-based certificates
Winkler et al. (2018)	Panel statistical analysis	Brazil, France, Italy, the Netherlands and South Africa	2005-2016	RE sources in general	Multiple RE policy instruments
Wiser et al. (2017)	simulation model	Selected USA states	Not specified	RE sources in general	RPS
Zhao et al. (2016)	A regression model	China	2001-2013	Wind energy	RE policy in general
Zhou & Solomon (2020)	A regression model	USA	1998 to 2017	RE sources in general	RPS

Source: Own compilation according to sources in the table.

Appendix C. Values of techno-economic potential on wind and solar electricity production (TWh) in EU-27 in 2050

Country_ID	Wind	Solar	Country_ID	Wind	Solar	Country_ID	Wind	Solar
BE	34,859	18,197	FR	207,327	60,102	NL	105,997	27,117
BG	7,782	7,493	HR	5,851	2,445	AT	19,625	13,762
CZ	9,502	6,373	IT	60,269	112,36	PL	80,024	12,562
DK	44,152	6,597	CY	0,94	4,227	PT	29,925	12,153
DE	146,385	145,881	LV	4,466	0,25	RO	25,365	12,160
EE	2,387	1,738	LT	5,636	2,502	SL	0,509	3,372
IE	36,302	1,750	LU	1,081	1,882	SK	3,884	3,365
EL	34,111	17,555	HU	3,132	9,733	FI	30,726	1,417
ES	160,063	117,778	MT	0	0,79	SE	49,813	2,959

Source: Based on data from database of European Commission *(EC, 2020).*

Appendix D.1. Wind electricity production (TWh) in EU-27 during years 2004-2021

Year	Belgium	Bulgaria	Czecz Republic	Denmark	Germany	Estonia	Ireland	Greece	Spain
2004	0,145	0,001	0,009	5,983	24,148	0,015	0,720	1,165	16,193
2005	0,227	0,005	0,021	6,614	27,774	0,054	1,112	1,266	21,176
2006	0,366	0,020	0,049	6,108	31,324	0,076	1,622	1,699	23,297
2007	0,491	0,047	0,125	7,171	40,507	0,091	1,958	1,818	27,568
2008	0,637	0,122	0,245	6,928	41,385	0,133	2,410	2,242	32,946
2009	0,996	0,237	0,288	6,721	39,420	0,195	2,955	2,543	38,117
2010	1,292	0,681	0,335	7,809	38,547	0,277	2,815	2,714	44,271
2011	2,312	0,861	0,397	9,774	49,858	0,368	4,380	3,315	42,918
2012	2,759	1,221	0,416	10,270	51,680	0,434	4,010	3,850	49,472
2013	3,665	1,374	0,481	11,123	52,737	0,529	4,542	4,139	55,646
2014	4,615	1,331	0,477	13,079	58,497	0,604	5,140	3,689	52,013
2015	5,574	1,452	0,573	14,133	80,624	0,715	6,573	4,621	49,325
2016	5,420	1,425	0,497	12,782	79,924	0,594	6,147	5,146	48,905
2017	6,521	1,504	0,591	14,780	105,693	0,723	7,444	5,537	49,127
2018	7,574	1,318	0,609	13,902	109,951	0,636	8,640	6,300	50,896
2019	9,755	1,317	0,700	16,150	125,894	0,687	10,019	7,266	55,647
2020	12,819	1,477	0,699	16,330	132,102	0,844	11,549	9,310	56,444
2021	11,998	1,434	0,602	16,054	114,647	0,733	9,776	10,483	62,061
Year	**France**	**Croatia**	**Italy**	**Cyprus**	**Latvia**	**Lithuania**	**Luxembourg**	**Hungary**	**Malta**
2004	0,634	0,000	1,921	0,000	0,046	0,001	0,044	0,006	0,000
2005	0,962	0,010	2,344	0,000	0,047	0,002	0,052	0,010	0,000
2006	2,182	0,019	2,971	0,000	0,046	0,014	0,058	0,043	0,000
2007	4,070	0,035	4,034	0,000	0,053	0,106	0,064	0,110	0,000

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2008	5,694	0,040	4,861	0,000	0,059	0,131	0,061	0,205	0,000
2009	7,912	0,054	6,543	0,000	0,050	0,158	0,063	0,331	0,000
2010	9,945	0,139	9,126	0,032	0,049	0,224	0,055	0,534	0,000
2011	12,372	0,201	9,856	0,115	0,071	0,475	0,064	0,626	0,000
2012	15,178	0,329	13,407	0,185	0,114	0,540	0,077	0,770	0,000
2013	16,127	0,517	14,897	0,231	0,120	0,603	0,083	0,718	0,000
2014	17,324	0,730	15,178	0,183	0,140	0,639	0,080	0,657	0,000
2015	21,421	0,796	14,844	0,222	0,147	0,810	0,102	0,693	0,000
2016	21,381	1,014	17,689	0,227	0,128	1,136	0,101	0,684	0,000
2017	24,609	1,204	17,742	0,211	0,150	1,364	0,235	0,758	0,000
2018	28,599	1,335	17,716	0,221	0,122	1,144	0,255	0,607	0,000
2019	34,722	1,467	20,202	0,239	0,154	1,499	0,281	0,729	0,000
2020	39,861	1,721	18,762	0,240	0,177	1,552	0,351	0,655	0,000
2021	36,831	2,062	20,927	0,246	0,141	1,362	0,314	0,664	0,000
Year	**Netherlands**	**Austria**	**Poland**	**Portugal**	**Romania**	**Slovenia**	**Slovakia**	**Finland**	**Sweden**
2004	1,763	0,852	0,116	0,887	0,000	0,000	0,005	0,123	0,853
2005	2,067	1,331	0,135	1,773	0,000	0,000	0,006	0,170	0,935
2006	2,734	1,753	0,256	2,925	0,000	0,000	0,006	0,156	0,984
2007	3,438	2,037	0,522	4,037	0,003	0,000	0,008	0,188	1,426
2008	4,260	2,011	0,837	5,757	0,005	0,000	0,007	0,261	1,998
2009	4,581	1,954	1,077	7,577	0,009	0,000	0,006	0,277	2,491
2010	3,993	2,064	1,664	9,182	0,306	0,000	0,006	0,294	3,487
2011	5,100	1,936	3,205	9,161	1,388	0,000	0,005	0,481	6,107
2012	4,982	2,463	4,747	10,259	2,640	0,001	0,006	0,494	7,164
2013	5,627	3,152	6,004	12,014	4,520	0,004	0,006	0,774	9,842
2014	5,797	3,846	7,676	12,111	6,201	0,004	0,006	1,107	11,235

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2015	7,550	4,840	10,858	11,607	7,063	0,006	0,006	2,327	16,322
2016	8,170	5,235	12,588	12,474	6,590	0,006	0,006	3,068	15,479
2017	10,569	6,572	14,909	12,248	7,407	0,006	0,006	4,795	17,609
2018	10,549	6,030	12,799	12,617	6,322	0,006	0,006	5,839	16,623
2019	11,508	7,450	15,107	13,667	6,773	0,006	0,006	6,025	19,847
2020	15,278	6,792	15,800	12,299	6,945	0,006	0,004	8,256	27,526
2021	18,005	6,740	16,234	13,216	6,576	0,006	0,005	8,507	27,244

Source: Based on *Eurostat.*

Appendix D.2. Solar electricity production (TWh) in EU-27 during years 2004-2021

Year	Belgium	Bulgaria	Czecz Republic	Denmark	Germany	Estonia	Ireland	Greece	Spain
2004	0,001	0,000	0,000	0,002	0,557	0,000	0,000	0,001	0,024
2005	0,001	0,000	0,000	0,002	1,287	0,000	0,000	0,001	0,048
2006	0,002	0,000	0,001	0,002	2,225	0,000	0,000	0,001	0,125
2007	0,006	0,000	0,002	0,002	3,081	0,000	0,000	0,001	0,515
2008	0,042	0,000	0,013	0,003	4,427	0,000	0,000	0,005	2,578
2009	0,166	0,003	0,089	0,004	6,604	0,000	0,000	0,050	6,064
2010	0,560	0,015	0,616	0,006	11,746	0,000	0,000	0,158	7,186
2011	1,169	0,101	2,182	0,015	19,599	0,000	0,001	0,610	9,399
2012	2,148	0,779	2,149	0,104	26,380	0,000	0,001	1,694	11,968
2013	2,644	1,392	2,033	0,518	31,010	0,000	0,001	3,648	13,096
2014	2,886	1,257	2,123	0,596	36,056	0,000	0,002	3,792	13,672

