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► To cite this version:

F. Grazi, H. Waisman. Urban Agglomeration Economies in Climate Policy: A Dynamic CGE Approach. 2009. hal-00799235

HAL Id: hal-00799235

<https://enpc.hal.science/hal-00799235>

Submitted on 11 Mar 2013

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No 17-2009

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November 2009

C.I.R.E.D.

Centre International de Recherches sur l'Environnement et le Développement

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ABSTRACT

This paper designs and solves a theoretical model in the light of the new economic geography to assess the role of urban land use in driving local energy consumption pathways that affect global climate change. To inform on the urban economic sectors of climate pressure we offer new modeling arguments and take the next step of testing them in simulations using computable general equilibrium (CGE) model for international climate policy. The exercise of embedding urban economies in a CGE framework is operationalized on the U.S. context. Both the modeling arguments and the simulations indicate that setting spatial policies for the control of long-run density patterns of cities is beneficial strategy to curtail national dependence on energy imports. When faced with international climate agreement that sets targets on carbon emissions, the national government may resort to urban infrastructure policies to offset the cost of an exogenous carbon tax (**JEL** C68, Q54, R12).

Keywords: CO₂ emissions, Energy use, Infrastructure investments, Urban and regional economics

RÉSUMÉ

Ce papier décrit et résout un modèle théorique fondé sur les principes de la nouvelle économie géographique et permettant d'évaluer le rôle de l'espace urbain comme déterminant des trajectoires de consommation d'énergie locale affectant le changement climatique global. Afin de mieux informer sur les secteurs de l'économie urbaine à considérer dans le cadre du changement climatique, nous proposons un cadre de modélisation innovant, testé numériquement au travers de simulations utilisant un modèle d'équilibre général calculable construit pour l'évaluation des politiques climatiques internationales. L'intégration des économies urbaines au sein d'une telle architecture est effectuée pour les USA. Aussi bien les principes de modélisation que les résultats numériques des simulations démontrent que la mise en place de politiques d'infrastructure pour le contrôle du développement de long-terme des villes est une stratégie bénéfique pour réduire la dépendance nationale vis-à-vis des importations d'énergie. Dans un contexte d'accord climatique international imposant des objectifs de réduction d'émissions de carbone, les gouvernements nationaux pourraient avoir recours à des politiques d'infrastructure au niveau urbain pour diminuer le coût de l'imposition d'une taxe carbone (**JEL** C68, Q54, R12).

Mots-clés : Emissions de CO₂, Consommation d'énergie, Investissements sur les infrastructures, Economie urbaine et régionale

Urban Agglomeration Economies in Climate Policy: A Dynamic CGE Approach*

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I Introduction

There is an increasing attention in climate policy literature towards the necessity of investigating the dynamics of the impacts of economic activities where they specifically arise (e.g., IPCC, 2001; Tietenberg, 2003; OECD, 2006; Grazi *et al.*, 2008). Urbanization, city growth, and economic development are strictly related phenomena that have many important implications on global environmental change. First, urban dynamics and climate change are related through emissions and energy consumption from economic activities located in cities. Second, spatial organization and its counterpart transport influence the extent of global warming, especially through reduced commuting distances from private automobiles and consequently lower carbon emissions. A serious search for sustainable systems requires therefore analysis of spatial patterns. Modeling regional/urban climate change is a logical next step of climate change research.

To study the relationship between spatial patterns at the urban and regional scale and climate (un)sustainability in a way that is consistent with microeconomic theory, we build up a model that can be incorporated in a Computable General Equilibrium modeling framework for climate policy analysis. In particular, we focus on how dynamic recursive modeling frameworks for the study of climate policy options capture the spatial dimension of an economy and the impacts of urban activities on climate. In analyzing where an economy chooses to locate and under what determinants it distributes across

*We are indebted to John Reilly for helpful discussions during the preparation of this article. We thank Jean-Charles Hourcade, Olivier Sassi and seminar audience at CIRED, Paris and MIT-EPPA, Cambridge MA for useful comments. This article has been first conceived while Fabio Grazi was visiting the *Joint Program on the Science and Policy of Global Change* at MIT. He gratefully acknowledges the institution for hospitality. The usual disclaimer applies.

