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An Emissions Offset Strategy to Accomplish 2 °C Long-Term Mitigation Goals in the European Union

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Abstract: Regional carbon budgeting in policymaking is underutilized despite its importance for achieving global climate goals, particularly the Paris Agreement's target of limiting global warming to 2 °C by 2050. In this work, we present the model PLEDGES, a novel system dynamic-based simulation tool that focuses on the European Union region to equitably distribute carbon budgets among the Member States and activate emissions offset strategies to manage unexpected deviations from the EU27 carbon budget. The emissions trading dynamic is based on the "Gains from Trade" approach. The tool also calculates the cost of the offset strategies based on the use of the abatement cost curves for the Member States. Using a case study of the recent increase in carbon emissions in Germany in response to reduced Russian gas supplies, different emissions scenarios for Germany's quota redistribution among the Member States are explored. The study reveals varied cost implications of between 30–60 Eur/ton CO_{2eq} to offset the emissions increase across other Member States. Final recommendations include promoting cross-border collaboration at the EU27 level.

Keywords: carbon budget; climate mitigation; green deal; abatement cost curve; gains from trade

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1. Introduction

A carbon budget is a framework utilized in climate policy to establish equitable and efficient emissions reduction goals. It assesses an upper limit of total net anthropogenic carbon dioxide (CO_2) emissions that is associated with a certain probabilistic temperature outcome related to global warming. The concept of a carbon budget has been defined and evaluated on a global scale [1–4] but only a limited number of countries worldwide have begun to explore its application [5] to establish cumulative emissions constraints at the regional level as opposed to setting carbon reduction targets which do not account for the total amount of carbon emissions that result over a period of time. Local carbon budgeting helps policymakers and stakeholders align global climate targets with their regional immediate and long-term policy goals and design successful climate actions. Setting endpoint targets like net zero by 2050 without a defined carbon budget can disconnect cumulative emissions from the global carbon budget and compromise the achievement of the 2 °C global warming target committed by the Paris Agreement, as a temperature limit concerns the cumulative emissions stocked in the atmosphere. To fill this gap, the EU-funded Pledge Limits Evaluation for Decarbonization: Goals of EU27 Strategy (PLEDGES) project [6] presents an innovative simulation tool aiming to comprehensively model the allocation of carbon budgets among the Member States of the European Union (EU27). Unlike other tools such as Contraction and Convergence [7], C-ROADS [8], and World Climate [9], which focus on aggregate regions, PLEDGES provides detailed insights into each country's carbon budget and its impact on mitigation actions.

PLEDGES is set to achieve the objectives outlined in the Green Deal [10] including reducing emissions by −55% from 2005 levels, attaining EU carbon neutrality by 2050, and meeting the 2 °C target. The EU faces barriers and opportunities for decarbonization across its member countries, but existing policies mainly focus on emission reduction targets. For

instance, the new Emissions Trading System [11] (ETS2) which aims to reduce emissions from fuel combustion in buildings, road transport, and additional sectors, (separate from the existing EU ETS), still focuses on a reduction rate of −42% of emissions by 2030 compared to 2005 levels. The Effort Sharing Regulation [12] (ESR) increased by at least 40%, compared to 2005 levels. Both of these measures do not consider constraints in cumulative emissions.

The PLEDGES model innovative approach provides EU policymakers with a tool to tailor climate mitigation policies at national levels based on countries' effort-sharing approach. The PLEDGES tool is tailored for the EU geographical area, but, in future works, it can be easily redesigned for other geographical regions.

After evaluating the carbon budget for the EU27 [13–16] the PLEDGES tool can handle potential deviations from this budget caused by unforeseen increases in emissions in a Member State (MS). PLEDGES can then dynamically redistribute any increases in emissions to other MSs in an efficient manner. For example, due to geopolitical tensions in Ukraine, Germany resorted to coal power plants to lower its reliance on gas and ensure national gas supply, with the consequence of emissions increase due to the change in the supply energy mix. The PLEDGES approach involves assessing the potential of each MS in trying to offset the increase, with the final purpose of keeping the EU27 budget within the established limit.

In distributing the responsibility for emissions reduction and in planning a strategy for compensating emissions, the model adopts "effort-sharing" principles like "inertia", which mirrors historical emission trends, "economic capability" that allocates budgets according to countries' economic wealth per capita, and "decoupling" which assesses countries' leadership in climate action based on current efforts to tackle climate change [17].

The PLEDGES tool starts from the initial configuration of nationally allocated carbon budgets and the distribution of possible decarbonization pathways for each country. The tool allows for the assessment of emission trading opportunities or needs among the Member States if any deviations from the established decarbonization target should arise. In this case, each MS is asked to recover the unexpected increase in emissions while minimizing the total cost of the compensation actions within the EU27. Indeed, the offset strategy relies on a "Gains from Trade" [18,19] dynamic, with the aim to exploit the advantages of recovering emissions surplus across the MSs due to their different characteristic, e.g., geography, natural resources, or established infrastructure.

As an example of PLEDGES application in the real world, we conduct simulations to estimate the cost of an EU27 compensation strategy in the short-term scenario introduced before, in which coal power stations are activated in Germany, specifically aimed at decreasing its dependence on gas, in response to reduced Russian gas supplies.

