Systematic Review

Coal Share Reduction Options for Power Generation during the Energy Transition: A Bulgarian Perspective

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Abstract: The sustainable energy transition to a low-carbon and climate-neutral economy by 2050 requires a consistent increase in the share of renewable energy sources (RESs) at the expense of the share of fossil fuels. The coal power plants in the Republic of Bulgaria have provided about one third of the annually produced electric power for decades, utilizing mainly locally available sources of lignite. The present work aimed to review the progress of the energy transition, its rejection and acceptance at the national and international scene alongside the available research for cleaner coal combustion in Bulgaria, as well as discuss a Bulgarian perspective for coal share reduction options for power generation during the energy transition. A comprehensive review was carried out, based on freely accessible data such as research and open media articles, officially published field reports, legislative and strategic acts as well as validated statistical data. Three groups of critical gaps (socioeconomic, sociotechnical and cultural and political) were indicated, claimed to be capable of guiding the just transition. Key factors influencing the process dynamics were identified and categorized in the context of the critical gaps. The peculiar policy criteria for the carbon-intensive regions are as follows: the dominant energy carriers, existing infrastructure, involved actors and choice of strategy. The observations allowed us to conclude that in addition to the efforts achieved and ambitious political will, the identification of reliable technological and socioeconomic measures is needed more than ever (accompanied by interdisciplinary research involving the technical, social and environmental and policy factors), while renewables still have long way to go towards complete substitution of the fossil fuels for power generation, transport, and manufacturing. Limited literature was found for reducing the share of coal from currently operating Bulgarian coal-fired power plants (CFPPs). Herein, short- and/or medium-term measures for carbon emission reduction were discussed, capable of promoting the limited operation of existing CFPPs, thus paving the road towards a sustainable, long-term transition. These measures concerned the typically used power units in the largest CFPPs located at the Maritsa Iztok Mining Complex (MIMC). Analyses of the biomass production, supply and cost for the same type of power units were proposed, considering the use of 100% biomass. Estimated costs, unit efficiencies and power generation were discussed along with the evaluations about the land use, ensuring a given annual productivity of wood chips from fast growing plants, e.g., Paulownia.

Keywords: carbon neutrality; reduced coal share; coal to green energy transition; renewable energy carriers

1. Introduction

The access to energy resources and their effective use are the strategic bases for the development of any country. In view of the ambitious environmental policy towards mitigating global warming, in 2015, overall, 178 alliances from all over the world adopted the Paris Agreement at the Climate Change Conference (CCC) of the United Nations
(UN) for global carbon emission reductions [1]. The European Union (EU) imposes a strong motivation and effort for the sustainable energy transition to a low-carbon and climate-neutral economy by 2050 [2]. The European Green Deal envisages by 2030 at least 40% of greenhouse gas emissions to be reduced in comparison to the levels in 1990. In addition, the share of renewable energy sources (RESs) shall be at least 32%, along with about a 32% improvement in energy efficiency [3]. The long-term perspectives (up to 2050) aim at reaching a gradual reduction of coal as an energy source, or at least for the purposes of power generation without carbon capture, utilization and storage (CCUS) as described in [4,5].

However, numerous energy transition scenarios [5–7] still need explicit validation and/or are only applicable under certain (very specific) circumstances. An extensive research [8] proposed two energy transition scenarios: (a) an economic transition scenario (ETS) as a baseline assessment of how the energy transition might evolve from today as a result of cost-based technology changes; and (b) a net zero scenario (NZS) describing an economics-led evolution of the energy economy towards achieving net-zero emissions in 2050. The second scenario combines a faster and greater deployment of RESs, nuclear energy and other low carbon technologies for power generation, with the uptake of cleaner fuels in end-use sectors. It also proposes hydrogen and bioenergy as the key driving factors towards the goals of the Paris Agreement. Another net zero emissions scenario (to be accomplished by 2050) of the International Energy Agency (IEA) suggests that all unabated coal generation should end by 2040 [7]. It requires an annual average reduction of emissions from the CFPP of around 8% until 2030. According to the same authors, to reach this goal in the decades to come, governments and the coal industry first need to develop less polluting and more efficient technologies.

Recent reports draw strategies for a rapid, secure and people-centered energy transition, with gradually increasing the focus on emission reduction from coal utilization in vicinity of the net-zero transitions [6,7]. A well-accepted concept for capacity improvement along with emission reduction is the implementation of CO$_2$ capture technology next to the upgraded, combined cycle power plants [9] or replacing coal with chemical carriers of renewable energy [10]. Thomas [11] impersonated the future of the so-called clean coal and CO$_2$ capture and storage technologies, with a focus on the currently existing technologies for clean coal utilization such as the following: (1) coal cleaning by washing to decrease the ash and SO$_2$ residuals; (2) electrostatic precipitators and filters to remove 99% of the fly ash; (3) flue gas desulphurization, for flue gas SO$_2$: reduction up to 97–98%; (4) low NOx burners and (5) advanced technologies for coal utilization, e.g., integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion (PFBC), enabling higher thermal efficiencies (up to 50%). Underground coal gasification is often discussed as a promising coal utilization method [12–14]. A recent concept promotes the complex mining of raw material mineral resources as a good perspective, e.g., for uncultivated coal mines [15], towards the sustainable development and diversification of the production of enterprises and the effective transformation of coal-mining cities from mono-product to multi-business production complexes, capable of complying with the environmental, social and governance (ESG) principles.

Substantial expectations are put on hydrogen, which is soon expected to have a prominent role as an energy carrier, but the amounts of low-carbon RESs and renewable hydrogen that are currently being produced are still insufficient [2]. On the other hand, the direct implementation of the existing natural gas infrastructure is questionable and still requires detailed research, especially regarding safety issues. The security of the energy carriers and their environmental concerns are questions of primary importance along with targeting the issues related to power production and supply, as well as the process efficiency in response to the end users’ demands [16].

The largest uncertainties are supposed to occur during the transition in the so-called carbon-intensive regions/countries (relying on fossil fuels for more than one third of their energy mix), especially in a short- and medium-term perspective. Most of the countries in
Eastern and Central Europe are still carbon intensive. The societies therein insist on the need for determining and implementing sustainable solutions, capable of ensuring the national energy system and security, socioeconomic status as well as stimulating the economy of the affected countries or geographic regions.

The present study was inspired by the political, economic and social tension of the European Green Deal in the context of the urgent need for emerging technologies capable of satisfying the forthcoming deadlines for the member states’ commitments. Particular attention was drawn to the current status of the energy transition and its rejection and acceptance from a national and international point of view. Considering the current circumstances, the global objectives of this work were to (i) identify the critical gaps and key factors known for being capable of guiding the transition process and influencing its dynamics and (ii) present technological options for a reduced share of coal use and carbon emissions from the existing national lignite-fired power plants, aiming to sustain the energy balance during and after the transition period.

The structure, role and capacity of the Bulgarian energy system has been well documented [17–19] alongside the positives and negatives of the socioeconomic and political strategies applied during the last decades [19–22]. The present study accentuates several key issues that cannot be resolved in single studies through the implementation of tactics, which contain unclear and imprecise perspectives, commitments and responsibilities. Essential for the successful implementation of any transition is building trust in the public masses and especially in the most affected communities. Thus, detailed interdisciplinary research (empirical and theoretical) is currently needed on the technological and socioeconomic measures required to ensure a sustainable and plausible transition and energy balance. The work is still in progress, and herein, only some preliminary observations were presented in the context of the above-described issues.

