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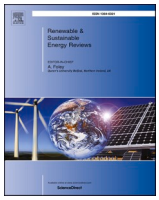

Unlocking European biogas and biomethane: Policy insights from comparative analysis

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ABSTRACT

The scaling up of renewable gases is now being presented as a critical and effective component of the EU's long-term decarbonization strategy. Yet, the support schemes implemented for biogas and biomethane are far less studied than the ones dedicated to renewable power generation (e.g., solar or wind). This work bridges this gap by reviewing the supporting policies implemented in the EU and conducting a retrospective comparative analysis of the mechanisms implemented in Germany, Denmark, and Italy. The analysis is based on primary data extracted from policy statements that have been harmonized. Results show that incentivizing the supply side lowers the risk associated with early investments and market development. Conversely, they highlight inhomogeneity among countries in accounting for demand and end-use in their policies. Finally, they point at the availability of feedstock and the geographic and economic structure of a country as factors influencing the development of a market for renewable gases. The analysis stresses the value of policy mix in promoting biogas and biomethane in the EU's energy mix, and it hinges on the importance of scrutinizing sectoral massification, novel business models, infrastructure integration, and enhanced financial accessibility to improve their competitiveness and market advancement within the energy landscape.

Nomenclature:

Abbreviations	MS-Member States	CHP-Combined heat and power
FIT-Feed in tariff	RES-Renewable energy sources	EU-European Union
FIP-Feed in premium	GC-Green certificate	
Units	MWh- Megawatt-Hour	MWh/d - Megawatt-Hour per day

1. Introduction

The EU's ambitious goal to reach carbon neutrality by 2050, as outlined in the 2019 EU Green Deal, necessitates a profound reconfiguration of the European energy system. This decarbonization effort requires increased end-use electrification and the large-scale deployment of low-carbon power generation, such as wind and solar. However, while these options are crucial, they are not the only solutions. Biofuels and hydrogen can also efficiently contribute to decarbonization, particularly in hard-to-abate sectors currently reliant on fossil hydrocarbon resources [1]. The methane pledge decided at COP27 and the REPowerEU Plan introduced in May 2022 following Russia's invasion of Ukraine further emphasize the importance of biomethane – a low-carbon substitute for natural gas – as a critical component of the decarbonization strategy. Specifically, the REPowerEU Plan stresses the significance of renewable gases, including hydrogen and biomethane, and insists on increasing their share in the EU energy mix [2].

In addition, In line with previous literature [3–5], this work adheres

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to the standard delineation between biogas and biomethane. Biogas is a combination of methane, carbon dioxide, and trace amounts of other gases produced through the anaerobic digestion of organic matter in an oxygen-free environment. Biomethane, on the other hand, is a refined/upgraded form of biogas, or gasified solid biomass, that can be injected into the gas network.

However, scaling up EU biomethane production from the current 3 billion cubic meters to the targeted level of 35 billion cubic meters poses significant challenges [3]. Achieving this requires attracting investment in biomethane production capacity, promoting easy market access, enabling grid connection, improving the price signal for biomethane, implementing an EU-wide Guarantee of Origin system, and finally, mobilizing sustainable feedstock [6]. Without dedicated supporting mechanisms, this envisioned deployment is unlikely to materialize as literature on biomethane consistently underscores the ongoing necessity of incentives as support systems are still necessary to ensure the profitability of biomethane plants [7,8].

In response, European countries have elaborated a variety of schemes combining subsidies and/or standards to support the deployment of biomethane and biogas, referred to as renewable gases hereafter. However, compared with the policies supporting solar, wind power, or hydrogen that have attracted considerable attention (see, e.g. Refs. [9–11], respectively), research on existing European biomethane supporting policies is limited [12].

The purpose of this work is thus to conduct a detailed evaluation of national supporting schemes to determine their effectiveness in mobilizing the European potential and meeting the EU's public policy goals. This analysis entails a meticulous review of the current supporting mechanisms implemented across Europe and an assessment of their performance in relation to the future social and physical functions that renewable gas will fulfill. By comparing the merits and limitations of various support schemes, this analysis seeks to provide valuable insights for policymakers, facilitating the identification of best practices and the formulation of tailored policy perspectives [13].

To delve into this analysis, we conduct a structured retrospective comparison of the key features of policies implemented in three distinct EU Member States (MS) during the "pre-crisis" period, evaluating their relative merits. Specifically, the work examines policy developments in Germany, Denmark, and Italy over the past decades. The aim is to ascertain the existence of an optimal policy strategy and instrument mix conducive to fostering the rapid development of low-carbon/renewable gases and enhancing their contribution to decarbonizing the gas grid. Additionally, this analysis aims to characterize the most effective approaches for promoting the adoption of renewable gases, ensuring alignment with the targets set by the European Commission.

Our analysis addresses whether renewable gas benefits from the same regulations that have effectively lowered the cost of renewable electricity toward the decarbonization of the EU energy system. Many MS have support mechanisms to incentivize biomethane, although very few have specific renewable gas targets [14]. If, on the one hand, some, such as France and Denmark, target a specific percentage of demand being covered by biomethane by 2030 (i.e., 10 and 100 % natural gas substitution, respectively), most EU countries subsidize renewable gas only in relation to its end-use, namely for the most part electricity generation (i.e., Germany) and transport (i.e., Italy) [13,15].

Since most of the policy developments are context-dependent, studying the substrate on which they have been built up is key to understanding how countries in the EU have transitioned to renewable energy sources (RES) in the last decade and how relevant a system approach to policy is in successfully delivering change. Most of the authors agreed that each MS's structural and regulatory factors heavily influence the architecture of the value chain. Hence, successful policies and policy support mechanisms in one country may not necessarily provide the same results in another since they rely on that country's larger context, policy, and economic framework [13,16].

Through the creation of a unique and novel database from primary data collection in sources documenting the energy policies and supporting schemes and incentives of different European countries (e.g., stakeholder's reports, public administration websites, and international organizations), the analysis provides an original perspective on the country's specificity of biogas/biomethane production. The work highlights similar supply-side strategies of incentivizing installed capacity for biogas/biomethane among MSs. An additional significant finding relates to demand and end-use supporting mechanisms between MS that have a different impact on the biogas/biomethane industry. To this end, what has emerged from the work is that support for biogas is much more complex than that for renewable electricity as it is the intrinsic nature of the considered energy vector, and the approach to subsidizing needs to account for this complexity.

The work unveils how the inclusion of the demand side in the subsidy discourse prevails in the country-specific best practices for biogas and biomethane, as opposed to the supply side, as in the case of renewable electricity. Indeed, countries that realized that the potential of replicating the electrical subsidy scheme was limited when dealing with biogas and biomethane and redirected subsidies to substitute fossil fuel on the demand side have created a stronger outlook for these energy vectors in their economy. To the best of our knowledge, there is no detailed and standardized analysis between different MS to investigate the relationship between "support scheme-deployment" for biogas and biomethane, using the case of Germany, Denmark, and Italy as a reference.

This work aims to fill this gap by presenting a framework to examine policies' influence on the trends and dynamics for biogas/biomethane support through a qualitative analysis of the evolution of biogas/biomethane sectors and a retrospective comparative analysis of the link between the gas market, the system's dependence on natural gas, and the presence of policies and incentives for biogas and biomethane in selected EU countries. While prevalent works typically center on delineating the policy landscape and the execution of policy instruments across diverse nations solely analyzing the literature and policy documents, this work adopts a distinct focus based on a direct search in multiple databases and policy guidance in different MS, with primary data selected and harmonized directly from policy statements. The work reviews the various schemes that have been implemented and examines their performances considering the public policy objectives that have motivated their implementation, linking them to the broader contexts and policy and economic frameworks in which they are inserted.

This work is organized as follows. Section 2 describes the literature review and the evolution of renewable gas-related policies at the EU level and in selected Member States over a decade (i.e., 2009–2019). Section 3 presents the methods and describes a comparative analysis of the key complexities of the evolution of renewable gas policy, analyzing and discussing the evidence and critical issues that have influenced the renewable energy policy scenario in selected EU Member States. The final sections summarize the findings, conclusions, and policy implications with key insights from the previous sections and provides future research directions.

2. Background

This section clarifies both the background and the motivation of our analysis. After a brief review of the literature review and the evolution of the policies supporting the deployment of renewable gas in Europe for the reference period 2010–2019, we present the essential features of the situation prevailing in Denmark, Germany, and Italy. Together, these three countries illustrate the diverse approaches currently prevailing in Europe.

