Strategic and intertemporal feedbacks in climate change mitigation *vs.* adaptation: The case of space heating and cooling

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Abstract

This paper examines the conflicting incentives between adaptation and mitigation faced by some heterogeneous regions of the world in the context of climate change. It focuses on space heating and cooling, which captures broad human-climate interactions: On the one hand, space heating and cooling needs are determined by outdoor temperature; on the other hand, they are satisfied through energy consumption, which generates CO_2 emissions and, ultimately, changes outdoor temperature. We discuss a differential game model of the problem which features two regions of equal weight, a warm one that is hurt by global warming (which increases its cooling needs) and a cold one that benefits (through lower heating needs). We find that in equilibrium, the warm region mitigates and the cold region adapts. The warm region will decrease its mitigation effort over time: It mitigates today in excess of what is optimal in the future, in order to have persistent energy savings and mitigate the temperature increase in the future. The cold region will behave like the warm one as long as energy consumption is more sensitive to energy efficiency investment than to temperature increase. Otherwise, the mitigation effort will be initially low to allow for some warming in the future and then increase.

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1. The problem

The projected impacts of anthropogenic climate change are highly heterogeneous across the globe. They can even, at least conceptually, be welfare-improving in some situations: Some level of warming may increase agricultural productivity and decrease energy consumption for space heating in a cold region, while deterring agricultural productivity and increasing energy consumption for space cooling in a warm one. In this disaggregated view, climate change is no longer the archetype of a global public bad: It generates negative externalities to some of its contributors and positive externalities to some others. This creates conflicting incentives for climate change mitigation *versus* adaptation across regions and, since the climate change problem is essentially dynamic, over time. Even though the net impacts of climate change are likely negative, the possibility of some positive impacts can explain the reluctance of some countries to join a global agreement and engage in costly mitigation measures.

The goal of this paper is to examine the feedbacks in space and time faced by heterogenous regions of the world in the context of climate change, acknowledge their implications in terms of mitigation *versus* adaptation strategies, and integrate them to discuss optimal consumption pathways.

The exposition focuses on energy consumption for weatherization services, that is, space heating and cooling in buildings. The motivation is threefold. First, these services play an important role in climate change: Worldwide, the building sector is responsible for 33% of energy-related CO_2 emissions (GEA, 2012); the share of space heating and cooling in this figure, though poorly known at the global level, is likely to be 40 to 70%; these energy services are expected to grow threefold by 2100 (Issac and van Vuuren, 2008). Second, this techno-economic system provides a small-scale model of the broader human-climate retroactions: On the one hand, space heating and cooling needs are determined by outdoor temperature; on the other hand, they are satisfied through energy consumption, which generates CO_2 emissions and, ultimately, changes outdoor temperature. Third, heterogeneity across regions is exacerbated: Cold regions, in which energy consumption for space heating prevails, may derive net benefits from global warming, while warm regions, where cooling prevails, may incur net losses. This adds contrast to the feedbacks under scrutiny.

