The Energy Transition: A Balancing Act*

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Abstract

As the need for drastic reductions in global greenhouse gas emissions becomes increasingly urgent, governments and policymakers are developing proposals for climate change policies that aim to achieve net zero emissions. However, the challenge lies in determining the most effective way to operationalize this transformation. While cost efficiency is often emphasized as a desirable property, experience shows that it is neither necessary nor sufficient to achieve an optimal policy portfolio. Instead, we advocate for a broader definition of economic efficiency: policies must also be feasible, fair, effective, and credible. Trade-offs between these criteria are common, and must be balanced to create a successful policy portfolio. The European experience provides interesting case studies with which to illustrate these efficiency dimensions and their implications.

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1 Introduction

In the face of the need for drastic reductions in global greenhouse gas emissions, governments and policymakers are putting together proposals for climate change policies that push towards a path of net zero emissions. Discussions are often about the degree of ambition and the best way to operationalize the needed transformation. The urgency for decarbonization has only strengthened amid the energy crisis, with several governments announcing policies to speed up the energy transition as a way to reduce fossil fuel imports.

Given this strengthened ambition to decarbonize the economy, how should climate policy be devised? What are the principles that should inform the policies guiding this transformation? What have we learned from the implementation of past policies that can help us be more effective this time?

We structure our discussion around a set of desirable properties that climate policies should satisfy. While the emphasis is often put on cost efficiency –no doubt a desirable property– experience tells us that it is neither necessary nor sufficient to achieve an optimal policy portfolio. Some of the most efficient policies might not be feasible. Additionally, as it is well known, a too narrowly defined notion of cost efficiency can lead to inefficient policies in practice. In this paper, we advocate for a broader notion of economic efficiency, which requires policies to be cost efficient but also feasible, fair, effective, and credible. As demonstrated in a comprehensive international survey spanning twenty countries (Dechezleprêtre et al., 2022), climate policies that incorporate these features garner increased social support, in turn a necessary condition for those policies to be proposed and implemented.

While these criteria must be kept in mind throughout, satisfying them involves a balancing act given the trade-offs that often exist among them. For example, ideal policies are a useful thought experiment, but they cannot be part of the solution to the problem if deemed infeasible. A lack of fairness can make some policies politically infeasible, just as a lack of credibility can reduce the effectiveness of ideal policies. On the contrary, carbon policies that reduce emissions only locally might prove to be highly effective if they become an example for others to follow, thus contributing to mitigation globally. A subsidy in one country may lead international firms to innovate more, leading to lower prices and increased adoption of clean technologies elsewhere. These are examples of the trade-offs that might arise across objectives.

Many of the trade-offs discussed above arise prominently in the European context, where carbon prices have already reached a record high of $100 EUR/Ton. The European Green Deal commits Europe to achieving climate neutrality by 2050 with interim goals. For 2030, the objective is to reduce emissions by 55% (with respect to 1990 levels), for which a series of policies have been implemented to promote renewable energy and investments in energy efficiency. Notably, the so-called *Fit-for-55* package extends carbon pricing to all sectors not previously covered by the emissions regulation (including transportation and buildings). At the same time, it plans to endow a Social Climate Fund with 25% of the expected emissions trading revenues for building and road transport fuels.

This paper discusses the issues that arise when assessing the fulfillment of the criteria a successful policy portfolio must satisfy.

2 A Broader Notion of Efficiency

To provide a systematic analysis, we structure our discussion around a simple optimization program for climate policy that includes a broad notion of economic efficiency. The framework is initially limited to just considering a narrow definition of cost efficiency. Additional ingredients will be subsequently added when discussing the other policy criteria that shape a broader notion of efficiency: effectiveness, feasibility, credibility, and fairness. We show how these criteria affect the objective function and the feasible set of the policy portfolio.

Problem Statement

Consider a social planner that needs to pick the optimal climate policy toolbox. There are several policy options, indexed by $j = 1, ..., J$. The policymaker needs to chose the intensity with which to implement each of these policy options at each period t, $\mathbf{x_t} = \{x_{1t}, ..., x_{Jt}\}$. At a broad level, the goal of the social planner is to balance the benefits and costs from implementing these policies. This can be simply represented as[1]

$$\max_{\mathbf{x}} B(\mathbf{x}) - C(\mathbf{x}).$$

where costs and benefits may depend on current choices $\mathbf{x_t}$, as well as past and future choices, i.e., $\{\mathbf{x_{t-1}}, \mathbf{x_{t-2}}...\}$ and $\{\mathbf{x_{t+1}}, \mathbf{x_{t+2}}...\}$.

Under certain assumptions, this framework is equivalent to individually applying a static cost-benefit analysis to each policy. Assume that benefits and costs from these policies are additively separable and that the damages from emissions are constant and equal to σ. Then, one can solve the optimal policy intensity for each policy tool separately. Assuming that the benefits are given by the damages avoided due to abatement A, the solution can be written as

$$x_j^* = \arg\max_{x_j} \sigma A_j(x_j) - C_j(x_j).$$

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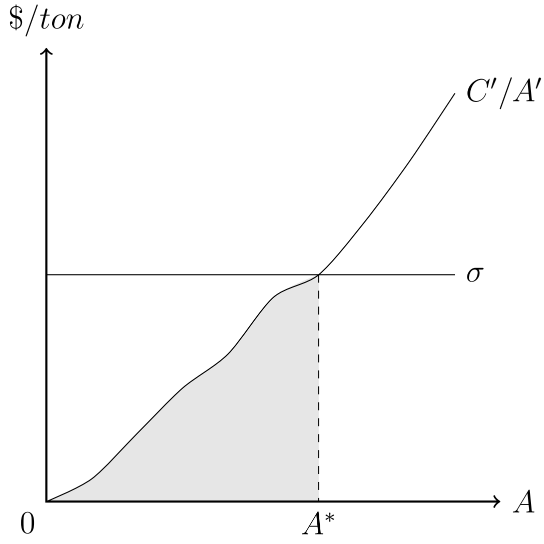
[1] This approach has been used in many seminal contributions, including Weitzman (1974).