2. Study Design and Data Selection

The present investigation was carried out using freely available data sources (most of which were limited to the last three decades), such as research and media articles, officially published field reports, legislative and strategic acts and related documents as well as validated statistical data from the last decades (see Table 1). The selection of materials was based on a keyword metasearch [23,24]. The following keywords are the focus of this study: (1) net-zero transition roadmap, (2) opposition and acceptance of coal phaseout/just transition, (3) coal consumption for energy production, (4) coal export–import, (5) energy transition models, (6) technoeconomic analysis of lignite-fired power unit and (6) emission reduction in lignite-fired power units. Regarding the last two keywords, the inclusion criteria merely accepted publications on power units relevant to the largest Bulgarian CFPPs. Finally, through a manual screening, the publications being out of scope of the current investigation were removed.

Table 1. Overview of the types of data sources used after the final screening.

<table>
<thead>
<tr>
<th>No.</th>
<th>Data Sources</th>
<th>Total Number</th>
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<tbody>
<tr>
<td>1</td>
<td>Research articles</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>Open media articles</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>Reports and statistical data</td>
<td>29</td>
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<tr>
<td>4</td>
<td>Legislative and strategic acts</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Software</td>
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The contemporary qualitative analysis of the freely available data in scientific/socioeconomic reports, gap analyses and records on good and/or bad practices helped in identifying and differentiating the so-called critical gaps and the related key factors, navigating the process and promoting the opposition or acceptance of the coal phaseout (see Table 2, Section 3.3). Benchmarking was applied to study the coal share for
power generation as well as coal extraction, production and consumption. For that purpose, merely officially available and validated statistical data were used [25–32], as well as global energy tracers (https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/, accessed on 5 February 2024; https://www.carbonbrief.org/mapped-worlds-coal-power-plants/, accessed on 5 February 2024). The considered legislative frame was mainly focused on the latest national policy acts regarding the transition process in Bulgaria [33–40].

3. Just Energy Transition

3.1. Progress of the Transition Process

The Net Zero Roadmap [41] indicates the global pathway for reaching this goal by 2050. For that purpose, the roadmap sets over 400 milestones to be accomplished to decarbonize the global economy in three decades. However, particular circumstances, such as the socioeconomic, political, and technological gaps, etc., in each state should not be underestimated. For instance, Merzic et al. [6] reported that overall, 41 regions in 12 EU member states are actively engaged in coal mining. The authors confirm that in the affected areas, there is a vast number of employees, “about 185,000 in the mining of coal and lignite and about 53,000 in CFPP”, having a limited or no alternative employment opportunity. Usually, it is due to a lack of qualifications (education, skills, etc.) outside their present occupation, with no alternative jobs. This perspective strongly correlates with the list of local/regional socioeconomic or psychological factors, which take precedence in shaping the prospects for a green transition.

Besides the numerous, thoroughly developed strategies for a carbon neutral society, coal is still a key energy carrier that is stabilizing the electricity production mix, because of which the transition policy and practice is currently facing dramatic challenges (socioeconomic, political, technological and even physiological and cultural) with regard to the affected population [16,42]. The premature decommissioning of existing CFPPs can cause devastating economic effects. Implementing facilities for carbon capture, utilization and storage (CCUS) coupled to the conventional coal-fired power plants is a well-accepted approach (e.g., for short-/medium-term measures), providing contemporaneous permits for some countries to use fossil fuels [43]. The implementation of carbon-free energy carriers such as metal fuels [10] is also foreseen as a promising coal substituting solution. However, such measures might require a reasonable, cost-effective compromise besides their uncertain long-term perspective.

According to Figure 1, most of the EU member states are still relying on a significant share of fossil fuels (solid, liquid or gas).

The legislative and social pressures on the coal and mining sector have gradually increased, but in fact, it is not just the CFPPs that must be decommissioned (Figure 1). On the other hand, the energy crisis across Europe and the wars in various hotspots around the world create fear in the supporters of the energy transition regarding coal’s comeback [44]. Recently, a small number of CFPPs within the EU were reported as being placed on temporary standby, which is believed to have a limited impact on the net emissions and climate engagements [45]. The updated data for 2020 confirm the primary role of coal for electric power production at the global scene; e.g., see [32]. All-time high global coal consumption was reported for 2022 [7]. However, latest European statistics show a lower-than-expected coal demand for electricity generation during 2022 and 2023 within the EU [46,47]. A record fall in coal, gas and emissions was reported in 2023, where fossil fuels dropped by a record of 19% to their lowest ever level at less than one third of the EU’s electricity generation [47]. The slightly delayed nuclear phaseout in Germany was duly reflected by the local social media [48]. Prior to the last plant closer, the nuclear-supporting organizations and some politicians insisted that it would have been best if the German government decides to keep these nuclear power plants in reserve, because the perspective for burning gas and coal is not a cleaner option to assure the country’s
energy balance. Environmental activists (Deutsche Umwelthilfe—DUH) [49] promoted the concept that district heating networks should also be transferred to renewable sources, which are expected to replace the fossil fuel-based heating supply systems. The report reviews the sectorial conditions in Germany and considers several key policy recommendations.

![Figure 1. Gross available energy by fuel type for 2021 (in %). Data source: Eurostat [26], with online data code: nrg_bal_c.](image)

Over several decades, Poland has been a net exporter of energy, relying mostly on coal combustion [50]. According to Jermain et al. [51], Poland’s coal transition is currently
limited to excluding its use for residential purposes, but raw coal is still extensively used for power generation and industry. Considering the present economic situation restricting the member states, the coal sector is considered inevitable [52]. Besides the war in Ukraine, another critical, well announced and accepted fact is that the miners’ community fears local politics [51]. The authors suggest this as one of the reasons why only insufficient mines are currently liquidated.

A case study for Bosnia and Herzegovina (BiH) by Merzic et al. [6] reports that short-rotation coppices and dedicated energy crops are foreseen as promising transition strategies for this country, involving the use of raw materials for the production of biofuel and its additional usage for electricity and heat generation. The authors assess the contribution of photo voltaic power plants (PVPPs) and biomass for the oncoming energy transition in BiH in terms of several key sustainability indicator groups, such as economic, environmental and social measures. Their aggregated economic analysis could not favor the development of a PVPP over the utilization of willow as an energy carrier. A multicriteria analysis by the same authors shows a sustainability ratio supporting the implementation of both RESs. An officially published news article [53] stresses that Serbia and BiH still plan to build new lignite power plants, contrary to their declarations to phase out of fossil fuels by 2050.

A perspective analysis for the United Kingdom (UK) reveals the long-term effects of implementing well-accepted CCUS technologies [43]. However, a possible longer energy payback period is foreseen by the authors, along with lower operating efficiencies and energy gain ratios in comparison to conventional power plants. The recent investigation of Walk et al. [54] on the driving factors of the UK towards a coal phaseout to net zero energy sector concludes that such an industrialized country has the required prerequisite to become carbon neutral sooner than 2050, thus laying down the foundation along with the historical responsibility for CO₂ emissions and economic premises that the countries in the so-called Global South still do not possess. According to the same authors the term Global South involves the relevant countries located in Central, South and Eastern Europe. The UK policy from the last decades stimulated a gradual reduction of the coal mining and utilization industry, dropping it down to about 2% [54]. Thus, it is well expected that the UK will become one of the major economies capable of reducing its net greenhouse gas (GHG) emissions by 100% until 2050 [55]. Any noncommittal contemporary study of the above discussed circumstances would lead to the conclusion that such a goal might be hardly achievable by 2050 for the carbon-intensive economies, like many of the member states in the so-called Global South.

