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23-12 Sequencing decarbonization policies to manage their macroeconomic impacts

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ABSTRACT

Decarbonization policies exhibit clear sequencing patterns within sectors and countries as well as across them. This paper explains these sequences using a Solow-Swan growth model with two distinguishing features. One is a variable elasticity of substitution production function with both fossil fuel–based and low carbon inputs. The second is a choice of decarbonization policy: a carbon price or low carbon investment subsidy. Their policy costs have significant macroeconomic impacts. One cost arises from a short-run tradeoff between decarbonizing productive activities and maintaining the level of output. There is also a second-round policy cost associated with the policy choice between a low carbon subsidy or a carbon price that varies with progress in decarbonization. The modeling shows how these policy costs can be managed by the observed policy sequence of a low carbon investment subsidy before a carbon price and initial use of this decarbonization policy in sectors where low carbon inputs are stronger substitutes for the incumbents. These macroeconomic explanations of observed decarbonization policy sequences complement others based on microeconomic considerations of efficiency in imperfect markets, distributional fairness, and economic interests in change.

JEL codes: O33, O44, Q43, Q54, Q58

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1. Introduction

Decarbonizing energy largely occurs through technological change and investment in low carbon alternatives to incumbent technologies and fossil fuels. This structural change involves the reallocation of capital and labor to expanding low carbon activities and away from declining ones that are based on fossil fuels. While changes in consumer preferences are important too, most households and firms in industrialized countries—and many in developing countries—must invest in low carbon technologies to reach net zero emissions of carbon dioxide from fossil fuels and halt their contribution to climate change.

The structural transformation of energy has significant macroeconomic impacts. If a country has ignored the climate externality, there can be a short-run policy cost from the tradeoff between decarbonizing productive activities and maintaining the level of output. More investment in low carbon technologies and less in the incumbents prompted by decarbonization policies can lower short-run economic output relative to "doing nothing." Although the policy cuts long-run societal losses from climate change, this short-run policy cost arises if climate externality was overlooked in past investment decisions and climate change losses do not affect short-run output. This paper shows that the size of this policy cost depends on the ease or difficulty with which low carbon inputs substitute for fossil fuel–based ones. Stronger substitutability mitigates the output loss.

There is, in addition, a second-round policy cost associated with choice of decarbonization policy: a low carbon investment subsidy or carbon price. This policy cost arises from the need to either fund a low carbon subsidy with taxes or mitigate the adverse distributional impacts of a carbon price with transfers. This paper shows that the relative scale of the two policies varies with progress in decarbonization. In early stages of decarbonization, a low carbon investment subsidy is a smaller-scale intervention than a comparable carbon price. But the relative scale of the two policies reverses with progress in decarbonization. If the decarbonization policy and existing tax system are well designed, the second-round policy cost increases with the scale of intervention and associated change in public finances. In principle, each decarbonization policy can efficiently induce a comparable substitution of low carbon for fossil inputs—the key first-round effect.

Decarbonization policy choices can manage these two policy costs, and two policy sequences over time are clearly evident: an early policy group used to initiate decarbonization within a country and sector and a later group implemented a number of years after the initial policies (Linsenmeier, Mohommad, and Schwerhoff 2022). The earlier group includes setting long-run decarbonization goals and subsidizing low carbon investments. In the later one, research, development, and deployment (RD&D) are targeted at low carbon technologies and carbon emissions are priced after five to 18 years. The second policy sequence involves variation across sectors. Decarbonization policies are initially implemented in sectors and countries where low carbon inputs are stronger substitutes for the market incumbents (Fries 2021, pp. 100–08).

This paper examines decarbonization policy costs, choices, and sequences using a Solow-Swan growth model with two distinguishing features (Solow 1956, Swan 1956). One is a variable elasticity of substitution (VES) production function with fossil fuel–based and low carbon inputs rather than a customary constant elasticity of substitution (CES) function. The VES function allows for the substitutability of low carbon and fossil technologies to increase as low carbon technologies gain a greater system role, a characteristic of some aspects of energy system decarbonization. The second feature considers two decarbonization policies—a low carbon investment subsidy and a carbon price—to prompt the substitution of low carbon for fossil fuel–based inputs. This feature allows for policy choices and sequences.

The approach is positive rather than normative. The paper aims to explain the observed decarbonization policy sequences from a macroeconomic perspective. Taking as given the normative case for climate action, it provides an answer to a pair of questions often asked by policymakers: what will happen to the economy if climate actions are taken and how can the impacts be effectively managed? The paper complements other explanations of observed policy sequences that are based on microeconomic considerations of efficiency in imperfect markets, distributional fairness, and economic interests in change.

Consistent with observed policy choices, the modeling shows that at the early stage of decarbonization, a low carbon investment subsidy is a smaller-scale intervention than a comparable carbon price. If the subsidy is well targeted and the existing tax system is optimal, public finance considerations point to the subsidy also having a lower second-round policy cost at this early stage (Klenert et al. 2018a, 2018b). A second, complementary explanation for initial use of the subsidy is that it has a stronger estimated effect at this stage in inducing low carbon innovation (Grubb et al. 2021). With this differing incentive effect, a low carbon subsidy can mitigate more of the short-run output loss through innovation over time. In some sectors, this loss can be more than offset by innovation and eventual scale economies (Way et al. 2021).

That decarbonization policies are initially implemented in sectors and countries where low carbon technologies are stronger substitutes also reflects their policy costs. A benefit of the sequenced approach across sectors is that it postpones the larger short-run output losses in harder to decarbonize sectors and allows time for their low carbon technologies to progress, assuming innovation can be induced in other ways. For example, evidence shows that long-run climate commitments like time-bound goals for net zero emissions can induce such innovations, even without a concurrent carbon price or low carbon subsidy (Kruse and Wetzel 2016, Nicolli and Vona 2016, Grubb et al. 2021). This sequence eases the output loss if a sectoral decarbonization policy is implemented once substitutability strengthens. A cost of this policy sequence is that it allows excessive emissions in harder to decarbonize sectors relative to a uniform decarbonization policy across sectors.

2. Low carbon substitutes for incumbent technologies and fossil fuels

Modern energy is an essential input to most goods and services produced in an industrialized economy. The incumbent energy-producing capital stock converts primary energy resources—

primarily fossil hydrocarbons such as coal, crude oil, and natural gas but also nuclear and hydro resources—into the supply of useful energy carriers like electric power and fuels.[1] The energy-using capital stock in buildings, transport vehicles, and manufacturing and industrial plants further converts these carriers into energy services and materials for comfortable and productive houses and offices, transport services for people and goods, and useful materials like steel, aluminum, cement, chemicals, and plastics for producing goods.

An energy system efficiently integrates the energy-producing capital stock with the energy-using capital stock. For example, coal mining and processing, rail transport of coal, coal-fired power plants for electricity generation, and the transmission of electricity by networks of wires and its various end uses in buildings (e.g., household appliances and lighting) and industrial plants (e.g., electric arc furnaces for steel production and aluminum smelters) form integrated value chains of incumbent technologies. The value of energy in a market economy ultimately derives from its various end uses in providing energy services and materials.

Another energy value chain is the extraction of crude oil; its refining into liquid transport fuels such as diesel, gasoline, and kerosene; their distribution networks; and use by internal combustion and jet engines in cars, trucks, ships, and airplanes to transport people and goods. Yet another is the extraction and processing of natural gas, its transport via pipelines, and use in boilers to produce space heating and hot water for building occupants and high-temperature heat for producing goods such as cement.

The decarbonization of energy systems requires the restructuring of energy value chains so that their primary energy resources are primarily wind, solar, hydro, and bioresources that are continually renewed by the sun, as well as nuclear resources, rather than fossil hydrocarbons.[2] This transformation of energy systems requires new ways of producing energy carriers from low carbon primary resources. Energy end use technologies must also adapt to these new energy supplies and their costs.

