DYNAMIC STABILITY PROBLEMS IN CLIMATE TRANSITIONS

ISHAAN SENGUPTA* and SAMPARNA MITTRA
St. Xavier's College (Autonomous), Kolkata

Abstract

We analyze descriptively and theoretically the recursive nature of climate change mitigation and adaptation measures. Climate mitigation technologies, such as green energy or electric vehicles, create further emissions and demand for energy and land. Adaptation measures generate similar issues with energy demand, land use, and financial constraints. These effects and their impact on the stability of climate change solutions are studied in this paper.

JEL Classification: Q16, Q21, Q28
Keywords: Dynamic Systems, Dynamic Stability, Partial Equilibrium, Climate Change, Renewable Energy, Input Coefficients

1. INTRODUCTION

As a scientific consensus on the threats posed by climate change has emerged, novel technological, scientific, and economic solutions have been proposed to tackle the crisis. These can be either mitigation measures that seek to minimize emissions, such as green energy technologies and electric vehicles, or adaptation measures that minimize the human cost of climate change, such as cooling technology and flood walls. Even as countries have made early efforts to implement these technologies, the problem of unstable growth in such climate change solutions is visible.

On the demand side, adopting mitigation technologies may create further spiraling demand for those technologies. For example, it is estimated that the projected increase in air conditioning use could quadruple the demand for electricity by 2050 (International Energy Agency 2018). This in turn would require further increases in renewable energy demand and emissions from non-renewable sources, which would further raise the need for cooling, leading to a spiral.

Supply problems may also emerge in the market for green technologies. Widespread use of green technologies may create bottlenecks in supply or raise prices for scarce inputs significantly, culling the supply of those technologies. Electric vehicles (EVs), an essential part of a future with green transportation, require six times as many rare minerals as conventional vehicles (International Energy Agency 2021). Natural gas plants require just one-tenth the minerals needed in an offshore wind facility (ibid.). As the rapid deployment of such technologies is set in motion, the prices of these scarce inputs will constrain supply and set a ceiling on technology adoption.

In sum, technological solutions to climate change create demand and constrain supply for themselves, creating stability issues in the markets for these technologies. These issues are further exacerbated by the problem of asymmetric adoption and geopolitical considerations.

Some of the demand effects could be exacerbated if emissions are exported from the developed world with a greener energy grid to the developing world with a more fossil fuel-heavy system. If increases in demand for raw materials are sourced from resource-rich emerging economies such as Ghana without restrictions, the additional energy required for mining, quarrying, and transportation may be met by dirty technology, creating further emissions and

Corresponding Author's email address: sengupta.ishaan01@gmail.com

demand. This is the problem of asymmetric adoption. Similarly, control of key raw materials or technol -ogies by geopolitical competitors could lead to sudden adverse supply shocks and the use of green technology as an economic weapon.

In Section 2 we perform a brief literature review of the fields of environmental economics, climate science, and economic theory. Section 3 describes the general methodology used in this paper. Section 4 introduces the partial equilibrium the theoretical framework used in the paper and provides empirically estimable stability conditions. Data from various climate scientific and economics studies are used to justify the presence of concerning feedback effects in Section 5. Some policy prescriptions and concluding remarks are left to Section 6 and Section 7.

2. LITERATURE REVIEW

The basic problem of climate change solutions leading to spiraling demand and constrained supply for themselves has been relatively understudied in the economics literature. (Wang 2015) sheds light on dynamic instability during critical transitions, such as the climate transition. Another general model of dynamic instability includes Marsili et al. (2009), where unstable asset markets are analyzed. Steenge (1990) analyses instability in a Leontief model while dynamic oscillations in a modern economy due to investment and innovation are analyzed by Goodwin (1990). However, none of these papers focus on the climate transition and analyze its components specifically.

The model most similar to the one employed in this paper is the Cobweb model developed by Ezekiel (1938) and Nerlove (1958). Tamari (1981) develops a model with dynamic effects on both the demand and supply sides to analyze the housing sector in Israel and analyzes stability effects in these markets.

The critical difference between these models and the one employed in this paper is that in the former, past equilibrium prices affect current demand and supply while in the latter, past equilibrium quantities play the same role.

We also make use of Kellogg (2014) to show the adverse effect that uncertainty in input or output prices has on investments with the example of oil drilling technology. Pescatori et al. (2021) analyze the climate transition from the perspective of rare metals.

