MODELLING EU27'S EMISSION OFFSET STRATEGY FOR ACHIEVING LONG-TERM 2°C MITIGATION TARGETS.

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ABSTRACT

In the realm of policymaking, the practice of regional carbon budgeting remains underexplored despite its critical role in advancing global climate objectives, notably the Paris Agreement's imperative of capping global temperature rise at 2°C by 2050. Within this study, we present the PLEDGES model, an innovative system dynamics-driven simulation platform tailored to the European Union's context. This tool aims to equitably distribute carbon budgets among Member States and institute an emissions offset strategy to address unforeseen discrepancies from the EU27's carbon budget. Grounded in the "Gains from Trade" framework, the emissions trading mechanism is deployed to facilitate equitable exchange. Moreover, the tool incorporates a mechanism to evaluate the financial implications of offsetting through the utilization of abatement cost curves specific to each Member State.

Keywords: carbon budget, system dynamics, decarbonization, gains from trade, Green Deal

1 INTRODUCTION

While the global framework for carbon budgeting has been extensively outlined and evaluated in several investigations (Committee On Climate Change, 2023), (Levin, 2013), (Rogelj *et al.*, 2019), only a few nations worldwide have begun to incorporate this concept (Green Economy Coalition, 2023) to establish cumulative emissions limits at regional levels. Neglecting to set regional carbon budgets implies potential challenges in meeting the 2°C global warming target stipulated by the Paris Agreement, as this target relies on the cumulative emissions stored in the atmosphere. To address this gap, the PLEDGES model introduces a pioneering simulation tool aimed at comprehensively distributing carbon budgets among the Member States (MSs) of the European Union (EU27), while aligning with the objectives of the Green Deal (European Commission, 2021)- specifically, reducing emissions by -55% compared to 2005 levels and achieving EU carbon neutrality by 2050 - as well as the 2°C target. Although the PLEDGES tool is currently tailored to the EU's geographical context, its adaptability for use in other regions will be the objective of future studies.

Once the carbon budget for the EU27 is assessed (Perissi *et al.*, 2018), (Trio, 2022), (Duscha *et al.*, 2019), the PLEDGES tool can dynamically manage potential emissions deviations from the budget due to unforeseen increases in emissions in a given Member State, reallocating these emissions to other states in an optimal manner. For instance, in response to the geopolitical situation in Ukraine, Germany may reactivate coal power plants to reduce its reliance on gas and secure its national gas supply, resulting in increased emissions due to changes in the energy supply mix. The PLEDGES approach involves evaluating each Member State's potential to offset such increases, with the ultimate goal of maintaining the EU27 budget within the established limit.

In distributing responsibility for emissions reduction, the model employs an "effort-sharing" approach based on factors such as inertia, economic capacity to fund mitigation efforts, and the degree of economic decoupling (Perissi and Jones, 2023a) in each Member State. An initial version of the model's objectives and structure has been previously discussed at the Simulation Workshop (2023) and documented in conference proceedings (Perissi and Jones, 2023b), providing a detailed description we don't repeat here.

This study advances the tool's implementation by considering emissions trading among Member States. The concept entails evaluating emission trading opportunities or requirements among states if deviations from established decarbonization targets occur. In such cases, each Member State is tasked with mitigating unexpected emissions increases while minimizing the total cost of compensation actions within the EU27. The offset strategy relies on a "Gains from Trade" dynamic (Samuelson, 1939), leveraging the benefits of redistributing emissions surplus across Member States due to their varying characteristics, such as geography, natural resources, or existing infrastructure.

As an illustrative application of the PLEDGES tool in a real-world scenario, simulations are conducted to estimate the cost of an EU27 compensation strategy in response to a short-term scenario where coal power stations are activated in Germany to reduce dependence on gas, due to the reduced Russian gas supplies.

The paper is structured into the following sections: "Materials and Methods," which elucidate the model's structure and features, and "Results and Discussion," where simulation hypotheses are outlined and analyzed.

