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Aude Pommeret – Francesco Ricci

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# Fueling the energy transition with fossil (not quite) stranded assets *

Aude Pommeret† , Francesco Ricci‡

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**Abstract**

The energy transition requires large quantities for raw materials to build the infrastructure needed to supply electricity from renewable sources. In the meanwhile, climate policies push out of the market some of fossil-based infrastructure, generating stranded assets. However, decommissioned infrastructure constitutes a stock of scrap, from which materials can be recovered and recycled to develop the infrastructure for renewable energy. We use a stylized dynamic model featuring the decommissioning rate as a control variable: it reduces the fossil-based infrastructure available for energy production, but also increases the scrap that offers recycling potential. With this model first we study the effect of recycling possibilities on decommissioning and on the extraction of fossil and mineral resources. Second, we can fully characterize the dynamics of the stock of scrap. Considering recycling of decommissioned fossil-based infrastructure, makes the stranded assets problem less severe, while mitigating the rise in the price of virgin materials.

JEL codes: Q42, Q53, L61, Q32

Keywords: Energy transition, Materials scarcity, Fossil infrastructure decommissioning, Scrap, Recycling

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†Université de Savoie Mont-Blanc (IREGE). aude.pommeret@univ-smb.fr.

‡CEE-M, Univ de Montpellier, CNRS, INRAE, Institut Agro Montpellier. francesco.ricci@umontpellier.fr.

# 1 Introduction

Mitigating climate change requires to make the transition from a fossil fueled energy system to one relying on electricity from renewable sources (IPCC, 2018).[1] Solar and wind electricity generations in particular have recently gained a lot of attention due to their sharp cost reduction. As noted by the International Energy Agency (IEA), solar PV is now one of the cheapest technology in most countries and in particular, it has become cheaper than new coal or gas-fired power plants (IEA, 2020). However, there remain obstacles to the development of renewable electricity infrastructures. First, electricity from photovoltaic solar panels is intermittent and variable. As a result, it is non-dispatchable and not continuously available. Pommeret and Schubert (2022) have analyzed the consequences of intermittency and variability on the energy transition. Second, renewable electricity generation infrastructure –namely the panels or wind turbines including permanent magnets– do require critical raw materials, as mentioned in the EU's Critical Raw Materials Act (EU, 2024). Also the equipment for dispatching and storing electricity from renewable sources is quite intensive in materials, including those with rare properties. Pommeret et al. (2022) consider the role of materials in building the infrastructure to produce and store energy from low-carbon sources. Third, the implementation of an efficient climate policy that directly limits the consumption of fossil resources faces political opposition. Schubert et al. (2025) characterize the additional costs resulting from the adoption of an indirect policy based of subsidizing low carbon technologies.

Undoubtedly, effective climate policies make some fossil fueled power generation capacity economically obsolete. We argue that fortunately these stranded assets constitute a stock of scrap, whose materials could be recovered, treated and used again to build new infrastructure for renewable electricity generation. In this paper, we extend the workhorse model of the energy transition developed with Katheline Schubert and used in the three above cited articles, to study how taking into account this possibility affects representations of possible futures in terms of decommissioning and extraction strategies, the value of fossil-specific capital and the timing of the energy transition.

The IEA in its 2021 report *The Role of Critical Minerals in Clean Energy Transitions* (IEA, 2021) stresses that energy systems powered by clean energy technologies need significantly more minerals, in particular copper, silicon and silver for solar photovoltaic panels. Recent price rises for copper or lithium highlight how supply could struggle to keep pace with world's climate ambitions. As a result, the IAE recommends that policy makers scale up recycling and promote technology innovation at all points along the value chain. France explicitly aims at supporting renewable energy industries by securing supplies of critical raw materials (lithium, nickel, cobalt, copper, aluminum, rare earths, etc.).[2] For this purpose France began investing public funds to leverage the development of primary

[1] Nuclear -that is in the EU green taxonomy- and carbon capture and storage are under consideration. However the new nuclear with current technology may become expensive (see for instance the LCOE evaluation made by Lazard bank in 2024, link) and fusion is still far from a usable technology

[2] Ministère de la transition écologique, de la biodiversité, de la forêt, de la mer et de la pêche (2025) *French strategy*

production, processing and recycling facilities of critical minerals and metals on its territory. In the same sprit, the EU expects the demand for rare earth metals to increase six-fold by 2030 and seven-fold by 2050, while for lithium, EU demand is expected to increase twelve-fold by 2030 and twenty-one-fold by 2050 (see background work in EU (2024)). This is perceived as a critical situation since Europe currently relies heavily on imports, often from a single third country, while recent geopolitical crises underscore EU strategic dependencies. The EU's Critical Raw Materials Act updates the list of critical raw materials for the whole EU economy and provides a specific list of strategic raw materials for green, digital, defense and aerospace technologies. The framework relies on member countries actions to improve the collection of critical raw material-rich waste and ensure its recycling into secondary critical raw materials. It allows to fast track identified investments and targeted State aids. It also sets fours benchmark collective targets: by 2030 least 10% of EU consumption should rely on extraction from domestic virgin materials deposits; moreover, at least 40% of annual consumption should be produced from domestic processing capacities, at least 25% of consumption should be supplied by its internal recycling industry, while no more than 65% of the EU's annual consumption should come from a single third country.

Climate policies push out some fossil fuel power generation capacity. The materials embedded in this infrastructure is usually not taken into account in economic analysis of the energy transition. It constitutes a stock of scrap whose materials could serve -through recycling- to build new infrastructure for renewable electricity generation and storage. What do we know about the material intensity of fossil-based energy system, and of the potential for recovering materials from its dismantling? This question is taken up in two articles. Le Boulzec et al. (2022) show that the material intensities of oil, gas and coal supply chains have stagnated for more than 30 years. In addition, gas is the main driver of current and future material consumption. Their prospective analysis finds that recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll: "[...] ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures." In their stock-flow analysis spikes in time trajectory of investment in refineries, oil and coal tankers, gas pipelines or liquefied natural gas plants, tanks and carriers are driving peaks in consumption of steel, aluminum, copper and concrete, which then translate into flows of scrap with lags at various time horizons. In this material flow analysis approach the rationale for recycling scrap from dismantled fossil infrastructure is the following. The primary production flow in tons/year feeds an in-use stock of materials embedded in the infrastructure. At the end of the lifetime of the infrastructure, the reduction of in-use stock corresponds to the flow of materials to be recycled (unless the demand for materials is low, in which case it adds to the stock of scrap). Hence the end-of-life recycling builds a recycled stock. They also account for losses during the recycling process which feed a cumulative stock of unrecoverable losses. In the specific

*for energy and Multiannual energy programming (2025-2030, 2031-2035)* (ACTION ENR ELEC.1 of the Draft EPP No. 3 submitted for consultation 05/03/25, link).

case of a reduction of the infrastructure stock, dismantling is anticipated (exogenously) before the (exogenous) end of the life span. An unused flow is then created, ultimately feeding an unused stock, which then follows a recycling path. This stock could eventually produce a reused flow for other infrastructures. As a result, Le Boulzec et al. (2022) conclude that "[...] ambitious decommissioning strategies could provide an additional way to increase materials recycling and reuse." Also Liang et al. (2025) propose prospective estimations of the quantities of steel, copper and aluminum that will be invested and recovered from the infrastructure producing, transporting and transforming fossil energies. They simulate an integrated assessment model for the "middle of the road" shared socioeconomic pathways (SSP-2) baseline scenario and the 2-degree Celsius scenario. Using a material-flow analysis module they compute the materials required to build the infrastructure, as well as those embedded in end-of-life equipment. Under the 2-degree scenario the amount of copper and aluminum in decommissioned equipment would be significantly larger than the quantity in new equipment devoted to fossil resources from the mid 2020's onward. Nevertheless, they find that the net amount of recoverable materials is not large compared to the global demand for the three materials, and write that "[...] the phasing out of fossil infrastructure will not advance far enough by 2050 to become a major source of secondary materials." This is because of continued investment in fossil infrastructures to expand the use of natural gas and to develop carbon sequestration and capture in the SSP-2 2-degree scenario. They conclude that "[...] accelerating the transition to renewable energy and reducing fossil fuel dependence could not only decrease the demand for new fossil infrastructure but also improve the availability of secondary materials within the system."

Relying on an analogous stock-flow logic, we propose an economic analysis where decommissioning of fossil infrastructure, accumulating inventories of scrap materials, recycling decisions, and extraction of materials from virgin ores, all result from intentional actions by optimizing specific agents. Initially, electricity production comes mostly from fossil sources. Effective climate change mitigation policies make them progressively more expensive through carbon pricing. This encourages investment in renewable electricity generation and storage capacity to replace them.