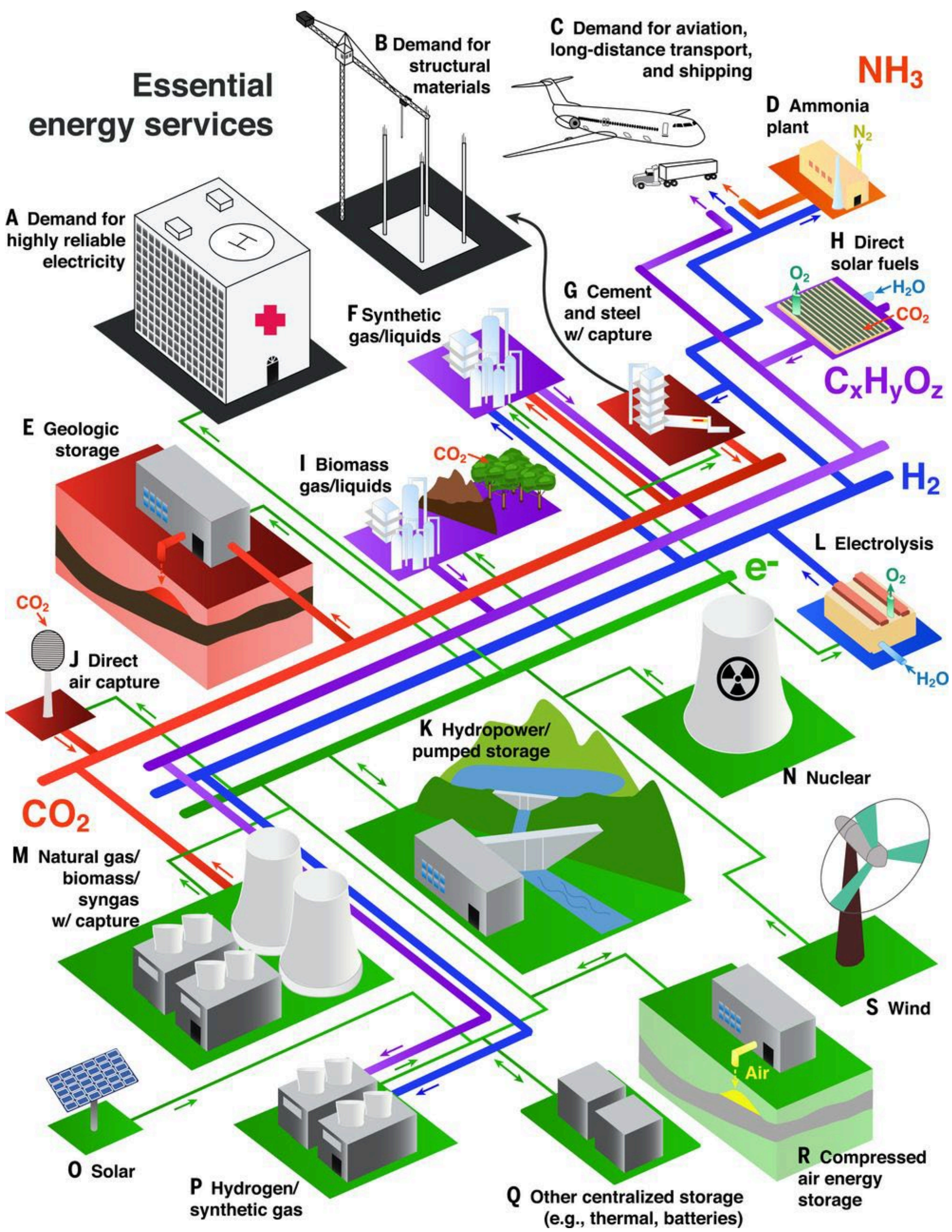
Figure 1 depicts a feasible future low carbon energy system—especially in terms of energy supply. Such a system would rely primarily on renewable and nuclear resources and transform them mainly into electric power (Davis et al. 2018, Clarke et al. 2022). Some power would be further converted into low carbon fuels like hydrogen and synthetic hydrocarbon fuels for use in sectors that do not appear amenable to electrification, such as heavy industry and transport.

[1] On average, current energy systems rely on fossil hydrocarbons for about 80 percent of their primary energy (IEA 2022a, p. 435).

[2] Most primary energy at the Earth's surface that technology can capture has as its initial source solar irradiance from the sun. This energy heats the land and water at the planet's surface, causes winds in its atmosphere, drives its water cycle, and provides energy for life on Earth. Fossil hydrocarbons are large stores of this energy in the organic remains of prehistoric plants and plankton that were buried, compressed, and heated by geological processes in the Earth's crust over millions of years. In addition, nuclear fission releases energy from fissile elements in the Earth's crust (e.g., uranium). Decarbonizing energy involves substituting renewable and nuclear resources for fossil hydrocarbons in producing electric power and fuels. These low carbon resources are abundantly and widely available relative to foreseeable demands for primary energy (IPCC 2011).

Bioresources would be a further source of low carbon fuels, although land use constraints would likely limit their supply. Technologies such as carbon dioxide capture and storage would manage emissions from any residual fossil fuel use and industrial processes like cement production.

Figure 1. Illustration of a technologically feasible low carbon energy system



Note: (A) to (S) indicate the dominant role of specific technologies and processes. Black (A – C): end uses of energy and materials; orange (D): ammonia production and transport; red (E, G, J): carbon management; purple (F, H, I): hydrocarbon production and transport; blue (L): hydrogen production and transport; green (K, M– S): electricity generation and transmission.
Source: Davis et al. (2018). Reprinted with permission.

All of the depicted low carbon technologies for energy supply have shown their feasibility at least in demonstration projects. Some, such as wind turbines, solar photovoltaics (PV), and hydroelectric and nuclear technologies for power generation, are proven commercially.

Energy end-use technologies in a feasible low carbon energy system would also differ from the incumbents. A low carbon system would have a much greater share of electric power in energy supply to end users, given the widespread availability of renewable resources and relatively low costs of transforming them into electric power (Clarke et al. 2022). Just as fossil hydrocarbons are first transformed into fuels, some of which are burned to generate electric power, renewable and nuclear resources are largely transformed into electric power. The further conversion of power into low carbon fuels is technically feasible but entails significant energy conversion losses and costs even with likely technological advances.

Transforming end-use technologies from fuels to electric power would thus be likely in a low carbon energy system (Babiker et al. 2022, Clarke et al. 2022). For example, light-duty road vehicles are feasible to electrify, and this transformation is increasingly cost effective (IEA 2022b). This substitution is facilitated by the greater energy efficiency of electric motors than internal combustion engines, rapid improvements in battery technologies for storing energy onboard vehicles, and progress in decarbonizing electric power.

Similarly, the main energy demand in buildings is for space heating and cooling. While cooling is largely produced with electric power and air conditioners, the incumbent technologies for producing heat are boilers that use fossil fuels. Heating too would likely be electrified—especially with efficient heat pumps—once buildings are adequately insulated and sealed to become more efficient at storing and managing heat (Babiker et al. 2022).

Heavy industries that produce materials such as steel, aluminum, cement, chemicals, and plastics would need to decarbonize their production in one of three ways: electrification, use of low carbon fuels, or carbon management. But these options would likely add costs (Babiker et al. 2022, Clarke et al. 2022). Electric power is already a feasible substitute for fuels, so electrifying industrial processes would entail costs even if low carbon electric power were to cost about the same as that from fossil fuels. For example, fuels can be better than electric power at providing uniform, high-temperature heat for manufacturing processes. Moreover, low carbon fuels would be more costly than fossil fuels with likely technologies, and some industrial emissions would need to be managed. For them, natural carbon sinks like reforestation or technologies like capture of carbon dioxide from emissions or the air combined with permanent storage can cut net emissions. These fuels and carbon management processes too would add to production costs.

Long-distance and heavy-duty transport would also likely require low carbon fuels (Babiker et al. 2022, Clarke et al. 2022). Because of heavy payloads and long travel distances, these transport services have large onboard energy storage requirements that are potentially better served by low carbon fuels with higher energy densities than batteries.

This description of a feasible low carbon energy system, its likely technologies, and expected cost characteristics has three important macroeconomic impacts:

1. A low carbon energy system is feasible. There is demonstration of sufficient low carbon technologies to enable provision of most current energy services and materials with net zero emissions.
2. Decarbonization requires substitution of low carbon technologies for the incumbent ones. A key macroeconomic implication arises from their substitutability.
3. The energy-related capital stock consists of interrelated and heterogeneous technologies, reflecting the range of primary energy resources, energy carriers, and services and materials they produce. This is a feature of both current and feasible low carbon systems.

Heterogeneity also characterizes the substitutability of these technologies. For example, a series of fossil energy price shocks since the 1970s induced waves of energy-related innovations (Popp, Newell, and Jaffee 2010; Popp 2019; Grubb et al. 2021). They included energy efficiency gains and low carbon technologies such as those for renewable power generation and battery and fuel cell electric drivetrains for road vehicles. The price shocks and policy responses to them directed innovations toward easier margins of substitution away from fossil fuels and toward new unconventional sources such as shale oil and natural gas. Market selection left the more difficult margins mostly undisturbed.

3. Decarbonization policies and their observed sequencing

To decarbonize production of most goods and services, it is necessary to select and foster feasible options for technological substitution, and governments use a combination of policies to facilitate this structural transformation of energy systems. The observed policy approach deviates from and extends beyond the orthodox policy prescription in economics. The conventional policies consist of carbon pricing to internalize the climate externality and government subsidies for R&D to compensate for knowledge spillovers from innovation in all technology fields (Jaffe, Newell, and Stavins 2005). They include low carbon innovations, and carbon pricing can direct private R&D investment toward these technology fields.

Orthodox economics, moreover, prescribes a carbon price that is approximately the same for all emissions over time because it is the atmospheric concentration of carbon dioxide from cumulative emissions that determines the extent of climate change (van der Ploeg 2018, Dietz and Venmans 2019). Following Joseph Stiglitz (2019), suppose there is a critical threshold for cumulative emissions, above which global temperature and other climate change impacts become socially unacceptable. Because the decay of atmospheric carbon dioxide through the Earth's carbon cycle is so slow, the timing of an emission within the cumulative budget does not matter. There is a shadow price associated with it that is approximately constant over time.

To the extent used, however, carbon pricing applies only to some sectors—typically heavy industry and power generation. Moreover, the carbon price level is typically an inadequate reflection of the shadow price of emissions or more general concepts of an adequate carbon price (World Bank 2023, pp. 19–20).