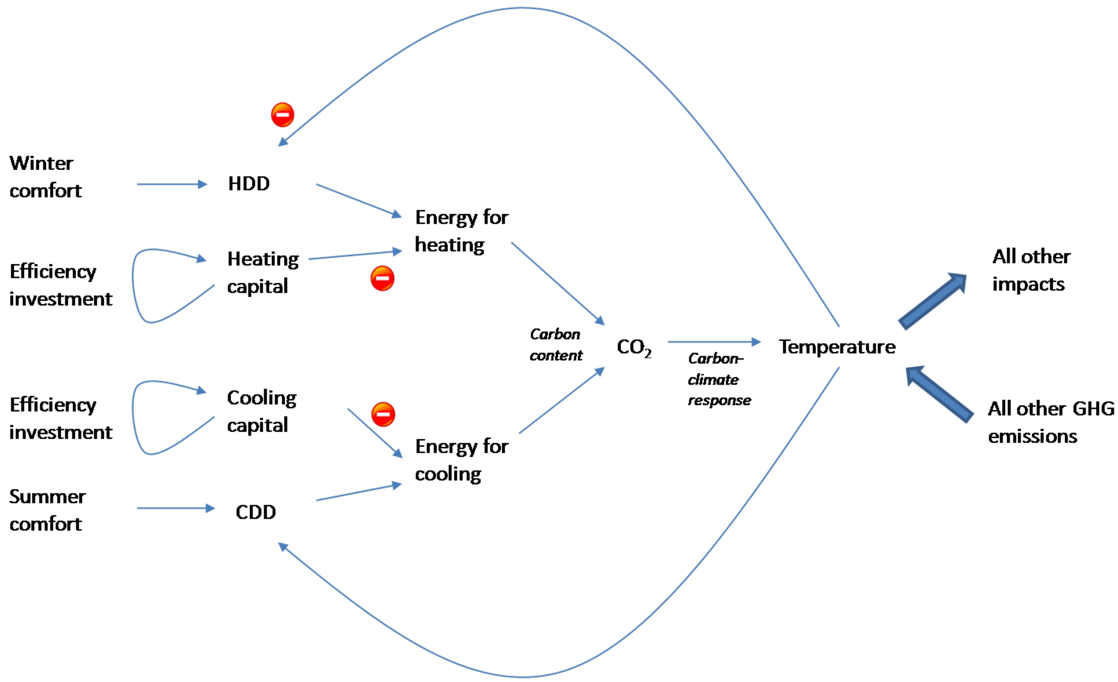
Such a focus has obvious limitations. Most of them relate to the fact that the system considered in not physically closed. Global warming is caused by GHG emissions from all sectors, not only weatherization services; this dilutes the retroactions building managers can anticipate from their actions. In turn, climate change impacts go far beyond changes in weatherization needs: Droughts, storms or sea level rise, which are unambiguously negative impacts, are overlooked in this paper. Hence, our framework may overemphasize some feedbacks. Nevertheless, we consider it exhaustive enough to allow one to think broadly about human-climate interactions, with applications to other sectors. For instance, our model suggests that cold regions may, at least in early years, want to let energy consumption for space heating go in order to reduce space heating needs in the future. This effect can easily be reframed as cold countries, such as Russia or Canada, delaying the implementation of costly decarbonization measures in their transportation sector to increase the productivity of their agriculture in the near future.

The outline of this paper is as follows. Section 2 provides background information that further motivates the weatherization focus. Section 3 analytically decomposes the elementary space and time feedbacks weatherization services are subject to: strategic interactions between cold and warm regions; energy-consuming capital and CO_2 accumulation; intensive and extensive margins of energy consumption. Section 4 provides concluding remarks.

2. Motivating example: Space heating and cooling in buildings

In this section, we draw a big picture of the system modeled in subsequent sections. The system is sketched in Figure 1. We also provide back-of-the-envelope calculations aimed to give an order of magnitude of the feedbacks analyzed. Calculations essentially play around projections of future energy demand for space heating and cooling published by Isaac and van Vuuren (2008). Their work does not incorporate the feedbacks we are analyzing; yet to our knowledge, it is the only modeling exercise that addresses the topic at the global scale.

Let us start with the microeconomic level. Weatherization-related energy consumption results from optimization over two margins. On the extensive margin, building managers (*i.e.*, a representative consumer owning and occupying the building) satisfy weatherization needs. Subject to ambient outdoor temperature, they set their thermostat to a targeted indoor temperature. The weatherization input is the difference, in absolute value, between indoor and outdoor temperature. It is measured, over the year, in heating degree-days (HDD) for heating, which is triggered when the difference is positive. It is measured in cooling degree-days (CDD) for cooling, which is triggered when the difference is negative. Consumers value weatherization for comfort at the outset, and, at some point, for health: There is compelling empirical evidence that outdoor temperature extremes lead to a significant increase in excess mortality (Deschenes, 2013).