We build a stylized model of the energy transition, extending the model of Pommeret et al. (2022) that integrates the use of scarce minerals to build up the infrastructure for the alternative energy base as in Fabre et al. (2020). The implications of the relative material intensity of renewable energy production for climate policy have already been studied inChazel et al. (2023) that adapts the simplified integrated assessment model in Golosov et al. (2014) and apply it to the case of copper, showing that the mineral constraint significantly hinders the development of renewables in the long run. In the latter two papers climate policy objectives result of a cost-benefit analysis, based on assumptions on the impact of carbon emissions climate change and on the damaged it brings about (Barrage and Nordhaus, 2024). The alternative approach assumes that climate policy determines a threshold on carbon concentration in the atmosphere, based on political consensus (hopefully related to scientific consensus) in any case exogenous to the economic modeling exercise.

The economic problem is thus one of cost-effectiveness: design policies accompanying the energy transition to minimize their economic cost while conforming to the target. This is the carbon ceiling approach in Hoel and Kverndokk (1996), Tahvonen (1997), and Chakravorty et al. (2006). We rely on a similar approach, as Henriet and Schubert (2019), accounting for the fact that the best predictor of climate change is the cumulative amount of carbon emissions.[3] the possible amount of cumulative future carbon emissions –compatible with a given target in terms of rise in temperature– is a non renewable exhaustible resource, called the carbon budget.

To focus on the consequences of the scarcity of mineral resources, we abstract from the intermittency problem assuming that investment includes effective devices for energy storage. Green capital is therefore composed of solar panels, wind turbines and the batteries necessary to make renewable energy dispatchable. For simplicity, fossil, hydro, wind and solar energy are assumed to be available at zero variable cost. It is also assumed that, at the beginning of the planning horizon, the available fossil-fired plants are sufficient and that they do not depreciate, so that virgin raw materials are exclusively –if at all– used for low-carbon infrastructure. On the contrary, it is assumed that the initial low-carbon capacity is small and requires investment in green capital. This investment embeds critical resources supplied either by producers of virgin materials from the mines, or from recyclers who recover the scrap from decommissioned fossil infrastructure. Alternatively, a significantly more expensive backstop technology can be used to build up green infrastructure, which represents the alternative to virgin or recycled materials. This assumption is useful to define a long-run steady state equilibrium of the economy which is invariable with respect to the options available in terms of recycling. We study how decommissioning and recycling affect the transition dynamics of the economy, across fictitious economies that are identical at their initial and final state, but differ in terms of recycling technology.

We present the analysis as the solution of the planned economy, rather that the dynamic partial equilibrium in a decentralized economy. The two are equivalent when one considers –as we do– the case of an effective climate policy, correcting for the unique externality in the economy. The social planner is confronted to a trade-off: on the one hand, fossil energy is expensive to use in terms of $CO_2$ emissions and, on the other hand, renewable energy is expensive because it requires costly investment in green capital. The latter relies on critical mineral resources that are being depleted, the costly recycling of materials from the fossil infrastructure, or –as a last resort– a very costly backstop technology. In our original framework, while brown capital is a productive stock, its decommissioning rate is a control variable: it reduces the brown capital stock available for electricity generation but also increases the scrap that offers recycling potential, a possibly valuable input to invest in green capital. With our model of the energy transition, we study the effect of such recycling on decommissioning and extraction strategies. We analyze the effect of recycling on

[3]See Mattauch et al. (2020) for an explanation of the (almost) linear relationship between temperature increase and cumulative emissions.

the dynamics of extraction and mineral prices. We also explain why the ability to recycle brings forward fossil phase-out through some effects on the cost of this phasing-out. In addition, we are able to provide an analysis of the dynamics of the stock of scrap, that exhibits a non-monotonic and discontinuous time profile. Finally, we show that such a recycling process could, in addition to easing the stranded assets phenomenon, contain the rise in the price of virgin material.

The extension we introduce to the previous versions of the model of the energy transition in Pommeret and Schubert (2022), Pommeret et al. (2022) and Schubert et al. (2025) is notable. There, energy from low-carbon sources is available at no marginal current cost and its supply is constrained by installed capacity, while the opposite holds for carbon-intensive energy. Here instead, both types of energy rely on a resource-specific capital which necessitates dedicated costly investment. To focus on an energy transition path based on low carbon sources, we abstract from the initial phase when materials are assigned to the accumulation of fossil-based energy infrastructure. Notwithstanding, the analytical framework we present can serve to conduct a sort of historical life-cycle analysis of minerals in the energy system: they were used to build the fossil-based infrastructure, before being eventually recovered from dismantled equipment to be allocated to investment in the low-carbon infrastructure. Another contribution of this paper is that it presents an original form of imperfect mobility of capital across (sub-)sectors. The source of friction in the workhorse model of the energy transition lies in the assumption that investment in low carbon infrastructure requires specific investment and is associated to capital adjustment costs. There, capital cannot be reallocated across the two sub-sectors, carbon-intensive and low-carbon infrastructure. Here instead, capital –in the form of the materials it embeds– is fungible, since it can flow from the carbon-intensive sub-sector to the low-carbon one, with some inertia. In fact, it implies the additional cost related to the activity of the recycling sector. This seems a meaningful extension, particularly useful to develop exchange between the materials-science and economics communities.

The model and the main trade-offs are presented in the next section. Section 3 characterizes the optimal trajectory along a specific sequence of phases, one where virgin ores are first exhausted, then fossil resources are exhausted, and finally the stock of scrap is exhausted. Comparative dynamics of the cases with and without recycling of materials from decommissioned fossil infrastructure is presented in Section 4. We conclude in the last section.

## 2 Modeling infrastructure conversion

To model infrastructure conversion, we use a simple analytical framework. It is highly stylized and relies on a number of simplifying assumptions as the objective is not to provide a very precise representation of the energy transition but rather to keep a parsimonious modeling so the main mechanisms at play remain clear. We now present the model in detail. Variables and parameters are summarized in Table 1.

The economy is meant to provide energy services –thereafter dubbed "electricity consumption", $e(t)$– while complying with natural resources and technological constraints. It is possible to produce electricity from two perfectly substitutable sources: fossil or renewable (or carbon-free) resources.

Renewable resources are not scarce in the Hotelling (1933) sense, since their increased use at one date has no implication for the possibilities of using them at any other date. Fossil resources are instead scarce, because their use implies carbon emissions which pile up in the atmosphere and exhaust the carbon budget. (i.e. an exogenous policy-target for the cumulative amount of emissions). This implies a first asymmetry: according to the Hotelling rule consumption of electricity from fossil resources is associated with a social cost that increases at the social time-discount rate, whereas that is not the case when consuming electricity from renewable sources. Therefore renewable energy becomes increasingly competitive over time.

In order to transform resources into energy services, the technology relies on resource-specific infrastructure. We refer to "brown", $Z(t)$ and "green", $Y(t)$, infrastructure as that for the production of electricity from, respectively, fossil or renewable sources of energy. Specifically, we assume that infrastructure is composed of physical matter, such as minerals, produced from natural resources and hereafter named "materials". For simplicity, we consider materials as a single element and assume that the coefficients of conversion from materials to energy services, $\theta$ and $\phi$ respectively, are constant.[4] We also normalize the quantity of materials per unit of infrastructure, so that $Z(t)$ and $Y(t)$ directly measure quantities of materials in use in the brown and green infrastructure. Production of electricity is therefore:

$$e(t) = \theta Z(t) + \phi Y(t) \tag{1}$$

Perfect substitutability reflects our definition of green infrastructure as including equipment for storage of variable or intermittent sources of renewable energy. Since each infrastructure provides useful services, a value is associated to their stocks: $\lambda(t)$ and $\mu(t)$ for brown and green infrastructure respectively. In our analysis we assume a second asymmetry: the initial conditions are such that brown infrastructure is abundant while the green one is scarce. This reflects our focus on an energy transition aimed at coping with climate change, along which brown infrastructure is decommissioned and investment is devoted to expand green infrastructure.

Under the two above mentioned asymmetries, our analysis characterizes two distinct cases for efficient electricity production. In a first case both sources of energy are used. It must then be that the source (i.e. renewables) with a null marginal cost is used at full capacity. Demand in excess of what is served by such capacity is met by the use of fossil sources whose marginal cost corresponds to the carbon price, which increases over time. However, as green infrastructure expands the share of

[4] Since in reality infrastructure encompasses several materials, our approach rules out of the analysis changes of the basket of elements composing the infrastructure, namely through substitution processes. Moreover, constant $\theta$ and $\phi$ rule out technological progress.

fossil sources of electricity production shrinks (unless the demand expands even faster). Eventually, green infrastructure will be sufficiently developed and the price of carbon high enough to drive fossil fuels out of the market. Thereafter electricity is exclusively produced from renewable sources. We refer to the date on which this phase begins as the date of "fossil phase-out". In this situation although the marginal cost of renewable resources is nil, the opportunity cost of consumption is positive because green infrastructure is used at full capacity. In fact there is no satiation of demand in the long-run, since investment in green infrastructure is costly and must be renewed as it wares out, at a constant depreciation rate $\delta_Y$.