Figure 1: The optimal policy toolbox under simple assumptions



Notes: This figure shows a supply curve of abatement options, ranked as a function of their efficiency. At the optimal amount of abatement, A^*, the marginal cost of the abatement equals the marginal value of abatement, given the damages from emissions, σ.

Graphically, this amounts to creating a supply curve of abatement options, such as the so-called "McKinsey curve". Policy actions are ranked in merit order, from low to high abatement costs. Policies are accepted until the marginal cost of abatement equals the social value of the marginal abatement, measured at the social cost of carbon σ, i.e., until $C'_j/A'_j = \sigma$, as shown in Figure 1.

This simple logic is behind the powerful notion of applying a simple cost-benefit analysis to climate policies using estimates of the social cost of carbon that can proxy for σ. Indeed, a benchmark for evaluating the efficiency of policies at reducing GHG emissions is to create standardized measures of the monetary costs of reducing a ton of CO2 of alternative policy tools, what is often called the Marginal Abatement Cost (MAC). Cost measures in dollars per ton of CO2 can be very useful to elucidate which policies are urgent, which policies are more in a middle area in which other trade-offs should be considered, and which policies are unlikely to generate enough benefits even if feasible. We next discuss broad categories, beyond individual cost efficiency, that can impact the optimal policy toolbox.

2.1 Cost efficiency

There are many reasons why deriving the optimal toolbox in practice is not as simple. Even focusing on a policy-by-policy analysis, representing the costs and benefits accurately and with certainty can be difficult given the long-lived nature of GHG emissions and the complexities in anticipating dynamic costs and benefits (Gerlagh and Liski, 2018). Furthermore, there might be interactions between policies that are ignored in this simple abstraction.

Furthermore, cost efficiency is not a static concept, but should incorporate the effects that accrue through time, some of which are probabilistic. There is a tension between relying on the technology that is available today, or promoting future technological improvements that we cannot predict today. The latter option might lead to high gains but it is also high risk.

The difficulty of measuring these dynamic effects introduces a challenge when selecting the cost efficient policies. A full assessment of dynamic efficiency should also take into account that some choices create lock-in effects, and others give rise to dynamic coordination issues.

Mathematically, dynamic effects can be incorporated as

$$\max_{\mathbf{x_t}} \, [B(\mathbf{x_t}) - C(\mathbf{x_t})] + \beta[B(\mathbf{x_{t+1}}) - C(\mathbf{x_t}, \mathbf{x_{t+1}})]$$

given that today's policy efforts might affect future costs, using the discount factor $\beta \in (0,1)$. Clearly, in the presence of learning economies, the costs of policy option j at $t+1$ are lower the higher the efforts at t, so the efficient effort level goes up. Similarly, in the presence of dynamic coordination issues, costs of policy option j at $t+1$ are lower the higher the efforts of policy option i at t, which would also imply a higher optimal effort level of option i.

In sum, dynamic effects create spillovers that complicate the policy assessment and implementation. Some of the resulting difficulties are illustrated through policy examples.

Learning effects when developing low-carbon technologies. It has been well documented that a static economic analysis may understate the impacts of policies that trigger technical change. For instance, in the case of solar panels, Gerarden (2021) shows that subsidies that were initially set above the level justified by the static environmental benefits boosted the adoption of solar panels and triggered significant cost reductions. In line with these findings, van Benthem et al. (2008) find that the solar subsidy schedule implemented by the California Solar Initiative was socially optimal taking into account the learning by doing effects. Without these, those subsidies would not have been justified by the benefits of carbon abatement alone. A similar conclusion applies regarding the Feed-in-Tariffs originally used in Europe to promote the early deployment of renewable energies (Fabra, 2015). It follows that dynamic considerations such as innovation and learning-by-doing should be incorporated into the efficiency assessment of alternative policies, which are ignored in the simple static cost assessment of Figure 1.

Peer effects and social interactions. Static economic analyses may also understate policy impacts in contexts where peer effects and social interactions matter. For instance, a person's decision to adopt a green technology may increase the likelihood of adoption by peers, such as neighbors, co-workers, or family and friends. Bollinger and Gillingham (2012) provide evidence of peer effects in solar adoption by households. Using data from California, they find that an additional rooftop solar installation increases the probability of adoption in the same zip code by 0.78 %.

Likewise, through the effect of social norms, comparison with peers may lead people to adopt more environmentally friendly behavior. Allcott (2011) and Allcott and Rogers (2014) evaluate the impact of social comparison-based home energy reports sent repeatedly to US households, allowing them to compare their electricity use to that of neighbors. They find that the program reduced energy consumption by 2.0%, an effect equivalent to increasing short-run electricity prices by 11 to 20%. Importantly, they also find relatively persistent effects, with households responding even two years after the intervention.

These findings illustrate that not considering the dynamic effects of policies can understate their cost-effectiveness. On the contrary, acknowledging them is important to designing the timing of policies in ways that help speed up the diffusion process of green technologies and energy conservation efforts.

Electric vehicles (EVs). Promoting EVs is faced with a chicken-and-egg problem: buyers would not buy EVs without a charging infrastructure while infrastructure owners would not have incentives to develop it without sufficiently many EVs on the road. Given these coordination problems, it might become efficient to provide support to one or the two sides of the market until both sides reach a critical size above which no further support will be needed.