2.1. Biogas policies in renewable energy transition

The research concentrates on studying an optimal policy combination defined as a comprehensive analysis encompassing country-specific

individual policies and their interplay, capturing policy strategies and instrument combinations in the historical evolution of biogas/biomethane support. The nuanced understanding of the dynamics and focal points of diverse policies across time and how they interplay to outline a coherent long-term strategy stands as imperative to discern their efficacy and alignment with their intended objectives.

Two streams of literature investigate the development of renewable energy policies. One stream emphasizes economic efficiency and cost-effectiveness within renewable energy policies, focusing on their implications within a techno-economic framework. These studies primarily center on economic facets pivotal to fostering a low-carbon economy, often attributing the subsequent reduction in greenhouse gas emissions as a direct or indirect consequence of policies [19–21]. Emphatically advocating for a carbon tax as the foremost mechanism driving energy transformation, these authors underscore the necessity for a well-functioning competitive market to enable pricing measures and subsidies to profoundly impact outcomes [22]. However, this stream's predominant economic focus creates a void in the exploration of political and social policy implications during the transition.

Conversely, the second stream, dedicated to optimal renewable energy policy design, identifies carbon pricing and subsidies as the most effective regulatory strategies supporting RES [23]. Authors within this stream highlight three primary concerns guiding policy design: the heterogeneous nature of intermittent natural resources, budget-neutral financing regulations, and incentives for carbon mitigation [24]. They stress the importance of financing RES, advocating for an optimal subsidy that reflects both the environmental and market values of the technology for firms and consumers [25]. In contrast to the former stream, this body of literature advocates for a blend of subsidies, taxes, and standards as the optimal approach [26]. The dearth of literature addressing the complexities of implementing a mix of policies and the lack of clear guidelines for policymakers to navigate these intricacies leaves an unaddressed space in understanding how to harmonize diverse policy tools for optimal renewable energy outcomes effectively. This void hampers the comprehensive understanding of the practicalities and complexities associated with implementing multifaceted policy approaches in the renewable energy sector.

In particular, previous literature has been investigating policies relating to biomethane and renewable gas, such as [11,12] on policy implication for biomethane production [13–15]; on a single country or single sector renewable gas policy and socio-economic assessments [16]; on quantitatively assessing the efficacy in decarbonizing the energy sector of selected supporting mechanisms to renewable gas across Member States [27]; on the dynamics within the supply chain, particularly focusing on transport costs vis-à-vis economies of scale in biogas production [28]; on the influence of spatial planning on the potential for biogas production and in optimizing the utilization of heat generated by biogas plants [17] on infrastructure competition; on the hazard of promoting biogas and finally [18] on the evolution and balance of policy mixes in a more extensive study conceptualizing and quantitatively measuring design features and a characteristic of policy mix over time. Although many different strategies have been proposed and analyzed by various authors both at the country and the EU level, the review suggests a lack of understanding of the dimension of biogas policies and how they specifically influence the production and use of biogas to create a market driver for renewable gases.

Overall, the complexity of transitioning demands a multifaceted approach, extending beyond technologies to encompass infrastructures, market arrangements, and social practices. Authors unanimously emphasize that policies are intricately linked to the structural and regulatory fabric of a nation, implying that successful policies in one context might not yield identical results elsewhere due to contextual disparities in policies, economics, and overarching frameworks.

This paper bridges a knowledge gap by introducing a comprehensive framework for evaluating policy impacts on biogas and biomethane support trends. It evaluates sectors' development, their links to the natural gas market, system dependence, and pertinent policies in specific EU countries. It assesses scheme performance within the context of public policy objectives and their alignment with broader policy and economic frameworks.

2.2. *The history and development of renewable gas policies in the EU over the decade 2009–2019*

Given natural gas's prominent role in the energy system today and moving forward, it is interesting to investigate how policy mechanisms have supported it in its renewable form and how that support compares to the support for other renewable energies in the same timeframe [17]. Another critical point is to understand whether having a strong dependence on natural gas for an energy system has made any difference in the presence of policies and the number of incentives for renewable gas.

The work focuses on the financial support for renewable energy for electricity generation, which policies have concentrated on over the last two decades.

When looking at the financial support of renewable energy for electricity generation, RES installations (i.e., including solar, wind, geothermal, hydropower, bioenergy, solid biomass, and biogas) were financially supported as early as the late 80s/early 90s, well before the first EU Directive on Renewable Energy was adopted in 2001 (2001/77/EU). In particular, as Table 1 illustrates, the collective EU weighted average support is now more than ten-fold in ten years (2009–2019), going from weighted average support per unit of gross electricity consumed of 9 €/MWh in 2010 to 97.95 €/MWh in 2019, with demand-pull support instruments favored over other types of support (see Table 1).

The strategy has developed from initially applying financial instruments to then evolving into market-based ones to help progressively integrate electricity generated from RES into the market. Support has moved from Feed-in Tariff (FIT) (2001–2017), a mechanism that does not operate under market conditions, falling under the financial instrument support mechanisms category, to market-oriented ones (2017-onwards), as both Feed-in Premium (FIP) and Green Certificates (GC) operate under market conditions.

Despite the heavy presence of gas in the primary energy demand and in different end-uses in 2019 [28], there has been a historical gap in support for developing renewable gases in different end-uses. Although biogas has been historically incentivized for electricity production at lower rates than other RES (e.g., wind, solar, and hydropower), it has received little support elsewhere in the end-use supply chain [15].

In the near future, a substantial portion of installations, primarily wind, and starting from 2024, solar PV and hydropower, will need to confront a new environment now that the FIT scheme is reaching the end of its supporting time [27]. Starting in 2021, RES have been forced to compete in full market conditions, increasingly having to integrate into

Table 1
RES supported electricity in the EU 2009–2019 (Source: Authors' elaboration on [18–21,23–27]).

Year	2009[a]	2010[b]	2012/13	2015	2017	2018	2019
Weighted average support per unit of gross electricity consumed (€/MWh)	7,2	9	110.22	110.2	96.29	99.62	97.95
Average support (€/MWh)	–	7	81.41	–	–	–	–

[a] RES supported accounted for 10 % of gross electricity generation.
[b] RES supported accounted for 8 % of gross electricity generation and 9 % of final electricity consumption.

the market.

To this end, although biogas and biomethane are still a small portion of the overall bioenergy consumption (<3 %) and a small share of the overall biogas output is upgraded, with biomethane representing 0.1 % of natural gas demand, there has been a significant increase in the total number of operating biogas plants in Europe. Europe is the leading region in biogas and biomethane production worldwide. From 2009 to 2019, as reported in Table 2, the total number of operating biogas plants in Europe increased three times, while the total number of operating biomethane plants saw a seven-fold rise in the same period (see Table 2). These statistics highlight the potential that biogas and biomethane could hold in the energy transition process, especially within the framework of the REPower EU plan [29].

3. Methods

To offer a nuanced evaluation of such an evolution, Gustafsson and Anderberg's model [31] served as a guiding framework, enabling a critical appraisal of the evolution of biogas and biomethane policies. As elucidated in Fig. 1, the investigation initiated an exploration into the dimensions and characteristics of biogas policies, specifically concentrating on European biogas policies and their associated literature. This thorough inquiry involved a review of renewable gas policy overviews and evolutions and additional policy literature and documents, alongside the creation of a harmonized database including historical data and metrics (2010–2019) to trace the evolution of the domestic biogas and biomethane sector.

This evaluation extended beyond production metrics to include a comparative examination of national biogas policies and their developmental trajectories. The culmination of this extensive research process led to the synthesis of empirical data and qualitative insights gleaned from scrutinizing national biogas policies in conjunction with empirical data on the evolution of the biogas and biomethane sectors across diverse contexts. Illustrating the concept in practice, this approach is subsequently employed to analyze various biogas and biomethane policies and support trends in three different Member States' markets.

This approach was instrumental in unraveling the developmental trajectories among the studied countries, thereby enabling a comprehensive investigation into the intricate interplay between established policy frameworks and the concurrent evolution observed in biogas and biomethane sector drivers. These amalgamated findings are fundamental pillars supporting the ongoing investigation and the broader scholarly inquiry into biogas and biomethane policies.

3.1. Selection of countries

With the goal of better gauging the dynamics of the evolution of policies and getting an insight into the efficiency of policy support in the promotion of biogas and biomethane, the following three Member States have been selected as benchmarks based on an established production of biogas as well as on recent developments in their biogas/biomethane policies (or lack thereof) to investigate the link between biogas/biomethane and RES policy and market creation: Germany, Denmark, and Italy. For practicality and to minimize redundancy and similarities, the present analysis considers that restricted sample of countries.

Table 2
Number of biogas and biomethane plants increase between 2009 and 2019 [29,30].