Green infrastructure may increase if dedicated investment more than compensates depreciation:

$$\dot{Y}(t) = I(t) - \delta_Y Y(t), \quad Y(t) \geq 0, \quad Y_0 \text{ given}, \tag{2}$$

where investment $I(t)$ relies on materials. The sources of materials for investing in infrastructure can be distinguished between "primary" and "secondary" natural resources.

We consider two primary natural resources for materials: "minerals" and a "backstop". The former is a non-renewable stock of resource, $M(t)$, which is exhausted in all scenarii through extraction, $m(t)$:

$$\dot{M}(t) = -m(t), \quad M(t) \geq 0, \quad M_0 \text{ given}. \tag{3}$$

Although we assume that extraction implies no direct costs, the social value of minerals, denoted $\zeta(t)$, grows over time at the social rate of time-discount, $\rho$, since virgin raw materials are a scarce resource. The backstop resource, $b(t)$, is a perfect substitute for minerals in infrastructure, which is not scarce in the Hotelling sense. It is available at a positive and constant cost, $\nu$, substantially higher than that of minerals.[5]

Materials from secondary natural resources can also be employed in infrastructure. In the energy transition we focus on, brown infrastructure is the source of secondary materials through decommissioning, and green infrastructure is its destination. The rate of decommissioning, $\delta(t) \in [0, 1]$, is a control variable, and the brown infrastructure evolves as follows:

$$\dot{Z}(t) = -\delta(t)Z(t), \quad Z(t) \geq 0, \quad Z_0 \text{ given}. \tag{4}$$

Investment in brown infrastructure is ruled out because it is incompatible with the climate problem in our setting.[6] Moreover, there is no exogenous depreciation of brown capital. Shall the deprecia-

[5]The assumption of a zero cost of producing minerals does not matter for the qualitative results, as long as the cost is much lower than that of the backstop. Considering a single element such as cooper or lithium, the case of minerals can be associated to the availability of highly concentrated and accessible deposits, while the backstop to their very dispersed presence in oceans or deserts. Another example is substitution between materials. In the manufacturing of photovoltaic cells, for example, overcoming some technical and economic challenges would allow to substitute cooper for silver, which is relatively rare. Alternative definitions of a backstop technology exist in resource economics (see Fodha and Ricci (2025) and references therein).

[6]In Liang et al. (2025) fo instance investment in fossil based infrastructure is important, because their setting allows

tion rate be high enough, it could be optimal to avoid decommissioning (choosing $\delta(t) = 0$) invest some materials in brown infrastructure despite the rise in the carbon price. In order to focus on the main mechanisms of the transition and consistent with a realistic low enough depreciation rate, we ignore this potential effect.

Decommissioned infrastructure then serves to recover some scrap. This scrap piles up and is stored at no cost to build a stock $K(t)$ that can be used for recycling at a rate $\alpha(t) \in [0, 1]$, which is a control variable:

$$\dot{K}(t) = \delta(t)Z(t) - \alpha(t)K(t), \quad K(t) \geq 0, \quad K_0 = 0. \tag{5}$$

To simplify the analysis, we assume that storage of scrap does not involve any cost, neither monetary nor in terms of degradation of the physical properties materials. One can expect that a strictly positive storing cost would both delay decommissioning and bring forward recycling, without further affecting the mechanisms of the energy transition. Nevertheless, introducing such a cost in the model would make the dynamics in the model, and its analytical resolution, significantly more complex.

Considering that, due to dispersion, only a share $\psi \in (0, 1]$ of scrap can be recovered for recycling, an amount of materials $\psi\alpha(t)K(t)$ can be invested in green infrastructure. Recycling is costly. The associated cost function is $R(\alpha(t), \psi K(t))$, assumed increasing and linear in the first argument, and increasing in the scale of the treated secondary resources $\alpha(t)\psi K(t)$. We further assume away any scale (dis)economies in recycling:[7]

$$R(\alpha(t), \psi K) \equiv \eta(\alpha)\psi K \quad \text{ with } \eta(\alpha) \geq 0,\ \eta(0) = 0,\ \eta'(\alpha) \geq 0 \text{ and } \eta''(\alpha) = 0.$$

We assume $\eta'(0) < \nu$, so that investing using at least some recycled green capital is cheaper than using the backstop technology. Summing up, investment relies on extracted materials, recycled materials or the backstop technology:

$$I(t) = m(t) + \alpha(t)\psi K(t) + b(t). \tag{6}$$

We conclude the presentation of the model with the constraint from climate policy. This takes the form of a carbon budget, i.e. an exogenous amount of cumulative carbon emissions $\overline{X}$ up to $T_3$, the date of fossil phase out:

$$\int_0^{T_3} \chi\theta Z(t)dt = \overline{X} \tag{7}$$

where parameter $\chi$ is the carbon emission intensity of electricity production from fossil sources.

to reallocate production across distinct fossil-based technologies that have heterogeneous carbon intensity (from coal to natural gas). In our model there are only two technologies, brown and green, characterized by uniform and constant carbon intensity.

[7]When all the scrap has been recycled, recycling has to stop. Hence complete recycling of materials cannot occur at steady state, even without ruling out the case $\alpha(t) = 1$.

| | | |
|---|---|---|
| $e(t)$ | consumption of electricity | physical units |
| $u(e(t))$ | utility from electricity consumption | value |
| $\rho$ | social rate of time-discount | coefficient |
| $Z(t)$ | stock of brown infrastructure | physical units |
| $\theta$ | productivity of brown infrastructure | coefficient |
| $\lambda(t)$ | social value of brown infrastructure | value |
| $\chi$ | carbon emission intensity of electricity from fossil sources | coefficient |
| $\overline{X}$ | carbon budget | physical units |
| $p(t)$ | unitary social cost of electricity from brown infrastructure | value |
| $Y(t)$ | stock of green infrastructure | physical units |
| $\phi$ | productivity of green infrastructure | coefficient |
| $\mu(t)$ | social value of green infrastructure | value |
| $K(t)$ | stock of scrap from brown infrastructure | physical units |
| $\psi$ | recoverable materials per unit of scrap | rate |
| $\kappa(t)$ | social value of scrap | value |
| $M(t)$ | stock of minerals | physical units |
| $m(t)$ | extraction of minerals | physical units |
| $\zeta(t)$ | social value of minerals | value |
| $\delta(t)$ | decommissioning of brown infrastructure | rate |
| $\alpha(t)$ | scrap recycling | rate |
| $R(.)$ | cost of recycling | value |
| $\eta(\alpha)$ | unit cost of recycled materials | value |
| $b(t)$ | backstop | physical units |
| $\nu$ | unit cost of backstop materials | value |
| $I(t)$ | investment in green infrastructure | physical units |
| $C(I)$ | adjustment cost of capital (parameters $c_1$, $c_2$) | value |
| $T_2$ | date of mineral exhaustion | time |
| $T_3$ | date of fossil phase-out | time |
| $T_4$ | date of exhaustion of old scrap of materials | time |

Table 1: List of variables and parameters

Climate policy sets the social value of carbon, $p(t)$, to ensure that this constrain holds. Recall that $p(t)$ follows Hotelling's rule (i.e. $p(t) = p(0)e^{\rho t}$) since the carbon budget is eventually exhausted. This implies to each value of the carbon budget, $\overline{X}$, corresponds an initial value of carbon, $p(0)$. In the analysis below, we abstract from the carbon budget constraint (7), and rather take into account the trajectory of $p(t)$ for a given initial value $p(0)$. However, when in Section 4 we perform comparative dynamics exercises, we apply an algorithm to modify $p(0)$ in order to attain the same cumulative emissions $\overline{X}$ across scenarii.

We study the case of optimal regulation. The social planner maximizes utility derived from electricity consumption $e(t)$ net of the potential costs incurred in developing the green infrastructure or in burning fossil resources to generate this electricity. The latter reflects the social cost of carbon resulting of the carbon budget, $p(t)$. The former encompasses two types of current cost: on the one hand, the capital adjustment cost due to investment, $C(I(t))$; on the other hand, the explicit costs of secondary materials, $\eta(\alpha(t))\psi K(t)$, and of primary materials from the backstop technology,

$\nu b(t)$. Therefore, the program of the planner is:

$$\begin{aligned} \max_{\delta(t),\alpha(t),m(t),b(t)} \int_0^\infty e^{-\rho t} \quad & \left[u(e(t)) - C(I(t)) - \nu b(t) - \eta(\alpha(t))\psi K(t) - p(0)e^{\rho t}\theta Z(t)\right] dt \\ \text{s.t.} \quad & (1) - (6), \\ \text{with} \quad & \delta(t) \in [0,1],\ \alpha(t) \in [0,1],\ m(t) \geq 0,\ b(t) \geq 0\ . \end{aligned} \tag{8}$$

The corresponding Hamiltonian, Lagrange function and first order conditions are provided in the appendix.