Indirect network effects in EV markets are studied by Li et al. (2017), Springel (2021), and Luo (2022), all of which find that car purchases and charging stations complement each-other. However, they also find that subsidies to the charging infrastructure are relatively more cost-effective. For instance, Springel (2021) finds that subsidies on charging stations are more than twice as effective in promoting additional electric vehicle adoption than EV subsidies.

In some cases, network effects can be enhanced through policy choices that do not require additional monetary support. For instance, Li (2021) shows that unifying standards for charging electric vehicles is welfare improving, as it boosts EV adoption while reducing the need to build as many charging stations as compared to when standards are incompatible.

Green Hydrogen. Currently, most of the efforts to support green Hydrogen involve supply-side measures (Moraga et al., 2018). However, a necessary condition for the production of Hydrogen to be profitable is demand for it. The need to develop both demand and supply may give rise to a dynamic coordination failure. The existence of learning economies and unpriced environmental externalities further justify implementing policies in support of green Hydrogen.

During their initial stages of deployment, renewable energies encountered market failures (Borenstein, 2012) similar to those faced by green Hydrogen now. However, the extent of coordination failures experienced by these two technologies differs significantly. The reason is that the electricity produced by the renewable plants is injected into the grid, with no need to find individual buyers for it. Additionally, the low variable costs associated with renewable electricity production ensure that, once the initial investment is made, it consistently displaces fossil-fuel power plants. Furthermore, the widespread use of electricity means that households and businesses do not have to make substantial adjustments to accommodate renewable energy sources.

The same cannot be said about green Hydrogen. While blending a small amount of Hydrogen into existing gas pipeline networks is possible, this practice is not the norm. Consequently, Hydrogen producers must actively seek buyers who, in turn, must adapt their equipment to substitute fossil fuels with green Hydrogen. Moreover, the production of green Hydrogen incurs significant variable costs, primarily related to the electricity cost, which means that investing in electrolyzers does not guarantee that Hydrogen will be actually produced.

These differences explain why regulators have relied on different support approaches for renewables and green Hydrogen. In the early stages, renewables received fixed payments for every megawatt-hour (MWh) they produced, typically through the so-called Feed-in-Tariffs (Fabra, 2015). Conversely, standard support methods for green Hydrogen involve either production subsidies on top of the price received by hydrogen producers or capacity subsidies. The uncertainty surrounding green Hydrogen investment and production costs and the prices buyers will be willing to pay for it makes it challenging for regulators to determine appropriate subsidy levels. For this reason, the European Commission's proposal is to implement an EU-wide auction to determine production subsidies for green Hydrogen, which will be paid upon delivery of certified green Hydrogen (European Commission, 2023a). Even though the Commission has not yet run any auction, some details of the first pilot auction are known. A fixed budget (800 M€) will be allocated to the lowest-bidding projects in a pay-as-bid format with a publicly known price cap (4.5€/Kg). The winning projects will be entitled to the subsidy for the quantities offered in the auction for 10 years.[2]

Governments are also starting to put in place a wide variety of policy instruments

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[2] This approach contrasts with the US Inflation Reduction Act policy, which grants green Hydrogen producers a transferable investment and production tax credit decided by the regulator (US Congress, 2023).

to support Hydrogen demand (International Energy Agency, 2021). For instance, the European Commission (2023a) explicitly states that *"For investments to be unlocked on the production side, more demand visibility is needed."* Accordingly, it plans to implement policies to connect renewable Hydrogen supply with the emerging demand by the off-takers.

Green Taxonomy. In some regions, it is difficult to fully substitute coal with renewable energies directly because of a lack of natural resources or other bottlenecks (e.g., grid stability concerns, local opposition, etc.) In some cases, expanding the gas infrastructure would facilitate the coal-to-gas substitution, allowing specific emissions to go down by two-thirds (e.g., the difference in coal and gas emissions rates). Yet, these investments would become stranded once the transition to renewable energies is fully achieved unless they are Hydrogen-ready, i.e., unless they can be refurbished to produce or transport Hydrogen in the future at low cost.

This issue has been the subject of an intense debate in Europe around the EU Green Taxonomy, which classifies sustainable and non-sustainable activities in order to guide green investment efforts. Ultimately, the European Commission has decided to include gas in the Green Taxonomy based on the premise that both gas and nuclear energy *"contribute to the transition to climate neutrality"* (European Commission, 2022). Implicit in this decision is the recognition that while some technologies may not be part of the future energy mix, they could still play a role in transitioning from polluting sources to renewables. However, considering the risk of lock-in, whether the decision to allow for transition technologies is efficient has to be carefully assessed on a case-by-case basis.

2.2 Feasibility

Policies typically need to have sufficient societal support to be adopted. For instance, cost-effective investments in renewable energy or transmission capacity often face local opposition. The same applies to carbon pricing and other climate policies which, despite bringing benefits for all, cannot be implemented because of a lack of social support. Likewise, it is often easier politically to introduce standards or low-carbon subsidies than carbon pricing, although these instruments are not equivalent from an efficiency point of view.[3] In some cases, feasibility will require that accompanying policies be put in place. For instance, carbon pricing coupled with a rebate of tax revenues via transfers may contribute to making carbon pricing more socially acceptable.