Recent research, sociological studies and social media promote that the economic and political issues are the key driving factors towards the just transition. Andreas et al. [20] investigated the relationship between renewable energy transitions and energy justice in Bulgaria. The authors found that whilst Bulgaria was able to reach its renewables targets for 2020 in advance, a mismanaged policy can break the long-term viability of the transition. The analysis confirms the importance of long-term strategies, effective policies and supportive macroeconomic targets, and highlights the negative consequences of RESs towards energy justice if these factors are omitted.

Energy transition modeling is certainly a valuable method for scenario evaluations of global energy systems operated in a city, country or even region [56,57]. The characteristic boundary conditions for each model limits its application under the conditions of a given simulation. Süsser et al. [58] criticized some modeling studies for being too technically focused and ignoring the environmental and social factors. The authors studied the user needs, omission impacts, and real-word accuracy within the EU and confirmed the need for continued efforts for model improvement. Savvidis et al. [59] compared 40 models overall and proposed a set of criteria, seeking to establish the gap between the challenges of the energy policy and the abilities of energy system models to provide answers on major socioeconomic and/or policy issues. The authors developed guidance on crucial model features and suggested potential funding priorities for future energy
system modeling. The so-called agent-based modeling is believed to have the potential to provide insights into complex energy transition dynamics from a social–scientific perspective [60]. In a recent study by Shi et al. [61], an agent-based model (ABM) was built to explore the role of an information platform for the diffusion of energy efficiency technologies (EETs) in small- and medium-sized enterprises. The authors observed that the information platform could behave as a double-edged sword that accelerates the EETs’ diffusion but may also spread negative information and as a result, slow the EETs adoption. The authors propose recommendations for modeling improvements. Although intensive interdisciplinary collaboration in the ABM development is still needed, ABMs are promoted for having the potential to be used for energy transition studies due to their practical application to the decision-making process [60].

The expected historical transformation shall be based on reliable and detailed research, developing the required technological prerequisites for an adequate and sustainable transition considering all related aspects. Recently, Roman-Collado and Economidou [62] concluded that the rapid replacement of conventional fossil fuel combustion technologies with low-carbon sources and RESs is generally possible, but the implementation of any energy transition strategy (e.g., at national level) must comply with reasonable legislative and governmental support, human resources and technological and financial capacities, allowing for the transition in a humanistic and environmentally friendly manner.

A current critical analysis [63] accentuates the hypothesis of the so-called energy trilemma in terms of the determined need to find a balance between energy security, equal resource accessibility and affordability and environmental sustainability. According to the same authors, in 2022, a record number of electric vehicles were produced as well as PVPP and battery installations, while the RESs are still far from replacing fossil fuels in the global energy mix. The study reports that the observed CO2 shrink by 2023 is insufficient, and the so-called clean energy is expected to reach 52% of the energy mix by 2050. The same authors warn that it is of vital importance for the governments worldwide to realize that the circumstances that might be slowing or even questioning the transition process should be faced in parallel to the needs and costs for adaptation to the climate change issues, e.g. the 1.5 degree Celsius critical target?. Thus, at present, the main debate is not for or against just transition, but rather, it is how it could be done in a fair enough way. The rate-limiting stage is the readiness and capabilities of the member states to accomplish their commitments, but this should not open the door to colossal abuses, by any means necessary.

3.2. Coal Consumption for Energy Production

Coal deposits are relatively evenly distributed around the world, unlike oil and natural gas deposits, which are concentrated mainly in the countries of the Middle East, Russia and the USA, whereas China and India are, respectively, the first and the second world’s biggest coal importers, for which the demand is expected to rise in the coming years [51]. A huge effort is put into mapping specific pollutants from coal combustion [64]. John Ainger [65] reported that between 2019 and 2021, the commercial banks in the USA directed about USD 1.5 trillion into coal. Jermain et al. [51] reported the existence of 2400 power plants operating in 79 countries, with a cumulative capacity of 2100 GW, which questions the energy transition, especially in short-term perspective. The same authors reported about 8500 CFPPs worldwide being in operation, and new generating capacities (about 1706 GW) being under construction at more than 189 plants and still planning more than 280 GW of additional capacity at existing power plants.

Although between 2018 and 2021, the EU reduced its consumption of the main types of solid fossil fuels by one fourth, fossil energy carriers such as oil, coal, natural gas and uranium are still accounting for over 80% of the world’s energy production [27].

The production and consumption of hard coal within the EU gradually reduced from 277.4 Mt in 1990 to 57.2 Mt in 2021, with Poland being the major producer through
the decades followed by Germany, Czechia, Spain and France [29]. Figure 2 shows officially published statistics [28] on the supply of fossil fuels and nuclear power within the EU (2005–2022). A post-pandemic increase in the fossil fuels and nuclear power sources in 2021 is observed in comparison to 2020, whereas a sharp drop is estimated in 2022 for nuclear power and natural gas due to meteorological and politico-economic factors. The brown coal and petroleum trends continue increasing, while hard coal decreases between 2021 and 2022. In fact, in many of the EU member states, over 90% of the used hard coal is imported, whereas brown coal is mostly produced in the countries of consumption, with negligible import and export rates [30]. In 2022, Poland (38%) and Germany (25%) consumed almost two-thirds of the total hard coal supply produced within the EU, followed by Italy, the Netherlands, France, Spain, and the Czech Republic [30]. The same data source shows that in 2022, the brown coal production increased up to 349 million tons (+5% compared with the previous year) along with its increased consumption of 454 million tons (+2%). According to the same statistics source, in 2022, Germany represents 44% of the total brown coal consumption (131 million tons) followed by Poland (19%), Bulgaria (12%), Czech Republic (11%) and less so, by Romania, Greece, Hungary, Slovenia and Slovakia. Brown coal is also regarded by the European Free Trade Association (EFTA) countries as an energy carrier, but the facts show that for many of the EU member states, it is still considered to be the largest source of electricity generation and CO₂ emissions. According to [28], the latest crises (such as environmental disasters, COVID-19, wars, etc.) are believed to be the main reason for the observable lignite/brown coal renascence in 2022 (Figure 2). The global crises and incidental extreme weather conditions are seen as threats, capable of reinforcing the role of coal as a critical energy resource [66,67]. At present, the decommissioning of CFPPs is foreseen as the greatest challenge to face in transitioning to low-carbon energy production across the EU and worldwide [7].