2 MATERIALS AND METHODS

PLEDGES has been crafted using System Dynamics methodology, bridging insights from diverse viewpoints and incorporating feedback from various subsystems. The model file ".mdl" is released in Vensim Professional ® (2018) and published in ".vpm" to be used with Vensim Reader. For details regarding the preliminary version of the model, please consult the SW23 conference proceedings (Perissi and Jones, 2023b)

2.1 Emissions Trading

This section details the integration of the PLEDGES tool for emissions trading, which operates on the principles of Gains from Trade dynamics(Samuelson, 1939) (Samuelson, 1962). In economics, the concept of supply and demand delineates the interplay between the quantity of a product that producers aim to sell at various prices and the quantity that consumers intend to purchase. This relationship forms the fundamental basis for determining market prices and involves a demand curve, representing consumer demand with a downward slope, and a supply curve, indicating producer willingness to supply with an upward slope. The point of equilibrium in this market occurs where demand equals supply. In the context of emissions trading, the commodities being exchanged are compensation quotas allocated to Member States (MSs) based on the effort-sharing principle. Each MS's stance on selling or purchasing their quotas is determined by their respective MS Abatement Cost (Ellerman and Decaux, 1998), outlined in a lookup table.

Figure 1 depicts a schematic illustration of the most recent iteration of the PLEDGES model. The structure retains its organization into a top-level window for EU27 carbon budget management, now incorporating market dynamics, and individual windows for each of the 27 Member States, housing the MS emissions abatement cost curve (MAC) within lookup tables.

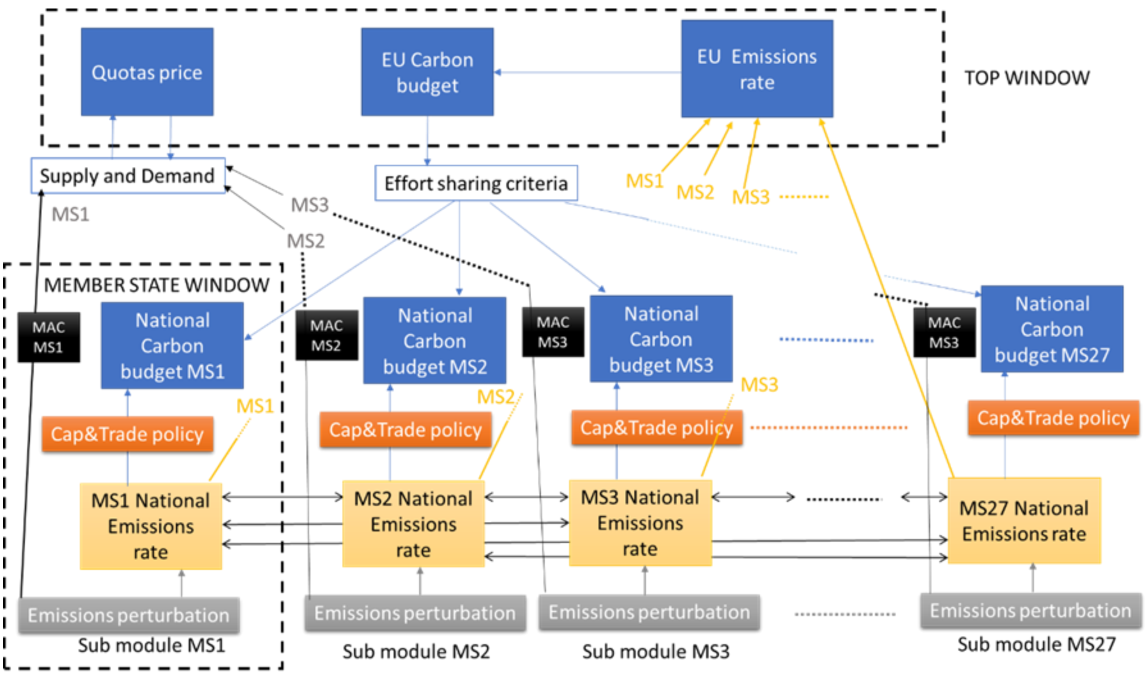

Figure 1. *Structure of the PLEDGES model, where the TOP window is responsible for overseeing EU27 carbon budget management and implementing Gains from Trade dynamics. Each Member State window, on the other hand, is dedicated to tasks such as carbon budget allocation, simulating unforeseen emissions increases (emission perturbation), and utilizing tools such as the Member State abatement cost curve (MAC).*

In Figure 2 below, we present the model outlining the dynamics of pricing. The pricing of quotas is contingent upon factors such as price change, the rate of price change, and the indicated price. The rate of price change is interpreted as a metric denoting how swiftly demand and supply can adjust in response to alterations in price, commonly referred to as elasticity. A higher value signifies a more rapid adjustment of price towards its equilibrium value. To elucidate the dynamics of the model, we set the elasticity to unity, indicating that a given percentage change in price results in an equivalent percentage change in the quantity demanded or supplied.