Literature from climate and agricultural science and reports of various international agencies have analyzed our problem, but in isolation from each other and without a dynamic economic analysis. We bring them together and analyze them in this paper using an economics-oriented approach. International Energy Agency (2018) alerts us to the significant climate repercussions of the increased demand for air conditioners in emerging countries over the next thirty years. The results are discussed in Section 4.1. International Energy Agency (2021) warns about the massive increase in input requirements of metals in green technologies and their associated shortages. This report is analyzed in Section 4.2. U.S. Geological Survey (2022) reported on the concentration of mineral commodities required for the climate transition in a few countries, which could cause supply disruptions due to geopolitical problems.

Our paper seeks to synthesize the scientific literature on various isolated technologies and bring it into an economic dynamics framework using first theory to conceptualize demand and supply effects (and the difference between them) and then empirics to justify the possible presence of instability effects.

3. METHODOLOGY

3.1 DATA SOURCES

Empirically, we focus primarily on descriptive data from scientific publications. Heavy use is made of International Energy Agency (2018) and International Energy Agency (2021), the two landmark reports on cooling and metals respectively.

Other scientific sources include various publications by IPCC (see IPCC (2019)) or in major journals such as Nature (see Vargas Zeppetello et al. (2022)) or various subject-specific articles on heating, pesticides, etc. We also make use of IMF data (Pescatori et al. 2021) to describe expected future fluctuations in metal prices.

A fairly simple econometric analysis is conducted to show how pesticide use intensity increases significantly when mean temperatures in a country rise, controlling for per capita GDP. This analysis uses data from the World Bank and Food and Agricultural Organisation.

3.2 EQUILIBRIUM FRAMEWORK

We build a dynamic partial equilibrium framework that can be taken as the market for any individual technology related to climate solutions. This helps us understand the dynamic stability problems as split between demand side problems and supply side issues, and find some relevant stability conditions.

The model is a partial equilibrium one since we take only one market for a given technology at a time. Dynamic questions appear since we contend that the equilibrium quantity in a given period influences the demand and supply of future periods – in general, higher quantity leads to steeper demand and lowered supply in the future. For such a market, stability occurs when the dynamic changes in demand and supply do not cause large enough fluctuations to disrupt a long-term transition.

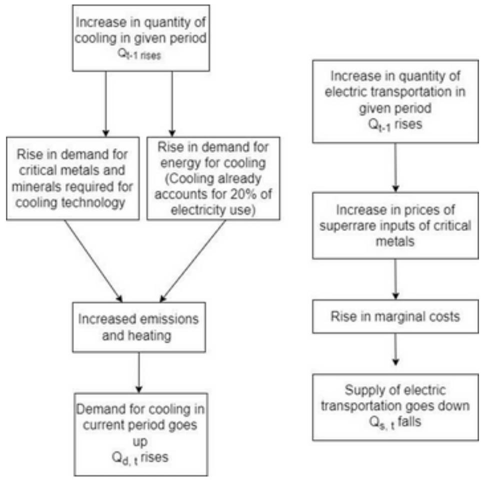
4. THEORETICAL FRAMEWORK

We conceptualize these stability problems within a standard partial equilibrium framework in each of the markets we are interested in. While this is unable to account for the inter-sectoral effects of these heavily interlinked markets, it helps us analyze the basic problem. The crucial addition to the model is that other than usual factors affecting demand and supply, we add the effects of the previous period's equilibrium quantity on demand and supply as the source of instability in the model.

Equilibrium quantity in a given time period adds to pre-existing demand and constrains supply in the next period through channels described earlier. We give two examples here, one in the market for cooling technology and one in the market for electric transportation. Further causation linkages of demand and supply effects with data are left to section 3. For the rest of this section, we develop our dynamic partial equilibrium model. First, we build a simple linear model and analyze its stability conditions.

Then we develop a more general model and repeat our analysis. Stylized examples of the effects discussed in this paper are provided in Fig. 1

Figure 1: **(L)** *Demand effects in the market for cooling technologies.* **(R)** *Supply effects in the market for electric transportation.*



Source: Authors' Descriptions

THE MODEL

First, we look at a basic linear model. This and the following generalized model holds for any technology related to the climate transition. The given functions and parameters differ from technology to technology.

Consider a market with the following demand and supply conditions:

$$Q_{d,t} = \alpha_d - \beta_d P_t + \gamma_d Q_{t-1}$$

$$Q_{s,t} = \alpha_s + \beta_s P_t - \gamma_s Q_{t-1}$$

The explanation behind this is that aside from the usual effects induced by α_d and β_d, we have a γ_d term. This term shows the fact that higher equilibrium quantities in a given period raise the demand in the next period, causing inter-temporal demand cycles. Similarly, the γ_s term shows how higher equilibrium quantity constrains supply in the future period via supply-side effects.