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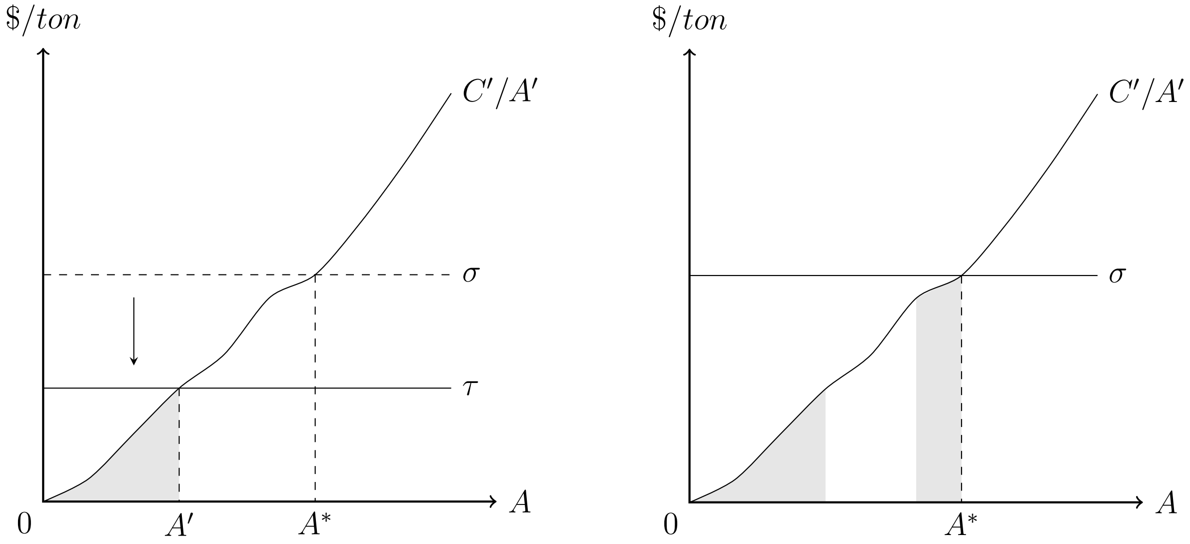
[3] Borenstein and Kellogg (2022) analyze this issue in the context of electricity markets, raising some doubts on the wide-spread idea that carbon pricing is always superior. In particular, they show that the emissions difference between carbon pricing and renewable mandates might be small. Moreover, the price increasing effect of carbon taxes might widen the departure from efficient prices, taking into account that retail prices currently incorporate cost components beyond marginal costs.

Figure 2: Feasibility constraints affect the optimal toolbox



(a) Reducing ambition for a feasible policy

(b) Implementing the optimal feasible set

Notes: These figures show a supply curve of abatement options, with different levels of ambition. The shaded areas represent the feasibility budget. On panel (a), ambition is reduced as the carbon price, τ, is reduced below the social cost of carbon, τ. On panel (b), ambition is not reduced yet some cheaper but unfeasible policies are not implemented in favour of costlier but feasible policies.

In mathematical terms, one can think of adding a feasibility constraint to the above problem, taking into account that different policies might eat differently into this feasibility budget (e.g., via cost of public funds, relative popularity, etc.):

$$\max_{\mathbf{x}} B(\mathbf{x}) - C(\mathbf{x})$$
$$\text{s.t.} \quad F(\mathbf{x}) \leq \overline{F}.$$

These feasibility constraints might force to reduce the level of policy ambition. For instance, while the efficient solution is to set the carbon price (τ) at the social cost of carbon (σ), this might prove socially unfeasible. If cheaper policies are also more feasible, the solution might have to involve reducing τ below σ.[4] As shown in Figure 2a, this would reduce the amount of carbon abatement below the optimal level A^*. Yet, the carbon price could be brought back to σ if it is implemented together with other policies that would make it socially feasible (such as compensations for the losers). Instead, if feasibility is not perfectly correlated with the cost of the policy, then the optimal policy could result in a different allocation such that some cheaper but unfeasible policies are dropped in favour of the feasible ones, as shown in Figure 2b. Importantly, the figure highlights that

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[4] Policy ambition could be brought back to σ if it is implemented together with other policies, $\mathbf{y}$ (such as compensations for the losers), that make it socially feasible, $F(\mathbf{A^{-1}}(\mathbf{A}^*), \mathbf{y}) = \overline{F}$.

implementing feasible and cost effective policies achieves more abatement than reducing the level of ambition.

Overall, this analysis suggests that it would not be optimal to delay investment in cost effective projects simply because there are other more efficient projects that have not yet been carried out. Since not all projects are competing for the same resources, nor have the same likelihood of a successful implementation, less efficient projects need not crowd out more efficient ones. Again, these issues can be illustrated though some policy examples.

Carbon policy and compensation schemes. The need to ensure political feasibility has often affected the preference over regulatory instruments in the space of carbon pricing. Cap-and-trade has been favored as it has explicit compensation mechanisms by means of awarding free emissions allowances (so called, grandfathering), even though this practice runs counter to the polluter-pays principle underlying environmental policy making.[5] In Europe, where a carbon market is in place since 2005, compensation schemes were introduced for industries under risk of leakage (Reguant and Fowlie, 2022; Martin et al., 2014).

However, when designing compensation schemes, regulators face asymmetric information regarding compliance and relocation costs. Asymmetric information encourages regulated firms to exaggerate their compliance costs and the risk of relocation to obtain higher compensations or more lenient environmental obligations. Taking asymmetric information into account, Ahlvik and Liski (2022) show that the optimal mechanism departs from the commonly-used compensation policies that effectively curb carbon prices, such as emission tax refunds, cheap offsets, and sector-specific exemptions.[6] Asymmetric information is also at the heart of the substantial overcompensation embodied in the existing compensation schemes to avoid carbon leakage in the EU (Martin et al., 2014).

While compensation schemes were initially necessary to make carbon pricing feasible, the introduction of the Carbon Border Adjustment Mechanism (CBAM) would make those compensations unnecessary as European manufacturers would be competing on a level playing field with the exporters (Fowlie et al., 2021).