Government support for private R&D investments, such as tax credits, applies to innovation activities rather than technology fields. These activities take their direction from the expected size of markets and relative prices, which government policies can influence. At the same time, public R&D investments and government subsidies for technology demonstration projects target technology fields that fiscal budgets prioritize.

The unorthodox decarbonization policy mix used in practice also includes

- direct regulation of energy efficiency and emissions,
- subsidies and incentives for low carbon investments (e.g., feed-in tariffs and tax credits for renewable power generation and purchase subsidies for zero emission road vehicles),
- energy-related information disclosure requirements and training programs, and
- direct government procurement of low carbon technologies.

These policies usually apply to specific energy-related sectors. There are in addition crosscutting reforms that set overall decarbonization goals and policy strategies.

Figure 2 shows the sequencing of decarbonization policies in 15 major emitting countries that had adopted carbon pricing by 2020.[3] Pooling policies across countries and sectors, carbon pricing is typically the last policy to be used in observed policy sequences. Pooling across countries by sector, it is the last policy deployed in each sector as well. Furthermore, 12 out of the 15 countries implemented carbon pricing in specific sectors only after all the other decarbonization policy instruments had been used.

In their analysis of decarbonization policies, Manuel Linsenmeier, Adil Mohommad, and Gregor Schwerhoff (2022) identified two policy groups. The first consists of four instruments that are used early in policy sequences: direct regulation of energy efficiency and emissions; grants, subsidies, and incentives for low carbon investments; energy-related information disclosure and education; and crosscutting policies that set overall decarbonization goals and policy strategies. The second group of later policies includes government support for RD&D projects targeted on low carbon technologies, voluntary agreements for private investments in them, their public procurement, and carbon pricing.

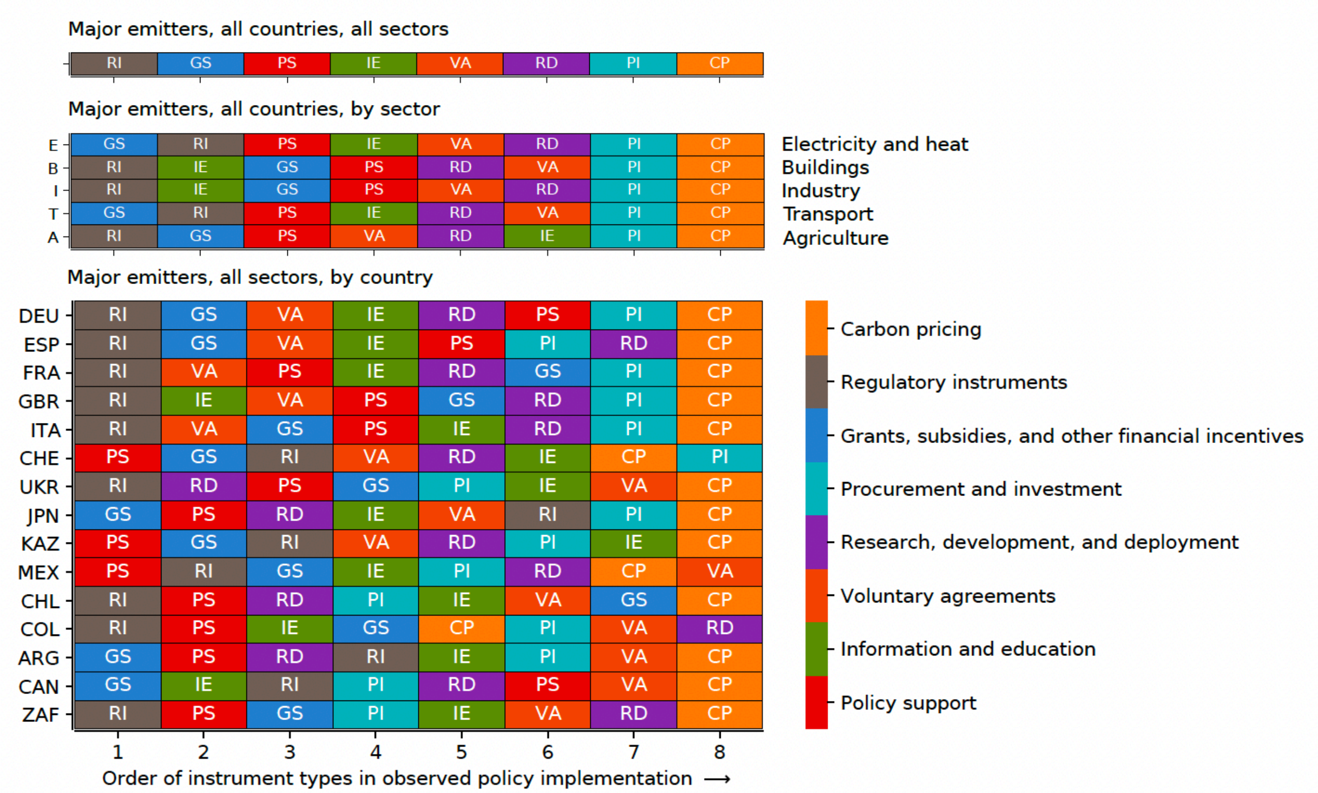
In addition to these policy sequences within sectors and countries, there is sequencing across them. Governments implemented decarbonization policies initially in sectors that experienced waves of low carbon innovations induced by a series of fossil energy price shocks since the 1970s. These policies were particularly prominent in countries that specialized in innovations

[3] The 15 countries are Argentina (ARG), Canada (CAN), Chile (CHL), Colombia (COL), France (FRA), Germany (DEU), Italy (ITA), Japan (JPN), Kazakhstan (KAZ), Mexico (MEX), South Africa (ZAF), Spain (ESP), Switzerland (CHE), Ukraine (UKR), and the United Kingdom (GBR).

and their manufacture (Fries 2021, pp. 100–08 and 202–12). There is thus likely causation from increasing substitutability of low carbon technologies to implementing decarbonization policies. The reverse causation, as assumed in the orthodox policy prescription, also occurs (Grubb et al. 2021).

There are several economic explanations of the observed decarbonization policy sequencing within sectors. One explanation sees the sequence as complementary policies that target market failures in addition to the climate externality and knowledge spillovers from innovation. These failures arise from inadequate innovation incentives in a market economy and scale economies external to individual firms (Bertram et al. 2015; Bataille et al. 2018; Stiglitz 2019; Fries 2022; Stern, Stiglitz, and Taylor 2022; Bristline, Mehrotra, and Wolfram 2023). External scale economies include direct and indirect network effects in energy systems and learning by doing.

Figure 2. Policy sequencing of major emitters with a carbon price by end-2020



Note: Emission cap and allowance trading schemes and carbon taxes are examples of carbon pricing (CP). Regulatory instruments (RI) pertain to requirements, codes, and standards for energy efficiency and emissions for appliances, buildings, equipment, and vehicles. Grants, subsidies, and other financial incentives (GS) include tax relief, feed-in tariffs, loan programs, and other fiscal incentives. Procurement and investment (PI) are public investments in infrastructure and low carbon technologies. Research, development, and demonstration (RD) include government tax credits for private investments specifically for low carbon R&D and public investment in R&D and demonstration projects for low carbon technologies. Voluntary agreements (VA) are negotiated agreements between the public and private sectors. Information and education (IE) pertain primarily to the provision of energy-related information and advice, energy labeling and certifications, and training programs.

Policy support (PS) refers to strategic planning for energy systems, creation of energy and climate governance institutions, and nonbinding and legally binding emission reduction targets.
Source: Linsenmeier et al. (2022). Reprinted with permission.

A second explanation focuses on regressive distributional impacts of carbon pricing and ways to manage them, including compensating transfers and carbon pricing differentiated by sector (Klenert et al. 2018a, Stiglitz 2019). These distributional impacts influence societal support for decarbonization policies and can contribute to their inconsistent implementation over time (Newbery 2016, Fries 2022).

A third explanation is more general. It sees the policy sequence as removing economic and political barriers to eventual implementation of the first best policy—carbon pricing (Meckling, Sterner, and Wagner 2017; Pahle et al. 2018; Dolphin, Pollitt, and Newbery 2019).

These explanations of sequencing low carbon investment subsidies before carbon pricing within sectors draw on microeconomic considerations of efficiency in imperfect markets, distributional fairness, and economic interests in change. But they do not explain initial policy targeting on sectors for which low carbon technologies are stronger substitutes and their phasing across sectors. An explanation for this observed policy sequence rests on the need to induce low carbon innovation, especially in harder to decarbonize sectors, and the ability to do so without a concurrent carbon price or low carbon investment subsidy.

For example, in a growth model with fossil and low carbon inputs and endogenous technological change, Daron Acemoglu and colleagues (2012) showed that both a carbon price and targeted subsidy for low carbon R&D can be needed to efficiently direct innovation toward low carbon inputs. Targeting R&D subsidies reinforces the relative price shift from carbon pricing to induce low carbon innovation and lessens the output loss from sole reliance on a carbon price. The ability to direct innovation toward low carbon technologies—aside from implementing a decarbonization policy that corrects the relative price distortion—creates scope for their sequencing across sectors while pursuing long-run climate stabilization goals.