Solving this model we obtain the following linear, first-order, autonomous difference equations:

$$P_t = \frac{\gamma_d + \gamma_s}{\beta_d + \beta_s} Q_{t-1} + \frac{\alpha_d - \alpha_s}{\beta_d + \beta_s}$$

and

$$P_t = \frac{\gamma_d + \gamma_s}{\beta_d + \beta_s} Q_{t-1} + \frac{\alpha_d - \alpha_s}{\beta_d + \beta_s}$$

These equations show the equilibrium prices and quantities evolve over time in the system. We see that a higher Q_{t-1} unambiguously raises the price in the current period, while its effect on Q_t is ambiguous.

The steady state for this model is given by:

$$\bar{Q} = \frac{\alpha_s + \beta_s \frac{\alpha_d - \alpha_d}{\beta_d + \beta_s}}{1 - \frac{\beta_s \gamma_d - \beta_d \gamma_s}{\beta_d + \beta_s}}$$

We know that this model will converge to the steady state iff

$$\left| \frac{\beta_s \gamma_d - \beta_d \gamma_s}{\beta_d + \beta_s} \right| < 1$$

Essentially this shows us that for a certain condition on the intertemporal parameters given by γ_i and the price derivative parameters β_i, the model may reach a steady state. We would interpret this as a successful climate transition where the dynamic demand or supply effects do not cause perennial shortages or inflation. We provide an elasticity interpretation of this condition in our generalized analysis.

We now repeat this analysis in a generalized framework.

In order to allow demand and supply to be influenced by the previous year's quantity in non-linear ways and also account for other variables, we consider a more general model as follows:

$$Q_{d,t} = \alpha_d - \beta_d P_t + f_d(Q_{t-1}) + g_d(Y_t, G_t, \text{other factors}),\ f_d'(.) > 0$$

$$Q_{s,t} = \alpha_s + \beta_s P_t - f_s(Q_{t-1}) + g_s(Y_t, G_t, \text{other factors}) - v,\ f_s'(.) > 0$$

Here Y and G stand for GDP and a government policy variable in year t respectively. v stands for a random supply shock variable. The interpretation of g_d and g_s are similar to the γ parameters earlier – they show the intertemporal demand and supply effects of equilibrium quantity in the next period.

Solving this, we get

$$P_t = \frac{(f_d + f_s)(Q_{t-1})}{\beta_d + \beta_s} + \frac{(\alpha_d - (\alpha_s - v)) + (g_d - g_s)}{\beta_d + \beta_s}$$

$$Q_t = \frac{\beta_s f_d(Q_{t-1}) - \beta_d f_s(Q_{t-1})}{\beta_d + \beta_s} + \left(\alpha_s - v + g_s + \beta_s \frac{(\alpha_d - (\alpha_s - v)) + (g_d - g_s)}{\beta_d + \beta_s} \right)$$

Once again, we see that a higher Q_{t-1} unambiguously raises the price in the current period, while its effect on Q_t is ambiguous.

While a general steady state cannot be computed from the above model, we state the condition required at the steady state $\bar{Q}$ for local stability as:

$$\left| \frac{dQ_t}{dQ_{t-1}}(\bar{Q}) \right| < 1$$

$$\left| \frac{\beta_s f_d'(\bar{Q}) - \beta_d f_s'(\bar{Q})}{\beta_d + \beta_s} \right| < 1$$

In elasticity form, we get a relatively simple condition. At the steady state we require that

$$\left| \epsilon_{s,P} \cdot \epsilon_{d,Q_{t-1}} - \epsilon_{d,P} \cdot \epsilon_{s,Q_t-1} \right| < 1$$

The interpretation of this, as earlier, is that for a certain condition on the intertemporal parameters and the price derivative parameters, the model may reach a steady state. We would interpret this as a successful climate transition where the dynamic demand or supply effects do not cause perennial shortages or inflation.

Moreover, once an empirical estimate of $f_d(Q_{t-1})$ and $f_s(Q_{t-1})$ using curve fitting techniques is obtained, a phase diagram analysis of Q_t will help us analyze global stability conditions as well.

REMARKS

1. For most markets, only one of the demand or supply effects is significant. E.g. demand effects are more prominent for ACs and pesticides, while supply effects are significant for EVs and renewable energy.