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the space our model draws upon the new economic geography (NEG), but modifies it, as it is made clear further below. Since its appearance, due to the work of Krugman (1991), NEG has brought up interesting contributions to the understanding of those patterns along which an economy locates. Comprehension of the spatial determinants of regional economic development is set at the core issue of NEG's investigation, which particularly looks at how firms (and consequently households) agglomerate or sprawl. The NEG approach employs a two-region, two-sector general equilibrium framework and makes use of a set of assumptions that combine monopolistic competition à la Dixit and Stiglitz (1977) and 'iceberg' trade costs à la Samuelson (1952) in a mathematically tractable manner.

In the present paper, a simple model is proposed that allows for regional economies where multiple urban agglomerations dynamically evolve and alternative configurations of city growth potentially emerge. In so doing, we need to slightly reformulate the theory described above. Indeed the NEG theory posits that manufacturing-like firms end up agglomerating in certain places (cities) may be true to some extent, but it is certainly not complete. Here we aim to show not only what optimal agglomeration (city) size arises from firms' location choice, but also determine under what conditions firms choose to locate in a wide, more realistic range of alternative agglomerations (cities). This suggests that a value of agglomeration may exist for fairly different industry types. To the best of our knowledge, this spatial 'disaggregation' of the firms' location preferences over multiple (endogenous) agglomerations is simply not available in the NEG framework. Yet, this is clearly what we observe in the real world. In order to render a realistic picture of spatial distribution patterns of an economy, we therefore consider households enjoying identical welfare levels except that they face some external benefits and costs that are both function of how close to the city-center their location preference falls. Similarly, we assume that all firms have identical fixed production costs structures but face different variable costs in that they internalize the workers' external benefits and costs through the wage rate. In line with the NEG theory, our approach distinguishes as external benefits the economies of scale that arise from economic agents (both firms and workers/households) being located close together (e.g., facilitation of interchange among firms, job flexibility, ability to support social and cultural events). On the other hand, external costs are reflected in the diseconomies that arise from congestion (e.g., increased land costs and higher commuting costs for workers, and larger salaries that the firms have to pay to compensate workers for the costs of living in urban areas).

In addition to allowing for spatial disaggregation of the production sector, our model introduces other significant features that make it diverge from the standard NEG framework. Dynamics is enabled through migration decisions of firms, whose location preferences go towards those agglomeration markets that offer the best investment opportunities. This is not the case in the standard NEG framework, in which dynamics is typically modeled

through interregional mobility of workers responding to utility maximization. This in turn introduces a conceptual innovation of our model that better fits the modern structure of the production sector, where decisions are taken as a result of trade-offs between firms' profits and managers' and shareholders' interests. Finally, we explain agglomeration spillover effects endogenously, in a less stylized, more realistic analytical framework. By breaking the duality of the production sector (two-region, two sectors, two factors of production) through the introduction of a third input factor of production (intermediate consumption), we model the benefits from reduced (transaction) costs of intermediate goods as a result of scale economies, while still maintaining the standard increasing returns structure on the production cost function of firms. Agglomeration spillover effects have been recognized in the economic literature on trade theory and urban economics since Marshall and Chamberlin, but their formal representation has turned out to be difficult and controversial (Ciccone, 2002).