The paper is organized into the following sections: Material and Methods which illustrate the model structure and characteristics; Results and Discussion, where the hypothesis of simulations is described and discussed.

2. Materials and Methods

PLEDGES has been designed by applying System Dynamics (SD), the method at the foundation of "The Limits To Growth" study [20]. SD [21,22] offers a systematic method for analyzing and understanding complex systems, typically characterized by interconnected variables influenced by feedback loops. These systems' evolution over time is usually described through sets of differential equations. SD software allows for representing and solving the equations by a visual representation of stocks and flows, which allows for setting up the system dynamics intuitively even for non-experts. SD is frequently used for assessing the feasibility of theories and scenarios across interdisciplinary domains [23,24].

The PLEDGES model is developed with the SD software Vensim Professional ® (2018) [25] installed on a DELL Inspiron 5502 Intel i7 HD 1000 GB and RAM 16 GB.

An early version of the model's aims and structure with a detailed description of the construction process, key variables, parameter settings, and data sources has been discussed at Simulation Workshop 23 (SW23) published in the Conference proceedings and reported in the Supplementary Materials link. An open-source version of the model

in Vensim Reader and the user guide are available as Supplementary Materials at the link provided at the end of the paper.

2.1. Emissions Trading

The present section presents the implementation of the PLEDGES tool of emissions trading based on the Gains from Trade dynamics. Gains from Trade refers to the benefits that can be achieved through the exchange of emission allowances or credits among different countries (or other entities) participating in a cap-and-trade system. Governments (here represented by EU27) set an overall cap on the total amount of emissions allowed that is represented by the EU27 carbon budget, allocated by MSs. The cap is gradually reduced over time to meet environmental goals, here represented by achieving net zero by 2050 while containing global warming within 2 °C. MSs can buy and sell these allowances (or quotas) among themselves with the aim that the total EU27 budget is not surpassed. Quotas trading is governed by supply and demand dynamics, which is the relationship between the quantity of a commodity that producers wish to sell at various prices and the quantity that consumers wish to buy. This relationship serves as the primary framework for establishing market prices and it involves a demand curve, which slopes downward to reflect consumer demand, and a supply curve that slopes upward, signifying the producer's willingness to supply. The equilibrium point in this market is the juncture at which the demand equals the supply. In this context, the commodities to be traded are the compensation quotas distributed to the MSs according to the effort-sharing principle. The supply and demand are determined by each MS's attitude to sell or buy their quotas. This attitude is established through the MS Abatement Cost [26], designed in a look-up table.

Figure 1 reports a schematic representation of the latest version of the PLEDGES model. The structure is organized in a TOP window for EU27 carbon budget management including the market dynamic, and in 27 Member States windows which host the MS emissions abatement cost curve (MAC) in lookup tables.

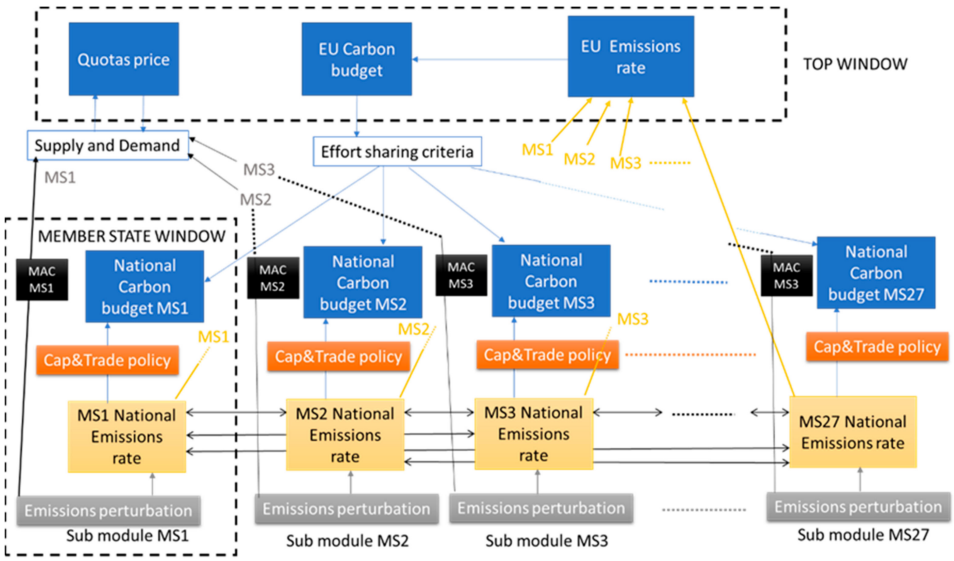

Figure 1. The PLEDGES model structure: TOP window deals with the EU27 carbon budget management and the Gains from Trade dynamics; Member States' windows deal with carbon budget distribution, the simulation of unexpected emissions increase (emission perturbation), and the MS abatement cost curve (MAC) tools.

In Figure 2, we show the model for price dynamics. Quotas' price depends on price change, price change rate, and indicated price. The price change rate is supposed to be a measure of how quickly demand and supply can change based on a price change (commonly indicated as elasticity). The higher the value, the faster the price changes towards its equilibrium value.