4. A Solow-Swan model of a decarbonizing economy

Consider a macroeconomic model that, assuming away for now much of the energy-related capital stock's heterogeneity, allows for differences between fossil and low carbon inputs. These differences relate to their relative productivity and elasticity of substitution. They create a tradeoff between decarbonizing productive activities and maintaining the level of output—at least in the short run—especially in countries that create the initial markets for low carbon technologies.[4] The tradeoff requires management.

[4] See Gross et al. (2018) for a working definition of initial markets for energy-related technologies as well as empirical evidence on their diffusion within and across countries. The countries that have through their decarbonization policies created the initial markets for low carbon technologies are primarily major industrialized countries in Western Europe, North America, and East Asia, including China.

Building on the work of Stephie Fried, Kevin Novan, and William Peterman (2022), assume that the economy has a single final good, Y, for consumers, which is produced competitively with an energy-related intermediate input, X, and labor, L. The population grows at a constant rate, n. With a Cobb-Douglas production function for the final good, output per capita is

$$y = x^{\alpha}, \tag{1}$$

where $0 < \alpha < 1$ is the intermediate input share of output.

The intermediate input consists of a low carbon input, x_{lc}, and a fossil one, x_f. In principle, they can be either complements or substitutes.

The production function for the intermediate input allows for the elasticity of substitution in final good production between low carbon and fossil inputs to vary with progress in decarbonization, an aspect of a decarbonizing energy system. It takes the form put forward by Nagesh Revankar (1971) and assumes constant returns to scale at the firm level,

$$x = x_{lc}^{a}\left(x_f + bax_{lc}\right)^{1-a}, \tag{2}$$

for $0 < a \leq 1$. Given constant returns to scale, the intermediate input production function can be expressed in per capita terms.[5] The parameter, a, is a share term and b a reaction term between fossil and low carbon inputs.

For $b = 0$ equation (2) simplifies to a Cobb-Douglas function and $b = -1$ to a Harrod-Domar function in which only the fossil input is relevant. For $0 < a \leq 1$ and $b > -1$, as well as for $-1 < b < 0$ and $x_f \geq bax_{lc}$, the first and second derivatives of (2) satisfy the standard properties of a production function.

The elasticity of substitution between the two inputs is[6]

$$\varepsilon = 1 + b\left(\frac{x_{lc}}{x_f}\right). \tag{3}$$

For $b > 0$, the low carbon input substitutes for the fossil input and becomes stronger with decarbonization of the intermediate input. So, it becomes "easier" to decarbonize the energy-related input the greater the ratio of the low carbon to fossil input. For $-1 < b < 0$, the low carbon and fossil inputs are complements, and it becomes "harder" to decarbonize with progress in decarbonization. In this case, an increase in the low carbon input leads to an increase in the fossil input, and increasingly so with decarbonization. For $b = 0$, the elasticity of substitution equals one and is constant, as in a Cobb-Douglas function.

[5] Empirical evidence finds significant scale economies in at least some aspects of decarbonization (Way et al. 2021). This model assumes that they are external to individual firms.
[6] See Revankar (1971).

What factors determine the elasticity of substitution and why might it change with progress in decarbonization? J. R. Hicks (1963, p. 120) suggested that in an aggregate economic model the substitutability of production inputs changes with substitution of production methods in a particular sector, intersectoral substitution mediated by consumer preferences, and technological innovation. Changes in institutions and infrastructure that affect technology choices and investments can also affect the elasticity (Knoblach and Stöckl 2020).

For example, Linus Mattauch, Felix Creutzig, and Ottmar Edenhofer (2015) suggested that investments in infrastructure, such as electric power grid integration across a large area to diversify generation across renewable resources, can strengthen the substitutability of renewable for fossil power generation. In general, infrastructure for distributing energy from producers to customers, optimized to incumbent technologies, affects the investments of energy suppliers and end users. This is the case not only for power but also for fuel distribution networks, such as natural gas grids (Pearson and Arapostathis 2017). Adapting infrastructures can facilitate changes in energy supply and end-use technologies.

There are also indirect network effects—or chicken and egg problems—with interdependent yet decentralized technologies, as with battery electric vehicles and their charging networks (Li et al. 2017). Investments in them increase the substitutability of battery electric for internal combustion engine cars and charging points for filling stations.

Ara Jo and Alena Miftakhova (2022) tested for a variable elasticity of substitution between low carbon and fossil inputs using panel data for approximately 30,000 French industrial plants in 19 industries from 1990 to 2017. Their study strongly rejected a constant elasticity of substitution between these inputs and finds that the elasticity increased significantly with the share of low carbon inputs.[7] This evidence thus supports use of a Revankar VES production function for a decarbonizing economy, at least in the early stages of decarbonization.

In these examples, low carbon investments strengthen the substitutability of low carbon for fossil technologies, and (2) captures such effects for given technologies.[8] But its one-sided and linearly increasing elasticity with progress in decarbonization $(b > 0)$ is a shortcoming of this VES production function. For example, a low carbon energy system would likely have features that impede the substitution of technologies, as does the current system.

[7] Hassler et al. (2021) also found that the series of fossil energy price shocks since the 1970s induced significant energy-saving innovations, which over time increased the substitutability of a composite capital-labor input for fossil fuels.

[8] As in Acemoglu et al. (2012), Fried (2018), and Jo and Miftakhova (2022), it is possible to extend this model to include endogenous innovation, which could be directed toward stronger substitutability for incumbent technologies. But such an extension is not essential for explaining observed policy sequences in the early stages of decarbonization, because at the outset they benefited primarily from the low carbon innovations induced by exogenous fossil energy price shocks.

So, at the end points of the continuum between fossil and low carbon energy systems, the elasticity of substitution between their respective technologies would likely be weak. It would be strongest when the technologies have relatively balanced system roles. A more general VES production function, as proposed by Koteswara Rao Kadiyala (1972), has such a nonlinear elasticity of substitution, but at the expense of analytical tractability.

This paper focuses on policy choices in the early stages of decarbonization and their impact on output, for which (2) is both suitable and tractable. However, the Kadiyala VES production function would be more suitable for analyzing the output path of an economy as it converges in the long run to net zero emissions.[9]

Using (3), the production function for the intermediate input simplifies to

$$x = x_{lc}^{a} x_{f}^{1-a}(1 - a + a\varepsilon)^{1-a}. \tag{4}$$

It consists of a standard Cobb-Douglas component and one that depends on the elasticity of substitution.

The function's limiting properties are

$$\lim_{x_{lc}\to 0} x = 0 \text{ and } \lim_{x_{lc}\to\infty} x = \infty$$

$$\lim_{x_{f}\to 0} x = (ba)^{1-a}x_{lc} \text{ and } \lim_{x_{f}\to\infty} x = \infty \text{ if } b > 0$$

$$\lim_{x_{f}\to -bax_{lc}} x = 0 \text{ and } \lim_{x_{f}\to\infty} x = \infty \text{ if } b < 0.$$

For $b > 0$, the low carbon and fossil inputs are substitutes and the latter is not essential for the intermediate input, so x remains positive even as $x_f \to 0$. In other words, net zero emissions are feasible at a positive intermediate input and output level. For $-1 < b < 0$, the fossil and low carbon inputs are complements, so the fossil input is essential, and net zero emissions are feasible only by forgoing the intermediate input and output.[10] Given the technical feasibility of a net zero emission energy system, the modeling assumes $b > 0$.

The intermediate input is produced by the capital stock that converts primary energy—fossil hydrocarbon, renewable, and nuclear resources—into electricity and fuels and these energy carriers into intermediate inputs such as various energy services and materials. The low carbon input is produced competitively from low carbon capital and mostly renewable and nuclear

[9] Jo and Miftakhova (2022) used the Revankar VES production function to analyze long-run decarbonization of an economy, albeit with the implausible implication that the elasticity of substitution between the low carbon and fossil inputs in time approaches infinity.

[10] Acemoglu et al. (2012) and Fried et al. (2022) obtained a similar result for a CES production function if $\varepsilon < 1$. A Cobb-Douglas production function would also deem the fossil input essential to production.

resources. Its production function is $x_{lc} = A_{lc}k_{lc}$. The fossil input is produced from fossil capital and hydrocarbon resources. Its Leontief production function is $x_f = min[A_f k_f , \mu f]$, with fossil fuel, f, a fixed proportion of fossil capital.[11] The parameter, μ, is a Leontief coefficient. A_f excludes economic losses from the climate externality—they are assumed for the sake of argument to occur somewhere else.[12] The unit cost of capital is a unit of the final good.

Fossil capital is specialized in producing and using fossil fuels and cannot be adapted to low carbon technologies. Examples include oil refineries and internal combustion engines not adapted to bioresources and low carbon fuels. Low carbon technologies are those consistent in the long run with a net zero emission energy system as described above.