The indicated price evaluates an initial price determined by the price multiplied by the "demand-supply ratio". If the initial demand surpasses the initial supply, the market favours "sellers", whereas the opposite holds for "buyers". Subsequently, the indicated price is substituted with the actual price, inducing the price change responsible for the evolution of pricing.

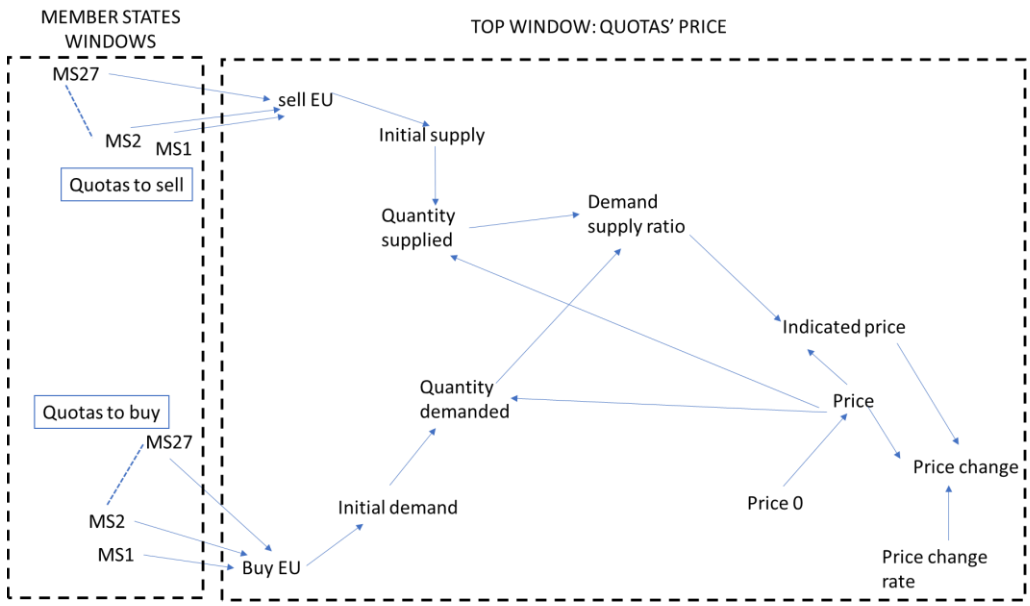

Figure 2. *PLEDGES] model Gains from Trade dynamic implemented at EU level.*

Based on the previous discussion, it's evident that the quantity demanded is contingent upon the initial demand and price, while the supply is influenced by the initial supply and price.

Figure 3 shows the model group concerning the abatement cost curves integrated into the Member States (MSs) window. It's important to note that abatement cost curves are implemented as static measures. Therefore, any price changes in the short term are determined by the utilization of existing abatement measures.

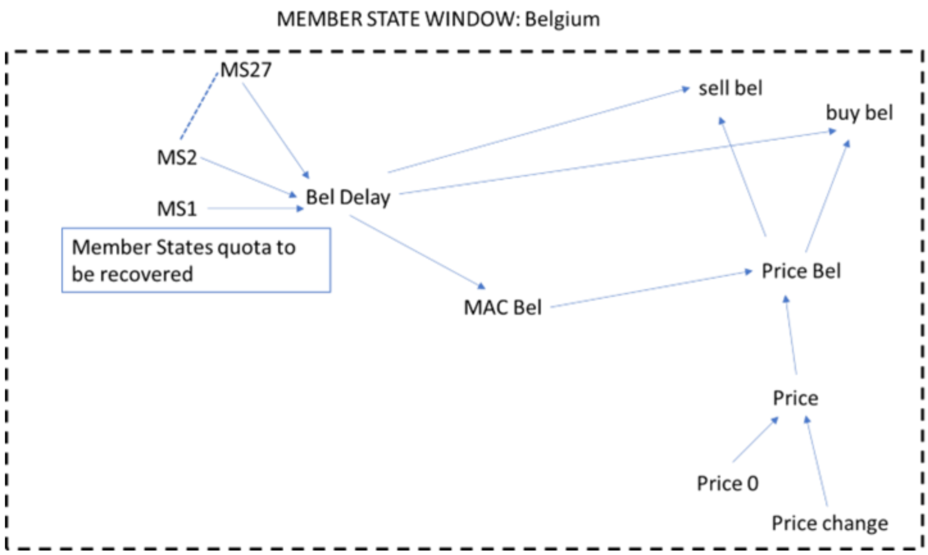

Figure 3 *A Member State window, in this case, Belgium, showcasing the implementation of the abatement cost curve.*