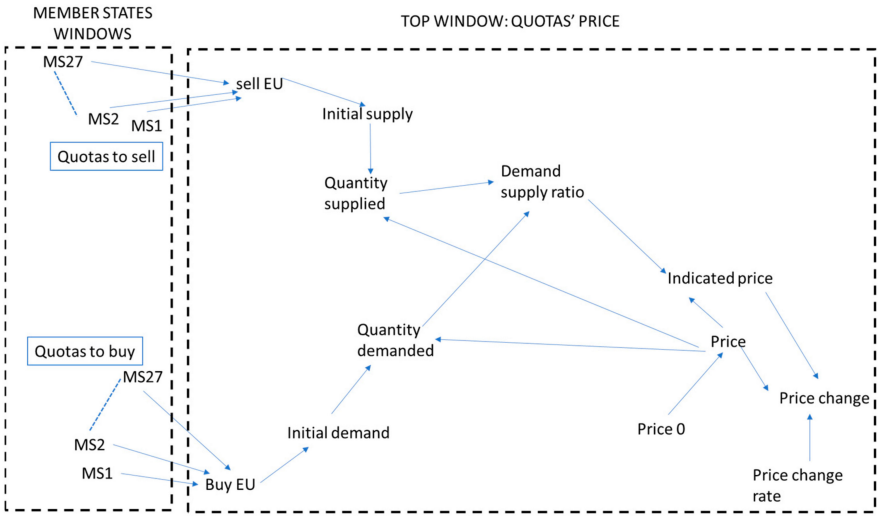

Figure 2. PLEDGES model Gains from Trade dynamic connections implemented at the EU level.

To illustrate the model dynamic, we set the elastic as unitary meaning that a given percentage change in price leads to an equal percentage change in quantity demanded or supplied. The indicated price assesses an initial price defined by the price multiplied by the "demand-supply ratio". If the initial demand is higher than the initial supply, the market is featured for "sellers", and vice versa for "buyers". From the above, it follows that quantity demanded depends on initial demand and price, and supply depends on initial supply and price.

The model group related to the abatement cost curves implemented in the MSs window is detailed in Figure 3. As a limit, abatement cost curves are implemented statically, so the price change will occur, in the short term, based on the exploitation of the already available abatement measures.

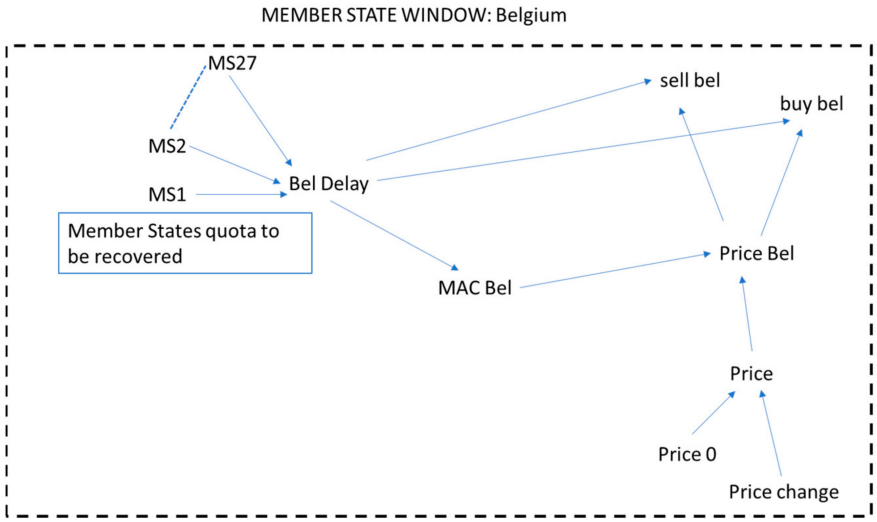

Figure 3. Example of Member State window—Belgium variables connections with a focus on the implementation of the MS abatement cost curve.

If the initial P0 for the emissions quota is set at the EU27 market level and the quota to be recovered (set in bel delay variable) from MSi (i = 1 to 27) results in a price lower than P, it implies that MSi can abate this quota at a lower cost than the market, enabling it to sell quotas to cover emissions elsewhere (sell bel). Vice versa, if MSi can abate emissions at a higher cost than the initial EU27 price, it will purchase quotas from other MSs whose abatement cost allows for a cheaper solution (buy bel). The quotas to be bought or sold for each MS are summed up in the top window (Figure 2, buyEU and sellEU): all the quotas

that can be sold across the MSs constitute the "supply", while all the quotas to be bought represent the "demand" which measures the cost of reducing one more unit of pollution. Then, the user makes the initial price evolves, which implies the spanning of the abatement costs within the MS window, until supply quotas offset demand quotas, establishing the new price at which the adopted compensation can be achieved across the MSs.