To meet weatherization needs, consumers invest on the intensive margin in energy-consuming durables that are more or less energy efficient. Efficient durables allow consumers to satisfy the same weatherization service with lower energy. Such technologies include roof and wall insulation, efficient heating, ventilation and air conditioning (HVAC) systems or high performance heat-pumps. It also includes architectural design aimed to use solar radiations. Experts estimate that by generalizing today's most efficient technologies, global final heating and cooling energy use could be cut by approximately 46% by 2050 (GEA, 2012).

Investment in energy efficient durables lowers the marginal cost of the weatherization service. As a result, consumers increase their weatherization input after investment, a phenomenon commonly referred to as the rebound effect. This leads to energy savings after investment that are less than proportional to the efficiency gain. Empirically, the share of energy savings taken back by the rebound effect ranges from 10 to 30% for heating and 1-26% for cooling in developed countries (Sorrell *et al.*, 2009). At least conceptually, increasing energy efficiency could lead to a net increase in energy consumption. This phenomenon is known as the backfire rebound effect, or Jevons' paradox, in reference to Stanley Jevons' interpretation of the increase in coal consumption as a consequence of the penetration of efficient steam engines. Little empirical evidence supports this claim (Gillingham *et al.*, 2013). Yet some analysts note that it may be a concern in certain situations, for instance when a technology is little developed in developing countries (Sorrell, 2009).

Intuition suggests that space cooling falls into this category: The adoption of air conditioning systems, virtually nonexistent today at the global scale, may soar in response to both income growth and temperature rise in developing countries.

At the global scale, Isaac and van Vurren (2008) found that in 2000, the final energy demand for heating was 25 EJ, far exceeding the demand for cooling (1 EJ). 80% of heating consumption was attributable to Europe, Russia, the US and China. Using the TIMER/IMAGE modeling framework, they made projections based on a medium assumptions scenario leading to a temperature rise of 3.7°C in 2100, compared to the pre-industrial age. They find a threefold growth in total energy consumption, with sharp contrasts among regions and services. Heating-related energy demand would slightly increase until 2030 then stabilize. Decreases in Europe and Russia would roughly compensate increases in the US and China. Cooling-related energy demand, in contrast, would increase steadily to reach 50 EJ in 2100. This demand would essentially originate from Southeast Asia, India for the most part.

The CO_2 emissions generated by weatherization-related energy consumption depend on the carbon content of the primary energy used. As of today, globally, heating is mostly done with fossil fuel and cooling with electricity (de Cian *et al.*, 2013). This makes any projection of future weatherization-related CO_2 emissions highly dependent on future electricity generation scenarios. In Isaac and van Vurren's projections, the growths in total primary energy consumption and CO_2 emissions follow very similar patterns. Though with very different time profiles, heating and cooling each generate cumulative emissions of approximately 75 GtC over the 21st century. The sum of these cumulative emissions accounts for 12% of total energy-related CO_2 emissions in 2100.

The specific contribution of weatherization-related CO_2 emissions to global temperature rise can be directly derived from the carbon-climate response (CCR) proposed by Matthews *et al.* (2009). This measure, estimated by the authors to be in the range 1.0-2.1°C per TtC emitted, is independent of both atmospheric CO_2 concentration and its rate of change. Applying an average of 1.55°C per TtC emitted to cumulative CO_2 emissions from both heating and cooling, we find that each service generates a temperature increase of 0.12°C in 2100. Compared to the base temperature of 18°C assumed by Isaac and van Vurren, this corresponds to a temperature increase of 0.7%.

Global warming feeds back to building managers across the world, who adjust their indoor temperature. This effect is getting increasingly documented (Auffhammer and Mansur, 2012). The relationship tends to be nonlinear: The response of energy consumption to extreme heat in US households is four times as large as the mortality response (Deschenes and Greenstone, 2011). This is consistent with consumers adopting air conditioning as an adaptation behavior. This interpretation seems confirmed by the reduction in heat-related mortality due to the diffusion of air conditioning observed in the US by Barreca *et al.* (2013). Overall, one limitation of existing literature is its incomplete geographical coverage: Most studies deal with OECD countries, and the US economy in particular (Scott and Huang, 2008).