Year	Biogas (number of plants)	Biomethane (number of plants)
2009	6227	91
2011	10508	187
2019	18113	630

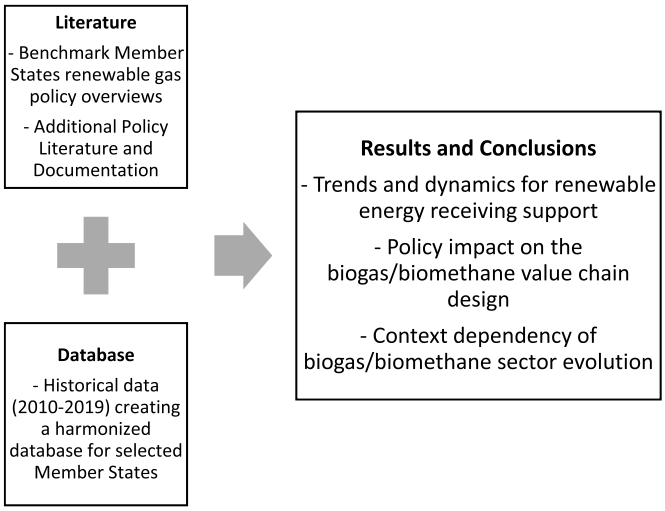

Fig. 1. Methods and outputs illustrative description (Authors' elaboration based on [31]).

In the selection of which countries' policy strategy and technological developments to analyze over a ten-year period (2010–2019), the preference criteria have been not only the degree of market maturity but also diversity concerning both recent developments of production levels and feedstock utilization.

Considering the transformative impact of the 2008 global financial crisis and the absence of the unprecedented disruptions caused by the COVID-19 pandemic, the period from 2010 to 2019 provides a unique lens to observe and assess the resilience, adaptability, and growth trajectories of countries' policy strategies and technological advancements in the specified domains.

As Fig. 2 shows, all three MS are among the top 10 EU MS based on the number of operating biomethane plants as well as their capacity and per capita electricity generation from biogas, with Germany being a pioneer and leader of gas production for combined heat and power (CHP) use, representing 53 % of the whole EU's biogas electricity; Denmark, with a third of Germany's per capita electricity production from biogas, being one of the most advanced markets in biomethane; and Italy being an active market in the shift toward biomethane for different end-uses, and one of the largest markets for natural gas in transports, contributing 13 % to the EU biogas electricity production in Europe [32,33] (see Fig. 2).

The three selected markets are not the only biogas/biomethane markets that have reached a significant level of maturity. Other developed markets in the EU are the UK, France, Sweden, and the Netherlands.

Several reasons concurred in not taking them into account as case studies. Although among the top biomethane producers, the UK and the Netherlands had no biomethane targets in place at the time of writing; hence, the pace for future development is not expected to be as dynamic as it is in less mature markets, such as Italy, for instance.

In contrast, Sweden has been investing in biomethane mainly for transport and filling stations because it does not have a comprehensive gas grid infrastructure. This last aspect, along with extremely low per capita electricity generation from biogas, makes it a less suitable case file for this study [29].

Finally, although France is a very active and mature market regarding the development of biomethane, the support shown for biomethane in Italy in the wider end-use supply chain has been highly favorable [13,32].

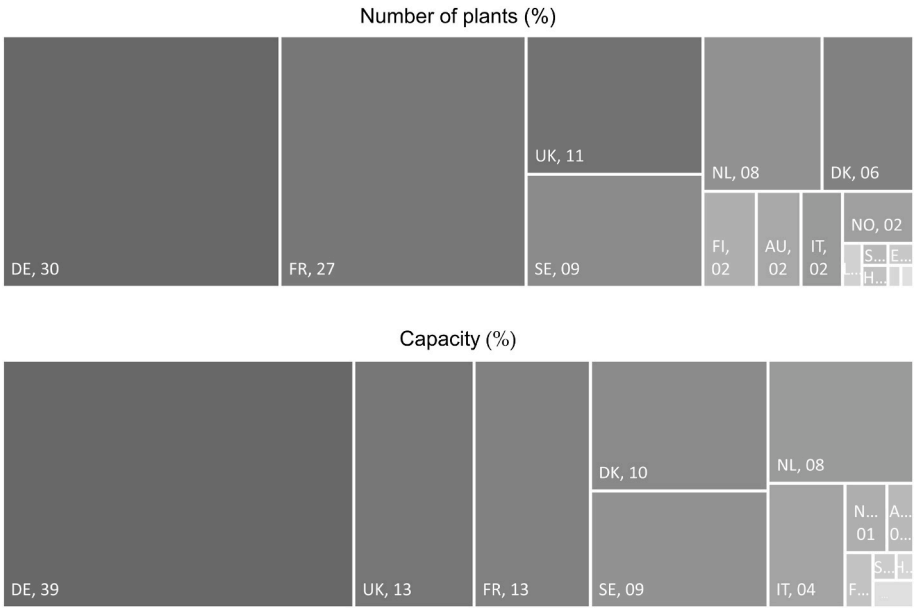

Fig. 2. Development of the European biomethane sector based on the number of plants (a) and capacity (MWh/d) (b) (%) as of 2021. (Source: Authors' elaboration on confidential data from Ref. [30]).

3.2. Data collection

The analysis relies on the information collected with an in-depth analysis of the evolution of policies for biogas/biomethane in the three selected Member States and the harmonized database created with historical data (2010–2019) by the authors from data collected from different sources both publicly and not publicly available, as listed in Table 3 and Table 4: CEER, IRENA, IHS, Our World Data, Eurostat, IEA, and FAOSTAT. In particular, the selection of the variables is consistent with the framework in Nicolini & Tavoni's econometric investigation of renewable energy subsidies effectiveness, which not only included data on RES production but also on incentives as well as energy-specific factors (e.g., electricity prices, CO2 emissions per capita, etc …) [34].

Gustafsson and Anderberg's framework [31] was employed to assess the data's precision, comprehensiveness, coherence, and timeliness. This assessment involved cross-referencing information from multiple autonomous sources, resulting in the determination that the data obtained from both literature research and database analysis in this investigation exhibits a respectable degree of accuracy.

Consistency was observed among several reports, wherein congruence and supplementary insights prevailed rather than contradictions. Furthermore, to ensure precision and coherence, quantitative data about biogas and biomethane were primarily sourced from commercial databases and cross-verified for consistency and any omissions using an extensive array of supplementary databases, as demonstrated in Table 4.

Regarding timeliness, most of the documents and reports forming the foundation of this study were published within the preceding decade (2010–2019), aligning with the temporal scope of the collected data. Additionally, as Table 3 and Table 4 showcase, the cumulative body of scrutinized literature and compiled data was deemed sufficiently extensive and comprehensive to serve the study's objective and substantiate its conclusions effectively.

Table 3
Source for policy evolution analysis.

	Country	Source
1	Germany	[3,14,15,29,32,35–38]
2	Denmark	[3,14,15,29,32,37–41]
3	Italy	[14,15,29,32,36,38,39,42,43]

Table 4
Source for data input bib3collection.bib3

	Data	Database source
1	Installed capacity	[18–21,23–26,44]
2	Energy volumes receiving support by technology	[18–21,23–26,44]
3	Energy volumes receiving support by supporting scheme	[18–21,23–26,44]
4	Natural gas end-use share volumes	[30,44,45]
5	Share of natural gas in the energy mix	[30,44,45]
6	Biogas total consumption	[44]
7	Biogas consumption by sector	[44]
8	Biogas and biomethane plants' number	[30,44]
9	Biogas and biomethane feedstock type	[30,44]
10	Land use data on agriculture and livestock	[46]
11	Electricity from natural gas	[47]
12	Natural gas per capita	[48]
13	GDP per capita	[44]
14	CO2 annual emissions	[49]
15	Natural gas price	[30,50]

4. Results and discussion

4.1. Three complementary approaches, the cases of Germany, Denmark, and Italy

General trends can be highlighted for the development of the biogas/biomethane sector in recent decades, as shown in Tables 5 and 6. In particular, from early 2000, the predominant model for the sector has been biogas from energy crops, high FIT, and electricity and local power generation via CHP units. The industry is now shifting toward a different model that is putting a greater emphasis on biogas upgrading into biomethane to be injected into the grid and away from electricity generation, on feedstock differentiation, and on subsidy reduction, where policies are pushing the sustainability of the sector and the reduction of costs for biogas production [32,33]. Hence, from FIT to FIP and from CHP to grid injection, the strategy has been to create a more competitive market and widen the scope of utilization for renewable gases, upgrading from biogas to biomethane (see Table 5 and Table 6).