Recent trends in the geopolitics of climate policies have opened the door to a politically feasible CBAM in Europe, highlighting the fact that previously unfeasible policies can become feasible over time. However, the timing of its introduction, with a gradual

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[5] Taxes also allow for similar compensations. For instance, rebates of environmental taxes are often used to subsidize energy-intensive industries. For instance, in Germany, industrial consumers have been exempt from the Renewable Energy surcharge used to cover the difference between the wholesale electricity prices and the fixed prices guaranteed to renewable power producers.

[6] Instead, it is optimal to combine high carbon prices (above the optimal price in the absence of reallocation risk), lump-sum compensations for the staying firms, and the possibility that the moving firms sell their emission reductions to the local policymaker.

ramp up, and the ability to effectively monitor emissions from imports will largely dictate its efficiency (Ambec, 2022; Garicano, 2021).

Social acceptance of renewable investments. Because of scale economies, investing in grid-scale renewables is more economically efficient than investing in smaller distributed generation projects. This fact remains true even when one accounts for the effects of distributed generation on the savings in future transmission and distribution network investments (Astier et al., 2022). However, even if economically efficient, massively deploying large grid-scale plants is often not feasible due to a lack of social acceptance. Wüstenhagen et al. (2007) describe three dimensions of the social acceptance of renewable projects: socio-political, community, and market acceptance. The first one regards acceptance at the broader level, i.e., whether society (including policymakers, key stakeholders, and the public opinion) supports renewable energies; the second refers to acceptance by local stakeholders, particularly residents and local authorities; and the third regards issues like households' demand for solar panels. While social feasibility has to satisfy all three dimensions, the lack of community acceptance currently makes the choice set binding. Local communities oppose renewable projects as they often perceive the costs and reap a small fraction of the benefits of grid-scale projects (Fabra et al., 2023; Germeshausen et al., 2021). Therefore, the higher social acceptability of small-scale projects recommends also relying on them despite their higher costs. In sum, social feasibility should also be part of a broader notion of efficiency.

Carbon taxes vs. efficiency standards. At large scale, renewable policies to support wind and solar in Europe and the United States have traditionally relied on subsidies. In the case of Europe, these subsidies have complemented carbon taxes already in place in the electricity sector. While higher carbon taxes would have been more efficient, these additional subsidies triggered additional investments and are still welfare enhancing for reasonable values of the social cost of carbon (Petersen et al., 2022). In the United States, federal carbon policies are nonexistent. However, as highlighted in Borenstein and Kellogg (2022), a clean energy standard is an alternative feasible policy that can achieve a substantial part of the benefits in a deep decarbonization context. The intuition is that when the goal is to fully decarbonize electricity production, the end result on the supply side is quite similar regardless of the policy instrument of choice. In addition, they highlight that in the presence of other pricing distortions that lead to high retail electricity prices (Borenstein and Bushnell, 2022), such a policy is not necessarily less efficient.

2.3 Fairness

The impacts of climate change will be unequal, and so will the effects of adopting climate change policies to mitigate them. Hence, inequality concerns are a big driver of feasibility, often acting as a barrier to passing policy. While some policies might be regressive in the absence of countervailing action, e.g., carbon pricing if the income-elasticity of energy demand is less than unity, other policies can be perceived as more regressive than they actually are (Douenne and Fabre, 2020; Cahana et al., 2023). There are other sources of heterogeneity beyond income differences. For instance, coal miners and other workers in carbon-intensive industries will be more adversely impacted. At the same time, rural areas might have more to gain from renewable investments than large cities. Labor market effects are also expected to be largely heterogeneous, depending on the workers' skills.

In our simple framework, inequality concerns could be captured in two ways. First, as mentioned above, distributional aspects significantly affect the feasible set. Sectoral issues such as how to deal with coal mine closures are probably easier to model as a feasibility constraint. One could also include a measure of changes in welfare based on equity notions as a constraint, e.g., limiting the losses for different income groups or individual households (see Wolak (2016) for water utilities and Feger et al. (2022) for electricity rates).

Second, the welfare function can directly include a notion of fairness., opening the door for several formulations depending on the type of fairness to be captured. If the concern regards the distribution of total surplus between firms and consumers, one approach would be to include the social cost of public funds in the welfare function *à la* Laffont and Tirole (1986), thus penalizing policies that leave excessive rents to firms:

$$\max_{\mathbf{x}} B(\mathbf{x}) - C(\mathbf{x}) - \lambda T(\mathbf{x}),$$

where λ denotes the costs of public funds and $T(\mathbf{x})$ denotes the transfers paid from consumers to firms to carry out the policy, e.g. abatement through investments in renewable energy (Fabra and Montero, 2023).

In order to favour fairness across income groups, one option is to take into account the declining marginal utility of consumption (Levinson and Silva, 2021). Consider consumption decisions at the household level. As the price of consuming energy goes up, the household consumes less of the other goods in order to satisfy its budget constraint. Because the marginal utility of consumption is decreasing, this reduces the household's utility more the lower its income, and thus calls for compensation schemes that favour the low income groups. This approach would suggest a problem formulation with weights

λ_j on different social groups, which could be an inverse function of their income:[7]

$$\max_{\mathbf{x}} \sum_j \lambda_j (B_j(\mathbf{x}) - C_j(\mathbf{x}))$$

In order to favour inter-generational fairness, several authors have proposed to take into account the declining marginal utility of income via the stochastic discount factor, which impacts the time path of the social cost of carbon.[8]

The following episode illustrates the importance of fairness as a criterion to assess climate policies, and to correct them when necessary:

Distributional concerns over carbon pricing. Carbon taxes are widely regarded as an efficient tool to induce carbon abatement efforts. However, they often face an obstacle: social opposition undermines their political feasibility. Concerns over the distributional implications of carbon prices could explain their lack of social and political support (Furceri et al., 2021), with ideology also playing an important role (Anderson et al., 2023).