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2015	3,057	1,382	2,264	0,604	38,726	0,000	0,004	3,900	13,859
2016	3,095	1,388	2,131	0,744	38,098	0,010	0,006	3,930	13,643
2017	3,308	1,403	2,199	0,751	39,401	0,014	0,012	3,991	14,397
2018	3,903	1,343	2,365	0,953	43,459	0,031	0,022	3,791	12,744
2019	4,253	1,417	2,337	0,963	44,383	0,074	0,040	4,429	15,103
2020	5,112	1,469	2,338	1,181	49,496	0,245	0,062	4,447	20,667
2021	5,618	1,467	2,316	1,309	49,340	0,354	0,093	5,251	27,098
Year	**France**	**Croatia**	**Italy**	**Cyprus**	**Latvia**	**Lithuania**	**Luxembourg**	**Hungary**	**Malta**
2004	0,008	0,000	0,029	0,000	0,000	0,000	0,009	0,000	0,000
2005	0,011	0,000	0,031	0,001	0,000	0,000	0,018	0,000	0,000
2006	0,012	0,000	0,035	0,001	0,000	0,000	0,021	0,000	0,000
2007	0,018	0,000	0,038	0,002	0,000	0,000	0,021	0,000	0,000
2008	0,042	0,000	0,193	0,003	0,000	0,000	0,020	0,001	0,000
2009	0,174	0,000	0,676	0,004	0,000	0,000	0,020	0,001	0,000
2010	0,620	0,000	1,906	0,006	0,000	0,000	0,021	0,001	0,001
2011	2,334	0,000	10,796	0,012	0,000	0,000	0,026	0,001	0,005
2012	4,428	0,002	18,862	0,022	0,000	0,002	0,038	0,008	0,017
2013	5,194	0,011	21,589	0,047	0,000	0,045	0,074	0,025	0,029
2014	6,392	0,035	22,306	0,084	0,000	0,073	0,095	0,067	0,068
2015	7,754	0,057	22,942	0,127	0,000	0,073	0,104	0,141	0,095
2016	8,660	0,066	22,104	0,146	0,000	0,066	0,100	0,244	0,128
2017	9,587	0,079	24,378	0,172	0,000	0,068	0,108	0,349	0,162
2018	10,925	0,075	22,654	0,199	0,001	0,087	0,119	0,629	0,190
2019	12,330	0,083	23,689	0,218	0,003	0,091	0,130	1,497	0,195

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2020	13,459	0,096	24,942	0,296	0,005	0,129	0,161	2,459	0,237
2021	15,732	0,149	25,039	0,468	0,007	0,191	0,180	3,796	0,256
Year	**Netherlands**	**Austria**	**Poland**	**Portugal**	**Romania**	**Slovenia**	**Slovakia**	**Finland**	**Sweden**
2004	0,034	0,018	0,000	0,003	0,000	0,000	0,000	0,002	0,002
2005	0,035	0,021	0,000	0,003	0,000	0,000	0,000	0,003	0,002
2006	0,037	0,022	0,000	0,005	0,000	0,000	0,000	0,003	0,002
2007	0,038	0,024	0,000	0,024	0,000	0,000	0,000	0,004	0,003
2008	0,040	0,030	0,000	0,041	0,000	0,001	0,000	0,004	0,004
2009	0,045	0,049	0,000	0,160	0,000	0,004	0,000	0,004	0,007
2010	0,056	0,089	0,000	0,211	0,000	0,013	0,017	0,005	0,009
2011	0,104	0,174	0,000	0,280	0,001	0,065	0,397	0,005	0,011
2012	0,191	0,337	0,001	0,393	0,008	0,163	0,424	0,006	0,019
2013	0,410	0,626	0,001	0,479	0,420	0,215	0,588	0,006	0,035
2014	0,725	0,785	0,007	0,627	1,616	0,257	0,597	0,008	0,047
2015	1,109	0,937	0,057	0,796	1,982	0,274	0,506	0,011	0,097
2016	1,602	1,096	0,124	0,871	1,820	0,267	0,533	0,022	0,143
2017	2,204	1,269	0,165	0,992	1,856	0,284	0,506	0,048	0,230
2018	3,708	1,455	0,300	1,006	1,771	0,255	0,585	0,090	0,407
2019	5,399	1,702	0,711	1,342	1,778	0,303	0,589	0,147	0,679
2020	8,568	2,043	1,958	1,716	1,733	0,368	0,663	0,219	1,051
2021	11,495	2,783	3,934	2,237	1,703	0,453	0,671	0,298	1,526

Source: Based on *Eurostat.*

Appendix E.1. Values of wind energy input and output variables across researched EU countries in DEA approach in 2018

Country_ID	*SUP_W*	*CAP_W**	*PR_W*	*ENV_W*	*SEC_W*	*JOB_W*	*W_speed*
BE	638,08	19499,2	7,46	1,62	8,46	7400	6,80
BG	74,87	6396,31	1,32	0,65	0,32	500	5,74
CZ	49,6	2969,21	0,61	0,36	0,15	1300	6,10
DK	450	73612,8	13,90	4,33	5,98	35400	8,16
DE	9652,93	534334	109,95	49,20	39,24	106200	7,16
IE	207,7	26226,739	8,64	2,85	3,24	4500	8,94
EL	310,33	24343,5	6,30	3,45	4,50	5100	7,46
ES	4061,74	300303,53	50,90	12,74	23,89	32300	6,70
FR	1195,26	101027,15	28,60	1,84	7,39	15700	7,07
HR	137,04	3172,4	1,34	0,25	0,67	1100	7,15
IT	1542,7	94977,82	17,72	6,20	8,95	8100	6,28
CY	14,72	1290,38	0,22	0,14	0,11	100	4,83
LT	80,36	3405	1,14	0,35	4,53	500	6,61
LU	12,17	977,07	0,25	0,03	0,42	100	6,29
HU	35,4	3379	0,61	0,22	0,43	900	5,65
NL	635,89	41289,11	10,56	4,95	18,74	6800	7,64
AT	464,03	24388,5	6,03	1,13	2,49	2500	7,60
PL	1,68	36858,56	12,80	11,30	4,68	3000	6,53
PT	464,11	54635,68	12,62	3,92	5,21	2600	6,52
SE	58,97	50081	16,62	0,90	3,32	4600	7,42

Notes: *here data of cumulative installed capacity (solar electricity) during 2009-2018, which corresponds with a researched period in context of measuring efficiency.

SUP - cost of policy support, *CAP* - cumulative installed capacity, *PR* - power production, *ENV* - energy environmental indicator, *SEC*- energy security indicator, *JOB* - direct and indirect jobs, *W_speed* – mean wind speed, *W* - wind energy.

Source: Based on data from *EC, 2020; Eurostat; EurObserv'ER; Global Wind Atlas*.

Appendix E.2. Values of solar energy input and output variables across researched EU countries in DEA approach (in 2018)

Country_ID	*SUP_S*	*CAP_S**	*PR_S*	*ENV_S*	*SEC_S*	*JOB_S*	*PV_potential*
BE	519,31	26086,60	3,90	0,84	4,42	1700	2,94
BG	263,53	7365,25	1,34	0,66	0,32	600	3,87
CZ	1138,23	18590,17	2,36	1,39	0,58	1900	3,08
DK	37,36	5166,41	0,95	0,30	0,41	1600	2,77
DE	9743,58	347886	45,78	20,49	16,34	41900	2,98
IE	0,46	53,91	0,02	0,01	0,01	200	2,53
EL	1016,08	18067,10	3,79	2,08	2,71	1800	4,45
ES	4522,32	48593,50	12,74	3,19	5,98	2200	4,58
FR	2747,16	53238,09	10,57	0,68	2,73	15000	3,48
HR	18,01	287,3	0,07	0,01	0,04	400	3,74