Figure 2. Supply of fossil fuels and nuclear power within the EU, between 2005 and 2022 (dimensionless index; the data for 2005 = 100). Source: Eurostat (nrg_cb_gas), (nrg_cb_oil), (nrg_cb_gas) and (nrg_ind_pehnf), in line with [28].
3.3. Opposition and Acceptance of Coal Phaseout

The social and industrial opposition towards the energy transition is of great political and socioeconomic interest [51,68–70]. Numerous measures towards just transition implementation worldwide were determined to be ineffective due to well-known socioeconomic and technology-related issues, as well as susceptible cultural particularities that strongly influence the economic and political circles [71,72]. Recent gap analysis studies confirm the essential role of good practices in policy development and implementation [51]. Steckel and Jakob [68] thoroughly investigated the social science literature on opposition and acceptance of the transitions in 15 countries overall located at seven geographical regions, and revealed critical gaps suspending the transition implementation such as (a) sociotechnical dynamics needed for sustainable transitions; (b) socioeconomic factors driven by social movements and public oppositions; and (c) cultural particularities and the locally adopted political philosophy (from long- and short-term points of view). Their findings show that the policy on the transition in carbon-intensive regions varies from country to country and strongly depends on the dominant energy carriers, the existing infrastructure, the involved actors, the chosen tactics, etc. All this shapes the outcomes and present states of the energy transitions in the examined regions. According to Stephenson et al. [71], the national field cultures determine the different energy and climate pathways, but they are easily cultivated by the affordable technologies, the economic dependency on fossil fuels as well as the state involvement in the energy and mining industry, etc. Sovacool et al. [70] investigated conflicted energy transitions over seven carbon-intensive regions in Asia, Europe and North America. The authors systematically explore the opposition to a wide range of energy infrastructures across 130 cases in 15 countries overall. Their typology and frequency analysis of the tactics and outcomes showed that the energy transition policy and practice varied from country to country, being greatly affected by the country’s democratic culture. A valuable output of their analysis is the identification of nine different classes overall (across the entire sample) of transition-related case opposition and acceptance, distributed by the type of examined infrastructure. Expectedly, the most frequently detected are the cases involving fossil fuels, in particular, coal (37%) and oil or gas (9%). According to the same authors, the key players shaping the population’s opinion and support for or against the transition implementation are as follows: local governments (often including the military authorities), public and private organizations (e.g., energy and mining industry, metallurgy and other heavy industry sectors), nongovernmental organizations and others. International pressure is also found to considerably shape the arena for action, but no clear relationship between the tactics and outcomes across the regions and cases is established in the same data source. Jermain et al. [51] examined the reasons behind the reluctance of the necessary coal transitions and the relation between ambivalent policy and lack of progress. Their work is focused on the transition policy and practice within the United States of America (USA). For that purpose, the authors reviewed three general case studies, focused on the following key aspects: the role of advocacy on just coal transitions in Australia, the challenge of sustained transition failures in West Virginia, USA and the intertwining of policy ambivalence and practice reluctance of the transition in Poland, EU. The authors recommend good practices from Australia, reminding us that reality exists in communities rather than in turgid concepts. Table 2 summarizes the global critical gaps of the just transition according to [68]. The literature review allowed for the identification of a list of key factors influencing the dynamics of rejection and/or acceptance of the transition process.
Table 2. Critical gaps suspending the just transition and related key factors influencing their dynamics.

|-----|------------------|-----------------------------------------------|------|
| 1.  | Sociotechnical dynamics needed for sustainable transitions | - The rapid replacement of the conventional technologies with low-carbon sources and RESs must comply with reasonable and long-term legislative and governmental support, human resources and technological and financial capacities, facilitating the transition in a humanistic and environmentally friendly manner.  
- The so-called energy trilemma determines the need to balance between energy security, equal resource accessibility and affordability and environmental sustainability.  
- The choice of the RES technologies should be capable to assure a due time, cleaner, population centered and sustainable transition at national and regional levels. | [62] |
| 2.  | Socioeconomic factors driven by social movements and public opposition | - The reality exists in communities rather than in the turgid concepts.  
- The supporters and community leaders could work for common objectives, but this collaboration is preferably established at the beginning and lasts throughout the entire process.  
No two social communities are alike, but if they coexist and work in common coal regions, their collaboration can promote and even reinforce the transition of the entire region.  
The influenced socioeconomic branches require sustainable and realistic (short- and long-term) solutions involving action plans for concomitant decarburization and reinvestment, alongside overwhelmed re-employment strategies for the affected population. | [51,72,73] |
| 3.  | Cultural particularities and the locally adopted political philosophy | - The transition policies in carbon-intensive regions vary from country to country and strongly depends on the following key criteria: the dominant energy carriers, existing infrastructure, involved actors, chosen tactics, etc.  
- The energy transition policy and practice vary from country to country, being greatly affected by the country’s democratic culture.  
- The key players, shaping the population’s opinion and opposition/acceptance of the transition implementation are as follows: local governments (often including the military authorities), public and private organizations (e.g., energy and mining industry, metallurgy and other heavy industry sectors), nongovernmental organizations and international pressures.  
The national cultures determining the energy and climate pathways are easily cultivated by the affordable technologies, the economic dependency on fossil fuels, the state involvement in the energy and mining industry, etc.  
Modeling the implementation of good policy practices is generally helpful but insufficient to eliminate the emissions gap.  
- The international pressures are seen as the most promising way for policy changes in carbon-intensive countries regarding the coal phaseout.  
- The pressure of the free market competition as the regulated segment gives way to the full market liberalization.  
- The implementation of the EU policies contradicts the demands of the electorate for secure employment and affordable electricity prices. All this is usually translated to a continuous delay and partial policy implementation of the just transition.  
- The energy injustice in terms of the mismanaged, opaque and corrupted policy framework is the key factor undermining the long-term viability of the energy transition.  
- The willingness to pay for renewables in Bulgaria was found positively linked to the higher level of education and the earlier age of respondents of a recent sociological study. | [68,70,71,74,17,19,20,75] |

Mayer [73] and Feng [76] stated that supporters and community leaders work for common objectives and can be cultivated and planted at the beginning and through the entire process. Jermain et al. [51] extracted the lessons learned from the coal transitions of several regions in China, the EU, the UK and the USA based on [68,77–79]. The authors confirmed that besides the efforts achieved, a clear gap between the commitments and ac-
tions on the transition is observed worldwide. Baptista et al. [74] summarized the good practice policies capable of bridging the emissions gap in the major emitting countries. The authors implemented the good policy practices of 11 integrated assessment models (IAMs) for Australia, Brazil, Canada, China, the European Union (EU), India, Indonesia, Japan, Russia, South Korea and the United States, as these countries have been considered capable of providing the least costly low-carbon scenarios up to 2050. As a global result, they confirmed the essential roles of the good policy practices for each of the investigated regions, but it was seen as rather insufficient to eliminate the emissions gap. The same authors further proposed that the rich economies should synchronize their activities towards a successful energy transition and limit global warming to fewer than 2 °C. A recent analysis [80] discusses the political and economic obstacles in achieving clean energy in 15 countries, exploring the difficulties at a national level for each case study. An important conclusion by [51] is that any research topic should not underestimate the role and value of the so-called social intermediates. According to these authors, no two communities alike can be determined, but if the communities are located in common coal regions, their collaboration can promote and even reinforce the transition inside the geographic region.