In what follows we adopt precise specifications for three functions. Recycling costs are assumed linear:

$$\eta(\alpha(t)) \equiv \eta_1 \alpha(t)$$

This implies that recycling cannot co-exist with extracted minerals or backstop.

In addition, we assume a log utility function:

$$u(e(t)) \equiv \gamma \ln e(t)$$

Finally, we consider convex capital adjustment costs, excluding technological progress, such as learning-by-doing:

$$C(I(t)) \equiv c_1 I(t) + \frac{c_2}{2} I(t)^2 \quad \Rightarrow \quad C'(I(t)) = c_1 + c_2 I(t), \quad C'(0) = c_1 \tag{9}$$

## 3 The optimal energy transition with infrastructure conversion

Let us first note that it is possible to exhibit a phase during which scrap is accumulated even though no recycling occurs. This happens if decommissioning is triggered by the carbon price, while recycling is still too expensive compared to virgin raw materials that are still available in large quantities. Scrap piles up and is stored at no cost to build a stock that could be recycled later to supply secondary materials for investment.

We incidentally specify that –differently from Pommeret et al (2022)– we do not allow for depreciated green capital to add to the stock of scrap. This implies that the backstop materials cannot be recycled. This assumption allows us to define the steady state of the economy independently of the recycling technology, facilitating the comparative dynamics exercise in Section 4.

We consider the following sequence of phases. First, the economy generates electricity with existing brown infrastructure and builds (and uses) green infrastructure to generate electricity with renewable energies. During this phase, the fossil infrastructure begins to be decommissioned, creating a stock of scrap materials which accumulates while it is not yet recycled. Do note that due to the linear structure of the recycling costs, there can neither be simultaneously extraction of virgin raw materials and recycling, nor simultaneously recycling and use of the backstop. Hence, a second phase starts when the shadow value of virgin minerals reaches the recycling cost, and minerals are exhausted while recycling takes place. Recycling is then the only source of materials for building green infrastructure. This phase ends when the brown infrastructure is completely abandoned. Yet, during this third phase, there is still a stock of scrap to be recycled. When the stock of scrap is exhausted the fourth phase starts, and thereafter investment in green infrastructure entirely relies on the backstop technology.

Any other sequence for these phases could theoretically appear, since the order of the phases is governed by the value of the parameters and the initial conditions. For instance, to ensure the order we have chosen to focus on, we need to start with an implicit price of extracted materials that is less than the cost of recycling. Similarly, the cost of recycling has to be smaller than the cost of the backstop to ensure that recycling takes place before the phase with backstop use. We have chosen to focus on this sequence because we think it is a meaningful representation of the energy transition. However, our approach could be used to analyze any other sequence for the phases that could be relevant for economies characterized by other parameters' values than those used for the simulations in Section 4.

In the reminder of this section we characterize the solution of program (8). Its detailed derivation is presented in the Appendix.

1st phase:

During the first phase, electricity is provided by both the green and the brown infrastructures while investment in green infrastructure relies entirely on extracted materials. In the meantime, brown infrastructure starts being dismantled and scrap is accumulated. Hence during this first phase: $m > 0, Z > 0, 0 < \delta < 1, b = 0, \alpha = 0$.

Since $Z$ and $Y$ are stocks, we have that at time zero $\theta u'(\theta Z(0) + \phi Y_0) = p(0)$, we assume that $Z_0$ (the stock of brown infrastructure before the start of the programme) is relatively large to be compatible with $Z(0) \leq Z_0$ (where $Z(0)$ is the optimal stock of brown infrastructure as soon as the programme starts), and $Y_0$ relatively low. Using equation(A.10), we obtain $\zeta(t) = \zeta(0)e^{\rho t}$, showing that the value of the stock of natural minerals follows the Hotelling rule. During this phase, equation (A.3) boils down to $\lambda(t) = \kappa(t)$, which is a no-arbitrage condition. It implies that even if reducing $Z$ allows accumulating scrap for recycling $K$, since $\delta$ is chosen in an optimal way, the gain in terms of additional value in the form of scrap is exactly compensated by the loss of value due to reduced fossil fuel electricity generation. Appendix 6.2 shows how this phase can be characterized analytically. In particular, we obtain that the stock of scrap monotonically increases in time. This phase ends at $T_2$ when the value of the minerals equal to the "full" cost of recycling, which adds to the current cost of recycling the opportunity cost of depleting the stock of scrap:

$\zeta(T_2) = \eta'(0) + \kappa(T_2)/\psi = \eta_1 + \kappa(T_2)/\psi$. At this date the optimal path of mineral extraction has exhausted the available stock: $\int_0^{T_2} m(t)dt = M_0$.

2nd phase:
During the second phase too electricity is produced using both the brown and the green infrastructure, with the former being decommissioned and the later developed. However, since the stock of virgin materials has been exhausted, investment in green infrastructure relies on secondary materials, obtained by recycling part of the scrap. During this we therefore have: $0 < \alpha < 1, 0 < \delta < 1, Z > 0, b = 0, m = 0$.

Appendix 6.3 shows how this phase can be fully characterized analytically. In particular, we obtain the optimal recycling rate of scrap, $\alpha(t)$. This phase ends at date $T_3$, when the carbon budget is exhausted, i.e. when (7) holds. At that time, the marginal utility of electricity generated from green infrastructures equals the shadow value of carbon, which provides a condition for $T_3$. Moreover, decommissioning is completed by setting $\delta(T_3^-)$ equal to 1 just before $T_3$, ensuring that the stock of brown infrastructure starts to be nil just after $T_3$. Finally, the stock of green infrastructure is continuous at $T_3$.

3d phase:
The third phase is fully decarbonized, as the whole brown infrastructures have been decommissioned. Green infrastructure is still developed using only recycled materials. Hence, we now have that: $0 < \alpha < 1, \delta = 1, Z = 0, b = 0, m = 0$.

The dynamics for the stock of green infrastructure $Y(t)$ together with that of its social value $\mu(t)$ are derived in Appendix 6.4. Again, the optimal recycling rate of scrap materials is characterized, so that $\alpha(t) \in (0, 1)$ during this phase. This phase ends with the last recycling activity and leaves not scrap for the following phase. At the very end of the phase, all remaining scrap is recycled, hence the recycling rate hits 100% at date $T_4$, $\alpha(T_4) = 1$. Moreover, at time $T_4$ the "full" cost of recycling equals the cost of the backstop: $\kappa(T_4)/\psi + \eta_1 = \nu$. We notice that the exhaustion of the stock of scrap depends on the time paths of both the decommissioning rate $\delta(t)$ and the recycling rate $\alpha(t)$. However, the choice of the initial instantaneous decommissioning rate $\delta(0)$ plays two roles: on the one hand, it determines the initial consumption level $e(0)$ according to (1), on the other hand, it establishes the initial level of scrap materials at $Z_0 - Z(0) = (1 - \delta(0))Z_0$.

4th phase:
In the fourth and last phase, investment in green infrastructure only uses the backstop technology as materials. There is no longer brown infrastructure, nor scrap to be recycled or natural material in the economy. Hence, we now have that: $\alpha = 0, m = 0, Z = 0, b > 0$.

Since the economy relies exclusively on renewables and the backstop, we hae that $e(t) = \phi Y(t)$ and $I(t) = b(t)$. As shown in Appendix 6.5 the dynamics of the economy is characterized by:

$\forall t \geq T_4$,

$$\begin{cases} \dot{Y}(t) = \frac{1}{c_2}\mu(t) - \frac{\nu + c_1}{c_2} - \delta_Y Y(t) \\ \dot{\mu}(t) = (\rho + \delta_Y)\mu(t) - \frac{\gamma}{Y(t)} \end{cases} \tag{10}$$

This system of differential equations admits a unique saddle path stable steady state, defined explicitly as follows:

$$\begin{aligned} Y^* &= \frac{1}{2c_2\delta_Y}\left\{\left[(\nu + c_1)^2 + \frac{4c_2\delta_Y\gamma}{\rho+\delta_Y}\right]^{1/2} - (\nu + c_1)\right\} \\ \mu^* &= \frac{\gamma}{\rho+\delta_Y}\frac{1}{Y^*} = \frac{2c_2\delta_Y\gamma}{\rho+\delta_Y}\left\{\left[(\nu + c_1)^2 + \frac{4c_2\delta_Y\gamma}{\rho+\delta_Y}\right]^{1/2} - (\nu + c_1)\right\}^{-1} \end{aligned} \tag{11}$$

In the next section we present the numerical solution of the energy transition characterized in this section.

# 4 The effect of recycling and decommissioning on the energy transition

In this section we present numerical solutions of the optimal energy transition characterized in the previous sections. We first explain the trajectories of all the endogenous variables. We then compare them to the case where recycling of decommissioned brown infrastructure is impossible to show its impact.