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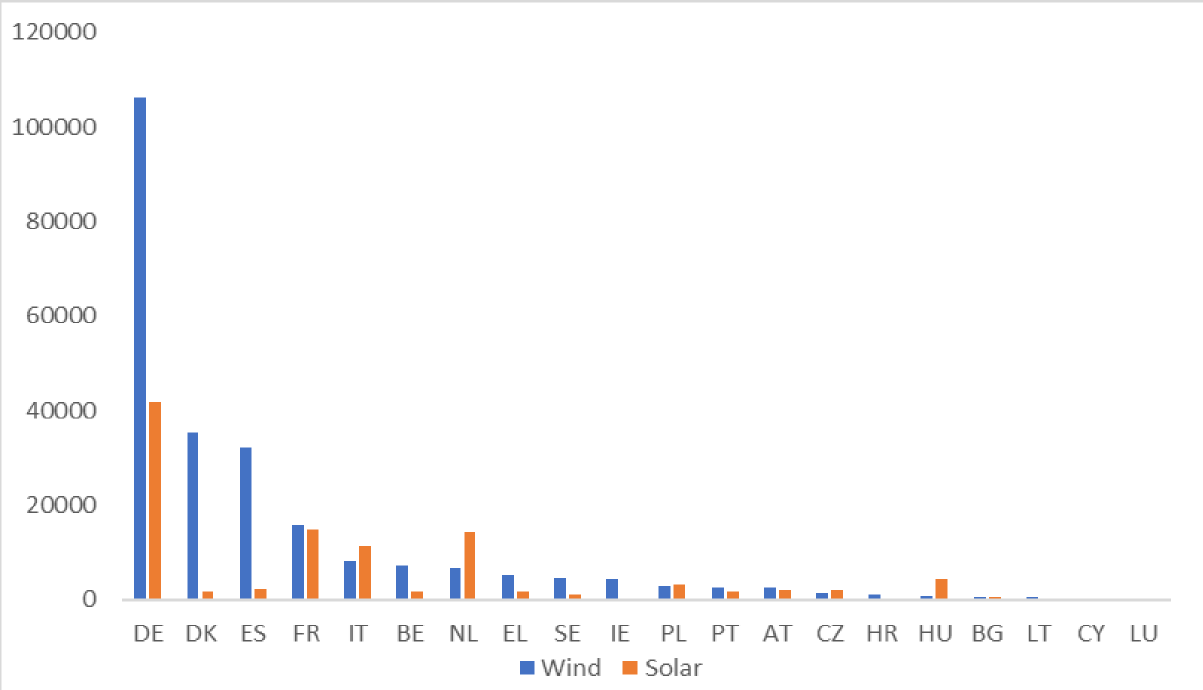
IT	6650,57	150314,88	22,65	7,92	11,44	11400	4,07
CY	9,89	530,53	0,2	0,13	0,1	200	5,21
LT	3,94	439	0,09	0,03	0,34	100	2,82
LU	25,13	1008,24	0,12	0,01	0,20	100	3,02
HU	14,46	1621,00	0,62	0,22	0,44	4500	3,52
NL	302,9	13833,50	3,69	1,73	6,55	14300	2,86
AT	160,04	6968,99	1,44	0,27	0,59	1900	3,21
PL	4,98	1175,07	0,30	0,27	0,11	3100	2,98
PT	117,36	3671,49	1,01	0,31	0,42	1600	4,57
SE	130,76	1128	0,41	0,02	0,08	1100	2,69

Notes: *here data of cumulative installed capacity (solar electricity) during 2009-2018, which corresponds with a researched period in context of measuring efficiency.

SUP - cost of policy support, *CAP* - cumulative installed capacity, *PR* - power production, *ENV* - energy environmental indicator, SEC- energy security indicator, *JOB* - direct and indirect jobs, *PV_potential* – average solar power theoretical potential, *S* - solar energy.

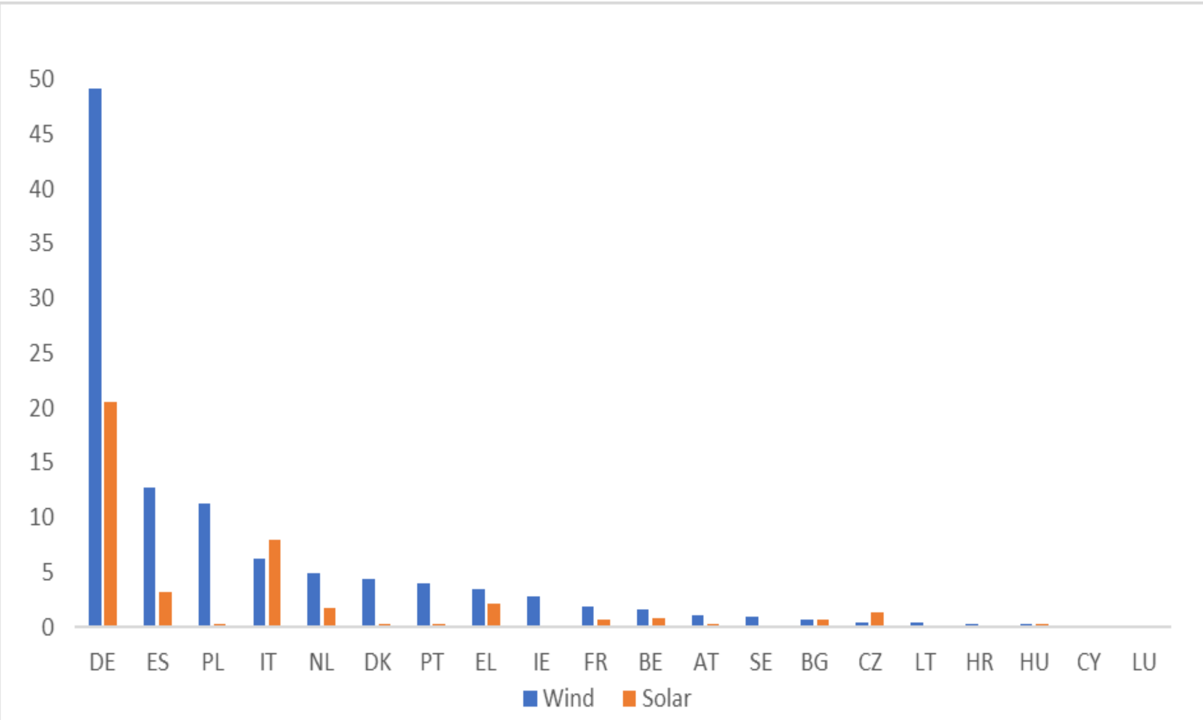
Source: Based on data from *EC, 2020; Eurostat; EurObserv'ER; Global Wind Atlas.*

Appendix F.1. Employment in wind and solar power sectors in EU member states in 2018



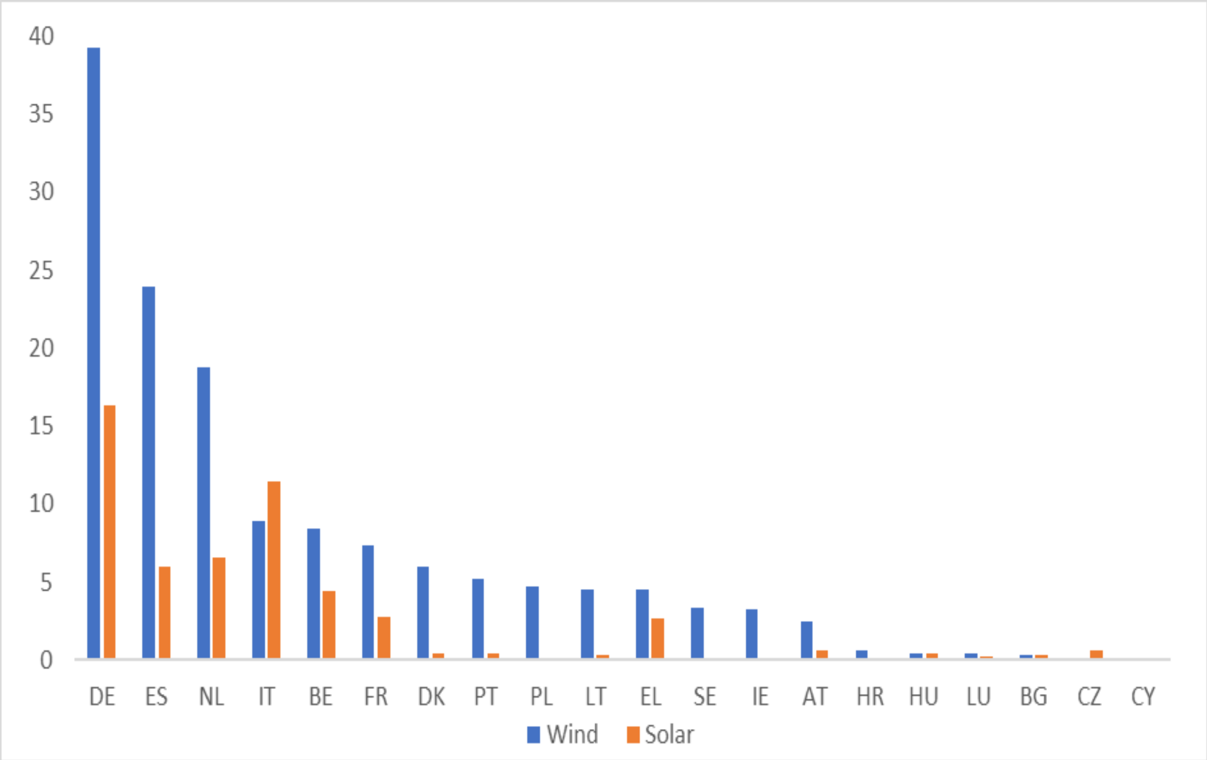
Source: Based on data from *EurObserv'ER.*