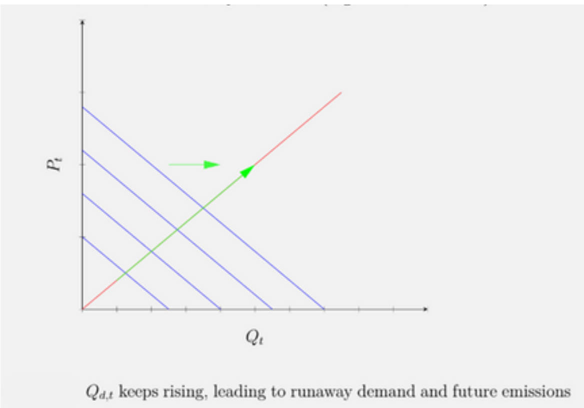
2. Within the renewable energy market, there is a trade-off between β_s (responsiveness of supply to price) and γ_s (self-constraining supply effect). This is explored in Table 5 and the following discussion.

3. When there is runaway demand, the equilibrium quantity keeps rising leading to adverse effects such as emissions (see fig. 2).

4. When there is chronic supply instability, equilibrium quantity keeps falling and there is a failed transition (see Fig. 3).

5. When both demand and supply effects exist and there is instability, there is runaway inflation of the good.

Figure 2: *Problem of Runaway Demand (e.g. in AC market)*



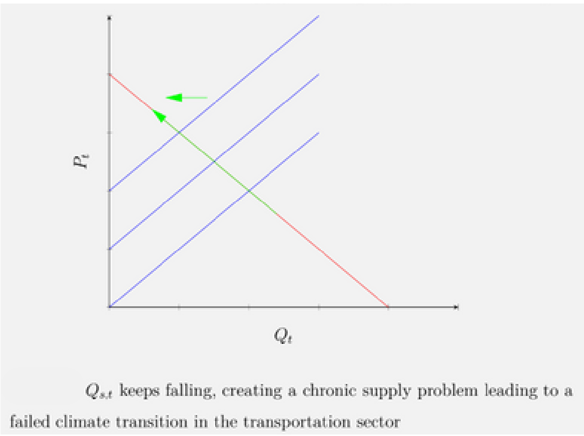
Source: Authors' Calculations

Example

Suppose we have obtained using curve fitting techniques

$$f_d(Q_{t-1}) = Q_{t-1}^{1/2}$$

Figure 3: *Problem of Chronic Supply Shortage (e.g. in EV market)*



Source: Authors' Calculations

To simplify our model suppose f_s, g_d, g_s and ν are 0. Then we have

$$Q_{d,t} = \alpha_d - \beta_d P_t + Q_{t-1}^{1/2}$$

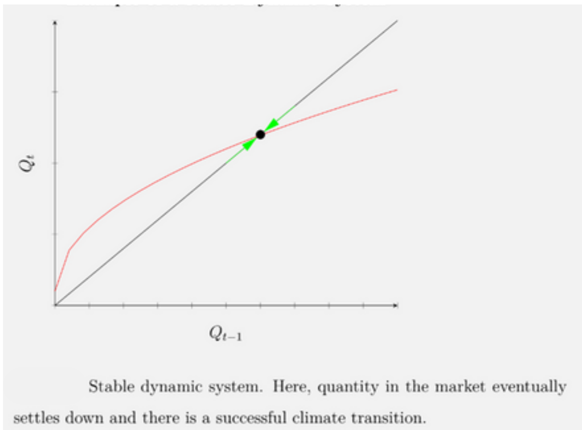
$$Q_{s,t} = \alpha_s + \beta_s P_t$$

The solution of this gives the following nonlinear, autonomous difference equations and phase diagram.

$$P_t = \frac{Q_{t-1}^{1/2}}{\beta_s + \beta_d} + \frac{\alpha_d - \alpha_s}{\beta_s + \beta_d}$$

$$Q_t = \frac{\beta_s}{\beta_s + \beta_d} Q_{t-1}^{1/2} + \frac{\alpha_s \beta_d + \beta_s \alpha_d}{\beta_s + \beta_d}$$

Figure 4: *Example of a Stable Dynamic System*



Source: Authors' Calculations

5. DATA AND FURTHER ANALYSIS

5.1 DEMAND SIDE EFFECTS

Several technologies needed in the climate transition create demand spirals for themselves and each other. The most concerning such technologies are air conditioners and other cooling technologies, pesticides, and hydraulic fracking, other than renewable energy sources themselves.

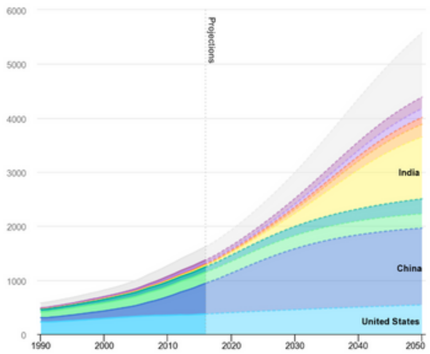
Air Conditioners and Cooling Technologies

The globe has already warmed by about 1.1•C above pre-industrial temperatures, and heatwaves are increasingly common and projected to increase in frequency and intensity in the near future (Vargas Zeppetello et al. 2022). Air conditioners and other cooling technology is therefore already a necessity to prevent mass mortality from heat-related deaths. However, the International Energy Agency warns us that

> the world faces a looming "cold crunch." Using air conditioners and electric fans to stay cool accounts for nearly 20 % of the total electricity used in buildings around the world today...But it will have a significant impact on countries' overall energy demand, putting pressure on electricity grids and *driving up local and global emissions* [emphasis added] (International Energy Agency 2018).