The political approach over ten years (i.e., 2010–2019) is well summarized in Fig. 3, where the stall in the market development for

Table 5
Policy implications in the biogas market development in Germany (DE), Denmark (DK), and Italy (IT) (2010–2019) [15], [32].

Biogas	DE	DK	IT
Main end-use	CHP	CHP; gas grid	CHP
Market development	Stall (2012/2014 FIT tariff reduction; 2017 auctioning and defined target growth)	Downturn since 2015 with tendering mechanism	Stall (2013 FIT reduction and shift to FIP)

Table 6
Policy implications in the biomethane market development in Germany (DE), Denmark (DK), and Italy (IT) (2010–2019) [15], [32].

Biomethane	DE	DK	IT
Supporting Scheme	Decreased in 2014 and shifted to auctions	FIP (3 components) (2012–2020)); Tenders with price ceiling (2020)	Certificates (2018 Biomethane Decree)
Main end-use	CHP	CHP; gas grid	Transport, gas grid
Future strategy	Integration in other sectors but limited potential	Upgrading development	Substantial upgrading in other sectors

biogas from 2012 to 2014 and the unclear strategy on biomethane (see Fig. 3) is apparent for Germany. For Denmark, the downturn in biogas in favor of biomethane starting from 2014; and for Italy, the reliance on biogas that has been stalling since 2013 as well as the timid uptake of biomethane following the 2018 Biomethane Decree, going from one biomethane plant in 2018 to twelve in 2019 and seventeen in 2020 [30,44].

In addition, similar to the global trend, in Europe, from 2010, installation costs and levelized costs of energy have been dropping significantly for solar PV and wind offshore thanks to the supporting mechanisms policy adopted by various European governments, closing the gap with biogas installations and levelized costs of energy costs, which were lower, to begin with. Levelized costs of energy in the EU27 countries have dropped −21 % from 2010 to 2018 for wind onshore, −80 % for solar PV- Rooftop, and −75 % for solar PV – Utility-scale since 2008. This has led to levelized costs of energy ranging between €41–89/MWh for wind in 2018, €70–188/MWh rooftop solar PV, €43–168/MWh for Solar PV Utility-scale in 2018, and €64–180/MWh for biogas-fired plants in 2018 [45,51].

The challenges to the development of biomethane are less linked to the scale of deployment if compared with other renewable energy sources (i.e., wind and solar), as Figs. 4 and 5 illustrate. However, they are linked to installation size, production costs (i.e., investment and operational costs, feedstock supply and costs, plant size and efficiency, and operations costs), as well as competition from the availability of much cheaper traditional fossil fuels, at least up until 2022. So, policies have started pushing the sector's sustainability and reducing biogas production costs [15].

In Denmark and Italy, there has been a solid push to upgrade biogas, and biomethane for various applications in different sectors spanning from transportation to chemical production to heat and injection into the grid. Greater attention has been paid to feedstocks: organic wastes, agricultural by-products, and sequential crops. Instead, in Germany and Denmark, subsidy schemes for biogas have been progressively reduced in favor of auctions and tenders. This has brought a stall and a downturn of the biogas market in those MS [33–36,38–41].

4.2. Key complexities of renewable gases policies evolution – a comparative analysis

As in the run-up to the decarbonization of the energy system, natural gas has substituted other more carbon-intensive fuels [52], and biomethane is starting to show its full potential [53]. We assess and compare the performances of the various supporting policies

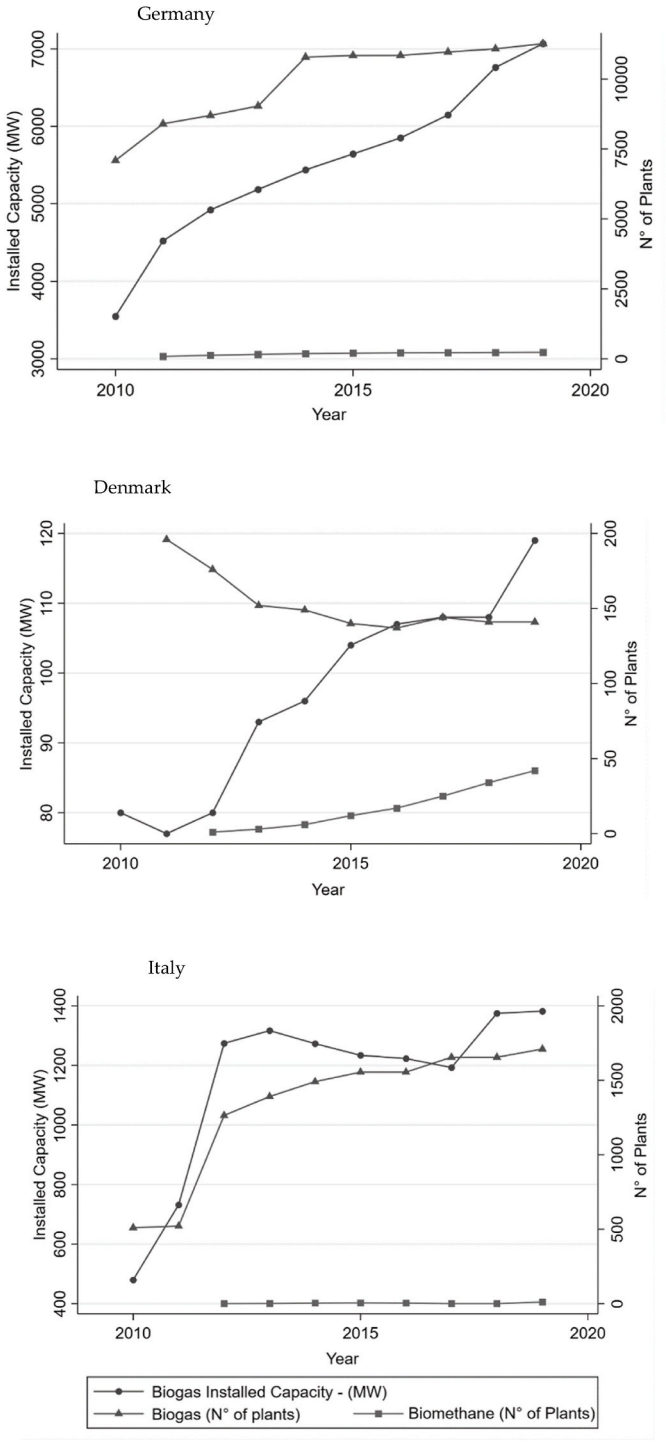

Fig. 3. Installed capacity (MW) by number of plants in Germany, Denmark, and Italy from 2010 to 2019 (Source: Authors' elaboration on [44]). (Only annual data are available).

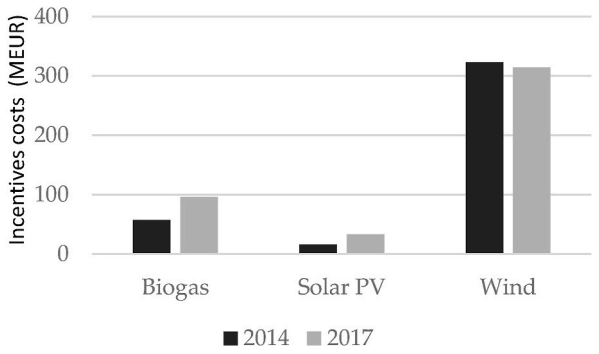

Fig. 4. RES incentives costs in Denmark in 2014 and 2017 (MEUR) (Source: Authors' elaboration on [18–21,23–26]).

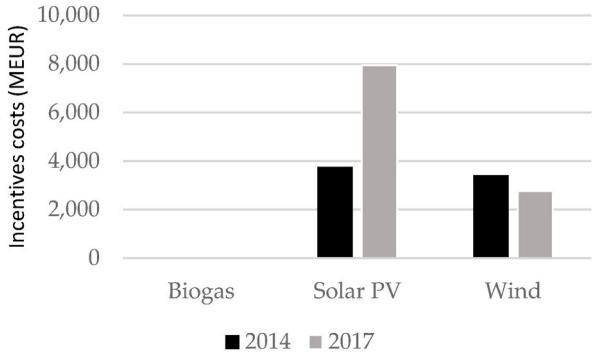

Fig. 5. RES incentives costs in Germany in 2014 and 2017 (MEUR) (Source: Authors' elaboration on [18–21,23–26]).

implemented in three MSs, conducting a preliminary comparative analysis to examine the link between the gas market, the system's dependence on gas, and the presence of policies and incentives [36].

The retrospective comparative analysis focuses on the link between first supporting mechanisms of RES with electricity production and then its synergy with natural gas, exploring how support has evolved based on the country's rate of dependence on natural gas in the energy mix, as well as the relative weight of the end-use of natural gas. In addition, we investigate how different policy approaches have supported other long-term objectives in the development of the biogas and biomethane market.