Appendix F.2. Energy environmental indicator of EU countries in 2018



Source: Own calculations based on data from *EDGAR* and *Eurostat.*

Appendix F.3. Energy security indicator of EU countries in 2018



Source: Based on data from *Eurostat.*

Appendix G.1. Standard DEA efficiency scores (with ranking) of wind energy policies across selected EU states during 2018. Five models

M1_PR			**M2_PR_ENV**			**M3_PR_SEC**			**M4_PR_JOB**			**M5_ALL**		
Rank	Country	Score	Rank	Country	Score	Rank	Country	Score	Rank	Country	Score	Rank	Country	Score
1	DE	1	1	DE	1	1	BE	1	1	BE	1	1	BE	1
2	FR	1	2	FR	1	2	DE	1	2	CZ	1	2	CZ	1
3	LU	1	3	CY	1	3	ES	1	3	DK	1	3	DK	1
4	PL	1	4	LU	1	4	FR	1	4	DE	1	4	DE	1
5	FI	1	5	PL	1	5	LT	1	5	FR	1	5	ES	1
6	SE	1	6	FI	1	6	LU	1	6	HR	1	6	FR	1
7	ES	0,865	7	SE	1	7	NL	1	7	LU	1	7	HR	1
8	CY	0,825	8	ES	0,865	8	PL	1	8	PL	1	8	CY	1
9	HR	0,810	9	HR	0,810	9	FI	1	9	FI	1	9	LT	1
10	BE	0,788	10	BE	0,790	10	SE	1	10	SE	1	10	LU	1
11	IE	0,760	11	IE	0,763	11	CY	0,825	11	IE	0,878	11	NL	1
12	LT	0,672	12	LT	0,732	12	HR	0,810	12	ES	0,865	12	PL	1
13	NL	0,657	13	CZ	0,682	13	IE	0,780	13	CY	0,825	13	FI	1
14	PT	0,639	14	NL	0,668	14	PT	0,668	14	HU	0,778	14	SE	1
15	IT	0,576	15	PT	0,645	15	IT	0,630	15	LT	0,759	15	IE	0,881
16	DK	0,540	16	IT	0,592	16	EL	0,618	16	NL	0,731	16	EL	0,794
17	HU	0,514	17	EL	0,572	17	DK	0,571	17	EL	0,688	17	HU	0,788
18	EL	0,508	18	DK	0,546	18	HU	0,514	18	PT	0,639	18	PT	0,668
19	CZ	0,505	19	HU	0,514	19	CZ	0,505	19	IT	0,596	19	IT	0,632

(see continuation of the table on the next page)

(continued)

20	BG	0,478	20	BG	0,513	20	BG	0,478	20	BG	0,519	20	BG	0,542
21	AT	0,418	21	AT	0,418	21	AT	0,439	21	AT	0,497	21	AT	0,498

Source: Own calculations.

Appendix G.2. Standard DEA efficiency scores (with ranking) of solar energy policies across selected EU states during 2018. Five models

M1_PR			**M2_PR_ENV**			**M3_PR_SEC**			**M4_PR_JOB**			**M5_ALL**		
Rank	Country	Score	Rank	Country	Score	Rank	Country	Score	Rank	Country	Score	Rank	Country	Score
1	DK	1	1	DK	1	1	DK	1	1	DK	1	1	DK	1
2	DE	1	2	DE	1	2	DE	1	2	DE	1	2	DE	1
3	IE	1	3	IE	1	3	IE	1	3	IE	1	3	IE	1
4	ES	1	4	EL	1	4	ES	1	4	ES	1	4	EL	1
5	HU	1	5	ES	1	5	IT	1	5	FR	1	5	ES	1
6	NL	1	6	CY	1	6	LT	1	6	HU	1	6	FR	1
7	PL	1	7	HU	1	7	HU	1	7	NL	1	7	IT	1
8	FR	0,999	8	NL	1	8	NL	1	8	PL	1	8	CY	1
9	CY	0,997	9	PL	1	9	PL	1	9	FI	1	9	LT	1
10	SE	0,947	10	FR	0,999	10	FR	0,999	10	CY	0,997	10	HU	1
11	IT	0,920	11	SE	0,947	11	CY	0,997	11	SE	0,947	11	NL	1
12	PT	0,854	12	IT	0,920	12	SE	0,947	12	IT	0,920	12	PL	1
13	EL	0,778	13	PT	0,854	13	PT	0,854	13	PT	0,854	13	FI	1
14	HR	0,714	14	HR	0,714	14	EL	0,778	14	EL	0,778	14	SE	0,947

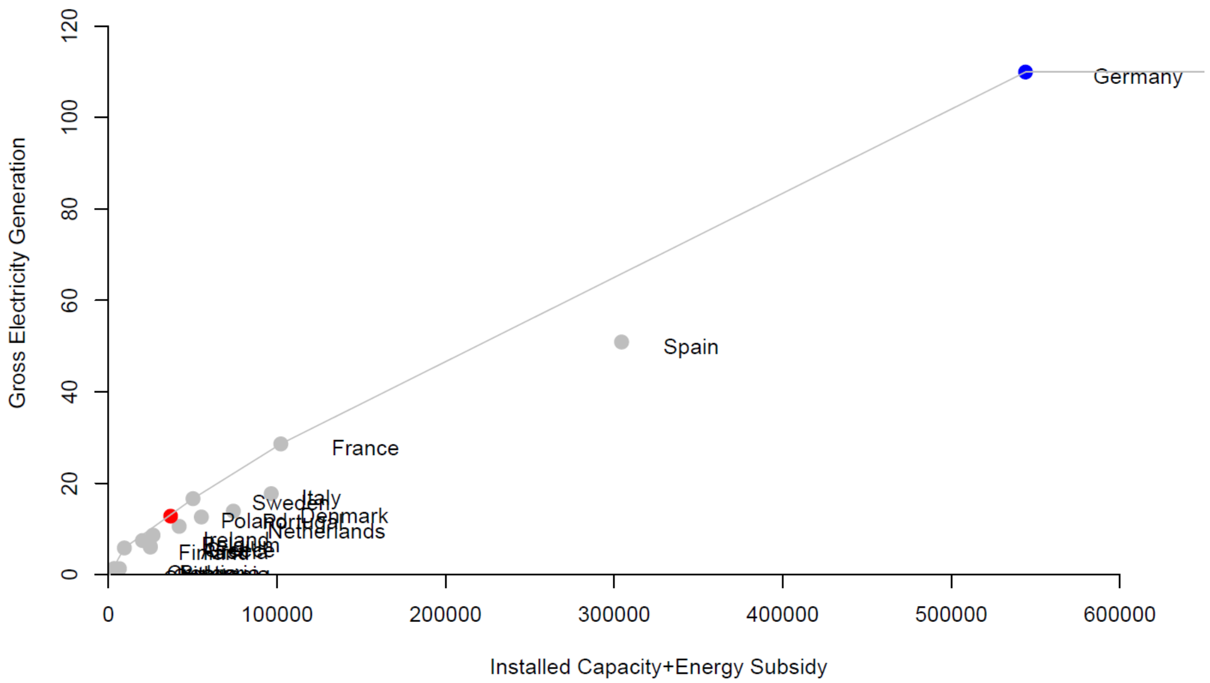
(see continuation of the table on the next page)

(continued)