4. Need for Plausible Energy Transition in Bulgaria

4.1. Coal Production in Bulgaria

Lignite is the main locally available energy carrier in the Republic of Bulgaria. In the last decades, the national coal deposits have been thoroughly investigated [81–84] and characterized [84–87], along with the emissions of hazardous byproducts [88–93]. Over the decades, coal has been revealed as being capable of ensuring the national energy system security upon request. The complex Maritsa Iztok, located southeast of the country’s territory, is the largest coal mining and power generation center, being in operation for about six decades [19]. This basin has proven available reserves of over 1450 million tons, having a long-term potential for the development of mines and the extraction of coal at least for the next 50–60 years. The major mining companies are Maritsa Iztok, Beli Breg, Stanyantsi and Kanina Section, in the town of Pernik, but the Maritsa Iztok Mining Complex (MIMC) contributes over 95% of the total production of lignite in the country [31,94]. Coal provides about one third of the gross power generation in the country. Recent EUROSTAT statistics [29] shows that in 2021, the estimated consumption of brown coal (manly lignite) in the EU was 60% less compared with 1990. During the 21st century, more that 90% of this fuel has been used for electricity production. Accordingly, overall, 28 million tons of coals were mined in 2019, whereas 95.6% of the total was used for the production of electricity and heat, 3.8% for briquette production, 0.1% for heating the population and 0.5% for the so-called personal needs of the mining enterprises.

The carbon emission allowances that any conventional power plant must purchase in order to operate directly affects the cost of the generated electricity. In February 2023, the price of the permits in the European Union’s carbon market reached EUR 100 per ton of CO₂ for the first time [95], whereas according to the forecasts from 2019, an emission price of 50 EUR/ton was expected to happen by 2030. This sharp increase in the prices of quotas requires the adoption of rapid but adequate political, technological and strategic solutions, through which the country’s energy security can still be preserved, for the issues regarding cleaner energy, the just transition philosophy as well as the overall socioeconomic factors in the largest national energy industry complex.

4.2. Coal Share for Electricity Production in Bulgaria

The Republic of Bulgaria has a diverse electricity production mix [31]. The national energy policy aims at guaranteeing the independent and sustainable development of the energy sector in line with the recent legislation. In 2022, the available capacity of the Bulgarian electricity system was 8300 MW [31,94]. The largest power generation capaci-
ties are at the Kozloduy nuclear power plant (KzNPP), having 2080 MW of the total installed power, and the condensing thermal power plants (for simplicity in the text, these power plants were denoted as CFPPs). Most of the large-scale CFPPs are located at the Maritsa Iztok Mining Complex. The total installed capacity of the major Bulgarian CFPPs (Maritsa Iztok 2, Kontur Global Maritsa Iztok 3 JSC, EI I EU-3C Maritsa Iztok I and Bobov Dol) is 3848 MW [96]. The largest CFPP in Bulgaria, Maritsa Iztok 2, currently consists of eight power generating units (with an installed capacity up to 1620 MW), and all of them are equipped with flue gas desulphurization (FGD) installations, proving an efficiency of over 98% [96]. The responsibility for covering the changes in the load in a 24 h and seasonal mode is attributed mainly to the large hydroelectric and pumped-storage plants.

The combustion of fossil fuels still plays a respectable role in the national power mix, especially during the winter season (see Figure 1). Between 2020–2022, about one third of the country’s gross electricity was produced from the sector [8,94], while during the first half of 2023, the share of electricity produced by RESs (merely from photovoltaic providers) increased by 49% in comparison to the same period in 2022 [8]. Over decades Bulgaria was a regional net electricity exporter, while Romania, Greece and North Macedonia [97] used to be the biggest importers [8,53]. However, solar and wind energy are already playing critical roles, especially in the energy transition process. The Greek government demonstrates a strong will to soon play the leading role in the sector within Southeastern Europe [98].

To achieve the carbon neutrality goals, the Bulgarian CFPPs need to be either retrofitted, transformed or replaced with RESs by 2050 [4,32–36]. According to [19], some countries such as Bulgaria will have to nondeliberately implement the coal phaseout as a result of the adopted EU policies. Thus, huge decarbonization investments in the energy sector need to be considered [35], such as tripling the renewable energy production by 2026, developing a large electricity storage capacity, significantly lowering the GHG emissions of the sector, working for a coal phaseout, etc. [53], but still, there is a long way to go. At present, it is more than ever of crucial importance to determine the general transition objectives and action plans. Thus, a huge framework is typically required to build on a business–academia–government cooperation beyond the political battles. Such a framework should be based on detailed technological and economic assessments on a regular basis, envisaging updates of the key technological and economical perspectives, solutions and even some of the commitments, in case of a justified necessity. Cooperation is also needed with the affected social and business communities throughout the entire process, aiming to consider all kinds of very particular territorial and other needs and prospects for a fair and plausible transition.

4.3. Prospects for Limited Uses of the Bulgarian CFPPs

Central and Eastern Europe have still a long way to decarbonization and a just transition [46,99,100], especially in the carbon-intensive regions [98,101], although these are not the only countries experiencing difficulties in transitioning the base capacities towards a gradual reduction in energy production from CFPPs. A sociological study by Rösch et al. [102] reports challenges and success factors for a just transition in seven of the EU countries from the region (Republic of Bulgaria, the Czech Republic, Estonia, Hungary, Poland, Romania and Slovakia). The authors apply a qualitative–quantitative methodological approach to conduct a survey, translated into seven languages, highlighting the following general challenges: (a) lack of transparency; (b) capacities on local/regional and national levels; (c) lack of access to good and up-to-date information; (d) lack of political will, power and division among civil societies as well as several success factors: (i) starting early; (ii) the need for persistence; (iii) using the media to build pressure; (iv) insisting on compliance with EU rules and regulations; (v) picking your battles; and (vi) networking and amplifying/supporting local efforts. Other research groups [51,68,70], emphasize similar issues. This region is still recovering from the consequences of contrasting political, social and economic transitions, which have been carried out over
three decades (e.g., the compromised postsocialistic privatization of the state properties). Therefore, each of the countries deserves particular attention due to their very particular socioeconomic, technological and political environments. Each society requires a fair and realistic transition policy and technology and implementation plan, capable of ensuring a dignified existence for the populations in the affected regions.

The roadmap for the reduction of Bulgarian GHG emissions in comparison to those in 1990 [103] draws attention on the expected CO₂ reduction from the sectors of energy, industry and transport (including CO₂ from aviation, except from maritime transport). According to the EC 14 legislative acts (Fit for 55 package), the increased climate target of at least 55% (2030 compared to 1990) shall be achieved considering the need for contribution from all sectors [32,103]. According to Zartova et al. [37], the main risks in a politically dynamic situation would be a spontaneous decision for closing power generation and mining industries without having a definite strategic framework capable of dealing with the economic, social and environmental consequences of the transition. The recent territorial plan for Stara Zagora [104] reports that the just transition could affect up to 80% of the jobs in the coal mining and power generation companies, as well as more than 80% of the total number of indirectly affected jobs in the influenced NUTS 3. The authors in [37] propose the following: (a) a technology transfer; (b) the establishment of local (e.g., national) and regional or even global supply chains, guaranteeing sustainable employment and requalification at the workplace; (c) the reinforcement of academic and business cooperation; and (d) the provision of conditions for developing clusters of support activities, small businesses and research centers involving the administrative authorities of the municipality’s administration.