Least-cost production by final goods firms using the two intermediate inputs must satisfy the usual first-order conditions for cost minimization. In a competitive equilibrium among final goods firms, the intermediate input prices equal their marginal products:

$$p_{lc} = \alpha y \left[\frac{a}{x_{lc}} + \frac{(1-a)ba}{x_f + bax_{lc}}\right] = \frac{\alpha y}{x_{lc}}\left[a + \frac{(1-a)(\varepsilon - 1)}{(1-a+a\varepsilon)}\right]$$

$$p_f = \alpha y \left(\frac{1-a}{x_f + bax_{lc}}\right) = \frac{\alpha y}{x_f}\left[(1-a) - \frac{(1-a)(\varepsilon - 1)}{(1-a+a\varepsilon)}\right]. \tag{5}$$

The marginal product of an input is proportional to its average product, as in a Cobb-Douglas production function, plus a term that depends on the elasticity of substitution. An increase in the low carbon input increases the elasticity of substitution and this adds to its marginal product. But an increase in the fossil input decreases the elasticity and this subtracts from its marginal product.

With a capital depreciation rate, δ, the optimal per capita capital stock and output decisions of firms producing the intermediate inputs must satisfy the usual conditions for profit maximization:

$$\max_{k_{lc}}[p_{lc}A_{lc}k_{lc} - (n+\delta)k_{lc}] \text{ or } p_{lc} = \frac{n+\delta}{A_{lc}} \tag{6}$$

[11] The Leontief production function for the fossil intermediate input assumes that there is no substitutability between fossil capital and fuel, so cuts in carbon intensity must come from substituting low carbon for fossil inputs and not from substituting fossil capital for fuel (i.e., energy efficiency).

[12] Cumulative carbon dioxide emissions from energy are mostly from industrialized economies, including China and Russia, and projected climate change impacts are largely in developing economies (IPCC 2022). The main projected climate change impact in the United States and Europe is increased mortality from extreme temperatures, especially among older populations (Hsiang et al. 2017; Ciscar et al. 2018, 2019; Carleton et al. 2022). This so-called nonmarket impact does not affect projected output. In addition to increased mortality, developing countries are projected to experience significant economic losses from unmitigated climate change impacts such as lower agricultural yields and to require greater investment in adapting production to climate change (Moore et al. 2017).

$$\max_{k_f}\left[p_f A_f k_f - (n+\delta)k_f\right] \text{ or } p_f = \frac{n+\delta}{A_f}.$$

Using the production functions for x_{lc} and x_f and solving (5) and (6) for the output-maximizing capital-stock ratio, Θ^*, yields

$$\Theta^* = \frac{k_f}{k_{lc}} = \frac{1-a}{a} - b\frac{A_{lc}}{A_f}. \tag{7}$$

In a competitive equilibrium, the ratio of fossil to low carbon capital depends only on the underlying technology parameters, a, b, A_f, and A_{lc}. For $b > 0$, Θ^* is decreasing in A_{lc} and b and increasing in A_f.

Consider now capital accumulation. Following Giannis Karagiannis, Theodore Palivos, and Chris Papageorgiou (2005) and using (1), (4), (7), and the production functions for the intermediate inputs, the nested production function for the final good simplifies to

$$y = [k_{lc}\bar{A}(1-a+a\varepsilon)^{1-a}]^{\alpha},$$

where (8)

$$\bar{A} = A_{lc}^{a}\left(A_f\Theta^*\right)^{1-a}.$$

Since the given technology parameters determine the ratio of low carbon to fossil inputs, final good output simplifies a function of low carbon capital and a weighted average of the productivity of low carbon and fossil capital, $\bar{A}$.

For a given saving rate, s, and output given by (8), capital accumulation follows

$$\frac{dk_{lc}}{k_{lc}} = sk_{lc}^{\alpha-1}[\bar{A}(1-a+a\varepsilon)^{1-a}]^{\alpha} - (n+\delta). \tag{9}$$

For $b > 0$ and hence $\varepsilon > 1$, the limiting properties of the capital accumulation equation are

$$\lim_{k_{lc}\to 0}\frac{dk_{lc}}{k_{lc}} = \infty \text{ and } \lim_{k_{lc}\to\infty}\frac{dk_{lc}}{k_{lc}} = 0.$$

A change in k_{lc} affects growth in two potential ways. One is via $sk_{lc}^{\alpha-1}$ for a given ε, which is decreasing in k_{lc}, and the second through ε, which is increasing in k_{lc}. But in competitive market equilibrium, the ratio of low carbon to fossil capital is constant for given technologies and so too is ε.

The balanced growth path for the market economy thus converges to a steady state in which

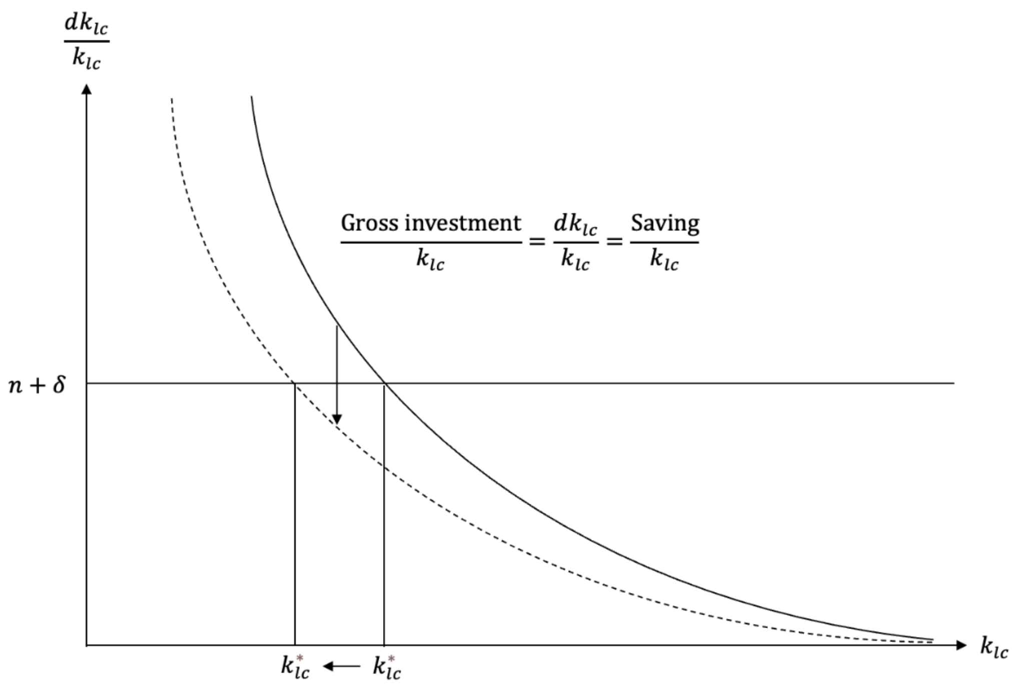
$$\frac{dk_{lc}}{k_{lc}} = n + \delta$$

and (10)

$$k_{lc}^{*} = \left\{\frac{s[\bar{A}(1-a+a\varepsilon)^{1-a}]^{\alpha}}{(n+\delta)}\right\}^{\frac{1}{1-\alpha}}.$$

As figure 3 shows, the net capital accumulation rate, $dk_{lc}/k_{lc} - \delta$, converges to the population growth rate, n, as the per capita low carbon capital approaches k_{lc}^{*}.

Figure 3. Balanced growth path with steady state and decarbonization policy



Note: Assumes $b > 0$. Introducing a decarbonization policy shifts down the balanced growth path, $dk_{lc}/k_{lc} =$ Saving$/k_{lc}$, and reduces the steady state capital stock, k_{lc}^{*}, as well as the fossil capital stock and output. See text for explanation of terms.

5. Decarbonization policies, their scale and impact on output

Now consider the consequences of introducing a decarbonization policy—a low carbon investment subsidy, σ, or a carbon tax, τ, expressed as a percent of fossil capital given the Leontief production function for the fossil input. Other policy designs are possible, but the key parameter is the basis to which the policy applies rather than its particular form.

The profit-maximizing capital stock and output decisions of firms producing the intermediate input satisfy the modified first-order conditions

$$\max_{k_{lc}}[p_{lc}A_{lc}k_{lc} - (1 - \sigma)(n+\delta)k_{lc}] \text{ or } p_{lc} = \frac{(1 - \sigma)(n+\delta)}{A_{lc}}$$

$$\max_{k_f}[p_f A_f k_f - (n+\delta+\tau)k_f] \text{ or } p_f = \frac{n+\delta+\tau}{A_f}.$$

The intermediate input firms face a unit price less the low carbon investment subsidy for $(n+\delta)k_{lc}$. The carbon tax is proportionate to the fossil capital stock and adds to the fossil input's cost. The reason for introducing either a low carbon investment subsidy or a carbon tax is the same: to correct the relative price of low carbon and fossil input for the latter's climate externality and induce the substitution toward the low carbon input.[13]

In addition to correcting the relative input price for the climate externality, there can be positive externalities associated with early investments in low carbon technologies, such as learning by doing and network effects. They too could warrant a subsidy. But while such external scale economies motivate use of the VES production function in this model, the endogenous elasticity of substitution does not by itself warrant a subsidy.

Assume that subsidies are funded from lump sum taxes on final goods consumers and carbon taxes recycled to consumers as lump sum transfers. The impact of decarbonization policies on the capital stocks and output thus arises only through the change in Θ. The next section considers more fully the public finance aspects of the decarbonization policies.