To our knowledge, de Cian *et al.* (2013) is the only reference that provides global estimates of the elasticities of energy consumption with respect to temperature. Based on econometric analysis, the authors find long-run elasticities of approximately -2.5 for heating and 2 for cooling in Fahrenheit Degrees, hence -5 and 4 in Celcius Degrees. Applying these elasticities to the 0.7% temperature increase calculated just above, we find that Isaac and van Vurren's projections of energy demand for heating and cooling lead to a decrease in heating-related energy consumption of 3.5% and an increase in cooling-related energy consumption of 2.5% in 2100. These values are doubled if regions where heating prevails anticipate not only their impact on temperature rise, but also the cooling regions', and reciprocally.

In this example, the figures may seem low: The cumulative actions of each region over a century change their actions in 2100 by more or less 5 to 10%. Yet the magnitude of these effects could be larger if we take into account other impacts which go in the same direction (*e.g.*, agriculture).

3. **Elementary feedbacks**

We build a differential game model of the problem. We assume a partition of the world into two players: A cold region, where energy consumption for space heating prevails over cooling (at least in the short term), and a warm one, where the reverse is true. In either region, energy consumption for weatherization services is subject to a variety of feedbacks, as summarized in Figure 1. Each player can engage in mitigation by investing in energy efficient capital (e.g. insulation). Adaptation corresponds to no investment. In addition, players have a second control over energy consumption: They can change the level of energy service (e.g. heating and cooling thermostat). This allows us to discuss rebound effects. The model incorporates three state variables: the level of energy efficient capital for heating, for cooling, and the atmospheric concentration of CO_2 due to past energy consumption for space heating and cooling.

In this section, we decompose the elementary mechanisms of the game by discussing the following questions: *How does one region's actions affect the other's? What is the optimal timing of energy* *efficiency investment in each region? What is the optimal timing of capital utilization in each region?*

3.1. **Strategic interactions between cold and warm regions**

Let us consider the static, non-cooperative game played by two regions of equal weight.

We take coordinated adaptation as the baseline scenario, which yields zero payoff to both regions. Mitigation by only one country yields 1 to the warm region and -1 to the cold region, plus a mitigation cost of 0.5 to whichever region mitigates. Coordinated mitigation yields 2 to the warm region and -2 to the cold region, plus a mitigation cost of 0.5 to both regions. This leads to the following payoff matrix:

		Cold region	
		Mitigates	Adapts
Warm region	Mitigates	1.5,-2.5	0.5,-1
	Adapts	1,-1.5	0,0

A dominant strategy Nash equilibrium emerges in which the cold region adapts and the warm one mitigates. This equilibrium does not coincide with the Pareto equilibrium, in which both regions adapt. There will be less emissions under *laissez-faire* than would be socially optimal.

The social optimum has dynamic implications which do not show in this static game. It would be rational that both regions cooperate to warm up until heating needs are fully cancelled out. Then, the world would turn into a global cooler and thus follow a mitigation strategy. Strategies in both regions would be coordinated (provided that transfers are possible). Note that under *laissez-faire*, 'the F of heating' will be delayed.

The location of the Nash equilibrium is robust to changes in the weights of each country (and thus the magnitude of the external effects), since the dominant strategies will always be the same. However, the Nash equilibrium may change if the game is repeated. In contrast, the location of the Pareto equilibrium may change if the symmetry is broken. For instance, coordinated mitigation can be socially optimal if the warm region is big enough (*e.g.*, its benefits are doubled):

		Cold region	
		Mitigates	Adapts
Warm region	Mitigates	3.5,-2.5	1.5,-1
	Adapts	2,-1.5	0,0

The takeaway of this overly simple game is: If the countries are of unequal weight and/or if the game is repeated, maybe the Nash and Pareto equilibria can coincide. We will explore this later on, but this points to the need of having a dynamic game.