Short- and medium-term measures for coal-fired stationary energy sources (e.g., the largest CFPP in the MIMC), could provide a tolerable allowance for the limited operation of the existing energy infrastructure in conditions of proven invulnerability. Such measures are expected to play an accelerating role in the just transition process, mainly because their main purpose is to provision a smooth energy transformation (political, socioeconomic and technological) while stabilizing the energy grid. However, the need and extent of such measures must be based on a validated evaluation [66,105]. Glensk and Madlener [106] developed a decision-making tool for a real options analysis of the enhanced flexibility of existing CFPPs. The study in [107] evaluated an existing lignite-fired power plant in Germany, and in particular, the influence of the CFPP’s value by a series of technical and economic variables (including subsidies). The authors proposed a four-step approach to determine the optimal operation strategy to an investment/disinvestment decision. Their case study proposed that the existing CFPP can only be operated profitably without any modifications until the end of its technical lifetime and under persistent subsidies. The same authors also discuss the profitable investments in a number of flexible retrofit measures, the ranking of which is found to depend on the costs and benefits related to the retrofitting measures, their implementation time, etc. In view of these observations, the limited operation of Bulgarian CFPPs was also discussed, based on officially published research and analyses. Most of the reviewed measures concern the typically used power units in the power plants located at the MIMC.

4.3.1. Efficiency Optimization and Emissions Control

The environmental control of any power plant requires the optimization and/or improvement of its efficiency [108,109]. Grigorov [108] proposes an exergy and energy efficiency analysis of a (Bulgarian) lignite-fired steam boiler of type P-62. The study is carried out for boiler loads between 70% and 100%, using three different loads. Low-calorific fuels at each load are used (deteriorated 5525 kJ/kg, guaranteed 5945 kJ/kg and improved 6700 kJ/kg). Based on the so-called “fuel-product efficiency” method, the obtained exergy efficiency in the examined conditions is reported between 31 and 34%. A recent study of Totov and Ignatov [109] presents technoeconomic and environmental performance analyses of the same type of lignite-fired boiler (P-62). The authors confirm
that this is the most commonly used power unit in the sector nationwide. Currently, eight boilers of that type are in operation at the CFPP “Maritsa Iztok 2” and the CFPP “Kontur Global Maritsa Iztok 3”, usually organized in monoblocks with a steam turbine. The analyses presented in [109] are based on computational modeling, carried out using GateCycle [110]. The model is developed to evaluate the performance parameters of such power units in the range of \( N_{\text{e}} = 145 \) to 225 MW and proposes operating conditions capable of achieving sustainable unit efficiencies and stable pollutant emission factors, all while increasing the unit’s load.

4.3.2. Combined Cycle Operation of Lignite-Fired Power Unit with Gas Turbine, including Utilization of Carbon-Free Fuels

Power generation systems are generally different depending on the fuel characteristics. The idea of using a primary gas turbine (GT) for supplementing coal-fired power dates back a few decades [109–113]. Szargut and Szczygiel [114] studied the thermodynamic effects of four variants of installation of primary GTs supplementing a CFPP. The authors report an exergy loss analysis to identify the thermodynamically efficient schemes of a combined thermal system.

Focusing on the Bulgarian CFPP, Totev and Ignatov [115] modeled a combined cycle operation of a GT and conventional power unit of type P-62, utilizing Bulgarian lignite from the Maritsa Iztok Complex. The GT flue gases are fed to the combustion chamber of the power boiler to utilize its heat. The choice of the GT power is set to reflect the following assumptions: (I) the existing power unit preserves its independent operating mode; (II) the initial operating range of the lignite-fired power unit (from 145 to 225 MW) must be preserved; (III) no significant changes to the existing facilities at the power unit are expected. Furthermore, the model of Totev et al. [115] assumes three scenarios of GTs having powers of 20 MW, 35 MW and 75 MW at blocked high-pressure heaters. The authors propose an assessment of the technical and ecological parameters of the simulated steam gas cycle, confirming that (i) the presence of GTs does not impair the operability of the existing power unit, thus retaining its ability to work independently; (ii) the best performance is observed for a GT power of 37.5 MW, reaching 262.7 MW, while maintaining the operating range of the conventional unit (from 145 to 225 MW); (iii) the combined cycle efficiency of a lignite-fired and GT power unit increases on average by about 3.5%; (iv) the lignite consumption is reduced by 36.0 t/h at a maximum load, which requires less energy, e.g., for the unit’s own needs and (v) the CO\(_2\) emissions from the energy unit are also reduced by 7.45% at a maximum load to 10.98% at a minimum load, leading to reduced carbon allowance costs. However, natural gas supply is still an issue, and such a perspective could be considered valuable if such an energy carrier is locally available or is substituted (entirely or partially) with RESs.

The recent focus on cleaner energy carriers [1,4,7,41] places hope on carbon-free fuels. Considering a case of combined operation such as the above-described lignite-fired power unit (of type P-62) with a gas turbine module (37.5 MW, with stopped high-pressure heaters), where 30% of the gas turbine’s heat is obtained from H\(_2\) or NH\(_3\) combustion, one can conclude that (a) the carbon emissions generated by the power unit can be reduced, compared to the case where 100% of the heat in the gas turbine only comes from natural gas combustion; (b) the emissions of SO\(_2\) shall also be reduced, which is expected to result in additional savings, e.g., from limestone supply, as well as the reduction of the unit’s own needs for the preparation of limestone and its subsequent use in the desulfurization unit; and (c) the reduction of lignite consumption should reduce the emissions of carbon oxides, dust, mercury, fluorides, chlorides, etc., as well as the unit’s own overall energy needs. The work of Totev et al. [109,115] confirms that upgrading an existing CFPP is a well-established and approved measure to increase the power plant’s capacity and operational flexibility. This results in decreased CO\(_2\) and other GHG emissions, thus promoting the shift to low carbon [116] or even carbon-free fuels [117–119].
4.3.3. Electric and Thermal Power Cogeneration Utilizing Biomass

In the context of the zero-net CO₂ policy, the biomass and the pumped storage hydropower are expected to play important roles in keeping the grid stable. Biomass as an energy carrier is assumed to be valuable in regions with sufficient stocks of resources, especially where the potential carbon-free renewables like wind and solar energy is confined due to specific environmental concerns. In such cases, biomass could ensure power generation through manageable safety, sustainability, cost production and CO₂ reduction [38,39]. To reduce the transition costs, biomass can be fired in existing power units, modified to fire or cofire biomass under well-predefined conditions [40,120]. A popular example within the UK is the DRAX [121], promoted as the first company to reach zero carbon emissions by 2030. According to the same source, three general options for CFPP conversion are proposed: option 1, limited cofiring (<10%); option 2, significant cofiring (>10%); and option 3, full conversion to biomass (100%), where the thermal efficiency and electrical output shall be the same as for the coal-fired mode. The costs and complexity of the biomass implementation strategy are usually driven by the type of equipment, which is currently in operation for coal combustion, as well as the desired level of cofiring or a full conversion of the existing plant. The company guarantees having tested more than 350 types of solid biofuels and reports the white wood pellets as preferably burned at the DRAX [121]. Besides their reported achievements (proven technology, lower cost in comparison to the black pellets and being readily availability at the global market), the most significant disadvantages reported by the company are expensiveness vs. wood chips, the potential for having high dust content and specific storage requirements (not being weather resistant) and increasing CAPEX for storage build.