If the initial price (P0) for emissions quotas is established at the EU27 market level and the quota to be reclaimed from a specific Member State, MSi (set in the bel delay variable), results in a price lower than P, it indicates that MSi can mitigate this quota at a lower cost than the market price. This enables MSi to sell quotas to address emissions elsewhere (sell bel). Conversely, if MSi can mitigate emissions at a higher cost than the initial EU27 price, it will procure quotas from other Member States whose abatement cost offers a more cost-effective solution (buy bel). The quotas earmarked for purchase or sale by each Member State are aggregated in the top window (Figure 2, buyEU and sellEU): all quotas available for sale across the Member States constitute the "supply," while all quotas targeted for purchase represent the "demand," reflecting the cost of reducing additional pollution. Subsequently, the user adjusts the initial price, prompting the adjustment of abatement costs within the MS window. This process continues until the supply quotas balance the demand quotas, establishing the new price at which the adopted compensation can be realized across the Member States.

2.2 Assessment of the Abatement costs for each Member State

The concept of abatement cost denotes the expenditure associated with reducing greenhouse gas emissions by one ton. This forms the basis for creating marginal abatement cost curves, which are widely utilized in policymaking due to their ability to rank emission reduction options from the least to the most costly. However, this methodology is inherently "marginal" in nature, primarily addressing incremental emissions reductions. Consequently, it possesses several limitations, such as assuming constant costs regardless of the pace of implementation options. For instance, transitioning all vehicles to electric vehicles over a shorter period incurs higher costs than doing so over a longer timeframe (Kesicki and Ekins, 2012) (Kesicki, 2013).

When striving to reduce emissions close to zero, the challenge of hard-to-abate emissions cannot be ignored. Recent studies have explored Long-term marginal abatement cost curves to account for sector interactions and technological advancements, aiming to minimize the total transition cost (Harmsen *et al.*, 2019), (World Bank Group, 2022).

Despite these limitations, the abatement curves approach remains highly promising, especially for modelling and simulations, as it can be easily implemented and updated using lookup tables (Huang *et al.*, 2016).

In the context of this study, obtaining abatement cost curves for all 27 Member States faced a significant challenge. While products like "Enerdata MACC" and the GAINS models provide such data, they are often tied to preset emissions scenarios, unsuitable for this study. Consequently, an estimation of potential abatement cost curves for each Member State was derived from a study by Enerdata (Enerdata, 2014). This study includes estimations of abatement costs relative to a reference case, assuming the achievement of targets set by the 2020 Climate and Energy Package (European Commission, 2009). 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.

The focus was placed on the costs associated with two scenarios: a -40% reduction compared to 1990 levels and a -50% scenario. Estimations were made considering that achieving a 50% reduction in greenhouse gas emissions by 2050, on average, incurs costs three times higher than those in the 40% scenario. These estimations are detailed in Table 1.

Table 1. *Estimation of EU27 abatement costs based on Enerdata projections (Enerdata, 2014).*

Countries	**A. emissions 1990 (GtCO2eq)**	**B. -40% in 2030**	**C. cost from Enerdata -40% (Million Eur)**	**D. Eur/Ton CO2 eq -40%**	**E. Eur/Ton CO2 eq 50% (3x col D)**
European Union - 27	4712.30	1884.92	30000	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

According to the assumptions made in the Enerdata study, the costs primarily pertain to implementing measures aimed at decarbonizing the energy sector. These costs align with recent estimates as indicated by Figure 1 in the CRU Group study (Butterworth, 2021). However, even at these price levels, renewable energy solutions are estimated to only mitigate around 7-20% of total EU27 emissions by 2030, rather than the targeted 40% or 50%. To achieve the desired 55% reduction in emissions, the CRU Group study suggests that a cost of approximately 140 euros per ton of CO2eq is necessary, which is roughly three times the 48 euros per ton estimated by the Enerdata study (column E, Table 1). This average cost includes various solutions such as emissions reduction for buildings, the implementation of carbon capture technologies, widespread adoption of electric vehicles in the transport sector, and the utilization of hydrogen fuel-based technologies.