3.2. Intertemporal linkages: Energy-consuming capital and CO_2 accumulation

In this section we assume away interactions between regions. We focus on the optimal mitigation effort in one region, over two periods. At each period t, a region consumes a quantity of energy $e(E_t, K_t)$ to satisfy a given weatherization service. Cumulative energy consumption E, which is the sum of past energy consumption e, increases outdoor temperature (by increasing the atmospheric stock of CO_2, which in turn increases radiative forcing, hence the temperature). This, in turn, decreases the energy needed to satisfy the same weatherization service ($e_E < 0$ in the cold region, $e_E > 0$ in the warm region, $e_{EE} \geq 0$ in either region)[1]. A region can invest in a certain mitigation effort k_t, at an increasing cost $M(k_t)$, with $M' > 0$ and $M'' \geq 0$). The accumulated capital lowers energy consumption: $e_K < 0, e_{KK} \geq 0$.

Over time, the region minimizes the discounted sum of expenditures $e(E_t, K_t) + M(k_t)$, with the price of energy normalized to 1. In a two-period framework in which E_0 is the initial stock of cumulative energy consumption, this leads to the following minimization program, with discount factor δ such that $0 < \delta < 1$:

$$\text{(1)} \qquad \underset{k_1,k_2}{\text{Minimize}} \left[e(E_0, k_1) + M(k_1)\right] + \delta \left[e(E_0 + e(E_0, k_1), k_1 + k_2) + M(k_2)\right]$$

The first-order necessary and sufficient condition that gives the optimal mitigation effort in the second period is:

$$\text{(2)} \qquad FOC_2(k) \equiv e_k + M' = 0$$

The first-order necessary and sufficient condition that gives the optimal mitigation effort in the first period is:

$$\text{(3)} \qquad FOC_1(k) \equiv e_k(1 + \delta(1 + e_E)) + M' = 0$$

[1]Unless otherwise stated, subscripts denote partial derivatives

Factor $(1 + e_E)$ in the FOC_1 function cpatures two intertemporal linkages between the two periods. Term 1 is capital accumulation: Mitigation investments undertaken in period 1 allow for further mitigation in period 2. Term e_E is a thermal linkage: Energy consumption in period 1 builds up the atmospheric stock of CO_2, which affects weatherization needs in period 2.

We can now discuss several cases. In the warm region, $e_E > 0$: A temperature increase due to past energy consumption increases cooling needs, hence energy consumption. The two linkages play in the same direction and, since $e_K = e_k < 0$, then $\forall k, FOC_1(k) < FOC_2(k)$. Thanks to second derivatives, the two FOC functions are strictly increasing. Therefore, we will have $k_1 > k_2$, *i.e.*, a decreasing mitigation effort over time. In period 2, the warm region does not take into account the implications of its action in the future and simply mitigates to the extent that marginal mitigation cost equalizes marginal savings in energy expenditures. In contrast, in period 1, the warm region mitigates in excess of its effort in period 2, in order to have persistent energy savings and mitigate the temperature increase in period 2.

Things are not as straightforward in the cold region, where $e_E < 0$: A temperature increase due to past energy consumption decreases heating needs, hence energy consumption. The two intertemporal linkages play in opposite directions. We can distinguish between three cases.

If $-1 < e_E < 0$, then the thermal linkage does not compensate the capital linkage: Energy efficient investments undertaken in period 1 still generate energy savings in period 2, despite a temperature decrease. Therefore, as for cooling needs, mitigation efforts will increase over time: $\forall k, FOC_1(k) < FOC_2(k) \Rightarrow k_1 > k_2$.

If $-1 - 1/\delta < e_E < -1$, then the thermal linkage compensates the capital linkage: The temperature increase due to past energy consumption is so high that it generates more energy savings in period 2 than energy efficiency investments undertaken in period 1. The mitigation effort will thus increase over time: It will be important in period 2 to minimize current expenditure, regardless of the future; in contrast, it will be refrained in period 1 to allow for some warming in period 2.