Comparing the distributional impacts of carbon taxes versus low-carbon subsidies has received much attention recently. First, the comparison depends on who pays the taxes versus who benefits from the subsidies. In turn, it depends on whether one compares taxes and subsidies in levels or relative to income. For instance, in the US, Borenstein and Davis (2014) find that tax credits (e.g., for homes weatherization, installation of solar panels, or the purchase of electric vehicles) have gone predominantly to higher-income households,[9] while high-income households predominantly pay carbon taxes. For instance, with US data, Hassett et al. (2009) report that the top income quintile would pay four times as much as the bottom quantile if carbon prices were introduced.[10] Globally, using 2019 data, Chancel (2022) reports that the bottom half of the world population emits 12% of global emissions, while the top 10% emits 48% of the total. The main underlying reason is that energy consumption tends to correlate positively with income, implying that high-income households benefit relatively more from investments that reduce energy consumption. For this reason, on distributional grounds, a carbon tax should be preferred over low-carbon subsidies such as tax credits.

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[7] For instance, this weighted cost-benefit approach is advocated by the White House (2023): *"Agencies may choose to conduct a benefit-cost analysis that applies weights to the benefits and costs accruing to different groups in order to account for the diminishing marginal utility of goods when aggregating those benefits and costs. Diminishing marginal utility means that an additional unit of a good is more valuable to a person if they have less of it than if they have more of it."*

[8] For instance, see National Academies of Sciences, Engineering, and Medicine (2017) and Newell et al. (2021).

[9] Borenstein (2002) finds a similar result in a study that focuses on tax credits for solar PV.

[10] See also Rausch et al. (2011), who perform a simulation analysis of the distributional impacts of carbon pricing depending on the precise formulation of the policy; in particular, depending on how is the revenue from carbon pricing distributed.

However, one arrives at the opposite conclusion if the incidence of taxes versus subsidies is computed relative to the households' income. Carbon taxes are found to be regressive because their incidence falls proportionally more on low-income families (Douenne, 2020). For instance, carbon prices often have a greater impact on households more reliant on private transport, who often are those living in rural areas where public transportation options are not available (Cronin et al., 2019). In line with this, Dechezleprêtre et al. (2022) find stronger opposition to climate policies by households in areas with lower availability of public transportation who rely more on private cars.

The distributional impact of taxes also depends on how the tax revenue is distributed. Similarly, the effect of subsidies depends on how the public resources to finance them were raised. For instance, using French data, Douenne (2020) finds that carbon taxes are regressive but could be made progressive by redistributing the revenue through flat-recycling. Progressive carbon recycling policies also provide social and political support (Beiser-McGrath and Bernauer, 2019; Dechezleprêtre et al., 2022).

This evidence of the social acceptability of carbon pricing illustrates a broader idea. Whenever climate policies raise a trade-off between their efficiency and equity properties, it is essential to offset their negative distributional impacts through specific policy design choices that do not undermine the goal of efficiently incentivizing emissions reduction.

Social protests and backfiring. The Yellow Vests movement in France illustrates that climate policies are often opposed by the losers of such policies (Douenne and Fabre, 2020). These can be the low-income households within society, who, e.g., live in rural areas, rely more on private transportation, and hence have higher carbon footprints. Likewise, households could oppose environmental policies, such as low-carbon subsidies, if a significant tax burden is needed to finance them. Groote et al. (2020) examine data from Belgium, where a generous program for rooftop solar adoption was funded through electricity surcharges for all consumers. They find that non-adopters in municipalities with high adoption rates changed their vote towards anti-establishment parties.

Losers of climate policies could also be the workers in the mining industry or at coal-power plants who lose their jobs due to the phasing out of polluting power sources such as coal. Or losers could also be countries within a broader region that suffer more from climate policy because they concentrate on the extraction of fossil fuels. For instance, this is illustrated by the opposition of Poland to increasing the ambition of European climate policy.

To address these distributional problems, the European Commission has implemented several types of compensation mechanisms. For instance, the Social Climate Fund has been created to temporarily finance direct income support for vulnerable households while supporting low-carbon investments for mobility and heating to reduce costs for vulnerable households. It will be funded with a fraction of revenues from the auctioning

CO2 permits (European Commission, 2021a). Likewise, the Just Transition Fund aims to compensate workers and regions particularly hit by the Energy Transition. It also fosters a reconversion of the economic activity of those regions, e.g., by training and reskilling workers, promoting the environmental rehabilitation of damaged areas, or supporting investments in clean energy and manufacturing capacity European Commission (2021b). These policies should both be seen as a way to promote social justice and also as a way to boost environmental policy ambition.

2.4 Effectiveness

The degree of certainty around the estimated reductions is another important aspect to consider. For instance, stopping the extraction and consumption of coal is likely to have immediate impacts on emissions, given that all likely substitutes, including natural gas, have smaller emission intensities. Carbon leakage also gives rise to weak effectiveness as it implies that the emissions reduced in one jurisdiction simply shift to another one. Weak ability to monitor compliance might also reduce the effectiveness of some carbon abatement policies.

Risk of failure could also increase the uncertainty about the scale of the future emissions reductions. For instance, carbon capture and sequestration can be more speculative over long horizons, making effectiveness more uncertain and harder to measure.