Given these considerations, the abatement cost curves for Member States were evaluated in proportion to the CRU study. Prices are projected to increase from 0 (column E) up to a reduction of -20% of 1990 emissions by 2030. From there, prices are tripled from the -20% to -50% reduction range, and then doubled at the -50% reduction mark, aiming to achieve a -75% reduction in 1990 emissions by 2030 for each Member State. An example of the resulting abatement cost curve is depicted in Figure 4.

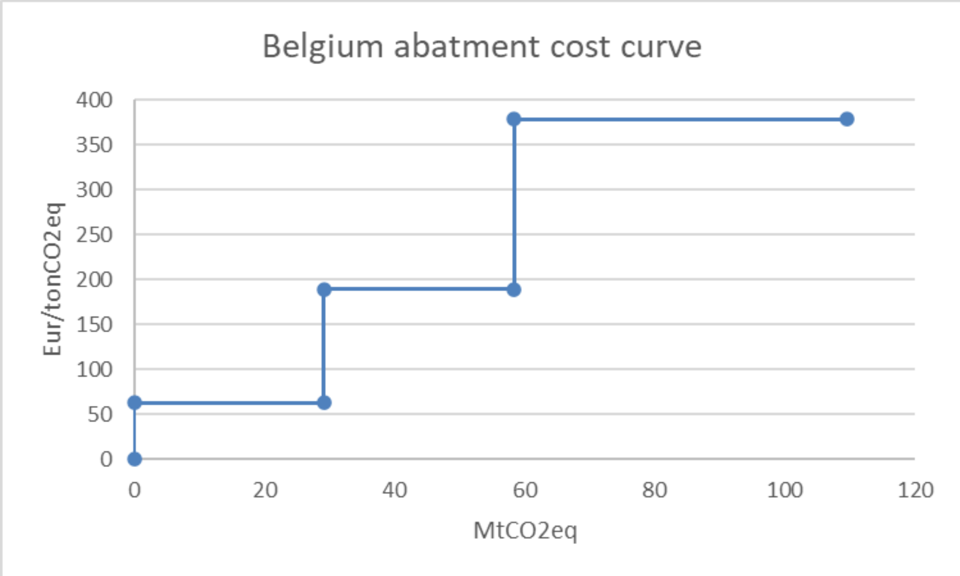

Figure 4. *An example of the Abatement cost curve for a member State (Belgium) is obtained by estimation in Table 1.*

This estimation is not intended to serve as a precise evaluation of current abatement costs, which are typically determined through top-down simulations utilizing Integrated Assessment Models (IAMs) or by experts who can identify emission reduction measures by combining engineering and economic insights about each solution (Sotiriou *et al.*, 2019), (Kesicki, 2013). However, these estimations are well-suited for elucidating the objectives of the PLEDGES project and can be readily updated as more accurate data becomes available.

3 RESULTS

In this section, we present a practical demonstration of how the PLEDGES model could be utilized to evaluate the cost of an emissions compensation strategy across Member States (MSs) in the event of a sudden increase in emissions, potentially compromising the attainment of the Green Deal objectives.

As a case study, let's consider the recent decision in Germany to decommission multiple large nuclear reactor facilities by 2022 following the Fukushima disaster. This has led to an increase in the utilization of gas and coal. Additionally, geopolitical developments in Ukraine have caused a decrease in gas consumption across the European Union, prompting Germany, heavily reliant on Russian gas, to increase its reliance on coal plants due to reduced Russian gas supplies. According to Pereira et al. (Pereira *et al.*, 2022), this shift has led to an estimated additional 20 to 30 million tons of emissions over the course of a year. Assuming Germany and the EU27 require two years to plan alternative energy sources, this impact on decarbonization policy amounts to an extra 60 million tons of CO2eq emissions to be offset.

To simulate this scenario, we've modeled the increase in Germany's emissions (perturbation) as a "pulse" with an amplitude of 30 million tons of CO2eq, starting in 2022 and ending in 2024 (a span of two years), corresponding to the estimated time needed to propose and implement new actions. The delay in emissions recovery is set to commence in 2024 for each Member State, with the recovery measure lasting two years.