Differences and similarities in their long-term strategies can be inferred and are discussed in the following sections. The analysis shows that, when supported, the installed capacity and renewable energy produced reflect the national renewable energy development strategies and the geographic characteristics of the country. Fig. 6 shows that in Germany and Denmark, greater support has been given to wind power; in Italy, incentives have favored solar photovoltaic, and the installed capacity has followed the same pattern (see Fig. 6). It also appears clear from the graphs in Fig. 6 that wind, solar, and biomass are preferred to biogas in terms of both installed capacity and supported energy (see Fig. 7).

In addition, considering the significant percentage of natural gas dependence accounted for in each of the three selected Member States (i.e., 15.7 % in Denmark, 26.5 % in Germany, and 42.1 % in Italy [54]), the share of biogas has been compared to the natural gas presence in the energy mix for each country. There is no apparent correlation between the natural gas share in a country's energy mix and the share of biogas in the total installed capacity in the same country.

Similar to what has been observed in the support received by biogas for total supported energy and total installed capacity, regardless of the significant reliance on natural gas in the energy mix of each of the

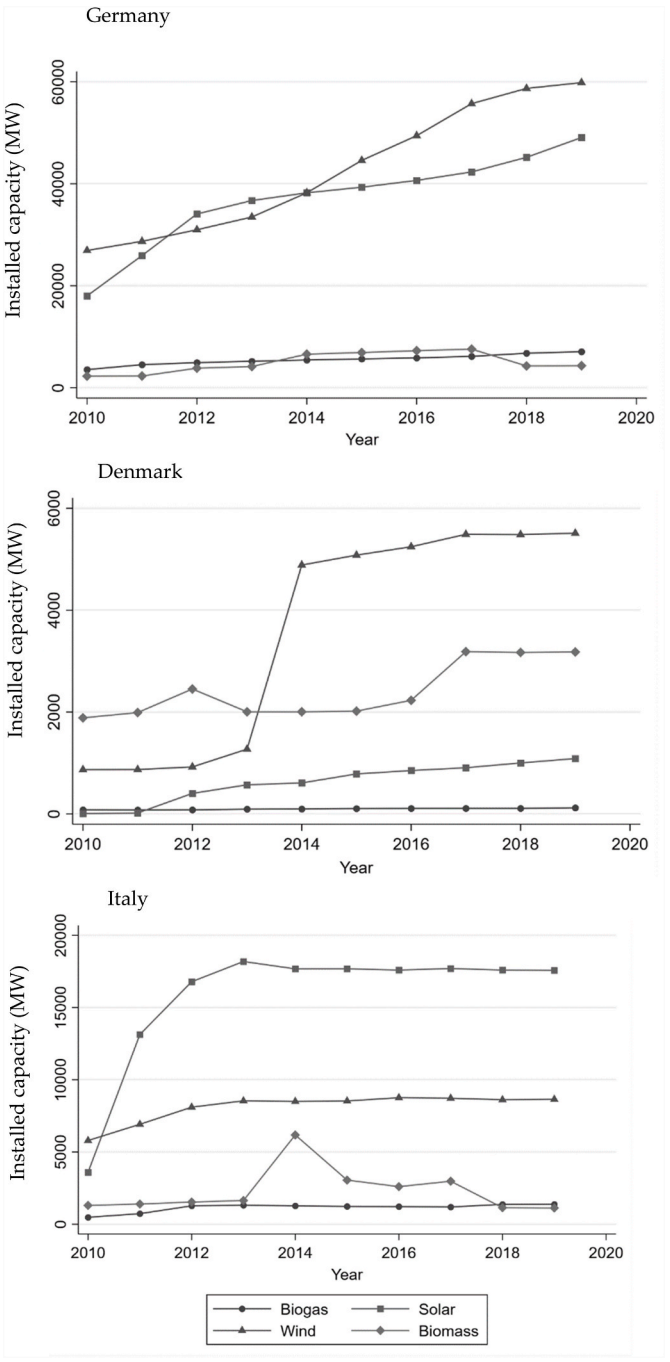

Fig. 6. Renewable energy installed capacity from 2010 to 2019 in Germany, Denmark, Italy (MW) (Authors' elaboration on own database).

Member States considered, Fig. 8 displays that the share of biogas was around 5 % or lower in a ten-year span in all three of the Member States included in the analysis (see Fig. 8).

This might be because renewable gases compete for the same infrastructure as fossil gas, which has been historically cheaper than the former, up to three times lower (i.e., 18€/MWh vs. 55–100€/MWh respectively) [6]. In addition, as mentioned in Section 2, other types of RES (i.e., wind and solar PV) had a more significant challenge ahead in terms of technology advancement and scale than biogas had, where technology costs sharply decreased over time as the scale of deployment increased [15].

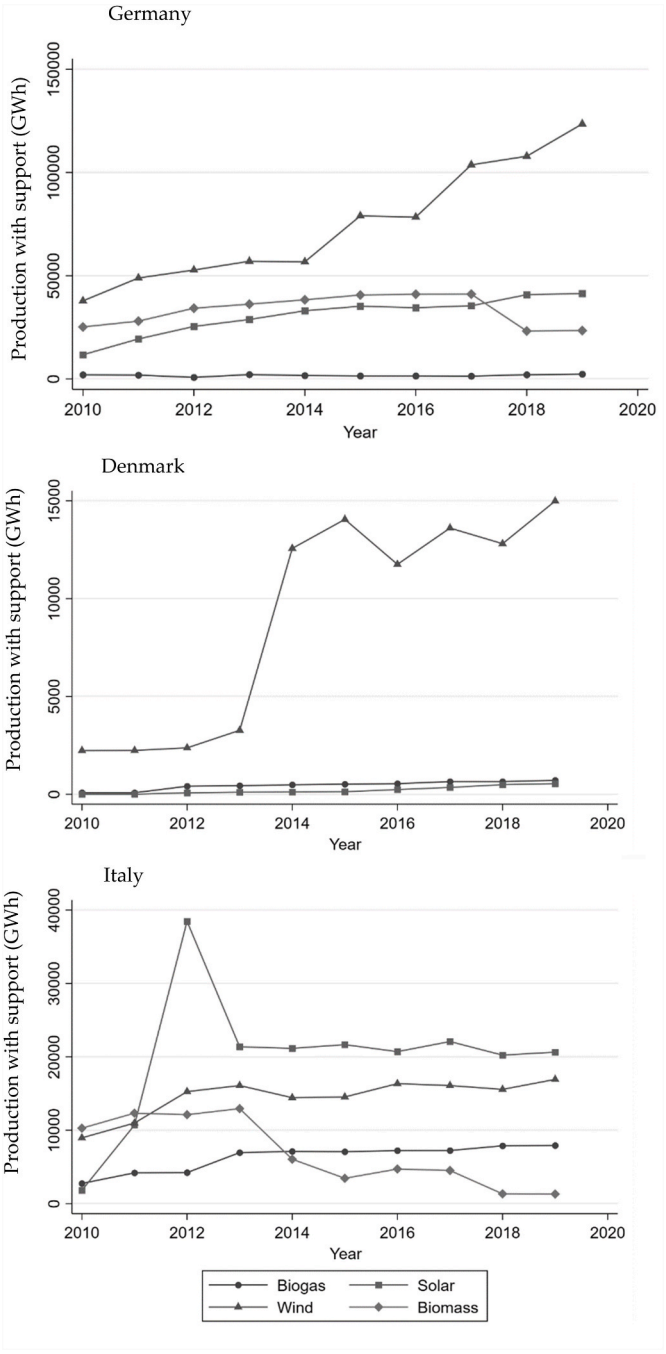

Fig. 7. Renewable energy produced receiving support from 2010 to 2019 in Germany, Denmark, Italy (GWh) (Authors' elaboration on own database).