Reflecting change in relative prices faced by intermediate input firms, the fossil to low carbon capital ratio in a competitive market equilibrium becomes

$$\Theta_{\sigma,\tau} = \frac{k_f}{k_{lc}} = \left(\frac{1-a}{a}\right)\left[\frac{(1-\sigma)(n+\delta)}{n+\delta+\tau}\right] - b\frac{A_{lc}}{A_f} < \Theta^*,$$

for $\sigma > 0$ or $\tau > 0$. Either decarbonization policy increases the incentive to invest in low carbon relative to fossil capital and decreases the equilibrium capital stock ratio.

The impact of introducing a low carbon investment subsidy or carbon tax on the equilibrium capital stock ratio is

[13] As discussed above, the socially optimal τ is approximately time invariant and reflects the social and economic losses from cumulative carbon dioxide emissions and resulting climate change. Since this paper is positive rather than normative in approach, the analysis is for a given carbon tax or an equivalent low carbon investment subsidy rather than necessarily the socially optimal policy.

$$\frac{\partial \Theta}{\partial \sigma} = -\left(\frac{1-a}{a}\right) d\sigma$$

$$\frac{\partial \Theta}{\partial \tau} = -\left(\frac{1-a}{a}\right)\left(\frac{1}{(n+\delta)}\right) d\tau. \tag{11}$$

A low carbon investment subsidy rate must thus be $1/(n+\delta)$ times larger than a carbon tax rate to provide an equally transformative investment incentive. However, the subsidy applies only to low carbon investment whereas the carbon tax applies to the fossil capital stock.

In a steady state, it is straightforward to show that for equally transformative policies, total spending on the low carbon investment subsidy is less in absolute terms than carbon tax revenues for $k_{lc}^* < k_f^*$ and vice versa for $k_{lc}^* > k_f^*$. It is the bases to which the comparable policies are applied, rather than their particular form, that determine their relative scale.

Introducing a decarbonization policy also affects the steady state capital stock, k_{lc}^*. Taking the derivative of (10) with respect to Θ,

$$\frac{\partial k_{lc}^*}{\partial \Theta} = \frac{k_{lc}^* \alpha(1-a)}{\Theta^*(1-\alpha)}\left[1 - \frac{ba\frac{A_{lc}}{A_f \Theta^*}}{1 + ba\frac{A_{lc}}{A_f \Theta^*}}\right] d\Theta, \tag{12}$$

shows two effects. One is to reduce the weighted average productivity of the capital stock, $\bar{A}$. The other is to increase the elasticity of substitution, ε. As the former is the larger effect, introducing a decarbonization policy reduces k_{lc}^* (figure 3). It also reduces the steady state fossil capital stock and thus final output. The decline is smaller for larger values of b and A_{lc}/A_f.

Fried, Novan, and Peterman (2022) used a related model to calculate the short-run output loss from introducing an economywide carbon tax. That model differs from the one at hand in several ways: It includes consumer preferences and endogenizes saving and labor supply. It also assumes a constant rather than variable elasticity of substitution between the low carbon and fossil inputs. Calibration of the numerical model used parameters for the US economy and an estimated elasticity of substitution of 3 (from Papageorgiou, Saam, and Schulte 2017). The elasticity was estimated from industrial sector data for 26 countries from 1995 to 2009. The carbon tax rate is \$51/tCO_2 and grows at a constant 1.7 percent. This rate is the National Academies of Sciences, Engineering, and Medicine (2017) estimate of the shadow price of carbon dioxide emissions used by the US government.

Fried, Novan, and Peterman (2022) found that the carbon tax would reduce output by 2.6 percent. However, the calculated output loss is likely an underestimate for two reasons. First, the elasticity used was for energy demand sectors and reflected mostly “easy” energy efficiency gains. The estimated elasticity for electricity generation was 2, for which there was a “harder” margin of substitution between fossil and low carbon technologies. Second, a recent estimate put the shadow price of emissions at \$185/tCO_2 using the National Academies methodology and up-to-date climate science (Rennert et al. 2022). An estimated short-run output loss from an economywide carbon tax that reflects a more plausible elasticity of substitution and up-to-date shadow cost would thus be significantly higher than 2.6 percent of GDP.

This growth model of a decarbonizing economy thus highlights two key macroeconomic impacts. One is that the scale of the two decarbonization policies depends on progress in transforming the capital stock (their scales are mirror images). The total outlays on a low carbon investment subsidy are relatively small and revenues of an equivalent carbon tax large when the fossil capital stock is large relative to the low carbon one and vice versa. This difference in scale can affect second-round policy costs. They are in principle equally efficient in their first-round incentive effects in correcting relative prices for the climate externality.[14]

The second is that the short-run tradeoff between decarbonization and output depends on the substitutability of low carbon and fossil capital. In a decarbonizing economy, output increases in A_{lc} and b, so policies that encourage their increase ease the output loss from decarbonization policies. This consideration points to potential benefits from sequencing decarbonization policies across sectors if the capital stock is heterogeneous. The decarbonization-output tradeoff could be mitigated if there are interim ways to induce low carbon innovations other than by concurrently implementing a decarbonization policy.

More generally, a decarbonizing economy requires innovation directed toward increasing A_{lc}/A_f and b to boost both the low carbon capital stock and output, a concept commonly referred to as green growth. In principle, either a low carbon investment subsidy or carbon pricing can so direct technological change. But as discussed below, the subsidy can have a stronger effect than a carbon price in inducing low carbon innovation, thereby mitigating more of the short-run output loss from implementing decarbonization policies.

Over time, moreover, the economy can attain higher output with sufficient low carbon technological progress and realization of scale economies. Renewable power generation technologies, batteries for energy storage, heat pumps for buildings, and electrolyzers and fuel cells for hydrogen production and use show such technological potential (Way et al. 2021). But this is not necessarily the case for all low carbon technologies.

6. Efficiency, equity, and decarbonization policy costs

A low carbon investment subsidy and carbon tax interact with the existing tax system in significant ways in their second-round effects.[15] For a subsidy, this effect is the marginal cost of the public funds raised to finance it. For a carbon tax, the second-round effect arises from its interaction with and potential substitution for existing income and consumption taxes to

[14] For evidence on efficient design of investment subsidies and other industrial policies, see Lane (2020).

[15] See Goulder (2013) on the interaction of an existing tax system with carbon pricing.

improve efficiency and equity. Both types of second-round effects depend on the optimality of the existing tax system.

An optimal tax system typically allows for the unavailability to policymakers of some crucial information and policy instruments, so the concept is second-best. The constraint generally believed to be most relevant in deriving optimal taxes is the unobservability of individual households' skill levels and the consequent inability to determine individualized lump sum taxes and transfers to heterogeneous households. An optimal tax system takes account of the distributional benefits from tax distortions and balances at the margin the additional distributional benefits of tax rate changes and their excess burdens (Jacobs 2018).[16] If they are balanced at the margin, the marginal cost of public funds is one.

The marginal cost of public funds to pay for a low carbon investment subsidy thus depends on optimality of the existing tax system. If it is optimal, the marginal cost of its funding from taxation is one and second-round policy costs of the subsidy are small if the additional outlay is small relative to total government taxation.[17]

In policy practice, however, funding of low carbon investment subsidies can be both regressive and inefficient. For example, feed-in tariffs for low carbon power generation in Europe are typically funded through electricity bill surcharges for customers. These fixed surcharges are particularly burdensome for lower-income households. They also raise the cost of electricity relative to natural gas, discouraging electrification of energy end uses. A policy priority is to change their funding to general taxation to improve efficiency and equity.[18]

The second-round effect of carbon pricing depends on the existing tax system as well. It is often asserted that substituting a carbon tax for reductions in existing distortionary tax rates would lower the cost of public funds, yielding both economic efficiency and environmental benefits. But if the existing tax system is optimal, there is a loss of distributional benefits from taxation that must also be considered, and this limits the so-called double dividend of environmental taxes (Jacobs and de Mooij 2015). If the system is optimal, it is possible to introduce carbon pricing and recycle its revenues as lump sum transfers to counter the regressive impacts of carbon pricing and leave inequality broadly unchanged (Klenert et al. 2018b).[19] But without individualized transfers, some households would inevitably be left worse off and others overcompensated.

[16] This characterization of the second-best optimum holds for linear and nonlinear income and consumption tax schedules. On the economic benefits of redistribution and greater equality, see Ostry et al. (2014).
[17] For a nonoptimal existing tax system, the marginal cost of public funds is less (greater) than one if the additional distributional benefits are larger (smaller) than the marginal excess burden of the higher tax rates.
[18] See, for example, Climate Change Committee (2023), p. 20.
[19] Regressive distributional impacts of carbon pricing arise in part from the larger expenditure shares of carbon-intensive goods and services in lower-income household budgets. See, for example, Berry (2019), Goulder et al. (2019), and Burke et al. (2020). There can also be regressive impacts through labor markets.