2.2. Assessment of the Abatement Costs for Each Member State

The abatement cost represents the expense associated with an action aimed at decreasing GHG by 1 ton. This concept underlies the creation of the well-known marginal abatement cost curves, which are largely used in the context of policymaking for their capacity to rank options to reduce emissions from the lowest to the highest cost. However, the methodology is fundamentally "marginal" in nature, it is formulated to address incremental emissions reductions and for this reason has several limits [27], including assuming that cost remains constant regardless of the pace of options implementation (e.g., transitioning all vehicles to electric vehicles over 10 years is more costly than doing so over 30 years). When the aim is to reduce emissions to nearly zero, we cannot overlook the challenge posed by hard-to-abate emissions. Some recent studies explore long-term marginal abatement cost curves [28,29] intending to take into account the interactions between sectors and technological changes and seek to minimize the total cost of the transition.

Nevertheless, the potential of the abatement curves approach remains of large interest [30], especially for modeling and simulations when such kinds of curves can be easily implemented and updated employing the use of lookup tables.

In the context of the present study, we faced the further challenge of gathering abatement cost curves for all 27 MSs. There are products on the market that can provide such curves for EU27 and other countries, like "Enerdata MACC" [31] specifically for MAC curves and the GAINS models [32] that provide mitigation cost scenarios for reducing air pollution impacts on human health and the environment while simultaneously mitigating climate change through reduced GHG emissions: However those data are related to preset emissions scenarios that do not allow for implementing PLEDGES purposes. For these reasons, the authors decided to assess an estimation of the potential abatement cost curve for each MS based on a study still from Enerdata [33]. This study includes estimations of the abatement cost relative to a reference case, where the 2020 Climate and Energy Package [34] targets for renewables and GHGs were achieved. The Scenarios diverge in their respective hypotheses after that time and assume that all sectors can be included together within an economy-wide ETS after 2030, which is pretty much the same commitment requested by the Green Deal. We focused on cost related to two scenarios: the −40% in comparison to 1990 reported in the Enerdata study, and the −50% scenario, estimating considering that, according to the same report, the cost to achieve −50% of GHG emission reduction in 2050 are, in average, three times larger than the one obtained in the 40% scenarios. The following Table 1 reports such estimations.

As for the assumption of the Enerdata study, those costs are mainly related to the implementation of measures to decarbonize the energy sector. These costs are still consistent with recent estimations according to Figure 1 in the CRU Group study [35] even if, at these prices, the renewable energy solutions can abate around 7–20% of the total EU27 emissions in 2030 instead of 40% or 50%. To achieve the desired abatement −55%, the CRU group study assesses that a cost of around 140 eur/ton CO_{2eq} is necessary, i.e., around 3 times the 48 eur/ton estimated by the Enerdata study (col E, Table 1). An average of 140 eur/ton includes solutions to reduce emissions for buildings, the deployment of carbon capture technologies, deep penetration of electric vehicles in the transport sector, and hydrogen fuel-based technologies. Taking into account those premises, the abatement cost curve for the MSs has been assessed in proportion to the CRU study: increase of prices from 0—column E up to −20% of the 1990 emissions in 2030; 3 times prices in column E from −20% to −50% and doubling the prices at −50% to achieve −75% of the 1990 emissions in

2030 for each Member States. An example of the obtained abatement cost curve is reported in Figure 4.

Table 1. Estimation of EU27 abatement costs based on Enerdata projections [20].

Countries	A. Emissions 1990 ($GtCO_{2eq}$)	B. −40% in 2030	C. Cost from Enerdata −40% (Million €)	D. €/$TonCO_{2eq}$ −40%	E. €/$TonCO_{2eq}$ 50% (3× Column D)
EU-27	4712.30	1884.92	30,000	15.92	47.75
Belgium	146.06	58.42	1230	21.05	63.16
Bulgaria	83.37	33.35	150	4.50	13.49
Czechia	192.82	77.13	300	3.89	11.67
Denmark	80.18	32.07	310	9.67	29.00
Germany	1299.38	519.75	5460	10.51	31.52
Estonia	36.69	14.68	40	2.73	8.18
Ireland	62.73	25.09	330	13.15	39.45
Greece	104.23	41.69	420	10.07	30.22
Spain	258.59	103.44	2700	26.10	78.31
France	531.05	212.42	2820	13.28	39.83
Croatia	25.64	10.26	290	28.27	84.82
Italy	522.31	208.92	4900	23.45	70.36
Cyprus	6.22	2.49	70	28.12	84.36
Latvia	13.90	5.56	80	14.39	43.18
Lithuania	43.22	17.29	190	10.99	32.97
Luxembourg	13.13	5.25	140	26.66	79.97
Hungary	92.13	36.85	270	7.33	21.98
Malta	2.82	1.13	20	17.75	53.26
Netherlands	233.57	93.43	1840	19.69	59.08
Austria	67.73	27.09	570	21.04	63.12
Poland	446.99	178.80	1720	9.62	28.86
Portugal	68.24	27.29	260	9.53	28.58
Romania	229.33	91.73	430	4.69	14.06
Slovenia	14.45	5.78	90	15.57	46.71
Slovakia	64.56	25.82	270	10.46	31.37
Finland	46.46	18.58	360	19.37	58.11
Sweden	26.49	10.60	530	50.01	150.03