For the simulation setup, we assumed that the EU27 carbon budget is divided among the Member States based on the inertia term, a significant criterion determining the emissions footprint of each Member State, as discussed in a recent study (Perissi and Jones, 2023a). To distribute the emissions perturbation among the Member States, we employed a customized criterion derived from a blend of inertia and capability, as outlined in our previous study. Once quotas are allocated, a "Gains from Trade" dynamic can be implemented across the Member States to minimize the cost of the compensation plan.

A carbon price quota is established at the EU27 level as the potential initial price to abate one ton of CO2eq emission, set at 45 euros per ton CO2eq (price0), which aligns with the estimation for the EU27 scenario of a -50% emissions reduction, as reported in Table 1. This initial price determines the distribution of recovery quotas into supply and demand, as explained in the methodology section. This initial condition is depicted in Figure 5.

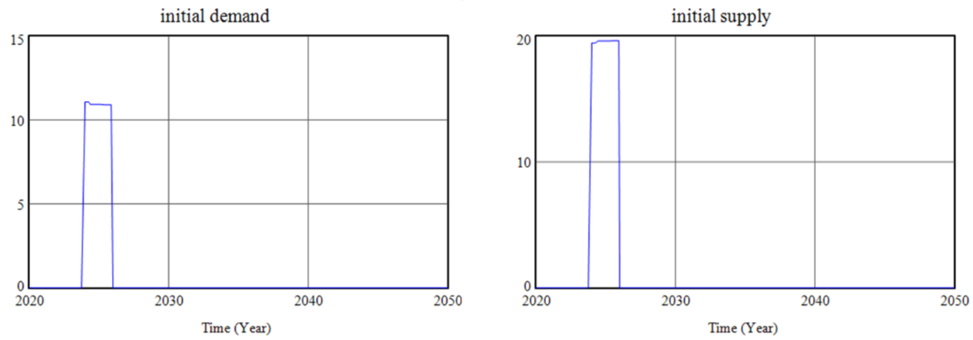

Figure 5. *An example of supply and demand for emissions quotas across the EU27 for the years 2024 and 2025, which are the years of the recovery strategy. The simulation imposes an initial price of 45 euros per ton of CO2eq and a customized distribution of emissions quotas among the Member States (MSs) based on an effort-sharing approach* (Perissi and Jones, 2023a)

Figure 5 demonstrates that setting a quota price of 45 euros per ton of CO2eq results in an oversupply of quotas, leading to a price higher than the equilibrium price. We can now fine-tune the initial price (price0) until achieving equilibrium, where supply matches demand and the price equals price0. After adjusting, we found that an initial price ranging from 33 to 39 euros per ton of CO2eq leads the system to equilibrium. This process allows to determine the price of the compensation strategy based on quota distribution according to the customized example outlined inPerissi and Jones (Perissi and Jones, 2023b) paper. The outcome of this adjustment is depicted in Figure 6.