One potential way to include effectiveness or risk of failure into the framework is to consider an assessment of the expected reduction of emissions from a certain policy. In the minimization framework used to derive optimal abatement, policymakers could consider a modified evaluation:

$$x_j^* = \arg\max_{x_j} \tilde{\sigma}_j A_j(x_j) - C_j(x_j),$$

where $\tilde{\sigma}_j$ corrects for the potential failure to deliver effective emissions reductions with an abatement strategy j. Under an approach based on the social cost of carbon, that would imply disregarding policies that are deemed too ineffective. Under a net-zero approach, it would imply shifting abatement strategies towards sectors in which the risks of under-delivering are the highest.

While proper estimation of $\tilde{\sigma}_j$ might be difficult, there is growing research quantifying the risks of seemingly efficient policies that end up being less effective than expected.

Carbon leakage. The shift of emissions from regulated areas to unregulated ones has been a longstanding concern when it comes to the effectiveness of climate policy (Böhringer et al., 2014). Under most leakage models, this would imply that abatement efforts in a given sector in a jurisdiction lead to emissions reductions that are less than nationally measured.[11] Leakage impacts, however, are difficult to quantify (Fowlie and Reguant, 2018). If carbon taxes can be avoided by shifting emissions to untaxed jurisdictions, the extent of carbon abatement is limited and the performance of a cap-and-trade market can be diminished (Reguant and Fowlie, 2022).

Additionality. For policies to be reducing greenhouse gas emissions effectively, they also need to be additional, i.e., they should incentivize measures that would not have occurred without such policies.

Additionality clauses can be used to remediate some of the challenges, albeit requiring substantial monitoring and reporting. For instance, Europe now requires the additionality of renewable investments for granting the green label to Hydrogen. Likewise, it will not provide support for green Hydrogen projects that do not comply with the additionality requirement.[12] It also requires that renewable and Hydrogen production occurs at the same time ('temporal correlation') and in the same area ('spatial correlation'). Otherwise, the risk is that the production of green Hydrogen to substitute gas or other forms of polluting Hydrogen (e.g., grey Hydrogen that is produced with fossil fuels) does not truly contribute to reducing carbon emissions.

While research on this topic is still limited, there are some recent exceptions. For instance, Ruhnau and Schiele (2023) perform electricity market simulations showing that a flexible definition of green Hydrogen without the hourly simultaneity requirement would not necessarily increase emissions in the power sector. Even without it, firms would have incentives to produce Hydrogen when electricity prices are low and renewables abundant while avoiding producing Hydrogen when prices are high and marginal power demand would be met with polluting resources. They also argue that the hourly simultaneity requirement would lead investors to build much larger wind turbines, Hydrogen electrolyzers, and Hydrogen storage, increasing Hydrogen production costs and delaying its adoption.

The issue of additionally also needs to be considered when evaluating a policy portfolio. For example, under a cap-and-trade mechanism, subsidies to one of the regulated sectors to reduce emissions might just make the emissions target easier to achieve, rather than increase stringency. This has come to be known as the 'waterbed effect'. Properly accounting for these interactions is critical for an effective climate policy portfolio (Perino et al., 2019).

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[11] Innovation is a channel by which leakage can even be positive, by spurring innovation and leading to cleaner international technology adoption.

[12] More specifically, the new auctions for production support European Commission (2023b) are open only to Renewable Fuel of Non-Biological Origin (RFNBO) Hydrogen *"produced by new production capacity (i.e., capacity for which, at the time of application, start of works did not yet take place)´´.*

Carbon offsets. Lack of additionality also underlays some of the problems faced by carbon offsets, which have traditionally been thought of as part of the toolbox for carbon abatement. For instance, the Clean Development Mechanism (CDM) was introduced as part of the Kyoto protocol to allow countries to fund carbon abatement projects in other countries and claim the saved emissions to comply with their own emissions targets. Experience has shown that CDMs have reduced the effectiveness of carbon abatement efforts: the ETS market was flooded with CDMs, which depressed the cost for emitting in Europe, without bringing in additional carbon abatement. Recent research suggests that CDMs were highly ineffective (Calel et al., 2021).

This raises the question of whether offsets should be part of a global cap-and-trade or should they be a separate market. While it might allow to harvest emissions reductions in unregulated jurisdictions, the risks for watering down the emissions reductions goal is large. Indeed, this discussion extends to the issue of whether negative emissions such as direct air capture should be included in a cap-and-trade program. While efficiency might dictate that, in an ideal setting, all emissions should be part of the same scheme, concerns over their additionality, effectiveness and verifiability would suggest keeping them as a separate market.

Other factors affecting effectiveness. Behavioural responses (Allcott and Mullainathan, 2010) or principal-agent relationships (Myers, 2020a) should also be included into the assessment of effectiveness. Some policies might be cost-effective if individuals act as planned, but behavioural biases or a conflict between the principal and the agent might imply weak or distorted responses that reduce effectiveness. This issue arises prominently in studies of energy efficiency in rented dwellings, in which the tenant pays the bill but the owner is responsible for making the investments Myers (2020b).

Investments in energy efficiency in buildings also provide an important lesson regarding policy effectiveness. While it is widely recognized they provide a highly promising strategy to reduce carbon emissions, economic evaluations have revealed that the actual energy savings achieved through these programs often fall short of expectations. In fact, in some cases, the realized savings may be as low as 30% of the projected savings, significantly undermining the cost-effectiveness of these initiatives; see Fowlie et al. (2018) and Burlig et al. (2020), among others.