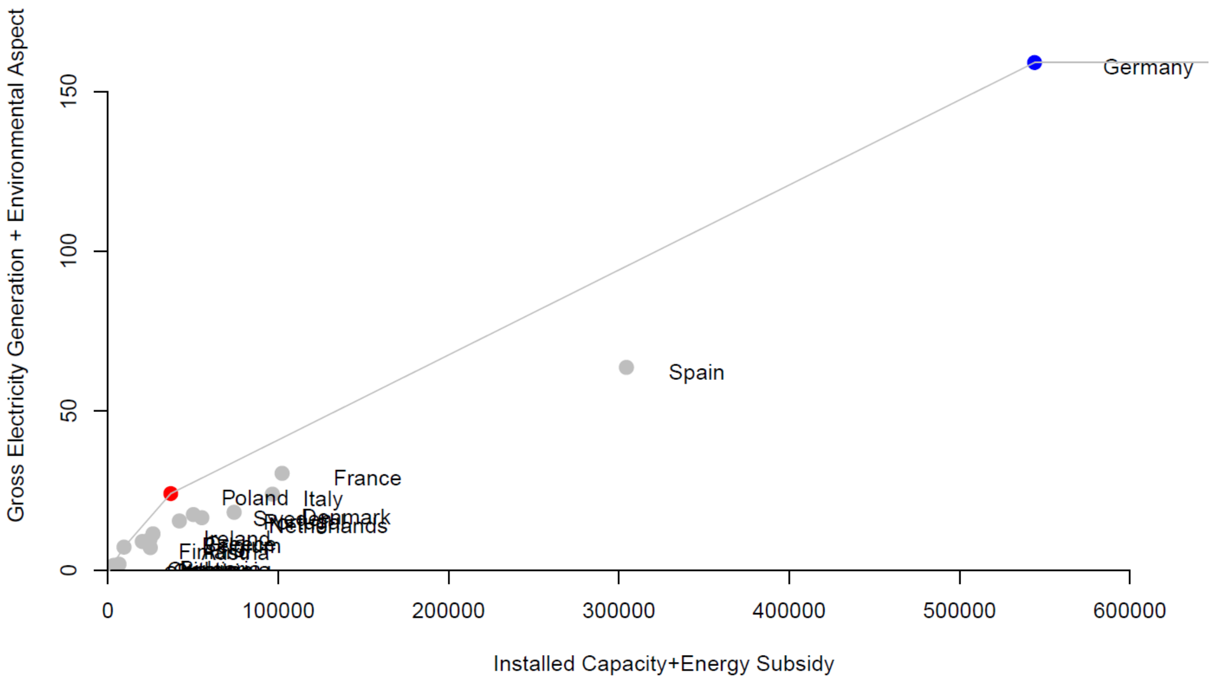
15	AT	0,698	15	AT	0,698	15	HR	0,714	15	HR	0,714	15	PT	0,854
16	FI	0,679	16	FI	0,679	16	AT	0,698	16	AT	0,698	16	HR	0,714
17	BE	0,673	17	BE	0,673	17	FI	0,679	17	BE	0,673	17	AT	0,698
18	BG	0,606	18	BG	0,654	18	BE	0,673	18	BG	0,606	18	BE	0,673
19	LT	0,537	19	CZ	0,584	19	BG	0,606	19	LT	0,537	19	BG	0,654
20	CZ	0,452	20	LT	0,537	20	CZ	0,452	20	CZ	0,452	20	CZ	0,584
21	LU	0,319	21	LU	0,319	21	LU	0,402	21	LU	0,319	21	LU	0,402

Source: Own calculations.

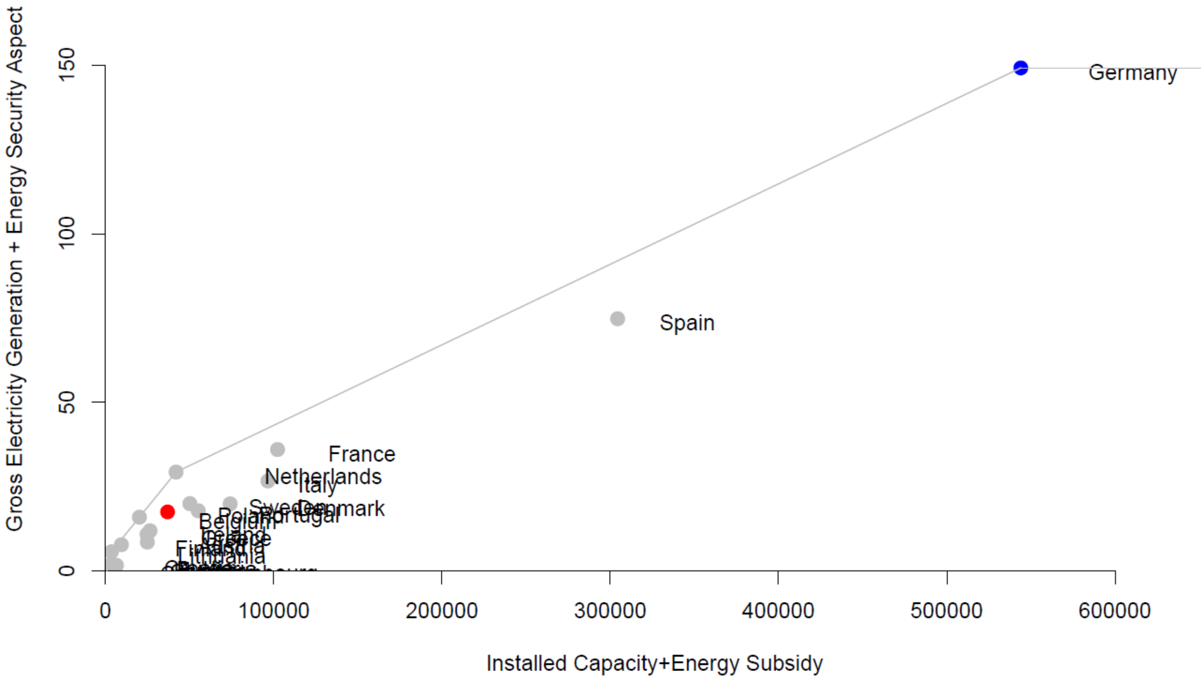
Appendix H.1. Illustration of obtained standard DEA efficiency scores for model M1_PR. Wind energy



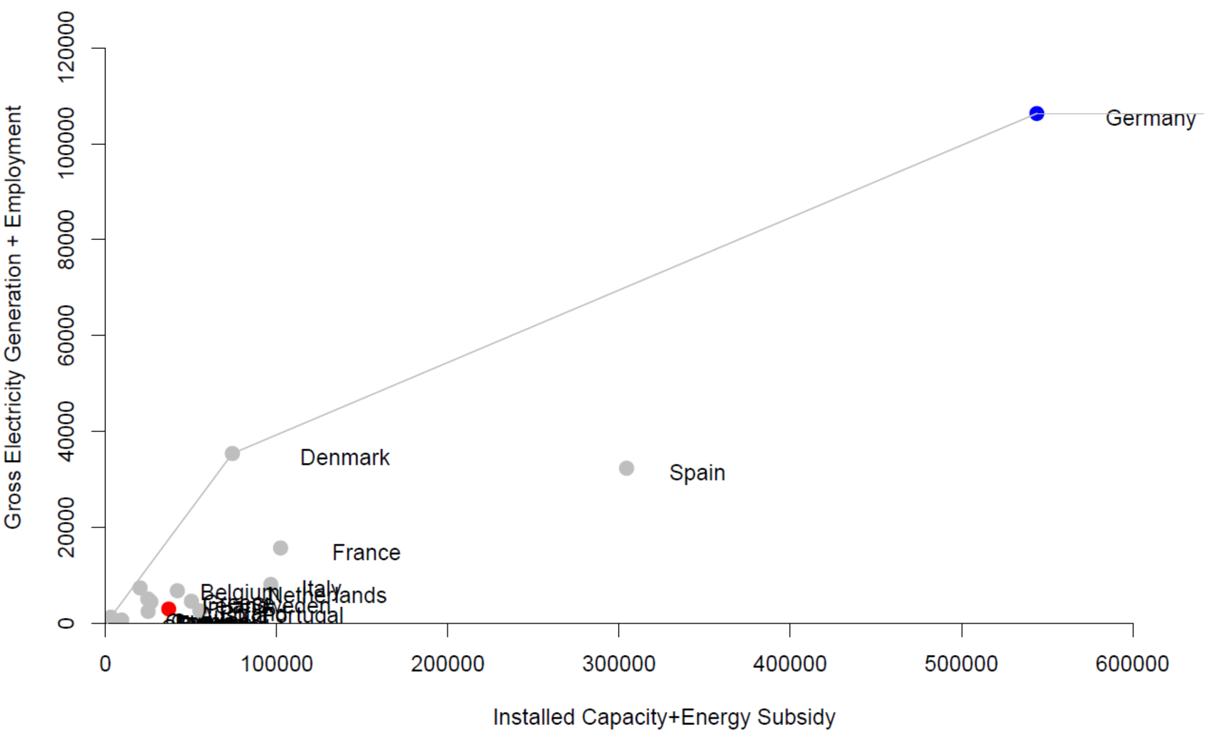
Appendix H.2. Illustration of obtained standard DEA efficiency scores for model M2_PR_ENV. Wind energy