The results we present are illustrative. They demonstrate the implementation of the applied version of the model. However, they do not provide conclusive quantitative evidence on the importance of decommissioning brown infrastructure. This is because we are unable to establish the values of all the parameters in a coherent empirically grounded way. This leaves us with some degrees of freedom, which allow us to choose some of the parameters to ensure that the economy evolves along the sequence of phases studied in the previous session: the constraint on the stock of minerals binds first, followed by the carbon budget, while the stock of scrap is exhausted the last.

The parameters' values are reported in Table 2. Here we explain how these values are chosen. First, we use data for the European Union averaged over 2017-21 concerning energy consumption. According to Eurostat, yearly average total final consumption amounted to 10,803.921 TWh, of which 1203.445 TWh from renewables and biofuels and 2472.335 TWh from electricity.[8] We compute the share of the electricity produced from low carbon sources (renewable sources and nuclear) from Eurostat, i.e. 56.7% on average, to obtain the yearly average at 1401.907 TWh. Summing the two components, the initial energy consumption from green infrastructure ($\phi Y_0$) is 2605.353 TWh, and

[8] We use data for "Share of energy from renewable sources", "Gross and net production of electricity and derived heat by type of plant and operator", "Electricity production capacities by main fuel groups and operator" accessed from the Eurostat Data Browser on 04/04/2023.

the complement 8198.569 TWh is from brown infrastructure ($\theta Z_0$). Next, we use Eurostat data on capacity and generation by technologies to compute the weighted averaged load factor across the low carbon technologies, and obtain 33.57%. Using the later and the initial consumption of green energy, we compute the initial installed green capacity as 886.07 GW. For brown energy we assume a capacity factor at 70%, which is on the upper end of the average monthly values reported by the Energy Information Agency for gas turbines with combined cycle, and obtain 1337.01 GW of initial capacity installed.[9] We use a material intensity of green technology at 4.000 Mt/GW to compute $Y_0$ from the initial capacity.[10] For brown infrastructure we assume that the material intensity is 13 times lower, and obtain $Z_0$. This ratio lies within the wide range of 11 to 40 times larger material intensity of renewable technologies than that fossil fueled ones proposed by Hertwich et al. (2015), but lower than the 17 times used by Vidal et al. (2022).[11] Parameters $\theta$ and $\phi$ are then computed from these initial values of materials embedded in infrastructure and initial energy consumption. The scale parameter $\gamma$ of the utility function is set to ensure that at the initial level of energy consumption the marginal utility equals the average purchaser price of electricity at 160€/MWh, in between the retail prices including taxes for households and for industry over 2017-21, from the EU Dashboard for energy prices of the European Commission.[12] The depreciation rate for green infrastructure $\delta_Y$ is set as the one used by the U.S. Bureau of Economic Analysis from the private "wind and solar" structures.[13] The discount rate $\rho$ is the close to French official rate, 3.2%.[14] We set parameter $\psi$ assuming a 10% loss of matter during recovery from brown infrastructure. The carbon emissions intensity of brown energy, $\chi$, is computed using the initial energy consumption from brown infrastructure and average yearly greenhouse gas emissions 3,493.129 $MtCO_2eq$ for the EU over 2017-21.[15] We calibrate the parameter of the square term in the investment cost function $c_2$ to ensure that materials in green infrastructure increase 13 times in the long run.[16] The values of the parameters characterizing the cost of recycling ($\eta_1$), of the backstop ($b$), and of investment ($c_1$), together with the carbon budget $\overline{X}$ and the stock of materials $M_0$ are chosen to ensure that the optimal energy transition involves the sequence of phases characterized in the previous section.

[9] See Chapter 6 of the EIA Electric Power Monthly, in particular Table 6.07.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels.

[10] Onshore wind installations use 3.888 t/MW of copper, which we increase by upper rounding above, to take into account power storage facilities. Source: Cooper Development Association, Market Data, Infograpichs, *Copper and the clean energy transition* (link), citing data from the consulting company Navigant/Guidehouse Research.

[11] We are grateful to Olivier Vidal for access to this background data from the DyMEMDS model.

[12] European Commission – Energy, Climate change, Environment – Energy prices and costs in Europe – Reports on energy prices and costs (link).

[13] See Table BEA Rates of Depreciation, Service Lives, Declining-Balance Rates, and Hulten-Wykoff Categories – Private nonresidential structures – Wind and solar, in *BEA Depreciation Estimates*, (link).

[14] See France Stratégie (2023) *Guide de l'évaluation socioéconomique des investissements publics – complément opérationnel I: Révision du taux d'actualisation* (by J. Ni and J. Maurice).

[15] We compute total greenhouse gas emissions (excluding LULUCF) for the EU27 combining historical data for 2017-2019 from the World Bank Development Indicators (Climate Watch) and the projections reported in 2022 by member states to the European Environmental Agency for 2020 and 2021 (link).

[16] Substitute $mY_0$ for $Y^*$ on the first line of (11) to write $c_2 = [\gamma - mY_0(c_1 + \nu)(\delta_Y + \rho)]/[(mY_0)^2\delta_Y(\delta_Y + \rho)]$, then set $m = 13$ and use parameters.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\theta$ | 19,929 | TWh/Mt | $Y_0$ | 3.54 | Mt | $\gamma$ | $1{,}729{\cdot}10^3$ | value/Mt |
| $\phi$ | 735.18 | TWh/Mt | $Z_0$ | 45.60 | Mt | $\nu$ | 1,000 | value/Mt |
| $\psi$ | 0.90 | rate | $M_0$ | 51.48 | Mt | $\eta_1$ | 100 | value/Mt |
| $\rho$ | 0.03 | rate | $\chi$ | 0.426 | $MtCO_2eq/TWh$ | $c_1$ | 1,000 | value/Mt |
| $\delta_Y$ | 0.03 | rate | $\overline{X}$ | 1,110 | $GtCO_2eq$ | $c_2$ | 450,928 | value/Mt$^2$ |

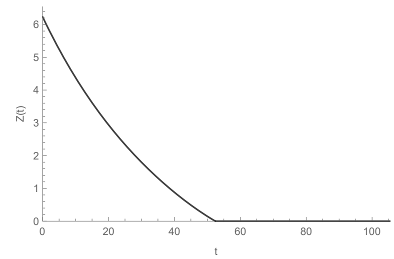
Table 2: Parameters for the baseline simulation.

The system of ordinary differential equations is solved using the backward shooting procedure from $\{\mu^*, Y^*\}$ until $Y(0) = Y_0$ (Brunner and Strulik, 2002). The guess for the initial value of minerals, $\zeta(0)$, the initial value of the carbon price $p(0)$ and the initial value of scrap $\kappa(0)$ are adjusted by trial and error until cumulative mineral use equals $M_0$, cumulative emissions equal $\overline{X}$ and residual scrap is zero once the backstop becomes less expensive than recycling (i.e. at $T_4$).

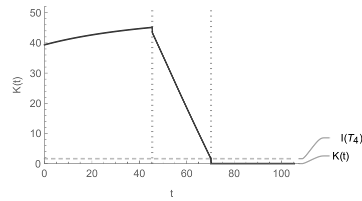
The numerical solution gives the dynamics illustrated in Figure 1 and values reported on the second line of Table 3. Virgin materials exhaustion occurs after 45.4835 periods, when recycling starts, fossil is phased out after 52.4188 periods and recycling stops at 70.2154 after 24.7319 periods of activity. Interestingly, the stock of scrap $K$ is non monotonic (see panel (b) of Figure 1). There is substantial initial decommissioning, since the brown capital is excessively high in light of the carbon budget. It then starts increasing, when decommissioning occurs but there is no recycling. It begins decreasing when the stock is high and recycling becomes sufficiently competitive compared to raw materials (from $T_2$ onwards). Later, when all the infrastructure has been decommissioned ($T_3$), it declines as recycled raw materials are used for investment but no old scrap is generated. At the time recycling starts ($T_2$), it falls instantaneously by the the amount of green investment. The discontinuity at $T_2$ is due to the fact that virgin raw materials need to be replaced by a similar amount of secondary materials from recycling in order to maintain the level of investment in green capital (see panel (d) of Figure 1). Inspecting panel (d) of Figure 1, we notice that materials used in green investment –therefore recycling– decrease over time. This is because there is ever less (and eventually none) fossil infrastructure to decommission, which increases the opportunity cost of using accumulated scrap. Eventually, at the time recycling stops ($T_4$), the full user cost of recycled materials (current cost plus opportunity cost of scrap) is as high as the current cost of the backstop technology (see panel (f) of Figure 1). At that date the stock of scrap again falls instantaneously (see panel (b) of Figure 1) when a non marginal investment based on scrap (recycled inputs) is replaced with a non marginal investment through the backstop (illustrated on panel (d) of Figure 1).

| | $T_2$ | $T_3$ | $T_4$ | $\zeta(0)$ | $p(0)$ | $\kappa(0)$ | $Z_0 - Z(0)$ |
|---|---|---|---|---|---|---|---|
| No recycling | 45.4956 | 52.4255 | | 255.397 | 271739 | | 39.37351 |
| Recycling | 45.4835 | 52.4188 | 70.2154 | 135.034 | 271702 | 98.5509 | 39.37305 |

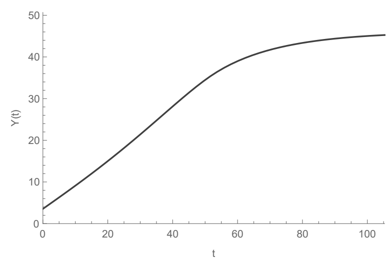
Table 3: Numerical results for the two cases.