International Energy Agency (2018) estimates that the demand for air conditioning units in buildings will triple (see Fig. 5) over the next thirty years. More significantly, this increase is concentrated in countries like India, China, Brazil, Indonesia, and the Middle East which have significantly fewer green electricity grids. Over the last thirty years, emerging countries accounted for only 12% of the increase in air conditioners used whereas over the next thirty, their share in the increase is estimated to be over 50%.[1] Since these countries have conventional energy-heavy electricity grids, the rise in emissions associated with this increased demand will be massive.

Figure 5: *Projected increase in demand for air conditioners.*



Source: International Energy Agency (2018)

Moreover, air conditioning is already a major part of worldwide CO2 emissions, accounting for nearly 5% of global CO2 emissions in 2016 . This could rise to 10% or more by 2050, thereby driving a significant proportion of future warming and hence demand for air conditioners.[2] As a result, air conditioners alone could cause close to 0.5 °C increase in global temperatures by 2050. This leads to a *tipping point effect*, where air conditioners are used in regions that did not require them previously. (e.g. Western Europe) pushes more regions across the tipping point, post which those regions also demand air conditioners (e.g. Scandinavian countries).

Direct emissions from the potent greenhouse gases used as refrigerants in ACs are also a major source of dynamic instability in this market. Hydro-fluorocarbons commonly used in air conditioners are extremely damaging to the climate. For instance, trifluoromethane has 11,700 *times* the warming effect of CO2 (Han et al. 2012).

Other Technologies

Other technologies required during and after the climate transition also pose serious risks to the transition. Pesticides, space heating, and hydraulic fracking are some glaring examples.

Warmer temperatures also create demand for pesticides, since agricultural pests grow better in warmer temperatures (IPCC 2019). We show this demand-side feedback effect using a relatively simple regression analysis in Table 2.

The equation we estimate is

$$pesticide = \beta_0 + \beta_1 temp + \beta_2 percapgdp + \epsilon.$$

This uses a cross-country data set of 143 countries comprising Food and Agricultural Organisation (FAO) data for pesticide use and temperature, and World Bank data for GDP per capita. Since richer countries (which are generally located in temperate regions) usually have higher pesticide use because of a wealth effect, we control for this in the regression. The result shows that at the 1% level of significance, an increase in mean temperature of 1 degree Celsius increases the kg of pesticide used per hectare by 0.214. This significance holds even when computing heteroskedasticity-robust errors. Studies such as Cech et al. (2022) and Heimpel et al. (2013) show how emissions-intensive pesticides are, completing the causal loop from warmer temperatures to increased pesticide use to finally more emissions and further warming.

Table 1: *Agricultural chemicals, fracking and heating have significant demand effects*

Technology	Data
I. Agricultural Chemicals	1. 5794.61 metric tons CO2 from pesticides in India alone[3] 2. $r = 0.42$ for nitrogen use and emissions 3. Pesticide use increases with increase in daily minimum temperature (Palikhe 2007)
II. Hydraulic Fracking	1. Significant emissions of methane 2. Leakage rates as high as 8%, worse than coal for emissions 3. Methane 10x to 25x more potent at warming than CO2 (Howarth 2015)
III. Heaters	1. Residential heating & cooling account for 7.6% emissions in the US 2. Heating emissions as a proportion of total has been increasing due to erratic winters (Leung 2018; Pistochini et al. 2022)

Source: Authors' Calculations

[1] Calculated by author from International Energy Agency 2018
[2] ACs account for 12% emissions from buildings, which in turn account for 40% total global CO2 emissions (International Energy Agency 2018; International Energy Agency 2019). More- over, this number has doubled over the last thirty years and we can expect a similar trend in the future.
[3] Author's own calculations from Vetter et al. (2017)

Climate change and global warming also lead to more extreme winters, raising the demand for heaters (Cohen et al. 2021). At the same time, heaters cause a large amount of emissions: Department of Energy and Climate Change, Government of UK (2012) estimates that close to 20% of total CO2 emissions in the UK were from space heating.