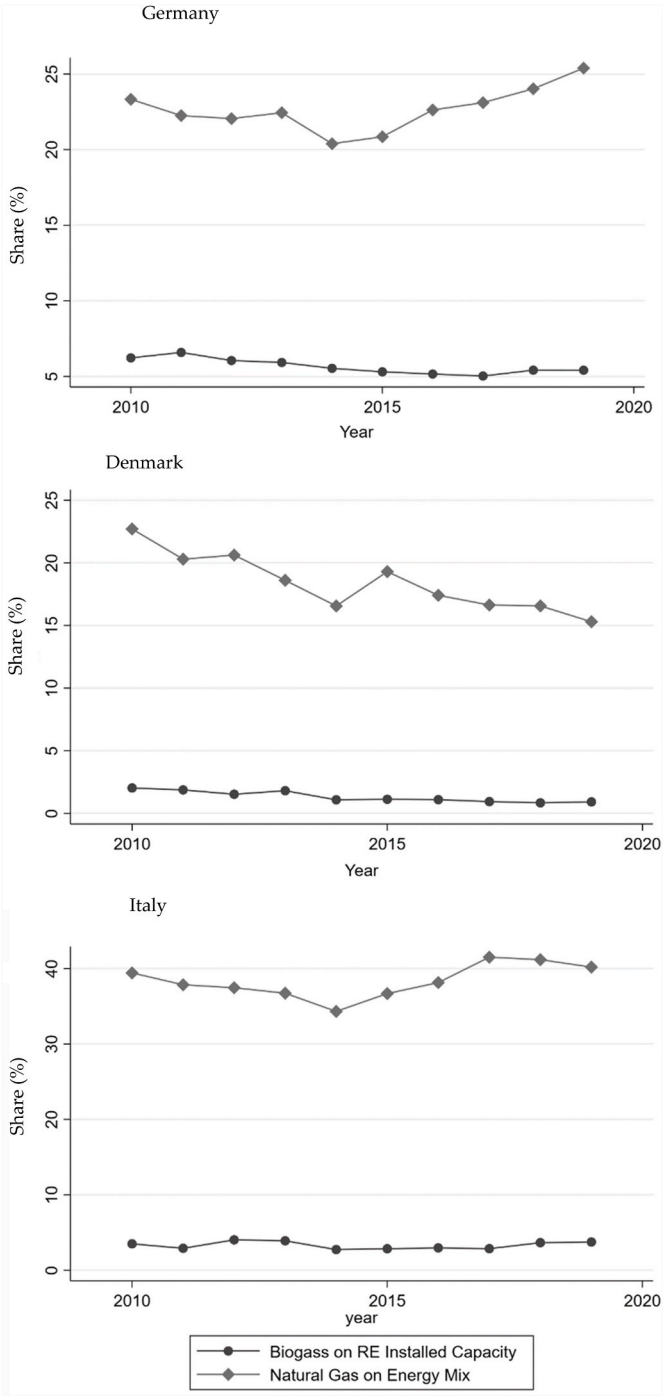

Fig. 8. Share of biogas on renewable energy total installed capacity and share of natural gas on total energy mix from 2010 to 2019 in Germany, Denmark, Italy (%) (Authors' elaboration on own database).

4.3. Support of biogas/biomethane based on end-use

When looking at consumption by sector in Germany in Fig. 9, favored sectors for biogas utilization are the commercial public and households, but not so much the industry sector, unlike in Denmark and Italy (see Fig. 9). A reason might be that Germany has many alternative sources, such as a high percentage of natural gas in the energy mix and coal [54]. In addition, biogas deserves further purification treatments before being considered for grid injection, hence the extensive use of CHP and district heating.

Sequencing in demand-pull policy measures in Denmark has led to the industry and commercial sectors being favored over households and transports, accounting for 44 %, 29 %, and 2 % of the total end-use, respectively. Both the Heat Supply Act of 2000, which required the biogas industry to deliver gas for district heating, and the Energy Agreement of 2012, which called for differentiated feed-in support and biogas/biomethane grid injection, have had an impact on the biogas industry structure and on how it developed from then on.

Feed-in support output for direct use of biogas for heat and power production (i.e., FIT) and final use in industry (i.e., FIP) were set higher than for households and transport. In addition, to incentivize the biogas upgrade for grid use, when upgraded into biomethane and injected into the grid, it receives more support (i.e., FIP) than when used directly in CHP and district heating [16].

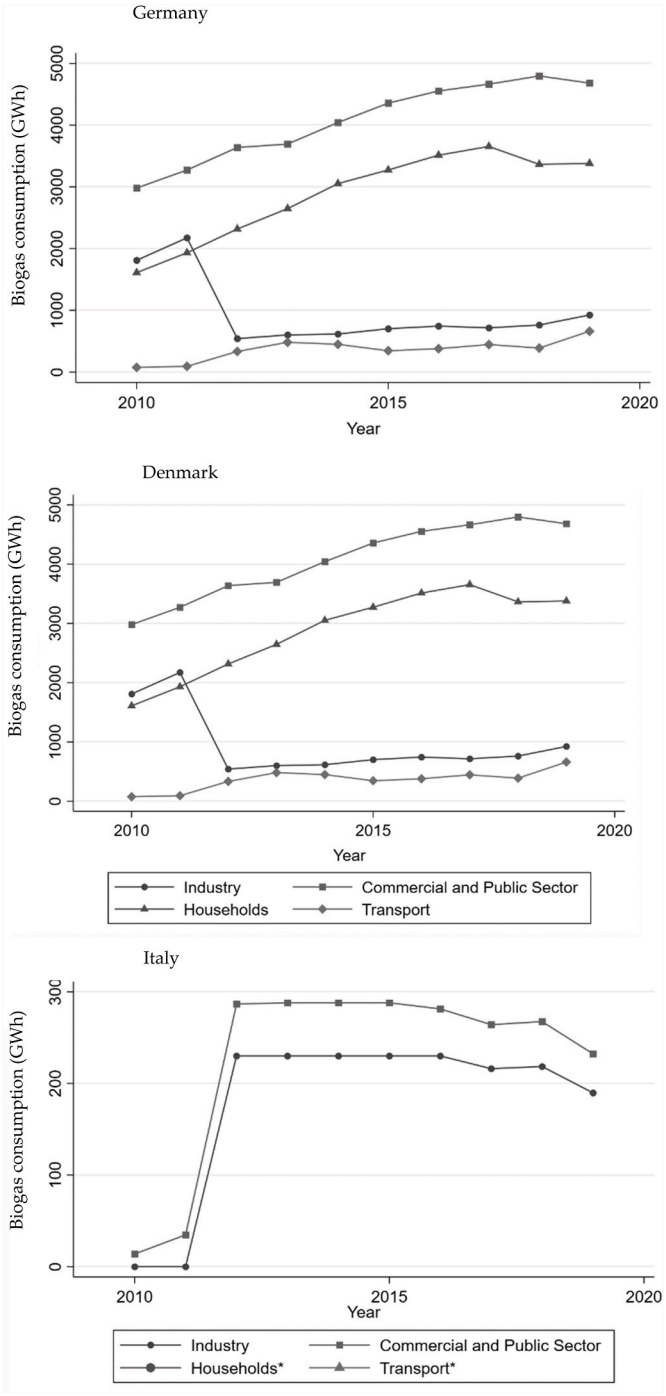

Fig. 9. Biogas consumption by sector in Germany, Denmark, and Italy from 2010 to 2019 (GWh) (Source: Authors' elaboration on own database) * Data not available.

Following the policy ambition of 100 % substitution of natural gas with biomethane in the grid by 2050 and 70 % of gas in the grid coming from biogas by 2030 in the Energy Agreement, starting in 2018, the strategy of Denmark has been twofold: (i) preventing increases in subsidy costs and (ii) opening up the demand market for biomethane to target those sectors in which biomethane had seen low adoption rates till then (i.e., transport and to a lesser extent households), hence, the introduction of tenders as a support mechanism of biogas/biomethane. Since then, the biomethane percentage in the grid has been increasing incrementally, going from 10 % in 2017 to 15 % in 2019 and reaching 21 % in 2020 and 25 % in 2021 [41].

4.4. Impact of policies on the evolution of the biogas/biomethane sector in Germany, Denmark, and Italy

Given the lower incentive support extended to biogas and biomethane and the concurrent and similar development path of the policy strategy in the three examined countries, the analysis has been to evaluate further whether policies had an impact on the evolution of the biogas and biomethane sector over the period 2010–2019. To this end, it can be observed in Fig. 11, Fig. 13, and Fig. 15 how those have been beneficial in helping the sector boom and how the market follows the enactment of the policies in all three countries examined (see Figs. 11, Figure 13, and Fig. 15).

One common trait in the evolution of the policies and their impact on the installed capacity of biogas in the three MS considered over the same ten-year timeframe has been the shift from FIT to FIP and then auctioning. As [55] points out in its analysis of the overall measures and public support framework for biomass for energy, this strategy has turned out to be faster and more flexible in adjusting the support levels of cost reductions and fully integrating biogas into the electricity market.