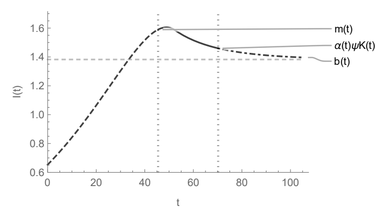

(a) stock of materials in brown infrastructure



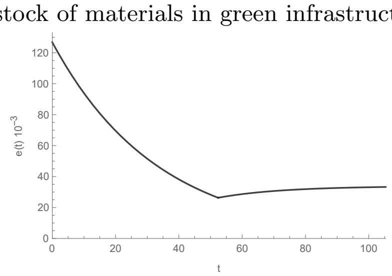

(b) stock of scrap materials



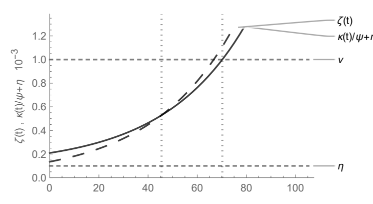

(c) stock of materials in green infrastructure




(d) materials invested in green infrastructure




(e) electricity consumption




(f) full cost of recycled (- -) and of virgin (—) materials

Figure 1: Optimal energy transition with recycling of decommissioned brown infrastructure.

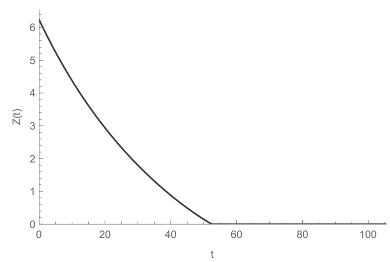
Panel (f) in Figure 1 shows that both the value of primary virgin materials and that of secondary materials from scrap follow Hotelling's rule, reflecting the fact that they are finite stocks doomed to be exhausted. It also shows that recycling starts when its cost, including the value of foregone scrap ($\eta + \kappa(t)$), becomes lower than the value of minerals ($\zeta(t)$). This positive and increasing value of the scrap implies that the fossil fuel infrastructure does not become a stranded asset, meanwhile the economy transitions towards renewable sources for electricity generation. In fact, although initially the bulk of the value of this infrastructure reflects its capacity to generate electricity, it becomes driven by its ability to provide useful scrap that is valuable to invest in low carbon infrastructure. Once the whole stock of fossil fuel infrastructure is converted into scrap and it is used only for green investment, the fossil infrastructure is not yet stranded since it is valuable as scrap. This is because it relaxes the material constraint on the transition, so much that all the initial stock of fossil fuel infrastructure is converted into a fully depleted stock of scrap. To the best of our knowledge, this is an original mechanism put forward in our analysis.

As shown on panel (e) in Figure 1 electricity consumption at first falls, reflecting the fact that the marginal unit of electricity consumed relies on fossil fuels, whose cost increases exponentially with the social cost of carbon. Recall in fact that the latter follows the Hotelling rule as the carbon budget becomes increasingly scarce is eventually exhausted. After fossil phase-out instead consumption increases along with low carbon production capacity, which is accumulated overtime. This feature is shared with Pommeret and Schubert (2022)

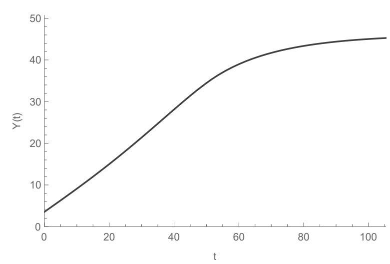
Let us now turn to a comparative dynamics exercise to better understand the leverage offered by the possibility of recycling materials in decommissioned brown infrastructure. For this purpose we compare the baseline optimal energy transition to the one in an similar economy, where however the recycling technology is unavailable. In the absence of recycling of the existing fossil infrastructure (see Figure 2 and Table 3), virgin materials is exhausted at time $T_2$= 45.4956, meaning that the backstop technology is used earlier (in panel (c) of Figure 2 investment directly switches from virgin materials to the backstop). Though the impact is quantitatively small, fossil phase-out is delayed as compared to the case with recycling. There are incentives to keep using fossil fuel for longer.[17] First, scrapping is no longer valuable, the value of fossil fuel infrastructure entirely results of its capacity to produce power. Second, investment in green capital is more expensive in the absence of recycling, slowing down the transition. We establish that taking advantage of the opportunity of recycling materials from the fossil fuel infrastructure reduces the cost of fossil phase-out. As a result, the carbon price compatible with the carbon budget is always higher in the absence of recycling than when recycling is economically feasible.

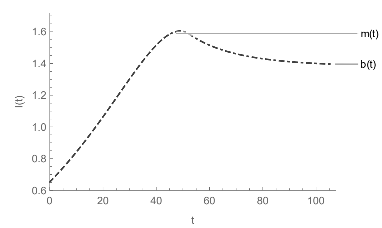
The value of virgin minerals is significantly higher (see panel (e) in Figure 2) because the only alternative is now the expensive backstop. According to Table 3 the initial price of virgin minerals

[17] Beyond the fact that the two mechanisms contributing to speeding up the transition are interesting per se, the impact may become quantitatively important with other parameterizations that could be relevant for other economies.

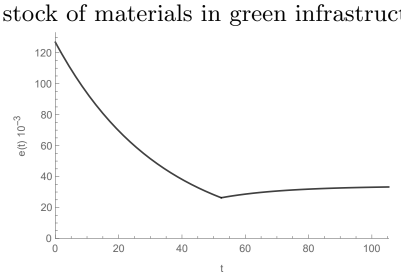


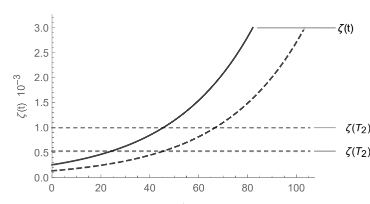

(a) stock of materials in brown infrastructure




(b) stock of materials in green infrastructure (c) materials invested in green infrastructure




(d) electricity consumption (e) value of minerals ( - - baseline)

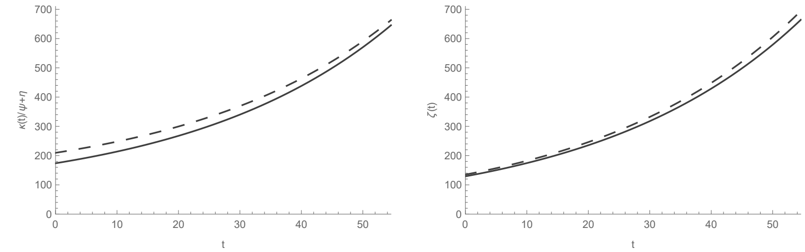
Figure 2: Optimal energy transition without recycling.

is 89% higher. This shows that the opportunity of recycling materials embedded in the existing infrastructure allows society to contain the increase in the price of minerals.[18] Without recycling the cost of virgin materials reaches the cost of the backstop ($\nu = 1,000$) by $T_2$. When recycling is possible instead, recycling starts almost at the same time when however the cost of the material input to investment is 485.7, sensibly lower than in the other case. A lower cost of materials should foster investment. However, we find that the investment trajectory is very close to the one prevailing with the recycling of the fossil infrastructures. To understand this consider that such a lower full cost of materials represents a very marginal gain in overall investment cost (0.05%). This is because the latter encompasses the capital adjustment cost ($C(I_t)$) which, under the chosen set of parameters, accounts for 97.3% and 98.5% of total investment cost upon exhaustion of virgin material resources in the scenarios without or with recycling, respectively. Moreover, the long run equilibrium of the economy is not affected by recycling, since from (11) the steady-state level of green capital $Y^*$ only depends on the cost of the backstop ($\nu$), on the capital adjustment cost function (i.e. $c_1$ and $c_2$), on the depreciation rate of green capital ($\delta_Y$), and on preference parameters ($\gamma$ and $\rho$). Given the small change in total cost of investment, the values of the virgin raw materials ($\zeta$) and of the scrap ($\kappa$), are determined to sustain the (almost same) optimal investment trajectory converging toward steady state $Y^*$.