Fracking, a relatively cleaner source of energy compared to more traditional sources, is touted as an intermediate source in the energy transition for poor countries. However, it releases the extremely potent greenhouse gas called methane in dangerous amounts either directly or indirectly through leaks (Howarth 2015).

Table 2: *Adjusted for GDP per capita, an increase in mean annual temperature increases pesticide use with a confidence level > 99%*

	Dependent variable:
	kg of pesticide per hectare
Mean Temperature	0.214***
	(0.075)
GDP per capita (2017)	0.0001***
	(0.00003)
Constant	−1.468
	(1.718)
Observations	143
R^2	0.085
Adjusted R^2	0.072
Residual Std. Error	6.217 (df = 140)
F Statistic	6.497*** (df = 2; 140)
Note:	*p<0.1; **p<0.05; ***p<0.01

Source: Authors' Calculations

5.1.1 THE PROBLEM OF ASYMMETRIC ADOPTION

Metal requirements for renewable energy are higher than conventional technologies (see section 5.2). Moreover, these metals are concentrated in certain emerging countries with dirty energy grids (see section 5.1.1). This leads to a demand spiral problem since the massive energy demand for mining these metals will be met by dirty energy, increasing demands for green energy, pesticides, air conditioners, etc.

Table 3: *Concentration of metals in emerging countries.*

Metal	Co	Cu	Ni
1	Congo (50%)	Chile (25%)	Indonesia (22%)
2	Australia (20%)	Peru (12%)	Australia (21%)
3	Cuba (7%)	Australia (11%)	Brazil (16%)
4	Philippines (4%)	Russia (8%)	Russia (7%)
5	Russia (4%)	Mexico (7%)	Cuba (6%)

Source: Author's own calculations from U.S. Geological Survey (2022)

5.2 SUPPLY SIDE EFFECTS

Green energy technologies and electric transportation requires a much larger input of metals and rare earths compared to their conventional counterparts. In table 4 we note that electric vehicles require more than six times the metals per car when compared to conventional vehicles. Moreover, this includes metals with deficient supply, such as lithium, nickel, and graphite, and not just the common copper. Similarly, in Table 5 we see that on a per megawatt basis, non-conventional energy requires significantly more metals. An offshore wind facility requires 13x and a solar PV requires 6x metals to produce a megawatt of power when compared to a natural gas facility.

Table 4: *Metals required in EVs and CVs.*

Metals (kg/car)	Cu [4]	Li	Ni	Mn	Co	Gr	Zn	Rare earths	Others	Total
Electric car	53	9	40	25	13	66	0.1	0.5	0.3	206.9
Conventional car	22	0	0	11	0	0	0.1	0	0.3	33.4

Source: Author's own calculations from International Energy Agency (2021)

Table 5: *Metals required in various green energy and conventional energy technologies.*

Metals (kg/MW)	Cu	Ni	Mn	Co	Cr [5]	Mo	Zn	Rare earths	Others	Total	Index [6]
Offshore wind	8,000	240	790	-	525	109	5,500	239	6	15,409	1,322
Onshore wind	2,900	403	780	-	470	99	5,500	14	-	10,166	872
Solar PV	2,822	1.3	-	-	-	-	29	-	3,979	6,833	586
Nuclear	1,473	1,297	147	-	2,190	70	-	0.5	94	5,273	452
Coal	1,150	721	4	201	307	66	-	-	34	2,484	213
Natural gas	1,100	16	-	2	48	-	-	-	-	1,165	100

Source: Author's own calculations from International Energy Agency (2021)

[4] Cu = Copper, Li = Lithium, Ni = Nickel, Mn = Manganese, Co = Cobalt, Gr = Graphite, Zn = Zinc
[5] Cr = Chromium, Mo = Molybdenum
[6] Here we have calculated the index of metal use taking natural gas total = 100

Some things are immediately clear. Nuclear energy requires significantly fewer metals than other renewable energy facilities and so it has fewer adverse supply effects in our dynamic system. On the other hand, it is significantly more costly and hence supply is less receptive to price. Solar energy requires around \$ 40 per MWh and onshore wind requires \$42 per MWh, while nuclear energy costs between \$112 and \$182 per MWh (WNISR 2019). This trade-off between two sources of instability must be resolved when the appropriate energy mix is selected by policymakers.

Therefore, the energy transition poses a twin challenge: (a) a rapid increase in input demand coefficients and (b) a shortage of inputs. These twin factors put tremendous upward pressure on input prices and raise marginal costs. Prices of key metals are forecast to rise to historically high levels and stay there for a decade or more following a net-zero transition (Pescatori et al. 2021).