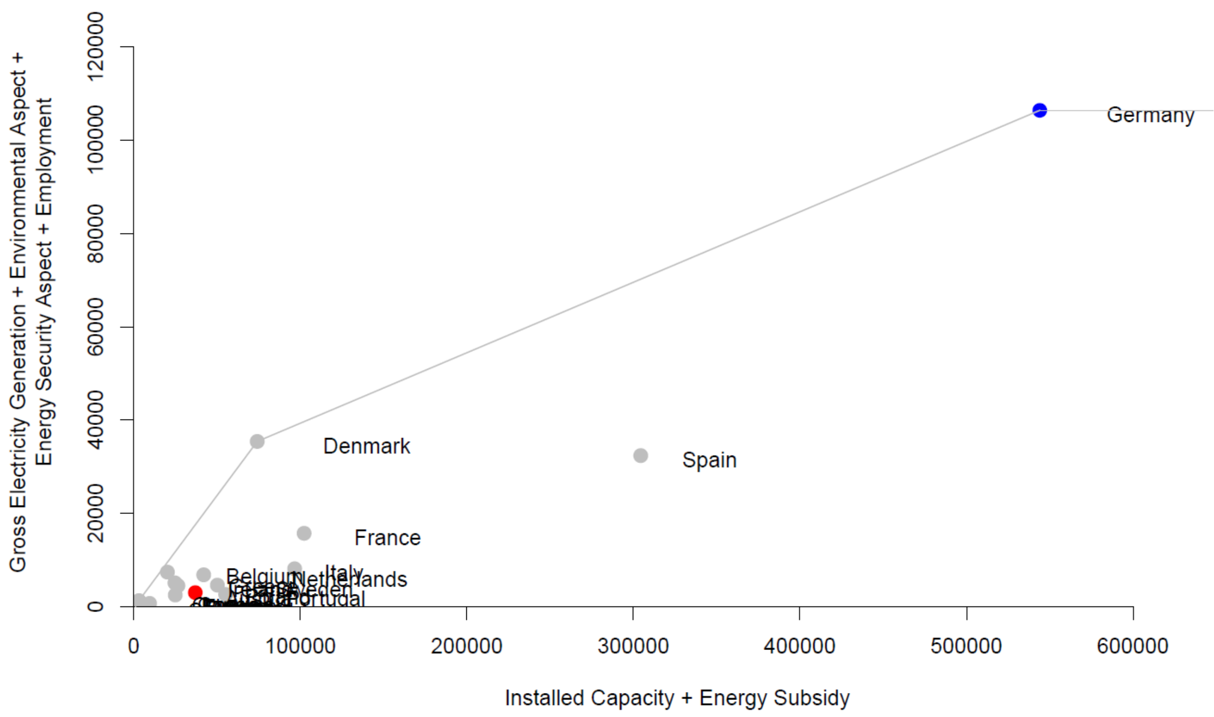
Appendix H.3. Illustration of obtained standard DEA efficiency scores for model M3_PR_SEC. Wind energy



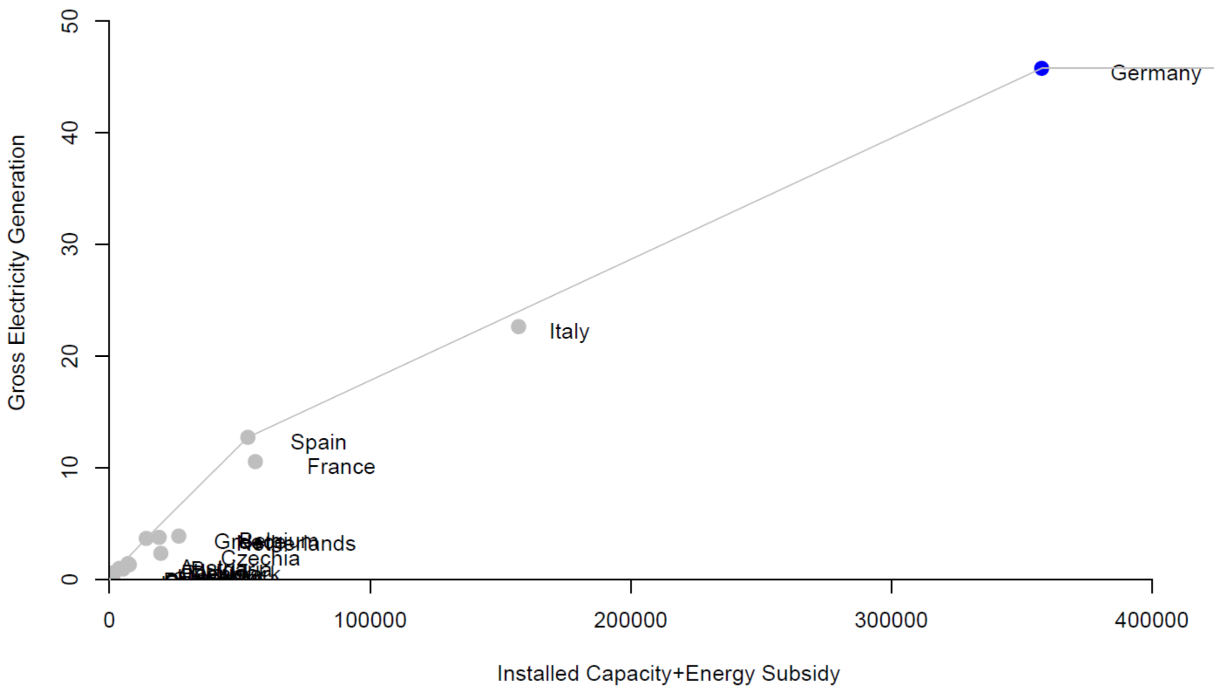
Appendix H.4. Illustration of obtained standard DEA efficiency scores for model M4_PR_JOB. Wind energy



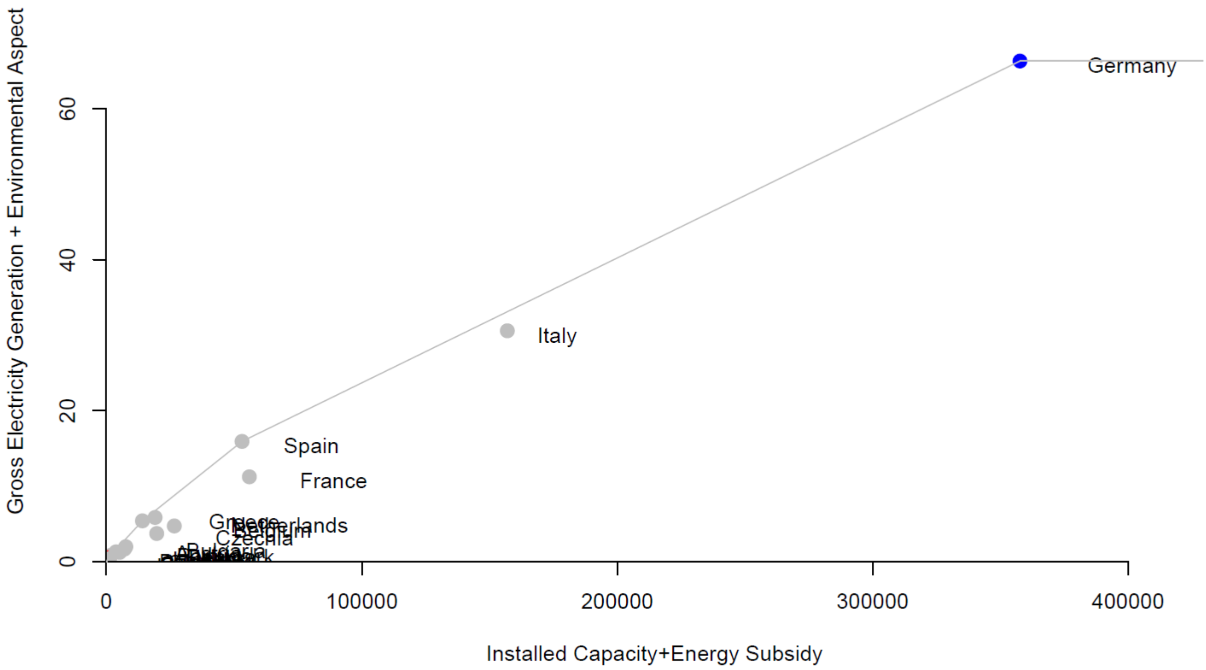
Appendix H.5. Illustration of obtained standard DEA efficiency scores for model M5_ALL. Wind energy