Recent studies propose biomass as “renewable” or “zero-net CO₂ emission solid biofuel”, but concerns still exists regarding the emissions of a variety of pollutants [122–124]. The biomass generation costs are often not competitive to those of fossil fuels as well as the electricity price in the free market. A recent study for Netherlands reported that biomass cofiring frequently requires subsidies [125]. The technical factors related to the fuel chemical composition, its production/supply chain and storage are usually the key drivers in estimating the possible transition costs. The fuel’s chemical composition determine the dimensions of the burner, which is typically designed for coal with a specific range of characteristics [126–129]. Thus, it drives the tube spacing and gas passage areas to mitigate slag and fouling, maximizes heat capture, etc. [129–131]. Because the biomass combustion process considerably differs to that of coal [123,129], the ash from the biomass is generally stickier and chemically more difficult to process [126–129]. Recent experiments [132–135] confirm that the cofiring mixing ratio can mitigate this but can cause problems with the available equipment if no measures are considered. Generally, increasing the ratio of the biomass cofiring mixture increases the need for customized equipment [135]. These and other factors directly affect the transition costs, because the original coal handling equipment is also designed for solid fuel with a specific calorific value, bulk density, moisture, ash content, etc., allowing it to be stored outdoors. Biomass is much lighter and has a lower energy density with a significant fraction of volatiles: this requires a larger transfer and storage area [136]. The storable volume might rely on the requirement for new processes and operational approaches, leading to just in time deliveries [137]. Higher levels of health and safety measures could be required when biomass is utilized, such as (i) respiratory problems during biomass transportation and handling, (ii) the risk of fire and explosions, (iii) dust removal, etc. Besides the fuel composition and material handling equipment, there are numerous technical factors driving up the transition costs, but globally, the logistic chains determine the solutions and the associated risks along with the type of storage required throughout the logistics chain [39,40].
Analysis (CAPEX + OPEX) of Biomass Supply and Cost of a Power Unit of 300 MW, Adapted to Operate with 100% of Biomass: Feasibility Study of the Power Unit

Currently, the Bulgarian CFPP, operating with low calorific coal (mostly lignite) are facing the following question: Would it be worth it to at least partially replace the lignite mined in the MIMC with alternative fuels, applying measures such as the co-combustion of coal and biomass, 100% biomass, the combustion of green hydrogen or green ammonia or hybrid solutions?

The present analysis aimed at estimating the operation of one power unit of 300 MW at the CFPP 3 Contour Global with 100% biomass, e.g., cultivated Paulownia. The analysis was based on the following assumptions: The annual usability of the power unit with a nominal power of 300 MW was about 4300 h (mainly during the heating season, as in the rest of the year, the energy market will offer enough green energy at prices below 40 EUR/MWh). An average annual load of 90% was assumed, with expected power generated from the power unit of about 1.16 TWh. Paulownia is a rapidly growing biomass due to its C4-pathway of carbon fixation, i.e., it captures CO₂ through the C4 type of photosynthesis [138,139]. The uniqueness of this tree genus is that almost 100% of its mass (stem, branches, leaves and flowers) is utilized, and in addition to the supply of wood and biomass, there are many auxiliary ecological benefits [140,141]. Paulownia wood has a low density of 0.208-0.282 kg/dm³ [141–143], and its plantation in urban environments or industrial areas with heavy pollution leads up to an 80% reduction in air pollution [144]. A large number of reports confirm that Paulownia is very suitable for combined production, the so-called forestry and agro crops [144–147]. The deep root system of the Paulownia species allows the planting of agricultural crops with more superficially located roots in the inter-rows.

In the present study, the gradual planting of Paulownia was considered on the reclaimed coal mining sites at the MIMC. The planting of 300 trees per acre (15 rows multiplied by 20 trees in a row) was assumed; thus, the estimated distance between the rows and the individual trees was 2 and 1.67 m, respectively. At this planting density, a harvest cycle of 3 years is foreseen, where only the first harvest takes place in the third year. The root system of the plants allows for seven harvests. In this mode, the expected annual biomass yield is about 5 tons per acre, with Paulownia chips containing about 50% moisture. The harvest of the Paulownia should be carried out by harvesters, and the yielded biomass should be used for the production of wood chips of a certain size. The obtained chips can be transported with trailers to a storage site at the CFPP 3 Contour Global, where the chips can be naturally dried for a period of about 45 days. An additional drying is also possible, e.g., immediately before burning in the combustion chamber of the boiler of the power unit.

Based on these assumptions, the required amount of biomass for the annual energy production of 1.16 TWh from the proposed power unit was estimated. The expected efficiency of the power unit with a capacity of 300 MW using Paulownia chips was 32%. The mean HHV of one kilogram of this type of chips with a 10% moisture content was about 5 MWh/t [142]. The expected yield of the wood chips (with 50% moisture) was 5 tons per acre. After drying, the moisture content can be reduced to 10%, which will result in a reduced mass of the chips of up to 3 tons per acre. For an annual energy production of 1.16 TWh from the power unit, the following amount of chips will be required: 1.16 × 10¹² Wh divided by the product of 0.32 and 5 × 10⁶ Wh/t, which equals 725 thousand tons of wood chips with 10% moisture or 1208 thousand tons with 50% moisture.

An annual productivity of Paulownia chips of 5 tons per acre requires the availability of an area of 1208 thousand acres divided by 5 t, which equals 242 thousand acres, e.g., an area with rectangular dimensions of 15 km multiplied with 16.2 km, which represents 0.218% of the country’s territory. At this scale of production of wood chips, the annual costs per acre are expected to be around 180 BGN/acre (at 230 BGN/acre for an area of 100 acres). These were the costs for growing the Paulownia trees (fertilizing, watering, hoeing and mowing), plus the costs for harvesting the biomass and the wood chip transportation.
to the CFPP 3 Contour Global. At an annual yield of 3 tons per acre, the estimated cost for Paulownia chips with a moisture content of 10% was about 60.7 BGN/t. Because the estimated efficiency of the power unit operating with chips (HHV of 5 MWh/t) was about 32%, the produced electric energy can be calculated as follows: \( 5 \times 10^6 \text{ Wh/t} \times 0.32 \), which equals 1.6 MWh/t. Thus, the estimated fuel cost for power generation using the 300 MW power units, mainly during the heating season (assuming zero CO\(_2\) quotas), was 60.7 BGN/t divided by 1.6 MWh/t, which equals 37.9 BGN/MWh.

The process of cultivating Paulownia requires exceptional technological skills [145,147]. The present analysis does not involve a detailed soil analysis, which is generally needed to evaluate the soil characteristics of any territory selected as a Paulownia field. One of the most critical parameters is the soil acidity, for which the value should be pH > 5, generally between 5 and 8.9 [139]. Other growth condition factors concern the water supply, ambient temperature, the soil’s clayey content and others. For instance, the tree’s root system cannot develop its depth with high clayey fractions in the soil.

### Biomass Supply and Cost Analysis (CAPEX + OPEX) of a Power Unit 210 MW

The present analysis aimed to determine the cost of electricity produced by an existing 210 MW power unit (available, e.g., in the CFPP “Maritsa Iztok 2”), when considering being converted to operate with 100% wood chips from Paulownia trees with a moisture content of 12% and an HHV of 4.5 MWh/t at an efficiency of the power unit of about 31%. The cost of the produced electricity \( (C_{ee}) \) was estimated using the following equation (in-house study):

\[
C_{ee} = C_{fuel} + C_{em} + C_{l.c.} + C_{r+c} + C_{depr} - C_{desulf},
\]

where

- \( C_{fuel} \): the fuel costs (estimated to be 60 EUR/ton of wood chips by 2025),
- \( C_{em} \): the emission costs (which is assumed equal to zero, since wood chips are defined as a carbon neutral fuel),
- \( C_{l.c.} \): the labor costs,
- \( C_{r+c} \): the annual costs for repairs and consumables,
- \( C_{depr} \): the depreciation costs, and
- \( C_{desulf} \): the total annual costs (which shall be reduced due to eliminated flue gas desulfurization).