The prices of metals are forecast to rise to historically high levels in this paper. More worryingly, there is significant uncertainty in future prices (reflected in a higher value of $Var(v)$), which acts as a deterrent to large-scale long-term green investments in the private sector. A similar study of the oil drilling industry showed firms reduce their drilling activity when expected volatility rises. (Kellogg 2014) Therefore there is a risk of chronic under-investment which may constrain supply further.

5.2 GEOPOLITICAL CONCERNS AND SUPPLY VOLATILITY

Another concern in the input markets for green technologies and electric vehicles is the concentrated control of these metals in certain countries. This adds to the price volatility (v in the given model) of these metals since their supply might be used as an economic weapon. The Herfindahl index for rare earth production is 0.37, with China alone controlling close to 60 percent of global production. Owing to its natural resource advantage, the manufacturing capacity for batteries required in EVs, with a Herfindahl index of 0.64, is also concentrated in China (U.S. Geological Survey 2022).

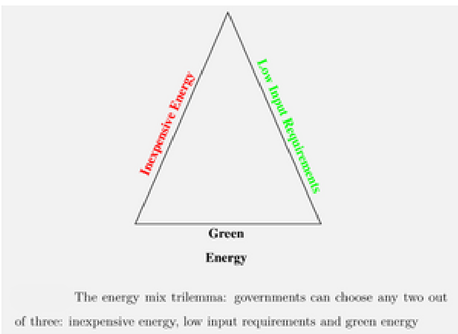
6. POLICY PRESCRIPTIONS

Government policy and regulations have a key role to play in the climate transition. Since dynamic effects are a cause for concern in this process, it is crucial that policy be made to manage these effects and minimize harm.

Energy efficiency standards in air conditioners, reduced usage of greenhouse gas-emitting hydrofluorocarbons (like the successful phasing out of chlorofluorocarbons after the Montreal Protocol), more organic agricultural implements, and efficient space heating technology can all boost demand stability. Since developed countries have an oligopsony in the market for key metals, they could subject purchases of these metals to be conditional on the use of green energy for mining. Improving the output of electric vehicles and electricity generation infrastructure per unit of metals used is especially relevant for culling supply bottlenecks. Sub-substitutability between metals and recycling batteries could ease these problems and augment flexible production capacities. Government purchase agreements for key technologies indexed for input price changes could reduce the uncertainty of investment and boost capacity.

Planning for the appropriate future energy mix must take into account input use and cost as well. The time and financial costs of marginal energy units from wind or solar energy are lower, but they require far more inputs than nuclear energy, which costs more. This trade-off must be accounted for while planning the national energy mix, a fact all too often disregarded in planning. Governments face the **energy mix trilemma** – to develop green energy, they must choose between costly technology (nuclear) and technology with large input requirements (wind and solar). Otherwise, they must choose dirty energy sources. (see Fig. 6).

Figure 6: *The Energy Mix Trilemma*



Source: Authors' Description

THE INDIAN CONTEXT

While the government has continuously set several targets and policies in alignment with eco-friendly policies, the result is insufficient. In August 2022, the Indian government set the policy of reducing emissions by 1 billion tonnes, reducing the carbon intensity of the Indian economy by 45%, and shifting at least 50% of total energy requirement to renewable sources of energy by 2030. This, if achieved within the time frame, would be a sufficient measure to reach the targets set by international treaties like the 1.5 ◦ C limit set in the Paris Climate Agreement. However, policies are conflicting while the government should try to remove coal usage completely from the generation of the energy sector by 2040, a recent report by the Central Energy Authority states that India's coal capacity would increase a lot by 2030. If India tries to justify its lack of climate change legislative frameworks by the excuse of it being a developing country, it seems to forget that some of the worst effects of climate change are occurring in the country itself, where farmers are facing famine and drought thereby affecting the food supply in the economy, while islands and coastal areas are sinking due to higher sea level, seriously affecting the trade portals in these coastal zones.

India produces 10% of the total GHG emissions due to air conditioning, approximately 146 million tonnes. This is backed by the fact that ownership of air-conditioners in India rose from 2 million units in 2006 to 14 million units in 2016, and this is projected to rise further. As shown by the author's calculations in Section 4.1, if air-conditioners emit 10% of international GHGs and cause a consequent rise of 0.5° C in 2050, then India alone may cause nearly 0.05° C rise in global temperature by 2050, solely due to emissions from ACs.

India has produced the largest amount of emissions from agriculture since 2011. This is not shocking considering India is a majorly agricultural nation. According to the Third Biennial Report submitted by the Govt. of India to the UNFCCC in 2021, 19.1% of emissions from the agricultural sector were due to pesticide and fertilizer use. Such a large amount of emissions is bound to push India into the cycle of overuse of pesticides causing climate change and in return high temperatures prompting an increase in pesticide use. Thus, the example of pesticides is demonstrated through the instance of India too.