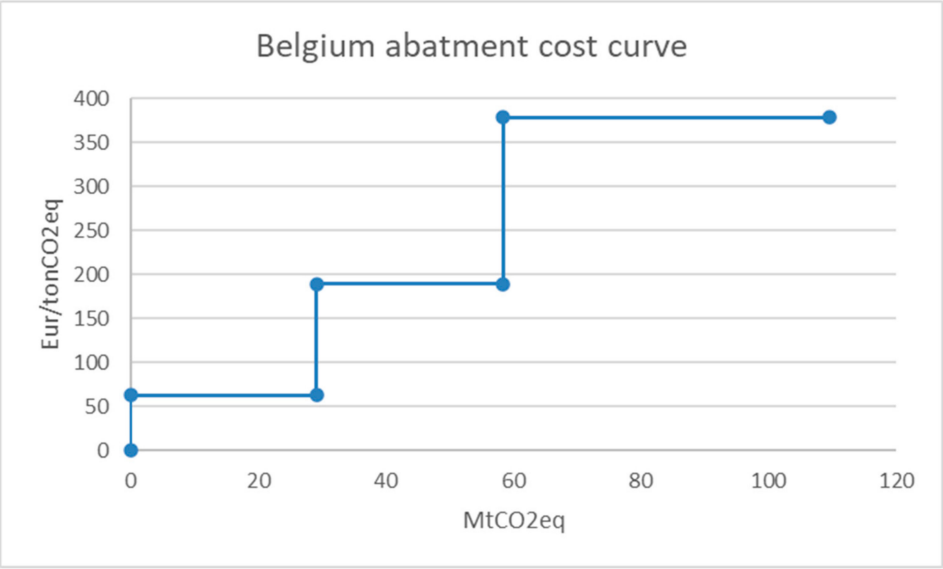

Figure 4. An example of the Abatement cost curve for a Member State (Belgium) is obtained by estimation in Table 1. Similar curves are obtained for all the other Member States with the data in Table 1.

The previous estimation does not pretend to constitute an accurate assessment of the ongoing abatement cost, which is assessed through top-down simulations with the aid of Integrated Assessment Models (IAM) or with the help of experts able to identify emission abatement measures combining engineering and economic information about each solution [36,37]. Nevertheless, they are suitable to explain the PLEDGES' purposes and can be easily updated with more accurate data.

3. Results and Discussion

In this section, we report a practical example of how the PLEDGES model could be used to assess the cost of an emissions compensation strategy across the MSs, in case a sudden increase in emissions in one or more countries might compromise the achievement of the Green Deal objectives.

As an example, consider the quite recent choice to close multiple large nuclear reactor facilities in Germany by 2022 following the Fukushima disaster which has resulted in an increase in the utilization of gas and coal. Furthermore, the geopolitical developments in Ukraine, as noted by Pereira et al. [38], have caused a decrease in gas consumption across the European Union, leading Germany, which heavily relies on Russian gas to ramp up its coal plants in response to reduced Russian gas supplies. As already reported by the authors in the work for the SW23, the Agora Energiewende estimated 20 to 30 million tons of additional emissions over the whole year. Hypothesizing that Germany and the EU27 need 2 years to plan alternative provisioning, the impact on decarbonization policy will be 60 MtonCO_{2eq} of extra emissions needing to be recovered. A detailed description of the scenarios is reported in the SW23 conference paper. Here, we recall that the increase in Germany's emissions (perturbation) is simulated as a "pulse" with an amplitude of 30 MtCO_{2eq} according to the Agora Energiewende assessment, starting in 2022 and finishing in 2024 (2 years), as the estimated time necessary to propose and implement new actions. The delay to emissions recovery is set to start in 2024 for each MS, and the recovery measure was set to last 2 years.

To set the simulation, we assumed the EU27 carbon budget is split among the MSs according to the inertia term, which is the relevant criteria driving the MSs' emissions footprints as discussed by the authors in a recent work [39]. To distribute the emissions perturbation across the member States we used a customized criterion obtained by blending inertia and capability according to our previous study. Once quotas are distributed, a "Gains from Trade" dynamics can be established across the MSs, in the way to minimize the cost of the compensation plan.

A carbon price quota is established at the EU27 level as a potential initial price to abate 1 ton of CO_{2eq} emission set as 45 Eur/tonCO_{2eq} (price0), which is of the same order of magnitude as the estimation of EU27 in the scenario of −50% of emissions reported in Table 1.

This initial price establishes the partition of recovery quotas in supply and demand as explained in the methodology section. This initial condition is represented in Figure 5.

Figure 5 shows that imposing a quota price of 45 Eur/tonCO_{2eq} generates an excess of quotas supply so that the price is higher than the equilibrium price. We can now adjust price0 since we obtain the equilibrium in which supply compensates demand and price equals price0. We found that within an initial price between 33 to 39 Eur/tonCO_{2eq} the system goes to an equilibrium, and we obtain the price of compensation strategy based on quotas distribution according to the customized example reported in the SW23 paper. This is represented in Figure 6.

The equilibrium price is not a single value in this case, representing different possible combinations of abatement costs across the MSs that can be achieved in this interval of prices.

However, the compensation strategy can assume different costs if we consider different MSs' recovery quota distributions. In the following example, we assume to redistribute compensation quotas only considering the decoupling criteria. We already argued that

any of the inertia, capability, and decoupling principles taken individually are insufficient to elaborate a reliable 'effort sharing' [17], but the following exercise further clarifies the potential of the model. We recall that the decoupling principle applied in sharing quotas according to the level of the MS economic decoupling assigns a smaller recovery quota to the less decoupled country and vice versa. The recovery quotas distribution is now quite different from the customized one and we obtained an initial scenario in which demand is higher than supply (Figure 7).