Nonetheless, Christensen et al. (2022) show how the effectiveness of retrofit and renovation programs can be substantially enhanced through a better allocation of the funds. They leverage the power of machine learning tools to improve the accuracy of energy savings projections, with the aim of better targeting program resources to homes that are more likely to yield higher returns. Their approach reveals that the net benefits of the program could increase from 0.93 USD to 1.23 USD per dollar invested, thus contributing to an improved effectiveness of the policy.

Last, effectiveness could involve metrics other than pure cost comparisons. For instance, a project could be socially effective if it empowers people and persuades them to act beyond the project under consideration. An example at hand is the social value of energy communities built within neighborhoods or around schools.

2.5 Long-term considerations

Given the long-run nature of the climate change problem, policies that are credible in the long run can provide additional benefits. Policy credibility reduces uncertainty, which could otherwise become a serious obstacle for low carbon investments given their often high upfront capital costs. Credibility could be at stake if the profitability of the investments depends on subsidies or prices paid over a long period of time. To avoid this, the optimal policy toolbox should put emphasis on those strategies that ensure that emissions reductions are credible in the long-run (Gerlagh and Liski, 2017). They should also put more emphasis on the risks of falling short in our decarbonization strategies, due to the non-linear impacts of climate change.

While it is difficult to embed these long-run considerations in our simple equation, one could reframe the objective function to Knightian approaches with uncertainty. More generally, integrated assessment models are gradually incorporating uncertainty and robustness in their evaluation of alternative policies (Gillingham et al., 2018) as well as tipping points, which account for non-linearities (Dietz et al., 2021).

When it comes to policy implementation, we discuss several examples in which long-run considerations can affect the choice of policy implementation.

Robust market design. Cap-and-trade programs were initially not stable and lacked credibility in the long-run. For example, the initial phase of the EU-ETS was disappointing, as it gave rise to very low prices, even close to zero. Thankfully, other markets have actively considered this experience in their market design in order to avoid the negative consequences of volatile price signals. For instance, the Californian market AB-32 included a floor and an implicit cap (Borenstein et al., 2019). The EU ETS also strengthened its long-term signal with its market stability reserve in 2019.

Credibility of renewable policies. The importance of credibility is illustrated by households' behavior regarding investments in solar PV. As shown by De Groote and Verboven (2019), households are more willing to invest in renewable energy when they receive upfront subsidies at the investment stage rather than when promised to receive output support over the lifetime of the assets. This is explained by households having low discount factors, which might, in turn, reflect a lack of credibility regarding future payments.

The concerns regarding the lack of credibility are well-founded, given that the electricity sector and its dynamics are rapidly evolving. For example, Nevada and California have changed their net metering policies retroactively, affecting the profitability of these installations. While not strictly modifying the rate at which rooftop solar is subsidized, tariff design is an implicit subsidy to solar energy (Borenstein, 2017). While retroactively changing policies can undermine the future credibility of these policies, these changes can be motivated based on equity and fairness concerns, which is another goal in this challenging balancing act (Feger et al., 2022).

The issue of credibility can also have consequences for large-scale projects. For example, Spain underwent a very ambitious solar program with large subsidies in the mid-2000s. Still, it ended up changing its original terms due to its significant burden to electricity costs and the impact of the financial crisis, which led to substantial litigation.[13] Ryan (2021) documents that the credibility problem is not only pertinent to subsidies but can also affect competitive power purchase agreements (PPAs) more broadly, even if auctions clear at competitive prices. In the context of India, he finds that auctions backed up by the central government tend to lead to lower prices than those that only have state backing.

Long-run innovation policies. When designing innovation policies, one needs to consider the risks of directing funding and R&D into technologies that are only effective if climate change policies have continued support or have support in all jurisdictions. The challenge is to identify which R&D investments will deliver enough cost reductions to make support unnecessary in the future, from those that will never be adopted unless they receive support and explicit enforcement. Cost-effective renewable power with batteries that can be cheaper than fossil fuels is an example of the former, while carbon capture capture and sequestration might be an example of the latter. From this perspective, more emphasis on green innovation, rather than remediation, is warranted (Blanchard et al., 2022).

Increasing social cost of carbon. Given all the difficulties in decarbonizing our economies, it is likely that the costs of climate change will continue to grow above and beyond what is predicted by integrated assessment models, which tend to have successful climate policies built-in. The empirical evidence regarding the consequences of climate change is also improving. As shown in a recent study, mortality-related damages from climate change are much greater than had previously been understood, making the cost-benefit analysis based on more optimistic prospects that were wrong ex-post (Carleton et al., 2022).

Several policies that have received substantial criticism for not being cost-effective

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[13] See, for example, a discussion of several arbitration cases in Reynoso (2019).

now pass the cost-benefit tests under the new costs of social carbon. Therefore, with what we know today, those policies should have been considered cost-effective even several years ago. This conclusion is all the more relevant because CO_2 is a stock pollutant, i.e., the damage is the same regardless of whether the emission occurred back then or today. Therefore, the optimal policy toolbox should adopt a threshold for the cost-benefit analysis that takes into account the impact of foreseeable failed climate policies on future climate damages, rather than evaluating damages on the optimal path or at its current values.

3 Concluding remarks

The urgent need to decarbonize our economies requires that we put in place policies that are not only efficient but also feasible, fair, effective, and stable over long-term horizons. These requirements give rise to a broader notion of efficiency that every optimal environmental policy portfolio should satisfy.

In order to illustrate the various dimensions of this broader notion of efficiency, we have provided examples of policies that currently constrain progress of climate action. The problem is not necessarily the lack of efficient tools to reduce emissions but rather the ambition and ability to implement those tools promptly and effectively. Throughout our discussion, we have emphasized that the public's acceptance of these policy instruments plays a pivotal role in their feasibility and the ultimate success of climate initiatives, making it a cornerstone of environmental policy.

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