Stylized analytical approaches typically fall short of rendering a complete picture of the complexity that animates sustainability debate, especially in the field of climate change, where CO₂ (major responsible for global warming) and other green house gas (GHG) emissions represent a global transboundary threat that can hardly be incorporated in a simplified analytical framework. Moreover, policy actions require long-run forecasting of complex dynamic systems affecting climate, as the whole economy. For these reasons, numerical analysis techniques like computable general equilibrium (CGE) models are seen as more reliable guides to address the relationship between determinants of economic development and forces inducing climatic variations (Böhringer and Löschel, 2006). Our NEG model of urban economies is developed to be integrated by CIRED *Impact Assessment of Climate Policies* (IMACLIM-R, hereafter) (Crassous *et al.*, 2006), a global CGE model of economic growth, international trade, and CO₂ (carbon) emissions. Modular integration with IMACLIM-R enables capturing the global environmental impacts stemming from all activities associated with urban land use and translate these through negative externalities into welfare effects. IMACLIM-R model has been applied to a number of international policy studies and it is recognized as an innovative analytical tool for policy scenario analysis. Two are the points of innovations that characterize IMACLIM-R with respect to other reknown CGE models in use to climate policy: i) the transition costs between two steady-state equilibria are endogenously generated by the interplay between non-perfect foresight and the inertia of technical systems ii) the physical technical coefficients allow for a transparent incorporation of bottom-up information and 'routine' behaviors as drivers of technical change. These modeling features are particularly well suited to analyze the complexity of urban phenomena as they allow capturing the uncertainty related to agents' spatial behavior when multiple locations are available. Like other recursive frameworks (Paltsev *et al.*, 2004), the dynamics in IMACLIM-R accounts for imperfect expectations of economic agents when taking decisions over equipment, technology, location.

The remainder of this paper is organized as follows. Section II provides a brief discussion on CIRED/IMACLIM-R model, the CGE modeling framework used for this study. Section III presents the static model, as well as the dynamic setting to be embedded in IMACLIM-R. Section IV presents our results. Section V finally concludes.

II The IMACLIM-R CGE modeling framework

CGE models are being increasingly used by research institutes and international organizations as well, as numerical instruments that are capable of providing policy makers with a wide range of information on the several economic sectors of climate pressure. Standard CGE models adopted in environmental economic analyses base on multi-regional, multi-sectoral analytical framework accounting for economy's efficiency and distributional effects of policy measures (mainly, carbon taxes/subsidies and emission trading permits) aimed at CO₂ abatement. They can in fact provide numerical outcomes under different policy scenarios, simulating what economic impacts arise from specific policy interventions. In consequence of the cost (benefit) pressure exercised on its sectors by a tax (subsidy), the world economy reacts adjusting production and consumption, as well as reallocating input factors according to prefixed factors of substitutability.

Most empirical CGE models are static models, mostly because a static framework allows for accounting of policy interferences, using counterfactual simulations on a calibrated equilibrium to investigate the effect of price measures of new introduction. However, a dynamic framework is essential in models that aim at accomplishing the twofold task of accounting for policy interference on economic welfare and forecasting carbon emissions from economic activities. Indeed, taking into account the dynamic dimension allows capturing the change in (both human and physical) capital stock as a consequence of some exogenous policy pattern, as well as addressing the issues of resource allocation over time, economic growth, environmental degradation.

The IMACLIM-R model used in this study is a *dynamic recursive* model in that savings and investments affect the capital stock as function of income only in the current period (Crassous *et al.*, 2006).¹ It is based on an explicit representation of the economy both in money metric values and physical quantities linked by a price vector. This dual vision of the economy, which comes back to the Arrow-Debreu theoretical framework, guarantees that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and consistent set of relative prices.

Calibration data rely upon the combination of GTAP dataset and explicit energy balances, the former providing detailed accounts of regional produc-

¹This is opposed to what occurs in *forward-looking* intertemporal optimization framework, where all economic variables account for future expectation.

tion, consumption and international trade, and the latter giving a complete picture of patterns of energy production and consumption. The base year used for policy scenario analysis is the 2001, and the model covers the period 2001-2100, in one year steps. The version of the IMACLIM-R model used in this paper divides the world economy into 12 regions and 12 sectors for which details are reported in Table 1. Two transport modes auto-produced by households (personal vehicles, and non-motorized transportation) are also included.