Now, we conduct the same exercise, spanning prices higher than 45 Eur/tonCO_{2eq} obtaining that supply and demand achieve an equilibrium in the price interval between 50 and 58 Eur/tonCO_{2eq} (Figure 8).

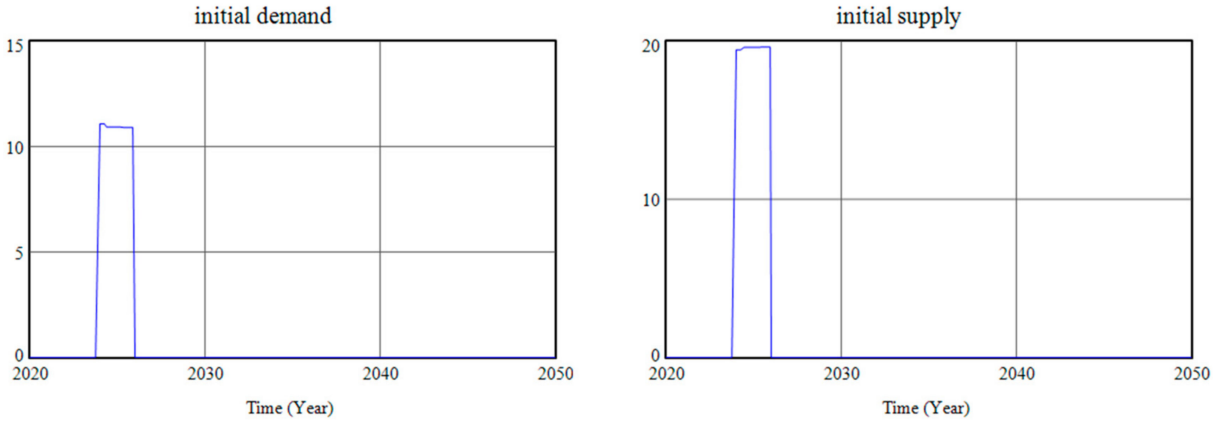

Figure 5. Example of supply and demand emissions quotas at EU27 for both years 2024 and 2025 (years of the recovery strategy) imposing an initial price of 45 Eur/tonCO_{2eq} and e with a customized distribution of emissions quotas among the MSs based on an effort sharing approach that blend inertia and capability principles [14].

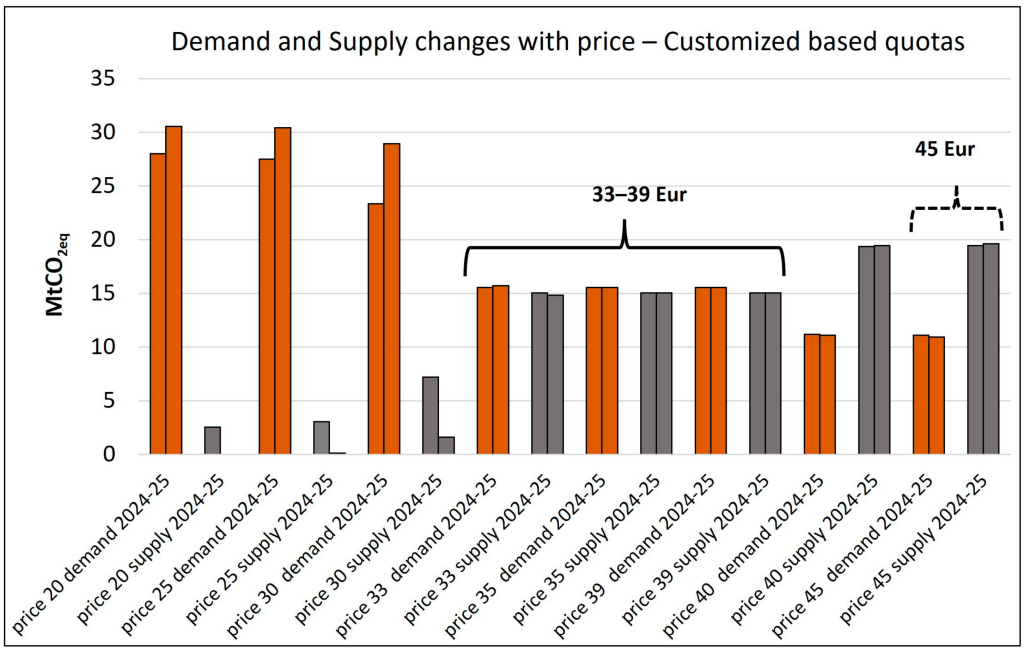

Figure 6. Supply (grey) and demand (orange) emissions quotas at the EU27 level impose different initial prices from 20 up to 45 Eur/tonCO_{2eq}. Supply equals Demands with prices between 33–39 Eur/tCO_{2eq}. The emissions quotas to be compensated are distributed among the MSs on the basis of customized criteria that blend inertia and capability principles [14].