Based on the above-described assumptions, the fuel costs \( (C_{fuel}) \) for 1 MWh of produced energy can be calculated through the following equation:

\[
C_{fuel} = \frac{60\€/t}{4.5 \text{ MWh/t} \times Eff.} = \frac{60\€}{(4.5 \text{ MWh} \times 0.31)} = 43 \€/\text{MWh}
\]

The estimated annual production of Paulownia chips (with 12% moisture and a price of 60 EUR/ton) from an area of one acre (planned to be planted on the recultivated areas of the MIMC) was about 3 tons.

The labor costs \( (C_{l.c.}) \), reduced to 1 MWh of electricity produced, were determined assuming that the reconstructed power unit with a capacity of 210 MW has about 150 employees with an average annual salary (including all social security, health and other assurances payments) of about 30 thousand EUR/year (by 2025). The estimated total annual costs for labor were about EUR 4.5 million. Assuming that the power unit operates on average for 7000 h a year with an average load of 90%, the annual energy produced \( (E_{annual}) \) will be:

\[
E_{annual} = 210 \text{ MWh} \times 0.90 \times 7000 \text{ h} = 1.323 \times 10^6 \text{ MWh} = 1.323 \text{ TWh}
\]

Converting these costs to 1 MWh leads to:

\[
C_{l.c.} = \frac{4.5 \text{ million}\€}{1.323 \times 10^6 \text{ MWh}} = 3.4 \€/\text{MWh}
\]

The annual costs for repairs and consumables \( (C_{r+c}) \) were determined under the following assumptions: (a) the current repairs are carried out every 3 years (about 20 thousand working hours), considering repairs on both the gas and steam turbines and all
other equipment: about EUR 4 thousand; And (b) the major repairs, every 6 years (about 40 thousand working hours): about EUR 9 thousand. Thus, the reported annual costs of current and major repairs were obtained as EUR 2.83 million. Following this, the reduced annual costs per 1 MWh of generated power were as follows:

\[ C_{r+c} = \frac{2.83 \text{ million } \varepsilon}{1.323 \times 10^6 \text{ MWh}} = 2.14 \frac{\varepsilon}{\text{MWh}} \]  

(5)

The depreciation costs \(C_{\text{depr}}\) were determined according to an expert assessment [147]. The estimated investments needed for the reconstruction of the power unit from coal to biomass were EUR 20 million. It was also assumed that these funds will be provided through a bank loan, with an interest on the remaining principal of 4% and a repayment term of 10 years, i.e., the owner must return EUR 24 million to the bank over a period of 10 years or an average of 2.4 million EUR/year. Then, the \(C_{\text{depr}}\) is reduced to 1 MWh of the produced power were as follows:

\[ C_{\text{depr}} = \frac{2.4 \text{ million } \varepsilon}{1.323 \times 10^6 \text{ MWh}} = 1.81 \frac{\varepsilon}{\text{MWh}} \]  

(6)

It was tentatively assumed that due to the elimination of flue gas desulfurization, the overall costs can be reduced to about 1 EUR/MWh.

\[ C_{\text{desulf}} = 1 \frac{\varepsilon}{\text{MWh}} \]  

(7)

Then, the cost of the produced power (without profit to the investor (owner) and without unforeseen costs) can be calculated as follows:

\[ C_{\text{e.e.}} = C_{\text{fuel}} + C_{\text{em}} + C_{\text{l.c.}} + C_{r+c} - C_{\text{desulf}} = 49.2 \frac{\varepsilon}{\text{MWh}} \]  

(8)

After the reconstruction investments are paid off, i.e., in a period of 10 years, the estimated energy production cost was \(C_{\text{e.e.}} = 45.04 \text{ EUR/MWh}\).

In summary, the estimated amount of chips required for the annual production of 1.323 TWh of electricity from a 210 MW power unit was as follows: 1.323 TWh divided by the product of 0.31 and 5MWh/t, which equal 883 thousand tons of chips (with a 12% relative moisture content or 1422 thousand tons with 50% moisture). The production of this amount of Paulownia chips, at an annual productivity of 5 tons per acre, requires an area of 284 thousand acres, e.g., a rectangle of 17 km times 17 km, which represents about 0.26% of the country’s territory. For comparison, in Germany, about 24 thousand km\(^2\) (6.7% of the country’s territory) are used for growing energy crops [148], and the use of biomass and, in particular, biofuels, has gradually been increasing during the last decade [149,150].

5. Conclusions

The present work aimed to (i) identify the critical gaps and key factors found to be capable of guiding the transition process and influencing its dynamics and (ii) open a discussion on the possible technological perspectives for reducing the share of coal use and carbon emissions from the large Bulgarian CFPPs, aiming to sustain the just transition and the energy balance. The present review was based on comprehensive analyses (see Section 2) of freely accessible data, such as research and open media articles, officially published field reports, legislative and strategic acts as well as validated statistical data (Table 1).

The progress of the just transition, its rejection and acceptance at the national and the international scene provided the needed overview of the present status of the process of implementation (Sections 3.1–3.3). Recent research and statistics show the roles of coal production and combustion for power generation and manufacturing worldwide. A large number of CFPPs are still in operation and are expected to still be in the coming decades, whereas more than one hundred CFPPs are planned for construction world-
wide. Huge efforts, funds and research potential are being invested in new generation technologies. Nevertheless, recent studies have confirmed that the low level of the transition implementation could question it. Moreover, the related climate change mitigation measures would have to eventually be considered alongside the reactions and costs for climate change adaptation.

The identified critical gaps, known for being capable of navigating the just transition, were extracted from the literature together with the key factors influencing the process’ dynamics. The data were summarized in Table 2, Section 3.3. The transition process in the carbon-intensive regions/countries (relaying on fossils for more than one third of their energy mix), is still uncertain. The main reason is in the lack of clearly identified measures towards sustainable, long-term solutions, capable of ensuring the national energy system and security, commercial interests, socioeconomic status and ability to stimulate the economy of the affected countries or geographic regions. The present literature review allowed for the determination of key policy development criteria for carbon-intensive regions as follows: the dominant energy carriers, existing infrastructure, involved actors and choice of strategy.

The need for a plausible energy transition in Bulgaria requires up-to-date data for coal production, consumption, etc., for power generation (Sections 4.1 and 4.2), in line with the key policy criteria (see previous paragraph). A Bulgarian perspective for coal share and carbon emission reduction options for power generation during the energy transition was discussed (Section 4.3). The proposed measures were based on the published research and technoeconomic analyses. The suggested coal share reduction for power generation considers the typically used power units at the largest CFPPs (300 MW and 210 MW), located at the MIMC. The analysis of biomass utilization, regarding the same type of power units, was suggested, considering the use of 100% solid biomass chips. The estimated costs, unit efficiencies and power generation were discussed along with the evaluations on the land use, ensuring a given annual productivity of wood chips from fast growing plants, e.g., Paulownia.

Besides the efforts achieved and the ambitious policy, the implementation of technological and socioeconomic measures is needed more than ever, while renewables still have long way to go for the complete substitution of fossil fuels in power generation, transport and manufacturing. Considering the limited number of available studies related to the Bulgarian conditions and circumstances, the present observations need to be further validated through interdisciplinary research (empirical and theoretical, as well as modeling) involving the related technical, social, environmental and policy factors.

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