TABLE 1:
KEY DIMENSIONS OF THE IMACLIM-R MODEL

<i>Region</i>	USA		
	Canada		
	Europe		
	OECD Pacific (JP, AU, NZ, KR)		
	Former Soviet Union		
	China		
	India		
	Brazil		
	Middle-East Countries		
	Africa		
	Rest of Asia		
	Rest of Latin America		
<i>Sector</i>	<i>Energy</i>	<i>Primary Energy</i>	Coal Oil Gas
		<i>Transformed Energy</i>	Liquid Fuels Electricity
	<i>Transport</i>	Air	
		Water	
	<i>Goods & Services</i>	Others	
		Construction	
		Agriculture	
		Energy-intensive Industry	
		Composite (including Services)	

Note: A number of primary energy carriers are used. Concerning liquid fuels, we consider oil, biomass (biofuels) and coal (Coal-To-Liquid). As for the electricity sub-sector, we consider coal, gas, oil, hydro, nuclear and renewables.

The IMACLIM-R model adopts a recursive structure that allows a systematic exchange of information between:

- i. An annual static equilibrium, in which the input-output coefficients

and labor intensity are fixed (a Leontief production function), capital is treated as a production capacity (partially or fully exploited) and demand from representative households result from utility maximization under income and time-budget constraints. Solving this equilibrium at date t provides a consistent set of physical and money flows linked by endogenous relative prices. As a closed model, monetary resource circularly flow internally to the system: all the revenues from the production are either redistributed among the consumers (as returns to capital and labor) or within the production sectors (as payment for intermediate goods), or given to government (as taxes). The (passive) government is seen as a collector of taxes and re-distributor of profits to the consumers.

- ii. Dynamic modules composed of a ‘growth engine’ with endogenous technical change, and sector-specific reduced forms of technology-rich models. The latter assess the reaction of technical systems to the economic signals stemming from the static equilibrium at time t (prices, wages, profit margins) and send back this information to the static module in the form of new production coefficients for calculating the equilibrium at time $t + 1$. In this putty-clay structure, technical choices can be made on the new equipment vintages every year, but do not change the coefficients of the average technology embodied in the pre-existing equipment stock.

Conventionally, the growth engine is composed of exogenous demographic trends and labor productivity changes, but constraints on investments (in a context of inertias on equipment and non-perfect expectations) lead to endogenous gaps between potential and real growth. This structure captures the existence of ‘transition costs’ due to non optimal responses of the economic system to random shocks around an optimal steady state (Solow, 1988).

Available domestic financial resources for investment are given by the sum of savings and the share of returns to capital that is directly re-invested. Since we assume that households’ savings are mostly linked to the dynamics of regional population, we set saving rates exogenously, as demographic trends. A share of available investments is traded internationally, and resulting net available financial resources are distributed among sectors according to their expected needs in terms of new producing capacities.

For the majority of traded goods in IMACLIM-R (exception being energy trade), international trade is modeled following Armington’s approach (Armington, 1969) for not perfect substitute goods. Armington assumption distinguishes domestically produced goods from imported commodities by the same industry on the base of the elasticity of substitution between them. The importance of Armington elasticity parameter can be seen in allowing the evaluation of economy’s response to a certain carbon cap policy set on a group of countries. Considering the production of a composite good, the increased costs of producing intensive energy goods of the composite in those

countries lead to a drop in domestic supply favoring imports from foreigner industries that are not burdened by the carbon constraint.

As noted above, the IMACLIM-R model has been conceived to accomplish a twofold task: computing the carbon emissions arising from economic activities and assessing the effects of emission control measures on the economy. In IMACLIM-R policy measures result from economic incentives modeled through carbon taxes differentiated across sectors and regions, infrastructure policy, and norms on equipment.