Of course, without recycling the fossil fuel infrastructure looses value and becomes fully stranded upon fossil phase-out. When recycling is possible and its role in the energy transition is duly accounted for, the initial capitalization of the fossil fuel infrastructure (partially decommissioned, partially active) amounts to 4494.3, but it is nil when recycling is impossible or not taken into account. The present value of revenues from sales of electricity produced from fossil fuels is 2573.09 lower with recycling than without recycling. In this numerical example therefore, the possibility to sale the scrap from decommissioning fossil fuel infrastructures increases the full value of ownership. This is not surprising because the carbon budget is met in both situations, as an appropriately stringent climate policy is implemented. It does not mean that the emission path is not affected: the emission path without recycling crosses the one with recycling. More precisely, without recycling, emissions are initially lower. After 25.7 periods, they become larger than the ones with recycling. Finally, emissions without recycling remain positive for a longer time, as the fossil phase-out occurs later. However, since emissions only affect the planner program through the constraint on the carbon budget, the change in the emission path does not affect the economy. Recycling creates some slack in making the economy wealthier, and ownership of the recyclable materials earns a share of this surplus.

Comparative dynamics exercises can also be performed between economies having access to recycling technologies at different costs. Considering a 40% decrease in the exogenous cost of recycling ($\eta$) leads to modest effects, under the chosen set of parameter values. The qualitative

[18]Nevertheless, the price of virgin materials increases over time at the rate of interest in any case.




(a) full cost of recycling (b) value of minerals
baseline (dashed lines) and 40% lower (solid lines) current cost of recycling ($\eta_1$)

Figure 3: Impact of lower cost of recycling.

results in Figure 3 are consistent with those obtained in the absence of recycling (that can be interpreted as a case with an infinite cost for the recycling). It shows that a reduced cost of recycling lowers the value of minerals. Although not clearly visible in Figure 3, the initial value of scrap, $\kappa(0)$, thus that of brown infrastructure, $\lambda(0)$, is approximately 4% higher for lower cost of recycling. This proves that the possibility to recycle decommissioned fossil-based equipment and structures mitigates concerns for stranded assets. Moreover, we find that time for fossil exhaustion now occurs after $T_3 = 52.4096$ periods, that is earlier than with for baseline recycling cost.

## 5 Conclusion

In this paper, we build a stylized model of the energy transition. Electricity is initially generated from fossil sources but climate policies make them progressively more expensive through carbon pricing. Investment in renewable electricity generation and storage capacity becomes then relatively less expensive and progressively replace fossil sources. This investment embeds critical resources that can be supplied by recyclers who recover the scrap from decommissioned fossil infrastructure which is an innovative feature of our model. Alternatively, an exhaustible virgin material from the mines or a relatively expensive backstop technology can be used to build-up green infrastructure. We study how decommissioning and recycling affect the transition dynamics of the economy. In addition, we analyze the non-trivial dynamics for the stock of scrap. Moreover, we show that the stock of fossil fuel infrastructures does not get stranded since it is valuable as scrap. This is because it relaxes the material constraint on the transition which is an original mechanism put forward in our analysis. Last but not least, we show that recycling decommissioned infrastructure allows containing the rise in the price of virgin material.

The risk of stranded asset is an obstacle to the adoption of climate change mitigation policies as it weighs on financial markets, making investors reluctant to support these policies. This may significantly delay the energy transition. Indeed, the shares' value reflects at least partly the dividends the company will distribute over the next years (before the full impact of climate damage materializes) and we observe a negative impact of bad climate news on the markets, that is mainly due to the risk that a tightening of environmental policies will weigh on the share prices of the most carbon-intensive companies through assets that become stranded. We have shown that the opportunity to recycle decommissioned fossil fuel infrastructures may mitigate the consequences of climate policies in terms of stranded assets. This may well help speeding-up the acceptability of these policies. Katheline Schubert expressed such a concern in the following terms:[19]

> “From a scientific point of view, it’s extremely simple: we can’t extract and burn all the fossil fuels we know we have underground. Obviously, these fossil fuels are currently very valuable, and if we don’t get them out of the ground and use them, their value will fall to zero. Quite naturally, the governments and companies that own these energies are not very happy, so obviously they are doing their best to prevent this from happening or to delay the stranding of these assets.”

[19]Translation of Katheline Schubert’s statement at the plenary session 4 - “Fin des énergies fossiles, nouvelles technologies, gérer le monde d’après”, Les Rencontres Économiques, Aix-en-Provence, 6/7/2024.

# 6 Appendix

## 6.1 Solving the program

The program of the planner (8) is:

$$\begin{aligned}
\max_{\delta(t),\alpha(t),m(t),b(t)} \int_0^\infty e^{-\rho t} \quad & [u(e(t)) - C(I(t)) - \nu b(t) - \eta(\alpha(t))\psi K(t) - p(0)e^{\rho t}]dt \\
\text{s.t.} \quad & e(t) = \theta Z(t) + \phi Y(t) \\
& I(t) = m(t) + b(t) + \alpha(t)\psi K(t) \\
& \dot{Y}(t) = I(t) - \delta_Y Y \quad \rightarrow \mu(t) \\
& \dot{M}(t) = -m(t) \quad \rightarrow \zeta(t) \\
& \dot{Z}(t) = -\delta(t)Z(t) \quad \rightarrow \lambda(t) \\
& \dot{K}(t) = \delta(t)Z(t) - \alpha(t)K(t) \quad \rightarrow \kappa(t) \\
\text{with} \quad & \delta(t) \in [0,1], \alpha(t) \in [0,1], m(t) \geq 0, b(t) \geq 0, \\
& M(t) \geq 0,\ Z(t) \geq 0,\ Y(t) \geq 0,\ K(t) \geq 0 \\
\text{and} \quad & M_0, Z_0, Y_0, K_0 = 0 \text{ given.}
\end{aligned} \tag{A.1}$$

where the arrows associate a costate variable to each state variable. To simplify notations we drop the time argument from the variables. The corresponding current value Hamiltonian is:

$$\mathcal{H}(.) = u(\theta Z+\phi Y)-C(m+b+\alpha\psi K)-\nu b-\eta(\alpha)\psi K-\lambda\delta Z+\mu(m+b+\alpha\psi K)+\zeta(-m)+\kappa(\delta Z-\alpha K-\delta_Y Y)-p(0)e^{\rho t}\theta Z$$

We denote by $\omega_i$ the Lagrange multiplier of the boundary conditions for each variable $i$, and write the associated Lagrange function that considers the constraints and write as follows:

$$\mathcal{L}(.) = \mathcal{H}(.) + \omega_m m + \omega_b b + \omega_\alpha^0 \alpha + \omega_\alpha^1(1-\alpha) + \omega_M M + \omega_Z Z + \omega_\delta^0 \delta + \omega_\delta^1(1-\delta) \tag{A.2}$$

The first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial \delta} = 0 \Leftrightarrow \lambda(t) = \kappa(t) + \frac{\omega_\delta^0 - \omega_\delta^1}{Z(t)} \tag{A.3}$$

$$\frac{\partial \mathcal{L}}{\partial m} = 0 \Leftrightarrow C'(I(t)) = \mu(t) - \zeta(t) \tag{A.4}$$

$$\frac{\partial \mathcal{L}}{\partial \alpha} = 0 \Leftrightarrow C'(I(t)) + \eta'(\alpha(t)) = \mu(t) - \frac{\kappa(t)}{\psi} + \frac{\omega_\alpha^0 - \omega_\alpha^1}{\delta(t)\psi Z(t)} \tag{A.5}$$

$$\frac{\partial \mathcal{L}}{\partial b} = 0 \Leftrightarrow C'(I(t)) = \mu(t) - \nu + \omega_b \tag{A.6}$$

$$-\frac{\partial \mathcal{L}}{\partial Z} = \dot{\lambda}(t) - \rho\lambda(t) \ \Leftrightarrow \dot{\lambda}(t) = \rho\lambda(t) - u'(e(t))\theta + p(0)e^{\rho t} + \delta(t)(\kappa(t) - \lambda(t)) - \omega_Z \tag{A.7}$$

$$-\frac{\partial \mathcal{L}}{\partial K} = \dot{\kappa}(t) - \rho\kappa(t) \Leftrightarrow \dot{\kappa}(t) = \kappa(t)(\rho + \alpha(t)) + \alpha(t)\psi\left[C'(I(t)) + \eta(\alpha(t))/\alpha(t) - \mu(t)\right] \tag{A.8}$$

$$-\frac{\partial \mathcal{L}}{\partial Y} = -\phi u'(e(t)) + \delta_Y \mu(t) = \dot{\mu}(t) - (\rho + \delta_Y)\mu(t) \Leftrightarrow \dot{\mu}(t) = (\rho + \delta_Y)\mu(t) - \phi u'(e(t)) \tag{A.9}$$

$$-\frac{\partial \mathcal{L}}{\partial M} = \dot{\zeta}(t) - \rho\zeta(t) \Leftrightarrow \dot{\zeta}(t) = \rho\zeta(t) - \omega_M \tag{A.10}$$

## 6.2 Phase 1

During this phase: $m > 0$, $Z > 0$, $0 < \delta < 1$, $b = 0$, $\alpha = 0 \Rightarrow \omega_Z = \omega_m = \omega_\delta^0 = \omega_\delta^1 = \omega_\alpha^1 = 0$, $\omega_b > 0, \omega_\alpha^0 > 0$.