7. CONCLUDING REMARKS

Possible future research on this topic can be along two pathways. One, computable advanced models taking into account sectoral interlinkages, GDP growth, and factor demands could be used for a more realistic view of the green economy. Two, empirical work needs to be done on estimating the various coefficients in the model under various policy and technological scenarios to help in policymaking.

Our paper looked at the crucial problem of dynamic instability in climate technology markets and developed a novel framework while separating demand and supply effects. We first developed a dynamic partial equilibrium model and described stability conditions for the same. Then, we used comprehensive data from research in climate science on various technologies to support our framework. Finally, we provided policy prescriptions and framed a future research agenda on one of the pressing issues of our day.

REFERENCES

1. Cech, R., Leisch, F., & Zaller, J. G. (2022). Pesticide Use and Associated Greenhouse Gas Emissions in Sugar Beet, Apples, and Viticulture in Austria from 2000 to 2019. Agriculture, 12 (6).

2. Cohen, J., Agel, L., Barlow, M., Garfinkel, C. I., & White, I. (2021). Linking Arctic variability and change with extreme winter weather in the United States. Science, 373 (6559), 1116–1121.

3. Department of Energy and Climate Change, Government of UK. (2012). Emissions from Heat.

4. Ezekiel, M. (1938). The Cobweb Theorem. Quarterly Journal of Economics.

5. Goodwin, R. M. (1990). The Structural and Dynamical Instability of the Modern Economy. In Chaotic Economic Dynamics. Oxford University Press.

6. Han, W., Li, Y., Tang, H., & Liu, H. (2012). Treatment of the potent greenhouse gas, CHF3—An overview. Journal of Fluorine Chemistry, 140, 7–16.

7. Heimpel, G. E., Yang, Y., Hill, J. D., & Ragsdale, D. W. (2013). Environmental Consequences of Invasive Species: Greenhouse Gas Emissions of Insecticide Use and the Role of Biological Control in Reducing Emissions. PLOS ONE, 8 (8).

8. Howarth, R. (2015). Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. Energy and Emission Control Technologies.

9. International Energy Agency. (2018). The Future of Cooling.

10. International Energy Agency. (2019). Global Status Report for Buildings and Construction.

11. International Energy Agency. (2021). The Role of Critical Minerals in Clean Energy Transitions. PCC. (2019). Special Report on Climate Change and Land.

12. Kellogg, R. (2014). The Effect of Uncertainty on Investment: Evidence from Texas Oil Drilling. American Economic Review, 104 (6), 1698–1734.

13. Leung, J. (2018). Decarbonising U.S. Buildings.

14. Marsili, M., Raffaelli, G., & Ponsot, B. (2009). Dynamic Instability in Generic Model of Multi-Assets Markets. Journal of Economic Dynamics and Control, 33 (5), 1170–1181.

15. Nerlove, M. (1958). Adaptive Expectations and Cobweb Phenomena. Quarterly Journal of Economics.

16. Palikhe, B. R. (2007). Journal of Agriculture and Environment, 8, 83–91.

17. Pescatori, A., Boer, L., & Stuermer, M. (2021). Energy Transition Metals (IMF Working Papers No. 2021/243). International Monetary Fund.

18. Pistochini, T., Dichter, M., Chakraborty, S., Dichter, N., & Aboud, A. (2022). Greenhouse gas emission forecasts for electrification of space heating in residential homes in the US. Energy Policy, 163, 112813.

19. Steenge, A. E. (1990). Instability Problems in the Dynamic Leontief Model: an Economic Explanation. Economic Systems Research, 2 (4), 357–362.

20. Tamari, B. (1981). Cobweb Model in the Housing Sector of Israel 1960 – 2010. Economics Quarterly.

21. U.S. Geological Survey. (2022). Mineral Commodity Summaries.

22. Vargas Zeppetello, L. R., Raftery, A. E., & Battisti, D. S. (2022). Probabilistic projections of increased heat stress driven by climate change. Communications Earth & Environment, 3 (1), 183.

23. Vetter, S. H., Sapkota, T. B., Hillier, J., Stirling, C. M., Macdiarmid, J. I., Aleksandrowicz, L., Green, R., Joy, E. J. M., Dangour, A. D., & Smith, P. (2017). Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation. Agric Ecosyst Environ, 237, 234–241.

24. Wang, J. (2015). Modelling and Estimation of Dynamic Instability in Complex Economic Systems.

25. WNISR. (2019). World Nuclear Industry Status Report.