III The Spatial Economy

A *The static model*

The world is composed of many regions each of which can be envisaged as a mass of urban agglomerations. Urban agglomeration land is conceived as monocentric, axi-symmetric city spread along one-dimensional space $x \in d$, where d is the overall city size. Like traditionally approached by urban and regional economics since von Thünen (1966), the central business district (CBD), situated at the origin $x = 0$, is the location where firms choose to distribute once they enter the agglomeration. All economic activities take place in the j -CBD, whereas the urban population is distributed within circular peripheral areas surrounding it. In our economy three types of decision-makers exist: governments, producers, and consumers. We purposely abstract from all income distributional issues, and assume that the government chooses housing policies that maximize the utility of the representative consumer. Profit-maximizing firms do not consume land, while utility-maximizing workers do. Urban workers settled at a certain point x of d consume $\lambda_j(x)$ units of land and commute x to the CBD. The number of urban workers L_j is given by:

$$L_j = \int_{0 \leq |x| \leq d_j} \frac{dx}{\lambda_j(x)}. \quad (1)$$

At the land market equilibrium, workers are indifferent between any x -location around the CBD of agglomeration $j \in J$. This comes down to assuming that all people living inside each peripheral rings at each point x face identical external costs resulting from the interplay between different commuting costs (being different the distance from each individual's residential place and the CBD, where jobs and all varieties of the differentiated goods are available) and housing costs (being heterogeneous the value and the consumption of land throughout the periphery).

Government owns the available land and decides of the spatial distribution of housing supply. Hence, heterogeneity of density within the agglomeration does not result from households' preferences over the available land but is rather exogenously set. We take the trend for the density function $\lambda_j(x)$ as

given and choose a power functional form for the sake of simplicity.

$$\lambda_j(x) = \widehat{\lambda}_j x^\xi, 0 \leq \xi < 1.^2 \quad (2)$$

As in Murata and Thisse (2005), each (urban) worker supplies one unit of labor. Considering *unitary* commuting costs $\theta > 0$ in the ‘iceberg form’ à la Samuelson (1954),³ the effective labor supply of a worker living in the urban area at a distance x from the CBD is:

$$s_j(x) = 1 - 2\theta_j |x|, \quad x \in [-d_j, d_j]. \quad (3)$$

Condition: $0 < \theta_j \leq \frac{1}{2d_j}$ ensures positive labor supply.

The total effective labor supply throughout the urban area is therefore:

$$S_j = \int_{0 \leq |x| \leq d_j} \frac{s(x)}{\lambda_j(x)} dx = \frac{2d_j^{1-\xi}}{\widehat{\lambda}_j (1-\xi)} \left(1 - 2\theta_j \frac{1-\xi}{2-\xi} d_j \right), \quad (4)$$

whereas the total potential labor supply is given by:

$$L_j = \int_{0 \leq |x| \leq d_j} \frac{1}{\lambda_j(x)} dx = \frac{2d_j^{1-\xi}}{\widehat{\lambda}_j (1-\xi)} \quad (5)$$

Letting w_j be the wage rate firms pay to laborers to carry out their activity within the j -urban area, commuting costs CC_j faced by one worker in agglomeration j result from the losses of effective labor. Combining (4) and (5), we obtain:

$$CC_j = \frac{(L_j - S_j) w_j}{L_j} = 2\theta_j \frac{1-\xi}{2-\xi} d_j w_j. \quad (6)$$

We normalize at zero the rent value of the land located at the edges of the city: $R_j(d_j) = 0$. Given that all urban workers are identical from a welfare perspective, and given the wage rate w_j laborers earn to work in urban area j , using (3) the value of worker’s income Υ_j net of commuting costs $2\theta_j x w_j$ and rent costs $R_j(x)$ is the same throughout the urban city. Precisely:

$$\Upsilon_j = s_j(x) w_j - \lambda_j(x) R_j(x) = s_j(-d_j) w_j = s_j(d_j) w_j = (1 - 2\theta_j d_j) w_j. \quad (7)$$

From (7), the equilibrium land rent for an evenly distributed urban work-

²Condition $\xi \geq 0$ ensures that $\lambda_j(x)$ is an increasing function, so that the empirical evidence of higher population density in the centre of the city is captured. Condition $\xi < 1$ is necessary to have population convergence in (1).