Introducing FIT as the first supporting measure to support the use of biogas/biomethane has its advantages. Indeed, FITs are long-term contracts that provide stability, driving technological development and maximizing production. In addition, by giving fixed-term support, they reduce the initial risk for investors [55]. However, as much as they prove

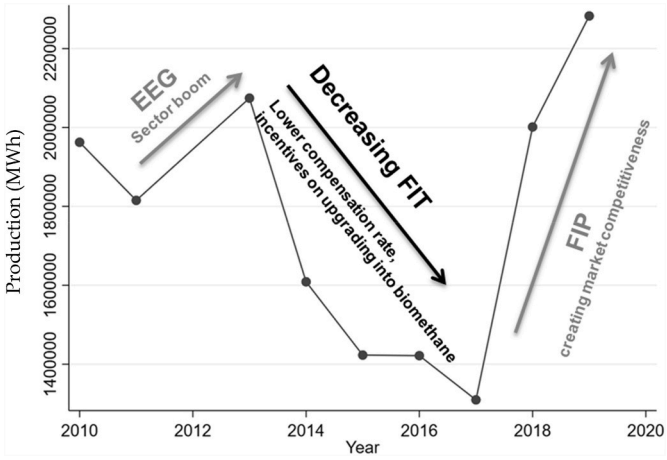

Fig. 10. Evolution of policies for biogas/biomethane support in Germany over a ten-year period (Authors' elaboration on own database).

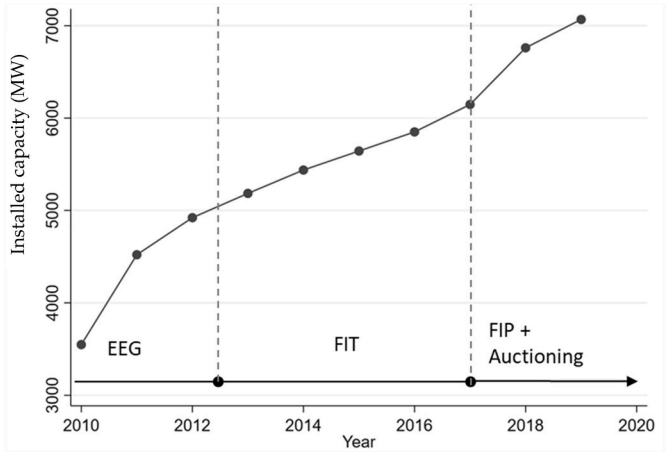

Fig. 11. Evolution of biogas/biomethane installed capacity in Germany over a ten-year period (Authors' elaboration on own database).

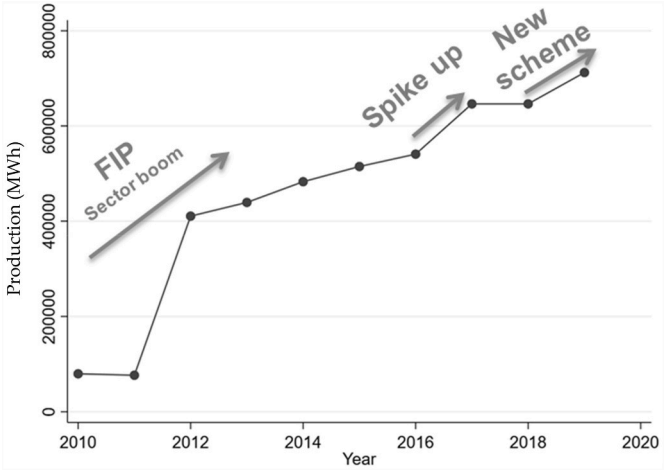

Fig. 12. Evolution of policies for biogas/biomethane support in Denmark over a ten-year period (Authors' elaboration on own database).

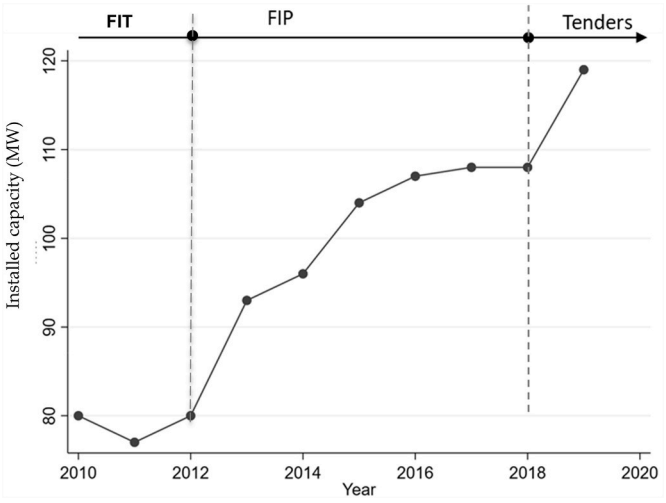

Fig. 13. Evolution of biogas/biomethane installed capacity in Denmark over a ten-year period (Authors' elaboration on own database).

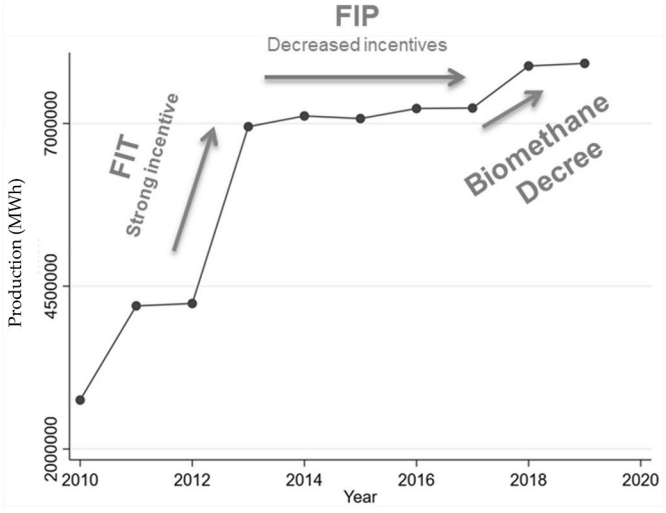

Fig. 14. Evolution of policies for biogas/biomethane support in Italy over a ten-year period (Authors' elaboration on own database).

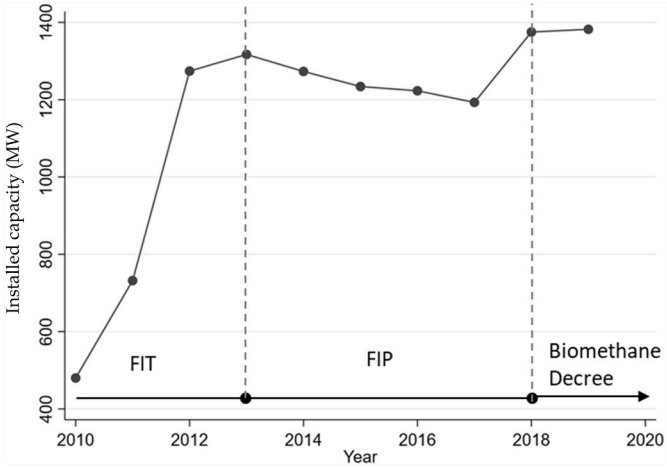

Fig. 15. Evolution of biogas/biomethane installed capacity in Italy over a ten-year period (Authors' elaboration on own database).

useful in the early stages of the creation of supply, they can be costly, as experienced in Denmark, where a new supporting scheme was introduced following a significant spike in the tariff between 2016 and 2017 [15].

In addition, FIT does not provide sufficient market integration to allow the new technologies to independently compete in the market, as they do not respond to price signals. Hence, the market's future development was contingent on the effectiveness of cost-cutting measures as well as a sector-coupling approach to policy [55].

As the analysis shows in Figs. 11, Figs. 13 and 14, the common strategy of MS has been to transition from FIT to FIP, followed by the current predominant support mechanism of tenders (see Figs. 11 and 12, and Fig. 15). The way FIP instruments work, and more so tenders, is that they respond to the price signals of the electricity market, allowing for an efficient combination of electricity supply with demand and for the opportunity of higher revenues than FIT as well as for effective policy mixes in the country, which include different policy domains (e.g., environmental, labor, etc. …) due to the selection of bids that can be based on specific criteria [55].

Contrasting the biogas/biomethane policy evolution over the biogas/biomethane receiving support with the installed capacity for biogas in Germany (see Figs. 10 and 11 respectively), Denmark (see Figs. 12 and 13 respectively) and Italy (see Figs. 14 and 15 respectively), it can be noted that when the policy support increases, so does the installed capacity, and vice versa when the support decreases, a plateau in the installed capacity can be observed. This is more evident in the Danish and Italian biogas and biomethane strategy. Still, it can also be recognized in the evolution of German policy with some caveats.