If the existing tax system is optimal, the second-round policy effects of low carbon subsidies and carbon pricing thus depend on their scale and the extent to which they disrupt the initial balance between marginal excess tax burdens and distributional benefits.[20] Put simply, the smaller-scale policy likely has the smaller policy cost because it is less disruptive of the initial balance of efficiency and distributional concerns. At early stages of decarbonization, the low carbon investment subsidy is well targeted, while carbon pricing requires a large-scale transfer scheme to offset its regressive distributional impact. For example, a US carbon tax of \$185/tCO_2 would require initially an annual transfer scheme equivalent to 3.6 percent of GDP to recycle its revenues and counter its regressive distributional impacts. But with progress in decarbonization, carbon pricing over time becomes the smaller-scale policy.

7. Heterogeneity and targeting decarbonization policies by sector

Now consider the decarbonization policy implications of heterogeneity in the energy-related capital stock and its output. Assume that there are two final goods produced separately by two types of fossil and low carbon technologies. Each has a production function of the form (8). They differ in terms of their relative substitutability. One good is easier to decarbonize and has relatively high b and A_{lc}/A_f. The other good is harder to decarbonize. The other production parameters, α and a, are the same for both goods.

Suppose, for example, that the “easier” good (in term of its energy value chain) is electrification of energy services in buildings and road transport and decarbonization of electric power. The “harder” one is heavy industry and transport and their decarbonization through electrification, low carbon fuels, and carbon management of industrial emissions and residual fossil fuel use.

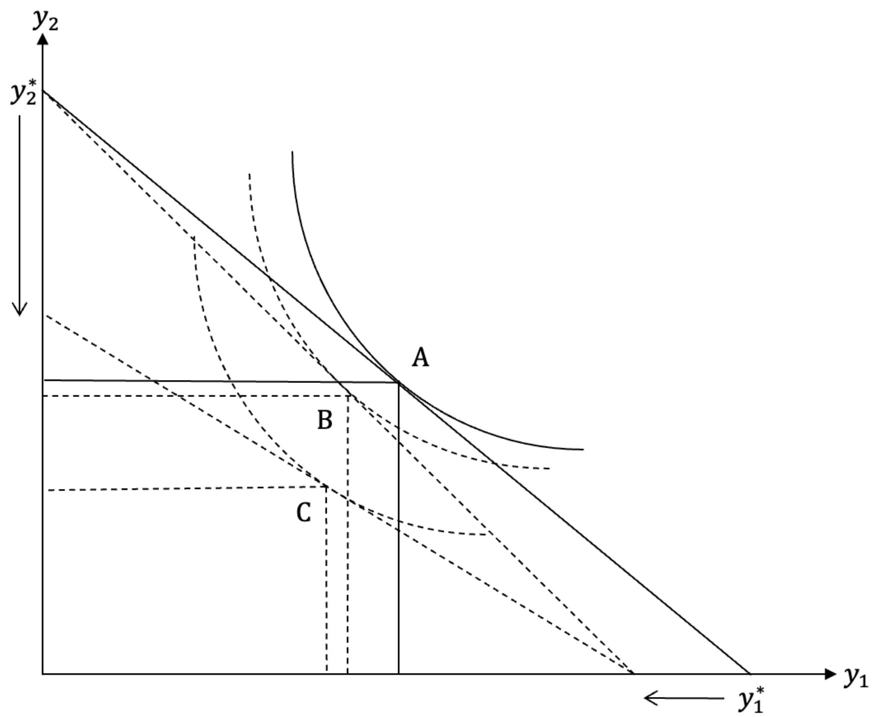
Decarbonization policies necessarily reduce the production possibilities frontier for the two goods. From (11) a decarbonization policy has the same effect on the ratio of fossil to low carbon capital in the two sectors, but its impact on the steady state capital stock from (12) is a decreasing function of b and A_{lc}/A_f. So, an economywide policy, such as a uniform carbon price across sectors, would shift the frontier more toward the origin for the “harder” good than the “easier” one (figure 4). A policy targeted on the easier to decarbonize good—a sector-specific carbon price or equivalent low carbon investment subsidy—would reduce only the frontier for this good.

This widely used policy approach minimizes the short-run output loss relative to an economywide policy but does little to cut emissions from the “harder” sector (point B versus C in figure 4). The costs of such a targeted policy are excessive production, consumption, and emissions from the harder to decarbonize good relative to a uniform decarbonization policy across sectors. As discussed above, the shadow cost of emissions is the same across sectors.

[20] If the existing tax system is nonoptimal, the two decarbonization policies must be evaluated on a case-by-case basis. Klenert et al. (2018a) set out such an approach to appraisal of a carbon tax. A similar approach to appraisal of a low carbon investment subsidy is also necessary.

A potential benefit is that the sequence postpones the output loss from implementing a decarbonization policy for the "harder" good to allow time for its low carbon technologies to become stronger substitutes for the incumbents through innovation. But this policy sequence requires inducing low carbon innovations in the sector by means other than implementing a concurrent low carbon investment subsidy or carbon pricing.

Figure 4. Production possibilities frontier and social indifference curves for two types of final goods



Note: An economywide carbon tax shifts toward the origin the production possibilities frontier for both y_1 and y_2, but the latter by more because it is the more difficult to decarbonize. A targeted decarbonization on the easier to decarbonize good only shifts in the production possibilities frontier for y_1. The tangency points between the social indifference curves and production possibilities frontiers depict economic outcome under doing nothing (A), a sectoral targeted decarbonization policy (B), and an economywide carbon tax (C).

8. Alternative ways to induce low carbon innovations

Fossil energy price shocks and implementation of decarbonization policies aside, one way that governments have induced low carbon innovations is through long-run climate stabilization goals and policy strategies. These reforms are used widely and early in observed policy sequences. To the extent credible, they aim to shift expectations of future decarbonization policies and their associated changes in relative prices and market sizes. For example, the commitment made in the 1997 Kyoto Protocol by industrial countries was to cut by 18 percent their greenhouse gas emissions by 2020 from 1990 levels.

Despite its relatively modest ambition, the Kyoto Protocol increased the responsiveness of low carbon innovations to fossil fuel price shocks and decarbonization policies. Jürgen Kruse and Heike Wetzel (2016) find that the responsiveness of low carbon R&D patents to energy prices increased significantly after 1998. They attribute this finding to a shift in expectations about future decarbonization policies after the Kyoto Protocol. Francesco Nicolli and Francesco Vona (2016) also find that after the Kyoto Protocol low carbon innovation increased significantly, other things being equal.

The international climate goal now takes the form of a time-bound commitment to achieve net zero emissions. The 2015 Paris Agreement commits countries to limit global warming to well below 2°C with a stretch target of 1.5°C. The latter requires net zero emissions by around mid-century.

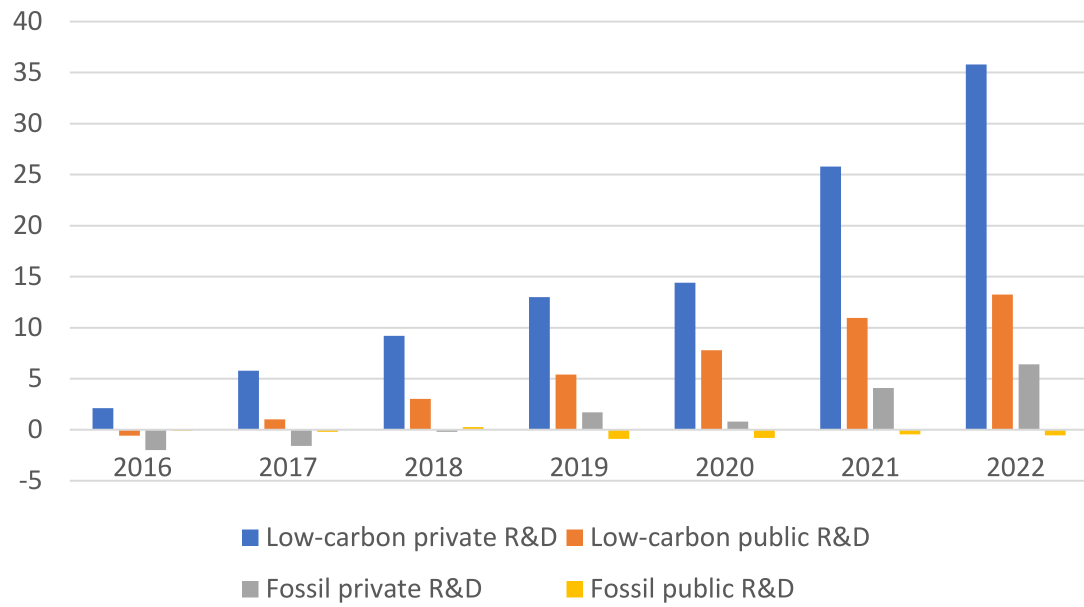
While it is not yet possible to assess patenting outcomes of energy-related R&D investments before and after the Paris Agreement, the scale and direction of such investments do appear to have responded. Figure 5 shows the change in total measured private and public investment in energy related R&D—largely in OECD countries and China. Total private investment by publicly listed firms in low carbon R&D increased by 2022$ 35 billion (55 percent) in 2022 from its 2015 level and public investment by 2022$ 13 billion (59 percent). During the same period, public investment in fossil R&D declined marginally, though private investment rose. There is thus an increase in but only partial reorientation of energy-related R&D investment toward low carbon technology fields since the Paris Agreement.