Equations (A.3) and (A.8) leads to $\kappa(t) = \lambda(t) = \kappa(0)e^{\rho t}$. As a result equation (A.7) provides $\theta u'(e(t)) = p(0)e^{\rho t}$. In addition, equation (A.9) leads to $\dot{\mu} = (\rho + \delta_Y)\mu - \frac{\phi}{\theta}p_0 e^{\rho t}$ from which we deduce $\mu(t) = \mu_0 e^{(\rho+\delta_Y)t} - \frac{\phi p_0}{\delta_Y \theta}\left(e^{(\rho+\delta_Y)t} - e^{\rho t}\right)$. Hence, using equation(A.4):

$$\mu(t) = (\mu(0) - \frac{p(0)\phi}{\theta\delta_Y})e^{(\rho+\delta_Y)t} + \frac{p(0)\phi}{\theta\delta_Y}e^{\rho t}$$

$$I(t) = m(t) = \left(\frac{\mu(0)}{c_2} - \frac{\phi p(0)}{\delta_Y \theta c_2}\right)e^{(\rho+\delta_Y)t} + \left(\frac{\phi p(0)}{\delta_Y \theta c_2} - \frac{\zeta(0)}{c_2}\right)e^{\rho t} - \frac{c_1}{c_2} \tag{A.11}$$

Using the dynamics of renewable infrastructures with equation (A.11) allows deriving $Y(t)$. Moreover:

$$Z(t) = \frac{\gamma}{p(0)}e^{-\rho t} - \frac{\phi}{\theta}Y(t) \tag{A.12}$$

and

$$K(t) = Z_0 - Z(t) = Z_0 - \frac{\gamma}{p_0}e^{-\rho t} + \frac{\phi}{\theta}Y(t)$$

The stock of scrap monotonically increases in time. Using the dynamics of renewables infrastructures with equation (A.11) allows deriving $Y(t)$. Using the dynamics of fossil infrastructures, together with (A.11) and (A.12) allows deriving the optimal scrapping rate $\delta$.

## 6.3 Phase 2

During this phase: $0 < \alpha < 1$, $0 < \delta < 1$, $Z > 0$, $b = 0$, $m = 0 \Rightarrow \omega_Z = 0$, $\omega_m, \omega_b > 0$, $\omega_\alpha^0 = \omega_\alpha^1 = \omega_\delta^0 = \omega_\delta^1 = 0$.

Equation (A.5) provides $c_1 + c_2 I(t) + \eta_1 = \mu(t) - \kappa(t)/\psi$. Using equation (A.8) we obtain:

$$\dot{\kappa}(t) = (\alpha(t) + \rho)\kappa(t) + \alpha(t)\psi\left[-\eta_1 - \frac{\kappa(t)}{\psi} + \eta_1\right] \;\Rightarrow\; \kappa(t) = \lambda(t) = \kappa(T_2)e^{\rho(t-T_2)}$$

As a result (also noting that $\dot{\lambda}(t) = \rho\lambda(t)$) equation (A.7) provides $\theta u'(e) = p(T_2)e^{\rho(t-T_2)}$. In addition, equation (A.9) leads to $\dot{\mu} = (\rho + \delta_Y)\mu - \frac{\phi}{\theta}p(T_2)e^{\rho(t-T_2)}$ from which we deduce $\mu(t) = \mu(T_2)e^{(\rho+\delta_Y)(t-T_2)} - \frac{\phi p(T_2)}{\delta_Y \theta}\left(e^{(\rho+\delta_Y)(t-T_2)} - e^{\rho(t-T_2)}\right)$. Hence, using equation(A.5):

$$I(t) = \alpha(t)\psi K(t) = \frac{1}{c_2}\left[\mu(T_2)e^{(\rho+\delta_Y)(t-T_2)} - \frac{\phi}{\delta_Y \theta}p(T_2)\left(e^{(\rho+\delta_Y)(t-T_2)} - e^{\rho(t-T_2)}\right) - \frac{1}{\psi}\kappa(T_2) - \eta_1 - c_1\right] \tag{A.13}$$

$$Z(t) = \frac{\gamma}{p_{T_2}}e^{-\rho(t-T_2)} - \frac{\phi}{\theta}Y(t) \tag{A.14}$$

Using the dynamics of renewable infrastructures with equation (A.13) allows deriving $Y(t)$. In addition, the dynamics of fossil infrastructures, together with (A.14), once differentiated, allow deriving the optimal scrapping rate $\delta(t)$. Using the dynamics of the stock of scrap with equations (A.13) and (A.14) allows deriving $K(t)$. Once $K(t)$ is known, equation (A.13) provides $\alpha(t)$.

This phase ends at date $T_3$, when the remaining stock of fossil capital becomes exhausted: $u'(\phi Y(T_3^+)) = p(T_3^+) = p(0)e^{\rho T_3^+}$, which provides a condition for $T_3$. We also have $\delta(T_3^-) = 1$ that makes sure that $Z(T_3^+) = 0$ (and $\dot{Z}(T_3^+) = 0$). Note that since $Y(t)$ is a stock, we have $Y(T_3^-) = Y(T_3^+)$. Using (A.14) (also differentiated), we have

$$Y(T_3) = \frac{1-\rho}{1-\delta_Y}\frac{\gamma\theta}{\phi p(T_3)} - \frac{1}{c_2(1-\delta_Y)}\left(\mu(T_3) - c_1 - \eta_1 - \frac{1}{\psi}\kappa(T_3)\right) \tag{A.15}$$

## 6.4 Phase 3

During this phase: $0 < \alpha < 1$, $\delta = 1$, $Z = 0$, $b = 0$, $m = 0 \Rightarrow \omega_Z, \omega_m, \omega_b > 0$, $\omega_\alpha^0 = \omega_\alpha^1 = \omega_\delta^0 = 0$, $\omega_\delta^1 > 0$.

Equation (A.5) is now $c_1 + c_2 I(t) + \eta_1 = \mu(t) - \frac{\kappa(t)}{\psi}$. Substituting the law of capital accumulation for $I(t)$, this provides:

$$\dot{Y}(t) = \frac{1}{c_2}\left[\mu(t) - \frac{1}{\psi}\kappa(t) - \eta_1 - c_1\right] - \delta_Y Y(t) \tag{A.16}$$

Using equation (A.8) we obtain: $\dot{\kappa}(t) = (\alpha(t)+\rho)\kappa(t)+\alpha(t)\psi\left[-\eta_1 - \frac{\kappa(t)}{\psi} + \eta_1\right] \Rightarrow \kappa(t) = \lambda(t) = \kappa(T_3)e^{\rho(t-T_3)}$. Using equation (A.9) we obtain:

$$\dot{\mu}(t) = (\delta_Y + \rho)\mu(t) - \frac{\gamma}{Y(t)} \tag{A.17}$$

The system (A.16)-(A.17) provides the dynamics for $\mu$ and $Y$. This phase ends with the last recycling activity and leaves not scrap for the following phase. At $T_4$, the end of the phase, $\alpha(T_4) = 1$. Moreover: $\kappa(T_4)/\psi + \eta_1 = \nu$. Since, during phase 3 $I(t) = \alpha(t)\psi K(t)$ while from (A.5) $c_1 + c_2 I(t) + \eta_1 = \mu(t) - \frac{\kappa(t)}{\psi}$, the recycling rate is

$$\alpha(t) = \frac{1}{c_2\psi K(t)}\left[\mu(t) - \frac{\kappa(t)}{\psi} - \eta_1 - c_1\right] \tag{A.18}$$

Together with $\alpha(T_4) = 1$ and $\kappa(T_4) = (\nu - \eta_1)\psi$, this condition implies the terminal condition

$$K(T_4) = (\mu(T_4) - \nu - c_1)/(c_2\psi) \tag{A.19}$$

## 6.5 Phase 4

During this phase: $\alpha = 0$, $m = 0$, $Z = 0$, $b > 0 \Rightarrow \omega_Z, \omega_m > 0$, $\omega_b = 0$, $\omega_\alpha^0 > 0$, $\omega_\alpha^1 = 0$.

During this last phase the economy relies exclusively on renewables and the backstop: $e(t) = \phi Y(t)$ and $I(t) = b(t)$. Hence $u'(e) = \gamma/(\phi Y(t))$, while (A.6) writes $b(t) = \mu(t)/c_2 - (\nu + c_1)/c_2$. Usign these two results in (A.9) and the law of motion of green capital in (A.1), the dynamics of the economy is characterized by the system (10) in the text $\forall t \geq T_4$. The isoclines are $\mu = \nu + c_1 + c_2\delta_Y Y$ for $\dot{Y} = 0$ and $\mu = [\gamma/(\rho + \delta_Y)]/Y$ for $\dot{\mu} = 0$. This system admits a unique saddle path stable steady state, see system (11) in the text.

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