³Considering different unitary commuting costs θ_j across the agglomerations captures the specificities of each agglomeration in terms of modal shares and transport infrastructures

ing population in region j is simply derived, as follows:

$$R_j(x) = \frac{2\theta_j(d_j - |x|)}{\lambda_j(x)} w_j. \quad (8)$$

In order to comprehend how the land rent is distributed over the urban workers by the local government, we first calculate the aggregated land cost by integrating $R_j(x)$ over the distance x that represents the available urban land, and then divide the resulting figure by the labor force that is active in the city:

$$RC_j = \frac{\int_{0 \leq |x| \leq d_j} \lambda_j(x) R_j(x) \frac{dx}{\lambda_j(x)}}{L_j} = 2\theta_j \frac{1}{2 - \xi} d_j w_j. \quad (9)$$

Combining (6) and (9) gives $\frac{CC_j}{RC_j} = 1 - \xi$, which determines the distribution of external costs between commuting and housing: the lower ξ , the more commuting costs are relatively important. From each laborer's income, an amount: $CC_j + RC_j = EC_j^L$ is deduced as compensation to live in the urban area. This amount is expected to affect consumer's purchasing power Υ_j .

Consumption We consider a regional economy entailing a continuum of agglomerations (labeled $j = (1, J)$), one composite sector (the IMACLIM-R industrial and service sectors) and one differentiated good q . We assume that the many firms of the industry-plus-service type composing our economy produce each one variety (labeled $i = (1, N)$) of one type of the differentiated good q under increasing returns to scale. Therefore, the number of available varieties in each agglomeration j , $n_j \in N$, is equal to the number of firms that are active in the same agglomeration. All goods can be traded internationally and each component of total demand is composed of both imported and domestic goods. Unlike the standard NEG literature, we avoid tracking bilateral flows, as this would excessively complicate our model due to the many agglomerations our approach allows for. For the purpose of our simulations, all trade flows are assumed to end up in an international pool (labeled h) that processes the exported varieties and re-allocates them across agglomerations. For a given fraction of the n_j varieties that agglomeration j exports to the pool h , it receives back n_h varieties of the same good from the pool h , such that: $\int_{j=0}^J n_j + n_h dj = N$.

We define a price index P_j of the composite good available in agglomeration j in order to be able to treat the various products as a single group.

$$P_j = \left[\int_{i=0}^{n_j} p_{jj}(i)^{1-\epsilon} di + \int_{i=0}^{n_h} p_{hj}^{1-\epsilon}(i) di \right]^{\frac{1}{1-\epsilon}}. \quad (10)$$

The economy employs a unit mass of mobile workers L . Wherever they are employed, the L laborers are both input production factors and output

end-users. Given a certain net income Υ_j based on the wage w_j that a laborer earns from working at a the j -agglomeration, she has to decide of its allocation over the consumption of the differentiated good D . We consider households that reach identical welfare levels and bare identical external costs EC_j^L stemming from being located in the j -agglomeration (see eq. (7)). Given individual's utility U_j defined over the disposable income Υ_j for consumption of the composite good D_j in each agglomeration j , welfare maximization behavior imposes:

$$\max U_j = U_j [D_j(\Upsilon_j)]. \quad (11)$$

Price and utility homogeneity throughout the j -city impose that aggregate consumption of the composite good is independent on the distance x from the j -core. Letting $c_{jj}(i)$ be the consumption of variety i produced domestically and $c_{hj}(i)$ the consumption of the variety coming from the pool h , the constant-across-city utility from goods aggregate consumption is:

$$D_j = \left[\int_{i=0}^{n_j} c_{jj}(i)^{(\epsilon-1)/\epsilon} di + \int_{i=0}^{n_h} c_{hj}(i)^{(\epsilon-1)/\epsilon} di \right]^{\frac{\epsilon}{\epsilon-1}}. \quad (12)$$

A consumer has to satisfy the following budget constraint:

$$\int_{i=0}^{n_j} p_{jj}(i) c_{jj}(i) di + \int_{i=0}^{n_h} p_{hj}(i) c_{hj}(i) di = \Upsilon_j. \quad (13)$$

Here Υ_j is the net disposable income for consumption, already discounted from external costs for laborers EC_j^L (see eq. (7)).