At the same time, R&D investment increasingly focused on low carbon fuels and industrial processes (IEA 2022c, pp. 172–79). This observation is consistent with an expected strengthening of decarbonization policies in harder to decarbonize sectors, a strengthening that to some extent has been fulfilled by provisions in the US Inflation Reduction Act and EU Green Industrial Plan.

Another way that governments can induce low carbon innovations while minimizing output losses over time is to choose a decarbonization policy that is more effective in encouraging innovation. In principle, a low carbon investment subsidy and a carbon price of comparable levels should be equally effective in inducing this innovation. But the credibility of the two policies can differ. Low carbon investment subsidies are typically provided when investments are made, including as legally binding commitments on governments. Carbon pricing applies over asset lifetimes and is subject to discretionary policy change; its implementation can be inconsistent over time (Newbery 2016, Fries 2022).

Evidence on the relative effectiveness of carbon pricing and low carbon investment subsidies is mixed but tends to favor subsidies. Raphael Calel and Antoine Dechezleprêtre (2016) found a significant increase in low carbon patenting activity by firms with plants above the size threshold for inclusion in the EU Emissions Trading System compared with those below, but the size of the effect was small. An oversupply of emission allowances, low carbon prices under the scheme, and slow reforms to correct its flaws dulled the EU system's potential effectiveness in inducing low carbon patents (Bel and Joseph 2018).

Figure 5. Change relative to 2015 in global private and public energy-related R&D investment, 2016–22 (2022$ billions)



Note: Public R&D includes spending on demonstration projects (i.e., RD&D) wherever reported by governments as defined in IEA documentation. 2022 is a preliminary estimate based on available data. State-owned enterprise funds comprise a significant share of the Chinese public total. The IEA Secretariat estimates US government R&D spending from public sources. IEA and country classifications of low-carbon R&D may differ. Private energy R&D spending includes reported R&D expenditure by listed companies active in sectors that are dependent on energy technologies, including energy efficiency technologies where possible. Low carbon technology fields include automobiles, electricity generation, supply and networks, nuclear, renewables, batteries, hydrogen and energy storage. Fossil technology fields are oil and gas, thermal generation and combustion technologies, and coal. While automobiles can include both fossil and low carbon technology fields, the assumption is that growth in automobile R&D since 2015 is low carbon.
Source: IEA (2023), Energy Technology RD&D Budgets Data Explorer, https://www.iea.org/data-and-statistics/data-tools/energy-technology-rdd-budgets-data-explorer, and IEA (2023), Spending on energy R&D by listed companies, 2015-2022, https://www.iea.org/data-and-statistics/charts/spending-on-energy-r-and-d-by-listed-companies-2015-2022. CC BY 4.0 for private R&D data.

Low carbon investment subsidies, in contrast, induced significant innovations. In particular, feed-in tariffs for renewable power generation were strongly associated with a significant increase in patenting activity for solar PV (Johnstone, Haščič, and Popp 2010; Nicolli and Vona 2016; Vincenzi and Ozabaci 2017; Palage, Lundmark, and Söderholm 2019). This effect was stronger if the policy was combined with complementary public R&D investment (Palage et al. 2019). But related findings for wind turbine patents were mixed (Johnstone, Haščič, and Popp 2010; Nicolli and Vona 2016; Grafström and Lindman 2017; Schleich, Walz, and Ragwitz 2017). A significant, positive association arose mainly in Denmark, Germany, Spain and Sweden, largely countries that specialized in wind turbine manufacturing (Lindman and Söderholm 2016).

9. Decarbonization policy costs, choices, and sequences

This assessment of the macroeconomic impacts of decarbonization provides two reasons for the observed sequencing of low carbon investment subsidies before implementation of carbon pricing within sectors. First, when the low carbon capital stock is relatively small compared to the fossil capital stock, the subsidy is the smaller-scale intervention. Its second-round policy cost is thus likely lower than a comparable carbon price if the decarbonization policies and initial tax system are well designed. Second, a low carbon investment subsidy appears to create a stronger incentive than a carbon price in inducing low carbon innovation and can over time mitigate more of the short-run tradeoff between decarbonization and output. This differing incentive effect may reflect greater policy credibility of a low carbon subsidy than carbon price in early stages of decarbonization.

The analysis also provides an explanation for the observed sequence of initial implementation of decarbonization policies in sectors and countries where low carbon technologies are stronger substitutes for the incumbents. This sequence across sectors reduces the larger short-run output losses in harder to decarbonize sectors compared to an economywide approach. A benefit is that it allows time for low carbon innovations to strengthen their substitutability for the incumbents. Governments use climate stabilization goals, such as time-bound commitments to reach net zero emissions, and can use targeted support for private low carbon R&D to spur such innovations. But these measures are not yet sufficient to induce the pace of innovation necessary to reach midcentury net zero emission goals (IEA 2022c, pp. 176–77). A cost of this approach is continued excessive production, consumption, and emissions in the harder to decarbonize sectors.

10. Model extensions and further empirical research

This model for assessing the macroeconomic implications of decarbonization can be extended in three ways. One is to endogenize household consumption, saving, and labor supply as well as the level and direction of R&D investment. For example, Fried (2018) and Jo and Miftakhova (2022) developed such a model with a CES and Revankar VES production function, respectively. This extension would allow consideration of the two decarbonization policies in inducing low carbon innovations as well as a targeted R&D subsidy. A second is to formally model the heterogeneity of final goods and services and their energy-related capital stocks. A third is to use a Kadiyala VES production function to examine plausible long-run output paths as an economy converges toward net zero emissions.

There are also two areas for further empirical research. One is the substitutability of low carbon and fossil inputs. Chris Papageorgiou, Marianne Saam, and Patrick Schulte (2017) estimated the elasticity of substitution for two technology fields—electric power generation and energy end-use technologies in industry—using sectoral data for 26 countries; and Jo and Miftakhova (2022) estimated the elasticity for French industry. But only the latter study allowed for the estimated elasticity to vary with decarbonization. More extensive estimations of the elasticity by sector and country, including identification of factors that influence it, are needed. A second research area is the effectiveness of low carbon investment subsidies and carbon prices in inducing low carbon innovation. Such research should allow for potential differences in policy credibility between these two policies, at least in early stages of decarbonization.

11. Conclusion

Two types of decarbonization policy sequences are clearly evident within and across sectors. Within them, an early group of policies is used to initiate decarbonization and a later group is deployed a number of years after. The earlier policies include subsidies and incentives for low carbon investments and crosscutting policies that set overall decarbonization goals and policy strategies. The later ones include government support for RD&D targeted on low carbon technologies and carbon pricing. Across sectors, decarbonization policies are initiated first in those where low carbon technologies are stronger substitutes for the incumbents.

This paper uses an appropriately adapted Solow-Swan growth model to assess macroeconomic impacts of decarbonization and explain the observed policy sequences. It complements other explanations based on microeconomic considerations of efficiency in imperfect markets, distributional fairness, and economic interests in change.

Two types of policy costs underpin the explanations. One is a short-run tradeoff—determined by the substitutability of low carbon for fossil technologies—between decarbonizing productive activities and maintaining the level of output. Stronger substitutability eases this tradeoff. The second type is the second-round policy costs of the two decarbonization policies—a low carbon investment subsidy and a carbon price—and depends on the relative scale and design of these policies and the existing tax system. In principle, their first-round effects in inducing substitution of low carbon for fossil technologies is the same.

The explanation for the prevalence of low carbon investment subsidies in the early stages of decarbonization is that it is a smaller-scale intervention than carbon pricing, with likely lower second-round policy costs if the policies and tax system are well designed. But their relative scales reverse with progress in decarbonization. A second, complementary explanation is that the subsidy can have a stronger effect than a carbon price in inducing low carbon innovation, perhaps reflecting differences in policy credibility in the early stages of decarbonization. This stronger effect mitigates more of the short-run decarbonization and output tradeoff over time.

This explanation contrasts with a more conventional one in which a low carbon investment subsidy would be preferable to a carbon price only if there are positive externalities from network effects and learning by doing (Bristline, Mehrotra, and Wolfram 2023). But, as shown in the model here, either a low carbon investment subsidy or a carbon price can correct the relative input price for the climate externality and induce efficient substitution of low carbon for fossil capital. So only this externality is necessary to motivate use of a low carbon investment subsidy, but such positive externalities can also be relevant considerations.

The explanation for decarbonization policies being implemented initially in sectors where low carbon technologies are stronger substitutes for the incumbents is that it postpones and can reduce the short-run output loss from implementing a decarbonization policy in the harder to decarbonize sectors. This approach allows time to progress low carbon technologies. Evidence shows that long-run climate goals like time-bound commitments to zero emissions can induce such innovation, but not yet at the pace necessary to reach the goals. This approach lessens the sector output loss from decarbonization policies if implemented once their substitutability strengthens. A cost is that it allows continued excessive emissions in harder to decarbonize sectors.

Finally, the paper identifies several ways to extend the model and areas for further empirical research to inform its application. These extensions could be used for a normative analysis of how best to accelerate the pace of decarbonization while minimizing output losses over both the short and long run.

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