The comparison for Italy and Denmark shows that with each increase in incentive or the introduction of a new supporting mechanism (e.g., the shift from FIT to FIP), the market has responded with an increase in installed capacity. In Denmark, since 2010, the market has seen constant growth. Upon the introduction of the FIP scheme between 2010 and 2012, as Figs. 12 and 13 present, the biogas sector boomed, to be followed by a sharp spike in installed capacity from 2018 on when there was a steep rise in the tariff and the introduction of a new supporting scheme (see Figs. 12 and 13). This is reflected in the renewable gas consumption by sector in Fig. 9, as it has been mostly used in the industry, commercial, and public sectors (see Fig. 9).

Similarly, Italy experienced strong market growth from 2010 to 2012 with the introduction of substantial incentives through the FIT scheme Still, the market immediately stalled when an FIP scheme was instituted with decreasing incentives. Thus, as shown in Fig. 15, from 2013 to 2018, the installed capacity curve flattened until 2018, when the biomethane decree was enacted to promote biomethane in uses other than

industry and public and commercial sectors where it had been solely utilized up until then (see Figs. 14, and Fig. 15).

Finally, in Germany, the first European MS in biogas and biomethane capacity, the market seems to have not followed the policy schemes' evolution, as the installed capacity has been steadily growing since 2010, as shown in Fig. 6. The sector started flourishing with the introduction of the Renewable Energy Source Act (EEG) in 2000. In 2013, there was a decrease in the compensation rate of FIT, but the installed biogas/biomethane capacity continued to surge.

The reason can be twofold. Firstly, the category "biogas" in the data collected in the database does not indicate the portion of biogas that is upgraded into biomethane. Consequently, the apparent upward trajectory observed in the graph might pertain to an augmentation in biomethane capacity rather than biogas itself. Secondly, it is worth noting that the German government incentivized a biomethane upgrade from 2013 to 2017. Hence, the upward installed capacity curve could have resulted from the policies put in place to advance biomethane in the energy system and curb biogas expansion (see Figs. 10 and 11). Concurrently, as Fig. 7 depicts, between 2013 and 2017, the very high development of PV and wind in the country might have drawn electricity prices down, disincentivizing due to the production from biogas CHP.

The comparison suggests that the development of the renewable gas market does not depend on a single policy measure or action. Hence, a static and rigid approach to policy implementation may not be effective in dynamic environments. Instead, as [56] also concluded, flexibility and responsiveness in policymaking to effectively address the evolving needs of the market and the changing EU regulatory landscape are crucial, as well as having a clear strategic vision as a foundation. This strategic vision should be supported by multiple policies, which are continuously evaluated, adjusted, and adapted to align with changing market conditions and regulatory requirements, as in the case of Germany, Denmark, and Italy.

The emphasis on a clear strategic vision implies that a long-term perspective and a comprehensive understanding of the goals and objectives a country wants to reach regarding market development are crucial. In this regard, Denmark and Italy are positive role models that champion the use of biogas to manage agri-food waste and transportation. The strategic vision provides a guiding framework within which various policy supports can be developed and modified as needed. The intent is to create a flexible and adaptable policy ecosystem that can effectively respond to new challenges and opportunities as they arise.

5. Conclusions

Employing a methodological approach that directly addresses the identified gap in the existing literature, the work provides a systematic and rigorous framework that facilitates a qualitative and retrospective comparative analysis of the relationship between "support schemes and deployment" for biogas and biomethane and renewable energy sources across different EU Member States, which was previously lacking in the literature, thereby enhancing the depth and breadth of knowledge in the field. The investigation gives an insight into the efficiency of policy support in promoting biogas and biomethane with a focus on electricity production, as it examines policy evolution, sector development, links to the natural gas market, and system dependence across specific EU countries.

What it has unveiled are missing support, market perspective, and policy framework, hindering the development of a more harmonious EU-wide framework for the deployment of biogas and biomethane in other sectors beyond electricity production, where they have been historically limited and financed.

As presented, (i) production costs, such as investment and operational costs, feedstock supply and costs, plant size and efficiency, and operations costs; (ii) competition from much cheaper natural gas availability, which was the case in Europe before the recent political turmoil; (iii) together with the lower economic support received by biogas if compared to other RES, have been among the main challenges to the development of biogas/biomethane over recent decades. The findings reveal several key points: the most effective deployment of incentives occurs when considering the entire value chain, with a focus on end-use applications and subsidizing demand-side deployment; there are similarities in supply-side incentives across Member States; there are different approaches among Member States to creating self-standing markets for biogas and biomethane, especially concerning end-uses; and the development of biogas and biomethane is country-specific. These findings hold significant relevance across multiple domains. Regulations can benefit from acknowledging the varying approaches among Member States, tailoring frameworks to accommodate diverse market dynamics while fostering self-standing markets. Energy systems and policy formulation stand to gain insights into bolstering decentralized energy production by emphasizing end-use applications and aligning incentives with broader sustainability goals. Furthermore, from a finance and ESG (Environmental, Social, Governance) perspective, recognizing country-specific development trajectories underscores the need for nuanced investment strategies that account for regional variations in biogas and biomethane projects, ensuring both financial viability and adherence to ESG criteria.

Looking at a ten-year timeframe (2010–2019), the retrospective comparative analysis presented in the study shows a clear connection between success and setbacks in biogas/biomethane evolution and policy changes among Member States. In particular, recognizing that the substitution of fossil fuels with biogas and biomethane could be most effective when applied along the whole value chain, emphasizing the end-use aspect rather than focusing solely on production, has shaped a distinct approach to deploying biogas and biomethane in best practice countries. To this end, subsidizing the deployment of demand-side initiatives brings synergies, as it directly incentivizes biogas and biomethane but indirectly subsidizes different end-use sectors (e.g., transport in Italy), going beyond the original aim of decarbonizing electricity production.

The analysis has revealed similarities across the Member States in how they incentivize the supply side, showing strong evidence with policy to decrease the risk connected to initial investments (i.e., FIT) and market creation (i.e., FIP). As highlighted, there is a link between the incentive and the installed capacity of biogas and biomethane.

Also, the analysis has revealed differences across the Member States in creating a self-standing market for biogas and biomethane, especially in how policies have accounted for demand and end-uses. To increase the market volume, most Member States focused on biomethane where the scope for its use widens (e.g., grid injection) compared to biogas, whose main end-use rests in CHP.

Finally, the development of biogas and biomethane is influenced not only by each country's geographic and economic structure but also, in great measure, by feedstock availability. To this end, there has been a limited value chain perspective, and policy efforts have been concentrated on production, whereas end-use and feedstocks have received little attention. However, when due consideration has been directed towards end-use, that is where best practices have been found.

Since specific policies are not interchangeable between one country and another, the comparative analysis presented in this work reveals the importance of the overarching and strategic level of policy design and how that can be applied to improve further the development of renewable gas in the EU energy system. However, alongside the debate on whether the electricity experience in supporting renewables can inspire the renewable gas sector, from the analysis additional paramount questions emerged that future works should pay attention to.

Some under-researched issues with potentially significant implications for policy design pertain to more sustainable production and increased supply and/or consumption of renewable gases. In relation to these three areas of focus, specific additional topics that should receive consideration from a policy perspective and by future research are: (i) a framework to ensure policy coordination and more comprehensive

policy integration across different sectors (i.e., agriculture, waste management, energy, and transport); (ii) the design for incentive gain sharing among participants in the value chain, drawing from Denmark's experience; (iii) the possibility to impose renewable portfolio standards and the need to examine the merits and limitations of such a policy in the context of biomethane; (iv) the role of Guarantee of Origin, which has been proposed as a crucial public support mechanism to promote a more harmonized use of renewable gas at the EU level to create a single EU cleaner energy market; and finally (v) the value of biogas and biomethane production as a way to valorize emissions in other sectors exploiting industrial, residential, and agricultural wastes in the context of the circular economy.

The evolving gas landscape following the onset of the conflict in Ukraine presents novel challenges that demand a reevaluation of energy security paradigms. Exploring the role of biomethane and biogas in fortifying supply security while aligning with ambitious net-zero objectives could offer crucial insights for steering policy and investment decisions in this dynamically changing context.

Since attaining the REPowerEU Plan decarbonization goals also depends on placing greater emphasis on biogas and biomethane, the future possibilities for biomethane and biogas rely heavily on the massification of sectoral dynamics, new business models, interaction with infrastructure issues, and increased access to funding. Looking more closely into those issues could further inform the policy debate to bolster biogas and biomethane's ability to compete against other energy sources and facilitate their market development.

CRediT authorship contribution statement

Marzia Sesini:conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing of the original draft, and review and editing. **Anna Cretì:** Contribution to conceptualization, investigation, methodology, and review and editing. **Olivier Massol:** Contribution to investigation, methodology, and review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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