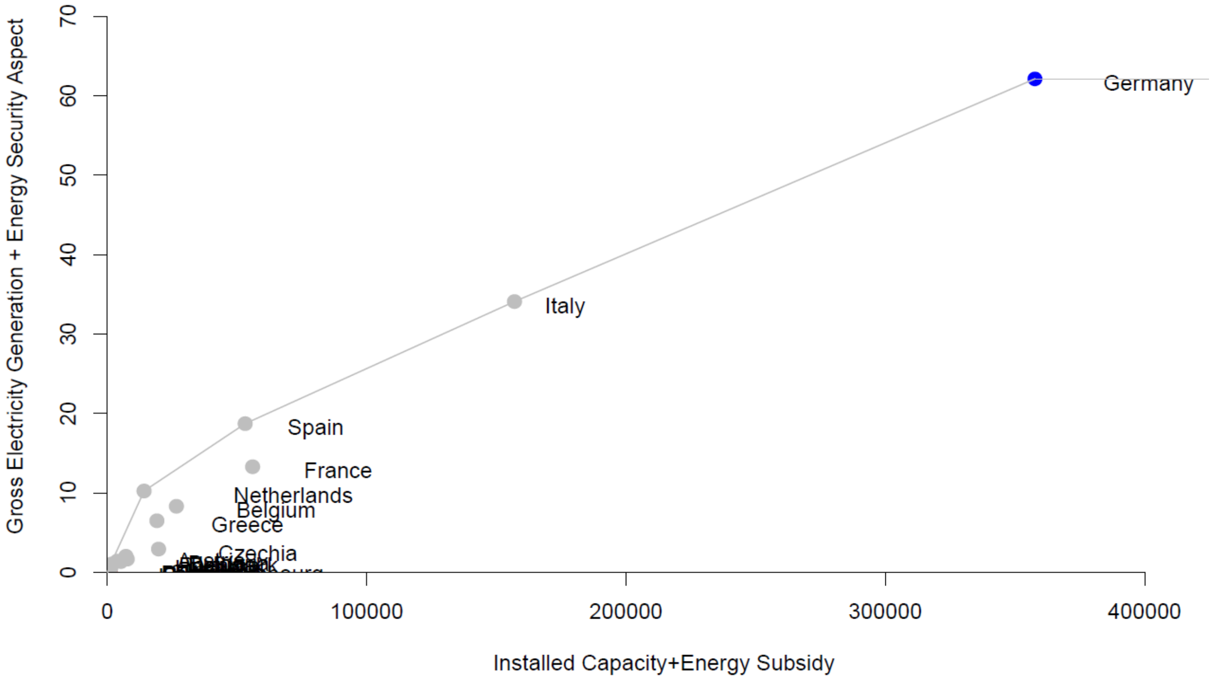
Appendix H.6. Illustration of obtained standard DEA efficiency scores for model M1_PR. Solar energy



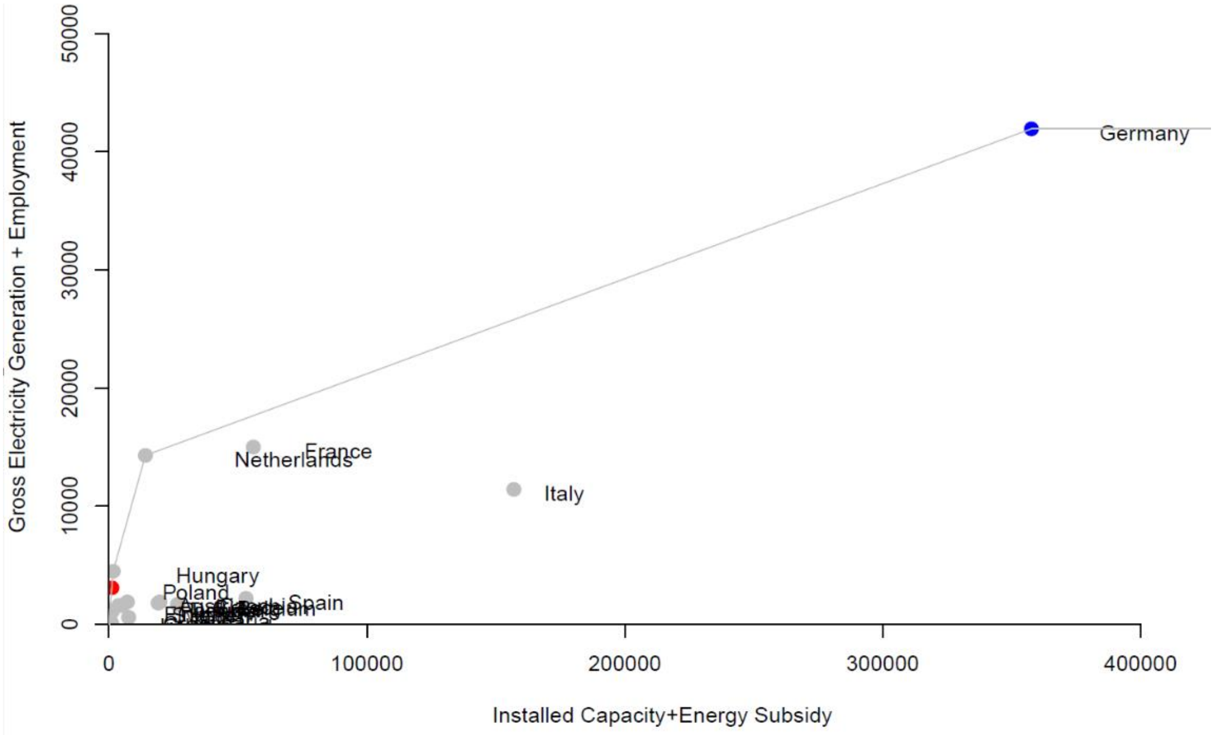
Appendix H.7. Illustration of obtained standard DEA efficiency scores for model M2_PR_ENV. Solar energy



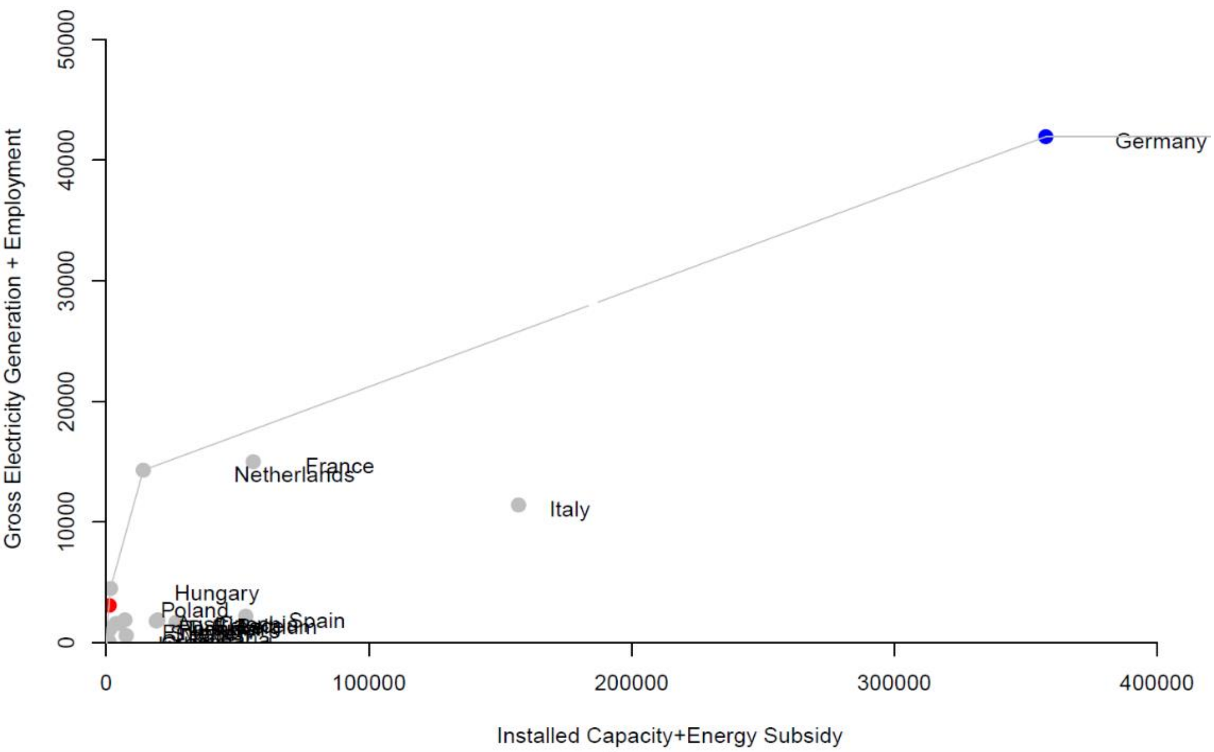
Appendix H.8. Illustration of obtained standard DEA efficiency scores for model M3_PR_SEC. Solar energy