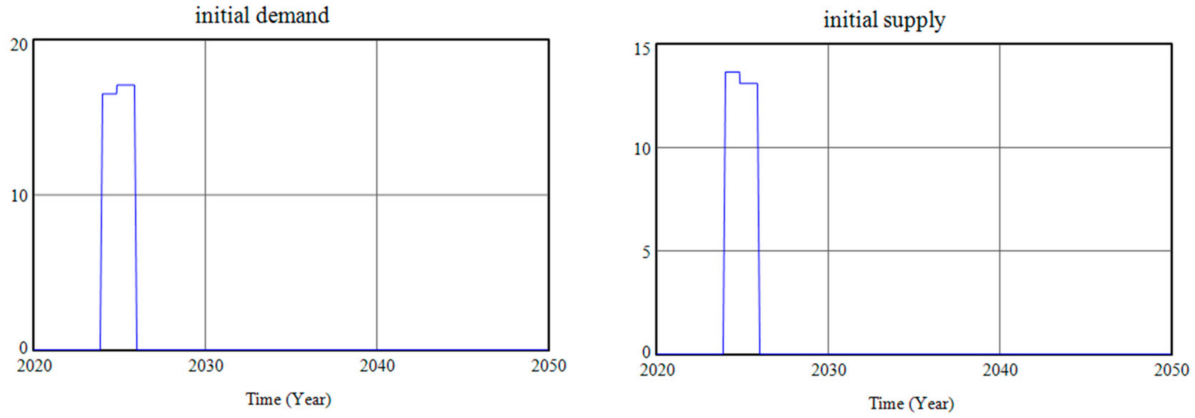

Figure 7. Example of supply and demand emissions quotas at EU27 for both years 2024 and 2025 (years of the recovery strategy) imposing an initial price of 45 Eur/tonCO_{2eq} and e with a customized distribution of emissions quotas among the MSs based on their economic decoupling degree.

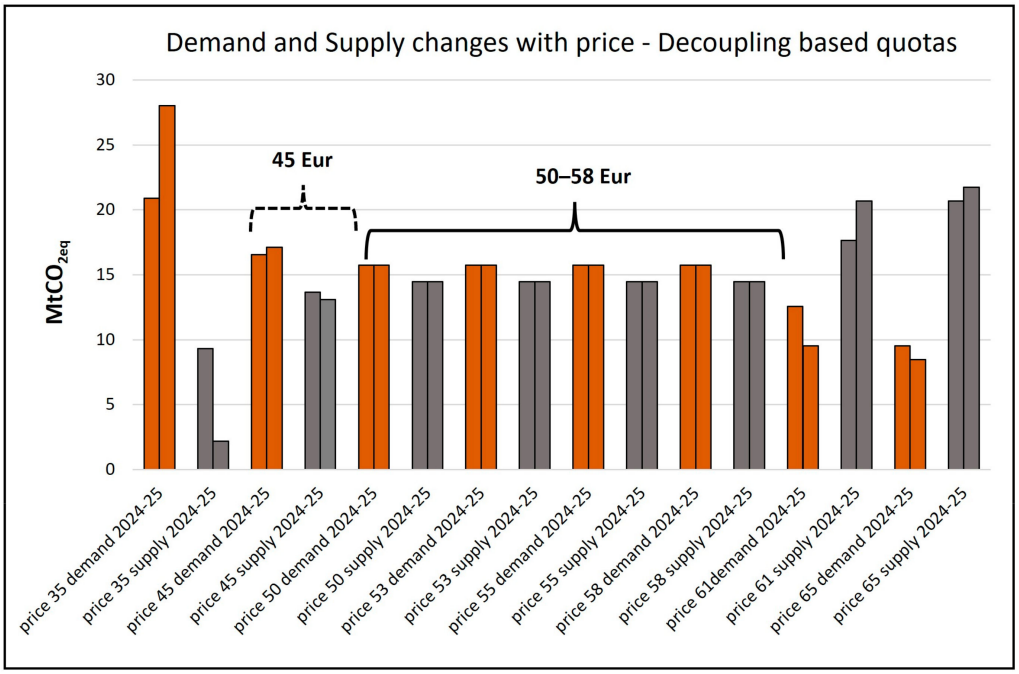

Figure 8. Supply (grey) and demand (orange) emissions quotas at the EU27 level impose different initial prices (price0) between 35 and 65 Eur/tCO_{2eq}. Supply equals Demands with prices between 50–58 Eur/tCO_{2eq}. The emissions quotas to be compensated are distributed among the MSs based on a decoupling index by Perissi and Jones [14].