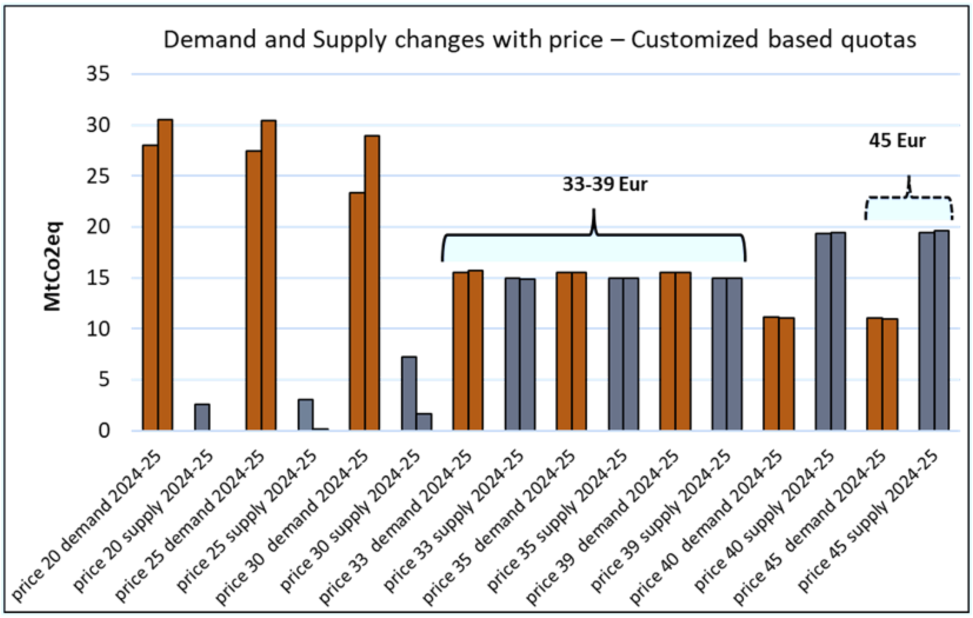

Figure 6. *The supply (grey) and demand (orange) of emissions quotas at the EU27 level, considering various initial prices ranging from 20 to 45 euros per ton of CO2eq. Equilibrium between supply and demand is achieved when prices fall within the range of 33 to 39 euros per ton of CO2eq.*

In this scenario, the equilibrium price isn't a fixed value but rather a range, reflecting various potential combinations of abatement costs across the Member States achievable within this price interval. Consequently, the compensation strategy may entail different costs depending on the distribution of recovery quotas among the Member States.

The exercise conducted aims to underscore some promising applications of PLEDGES, which introduces an innovative framework leveraging regional socio-economic differences to address climate change mitigation. This approach enables the development of a decarbonization strategy that fosters synergies across Member States, a concept not yet explored in the EU27 Green Deal or the 2050 Roadmap. However, it's essential to acknowledge that the model primarily explores a new conceptual framework, leading to several limitations when considering quantitative estimations.

For instance, the reliance on estimated abatement cost curves for each Member State, based on a limited number of existing studies and data, may not precisely reflect true abatement costs, which can vary significantly in practice. Nevertheless, the model's structure facilitates the easy replacement of proposed abatement curves with more accurate ones using lookup tables.

Furthermore, the simulation tool doesn't account for uncertainties regarding unexpected emissions increases or the effectiveness of compensation strategies, necessitating external monitoring and assessment. Despite this, the model's simple structure enables swift updates according to scenario changes.

Moreover, PLEDGES can be integrated with other existing system dynamics-based Integrated Assessment Models (IAMs), such as pymedeas (Solé *et al.*, 2020), which models the EU's transition to a zero-carbon economy. Efforts to couple PLEDGES with pymedeas are currently underway. Additionally,PLEDGES can serve as an aggregation point to connect emissions trajectories from country-level models/tools, contributing to the development of a European carbon emissions offset tool.

In this context, PLEDGES offers added value to climate mitigation strategies that, to the best of my knowledge, have not been addressed by other research endeavours.

4 CONCLUSION

This study concerns managing carbon budgets at regional levels, with a specific focus on the European Union (EU27). While the concept of a global carbon budget is widely understood, the implementation of regional carbon budgets is crucial to meeting the ambitious goal of limiting global warming to 2°C, as outlined in the Paris Agreement. To address this challenge, the PLEDGES project introduces an innovative simulation tool aimed at distributing carbon budgets among the EU27 Member States while aligning with the emission reduction objectives of the EU Green Deal and the 2°C target.

Built upon System Dynamics, the PLEDGES model facilitates the incorporation of emissions trading among Member States to manage unforeseen deviations from the EU27 carbon budget. It employs the "Gains from Trade" approach, enabling countries to offset emissions surpluses by considering factors such as inertia, economic capability, and economic decoupling. The paper illustrates the model's practical application through a real-world scenario, simulating a short-term situation where Germany increases emissions by reactivating coal power plants due to geopolitical factors. Through simulations, the model estimates the cost of a compensation strategy across EU27 Member States to ensure emissions remain within the established budget.

Central to the emissions compensation strategy are the abatement cost curves for each Member State, which play a vital role in determining mitigation measures. While these curves have inherent limitations, they serve to elucidate the PLEDGES framework and can be refined with more accurate data over time.

Overall, this research showcases the potential of the PLEDGES model in effectively managing regional carbon budgets within the EU27. It provides valuable insights into how emissions trading and compensation strategies can be leveraged to address unexpected increases in emissions while striving to achieve ambitious decarbonization goals. By offering an innovative approach, this tool enhances the EU's capacity to fulfill its climate commitments and contribute to global efforts in mitigating climate change.

ACKNOWLEDGMENTS

This research was funded by PLEDGES project European Union’s Horizon 2020 MSCA IF GA ID: 101023109.

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