Appendix H.9. Illustration of obtained standard DEA efficiency scores for model M4_PR_JOB. Solar energy



Appendix H.10. Illustration of obtained standard DEA efficiency scores for model M5_ALL. Solar energy



Source: Appendices H.1- H.10 are own compilation.

Appendix I. Quantified data of main wind and solar energy policy instruments' presence* during a 2009-2018 period

	Wind energy				Solar energy			
Country_ID	FIT_w	$QUOTA_w$	$TNDR_w$	TAX_INV_w	FIT_s	$QUOTA_s$	$TNDR_s$	TAX_INV_s
BE	0	1	0	0	0	1	0	0
BG	1	0	0	0	1	0	0	0
CZ	1	0	0	0	1	0	0	0
DK	1	0	1	0	1	0	1	0
DE	1	0	0,22	0	1	0	0,22	0
IE	1	0,22	0,001	0	1	0,22	0,001	0
EL	1	0	0,22	0	1	0	0,22	0
ES	0,64	0	0,36	0	0,64	0	0,36	0
FR	1	0	0,57	0	1	0	0,57	0
HR	0,5	0	0,22	0,5	0,5	0	0,22	0,5
IT	0,43	0,57	0,43	0	1	0	0,36	0
CY	0,71	0	0	0,29	0,71	0	0	0,29
LT	1	0	0,22	0	1	0	0,22	0
LU	1	0	0,22	0,14	1	0	0,22	0,14
HU	1	0	0,22	0	1	0	0,22	0
NL	0,85	0	0,36	0,64	0,85	0	0,36	0,64
AT	1	0	0	0	1	0	0	0,64
PL	0	0,85	0	0	0	0,85	0	0
PT	1	0	0	0,22	1	0	0	0,22
SE	0	1	0	0,36	0	1	0	0,36

Note: *presence of the certain policy instrument is measured proportionally to the active period.

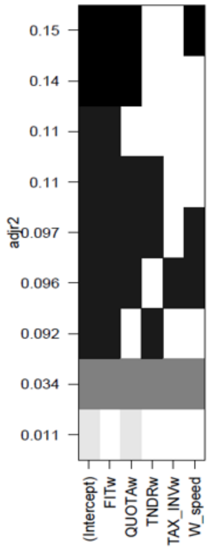
FIT - Feed-in tariff, *QUOTA* - quota-based instrument, *TNDR* – tenders, *TAX_INV* – tax incentives and investment grants, *w* – wind energy, *s* – solar energy.

Source: Own calculations based on data from *Ragwitz et al., 2015*; *CEER; RES-LEGAL; REN21 (2021); EurObserv'ER.*

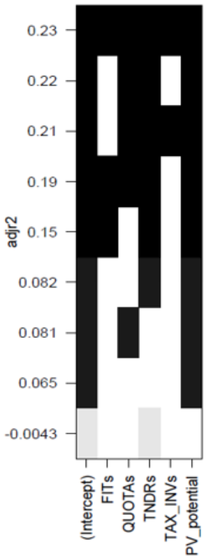
Appendix J. Variable selection technique based on the adjusted R-squared in 5 models for wind and energy policies

1) Model M1_PR

Wind

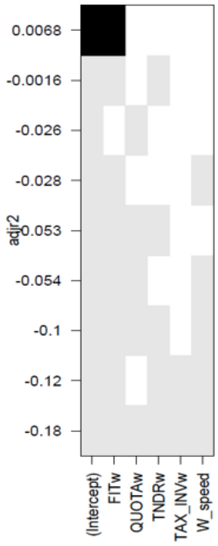


Solar

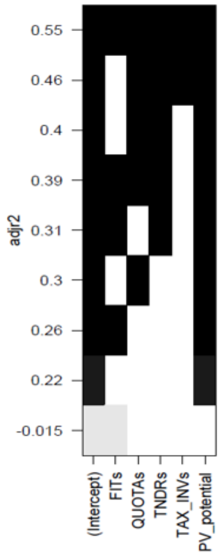


2) Model M2_PR_ENV

Wind

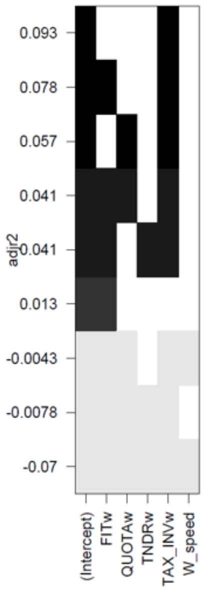


Solar

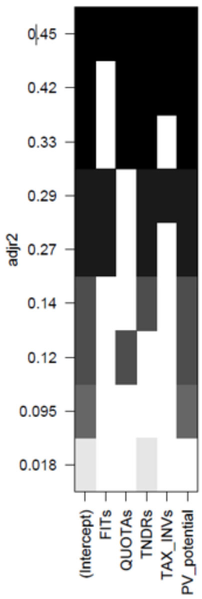


3) M3_PR_SEC

Wind

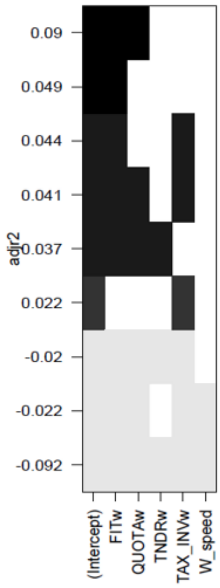


Solar

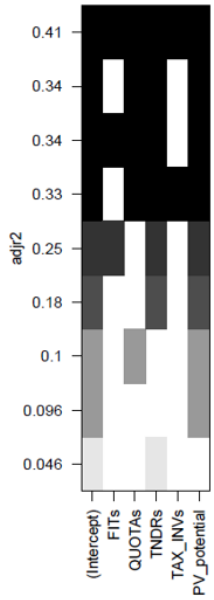


4) M4_PR_JOB

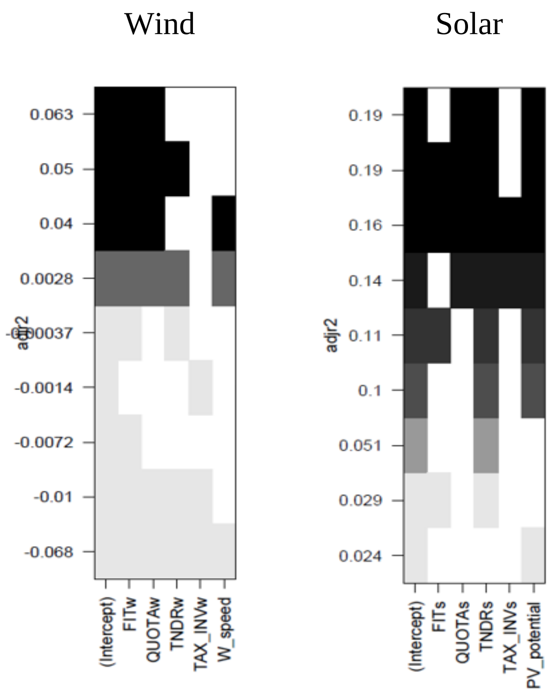
Wind



Solar



5) M_ALL



Source: Own compilation.