If $e_E < -1 - 1/\delta$ then $\forall k, FOC_1(k) > 0$. The solution k_1 will be at corner: Mitigation effort in period 1 will be at its minimum level.

The model commented above overlooks the important feature discussed in the previous section: As the pool of past energy consumption is global, the way e_E affects one region's action over time is not only the result of its own past actions, but also the other region's.

3.3. **Intensive and extensive margins of weatherization services**

We now complexify the previous model by considering on a second control or consumption margin for each region: the weatherization service s, which provides utility $V(s)$ (with $V' > 0$ and $V'' \leq 0$). We focus on heating and introduce a heating-degree-day function h, which increases in s and decreases in E. The maximization program used by the cold region is:

(4)
$$\underset{s_1,s_2,k_1,k_2}{\text{Maximize}} \left[V(s_1) - e(h(s_1,E_0),k_1) - M(k_1)\right] + \delta \left[V(s_2) - e(h(s_2,E_0 + e(h(s_1,E_0),k_1)),k_1+k_2) - M(k_2)\right]$$

The first-order conditions giving optimal actions in period 2 are:

$$V' - e_h h_s = 0 \tag{5}$$

$$-e_k - M' = 0 \tag{6}$$

The first-order conditions giving optimal actions in period 1 are:

$$V' - e_h h_s (1 + \delta h_E) = 0 \tag{7}$$

$$-e_k (1 + \delta(1 + e_h h_E)) - M' = 0 \tag{8}$$

Despite the introduction of function h, the resolution of optimal investments k_1 and k_2 follows the exact same pattern as in the previous section.

We thus focus on energy service consumption, which is subject to the thermal linkage only. By the same type of reasoning as in the previous section, in cold regions, where $h_E < 0$, the FOC function in period 1 will be higher than in period 2 for all s. Since the FOC functions are strictly decreasing in s, this will determine a decreasing energy service over time: In the second period, the cold region does not consider the future and consumes energy service to the extent that marginal benefits equalize marginal energy expenditure savings; in the first period, in contrast, it will let energy service go in excess of what is needed in period 2, in order to warm the climate and thus decrease energy consumption in period 2. The energy service in period 1 will even be at corner if $h_E < -1/\delta$.

This will retroact and affect the temporal profile of energy efficiency investment: Compared to the 'constant energy service' case treated in the previous section, it will speed up the 'decreasing investment' regime and slow down the 'increasing investment' one.

The reverse will be true in warm regions: As $h_E > 0$ there, energy service consumption will increase over time. Compared to the 'constant energy service' case treated previously, this will slow down the decrease in energy efficiency investment.

4. **Concluding remarks**

This preliminary analysis examines the conflicting incentives between adaptation and mitigation faced by some heterogeneous regions of the world in the context of climate change. It focuses on space heating and cooling, which captures broad human-climate interactions: On the one hand, space heating and cooling needs are determined by outdoor temperature; on the other hand, they are satisfied through energy consumption, which generates CO_2 emissions and, ultimately, changes outdoor temperature. We discuss a differential game model of the problem which features two regions, a warm one that is hurt by global warming (which increases its cooling needs) and a cold one that benefits from global warming (through lower heating needs). Both regions manage their energy consumption by optimizing both energy efficiency investment and energy-consuming capital utilization. Considering regions of equal weight, we find that in equilibrium, the warm region mitigates and the cold region adapts. However, the mitigation effort by the warm region will increase over time. The cold region will lower its energy-consuming capital utilization over time, but the energy efficiency investment path depends on the sensitiveness of energy consumption to climate change relative to investment.

The long-term equilibria of this game are unclear and still to be found. One important aspect is the characteristics of the players over time. One interesting pathway involves coordinated mitigation towards a steady state that can be seen as 'the end of heating'. At the end of heating, global warming has fully cancelled out heating needs in the cold region. The world subsequently turns into a global cooler and both regions follow a mitigation strategy. Because of intertemporal feedbacks, the two regions will in fact coordinate their mitigation efforts so that the cold region converges towards the end of heating without ever passing it.

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