Designing and implementing PLEDGES compensation strategies can be complex and faces challenges such as administrative burdens, political considerations, and most of all, efficient coordination among MSs. Adjusting carbon prices and redistributing emissions quotas have economic and social [39] implications for MSs and their industries. External factors, such as technological advancements, changes in energy markets, or geopolitical developments may influence emissions trends and force an initial compensation strategy to be frequently adjusted. Nevertheless, the previous exercises aim to highlight some promising applications of PLEDGES which points out an innovative framework to take advantage of regional differences in socio-economic characteristics to mitigate climate change. Traditional methods like allocating carbon budgets based only on MSs' historical emissions trends (grandfathering) discourage proactive action in wealthier countries capable of reducing emissions independently. Instead, the model emphasizes the potential for decoupling economic growth from emissions, allowing also for a preliminary assessment

of the costs of these alternative strategies. PLEDGES enables a decarbonization strategy creating synergies across the Member States, an approach not yet explored in the EU27 Green Deal or the 2050 Roadmap. However, the authors are aware that, at the moment, the model explores mainly a new conceptual framework, resulting in several limitations while considering quantitative estimations:

- The model relies on estimated abatement cost curves for each Member State based on a limited number of existing studies and data. These estimations may not accurately reflect the true abatement costs, which can vary significantly in practice. However, the model structure allows for an easy replacement of the proposed abatement curves with more accurate ones by means of the use of lookup tables. The updated abatement curves should incorporate technological advancements and cost data for each specific country, along with projections for future technology evolution, ensuring a comprehensive picture of long-term trends, as suggested by Harmnes et al. [40].
- The model relies on data from various sources, including historical emissions, economic indicators like GDP and the decoupling index [17]. Uncertainties in these data, such as measurement errors or outdated information, can introduce inaccuracies into the simulations.
- The simulation tool does not address uncertainties in terms of unexpected emissions increases or the success of compensation strategies, which must be monitored and assessed outside the model. However, the simple structure allows us to quickly update it according to the scenarios' changes.

Moreover, PLEDGES can be linked with other existing system dynamics-based IAMs: in particular, how to couple the MEDEAS [41] model, which aims to model the energy transition towards a zero-carbon economy in the EU, and the PLEDGES model is under investigation. PLEDGES can also represent an aggregation point to link emissions trajectories from models/tools at the country level [42,43] to build up a European carbon emissions offset tool.

Based on these initial results, we highlight the following recommendations, in terms of future research and effort required by the European Union to reinforce the Climate mitigation strategy:

- Carbon budgeting should be introduced as a national objective in the MSs' National Energy and Climate Plans [44], facilitating the shift from emission reduction targets to effectively managing cumulative emissions objectives.
- Promotion of Cross-Border Collaboration [45]: encourage cross-border collaboration among Member States to optimize emissions trading opportunities and share best practices in climate mitigation. This could involve the establishment of joint initiatives and partnerships aimed at achieving common emission reduction goals.

Member States abatement cost curves: establish a task force of stakeholders, including industry representatives, policymakers, economists, and scientists in the design and implementation of the abatement cost curves of Member States. Abatement Cost curves should be regularly updated to allow an efficient emissions trading scheme. In this regard, PLEDGES will provide an added value to the climate mitigation strategies not yet covered, to our knowledge, in the models accounted for by the Modelling Inventory and Knowledge Management System (MIDAS) [46] of the European Commission.

4. Conclusions

The research of the PLEDGES project directly addresses the academic question of how to effectively manage emissions trading among EU Member States to achieve climate goals such as net zero emissions by 2050 and limiting global warming to 2 °C. We address the critical issue of carbon budget management at regional levels, focusing on the European Union (EU27). While the concept of a global carbon budget is well-defined, the implementation of regional carbon budgets is essential to achieve the 2 °C global warming target outlined in the Paris Agreement. The PLEDGES project introduces an innovative simulation tool

designed to distribute carbon budgets among the EU27 Member States while aligning with the EU Green Deal's emission reduction goals and the 2 °C target.

PLEDGES model, which is built upon System Dynamics, facilitates the integration of the concept of emissions trading among Member States to manage unexpected deviations from the EU27 carbon budget, using the "Gains from Trade" approach, which enables countries to compensate for emissions surpluses based on factors like inertia, economic capability, and economic decoupling. The paper presents a real-world example, simulating a short-term scenario in which Germany increases emissions by reactivating coal power plants due to geopolitical factors. The model's simulations aim to estimate the cost of a compensation strategy across the EU27 Member States to keep emissions within the established budget. The assessment of abatement cost curves for each Member State forms a crucial element in the emissions compensation strategy. While the presented curves have limitations, they explain the PLEDGES framework and can be updated with more accurate data.

The research demonstrates the PLEDGES model's potential in managing regional carbon budgets within the EU27 and provides insights into how emissions trading and compensation strategies can be applied to address unexpected increases in emissions while pursuing ambitious decarbonization goals. We present a case study of a sudden, short-term rise in emissions in Germany. Using PLEDGES, we can evaluate the diverse cost implications, ranging from 30 to 60 Eur/tonCO_{2eq}, for implementing compensation measures across the EU27 countries.

The PLEDGES model offers additional value to climate mitigation strategies not currently accounted for in the European Commission's MIDAS models. Recommendations include implementing harmonized emissions trading mechanisms based on PLEDGES effort sharing principles, promoting cross-border collaboration for optimizing emissions trading, and establishing stakeholder task forces for designing and updating Member States' abatement cost curves to enhance emissions trading efficiency.

Supplementary Materials: The PLEDGES model and user guide can be downloaded at: https://aru.figshare.com/projects/PLEDGES_Pledge_Limits_Evaluation_for_Decarbonization_Goals_of_the_EU27_Strategy/134330 (accessed on 3 June 2024).

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