Maximizing utility given in (12) subject to (13) gives the aggregate demand in region j for a variety i domestically produced and coming from the pool h , respectively:

$$\begin{aligned} c_{jj}(i) &= L_j \Upsilon_j \frac{p_{jj}(i)^{-\epsilon}}{P_j^{1-\epsilon}} \\ c_{hj}(i) &= L_j \Upsilon_j \frac{p_{hj}(i)^{-\epsilon}}{P_j^{1-\epsilon}} \end{aligned} \quad (14)$$

Production All firms producing in a given agglomeration j incur the same production costs and rely upon the same input factors: intermediate consumption Z_j , capital X_j , and labor l_j . Capital and labor are spatially mobile. Intermediate consumption is referred to as 'material' and corresponds to the aggregate IMACLIM-R sector that includes consumption of goods and transport. We consider intermediate consumption as subject to external economies of scale resulting from improved production process through some agglomeration-specific technology spillover, as follows:

$$Z_j = \frac{Z_0}{n_j^\alpha}. \quad (15)$$

Here n_j is the given number of active firms in region j , Z_0 is a constant that homogenizes the units of measurement and $\alpha > 0$ is a parameter that

captures the non linearity of the external ‘agglomeration effect’ (Fujita and Thisse, 1996; Grazi *et al.*, 2007).

Due to the fixed input requirement χ , the amount of productive capital in agglomeration j , X_j , is proportional to the number of domestic firms, n_j :

$$X_j = \chi n_j. \quad (16)$$

Firms of the above type find it profitable to join a certain agglomeration j to benefit from a specialized labor market. This brings about differences in terms of labor productivity between producing inside and outside the agglomeration. To avoid all firms collapsing at the same place because of absent specific differentiation, we introduce inherent reasons for differential location choices. We therefore posit that firms choose to locate according to the trade-off between production benefits and costs that are specific of the agglomeration j . Concerning the former, they take the form of heterogeneous labor productivity across different urban agglomerations (that is, $l_j \neq l_k, \forall j, k \notin (1, J)$), whereas the latter are indirectly captured by the different labor costs (namely, the wage rate w_j) firms face across the different agglomerations to compensate laborers for the agglomeration-specific external costs.

Letting r_j, w_j, p^Z be the unitary returns of, respectively, capital X_j , labor l_j , and intermediate consumption Z_j , the total cost of producing q_j for a firm $i \in n_j$ in region j is expressed as:

$$TC_j(i) = r_j \chi + (l_j w_j + p^Z Z_j) q_j(i). \quad (17)$$

In the short-run model, χ , l_j , Z_j and p^Z are known, as they result from the spatial disaggregation of the aggregate macroeconomy.

Given its monopoly power, it is clear that each firm acts to maximize profit:

$$\pi_j(i) = p_j(i) q_j(i) - [r_j \chi + (l_j w_j + p^Z Z_j) q_j(i)]. \quad (18)$$

In order to allow the model for the spatial dimension, trade is allowed between the agglomerations. We use the ‘iceberg’ form of transport costs associated with trade of the composite goods (Samuelson, 1952). In particular, if one variety i of manufactured goods is shipped from region j to region k , only a fraction $\tau > 1$, will arrive at the destination: the remainder will ‘melt’ during the shipment. This means that if a variety produced in location j is sold in the same agglomeration at price p_{jj} , then it will be charged in consumption location k via the pool h a price $p_{jk} = p_{jh}$, which equals:

$$p_{jk} = p_{jh} = \tau p_{jj}. \quad (19)$$

Short-run market equilibrium At the labor-market equilibrium, in an urban agglomeration j in which n_j firms are set up, the total labor effectively supplied S_j (see eq. (4)) must be equal to the total labor requirements by

production $l_j n_j q_j$.

$$S_j = L_j \left(1 - 2\theta_j \frac{1-\xi}{2-\xi} d_j \right) = l_j n_j q_j. \quad (20)$$

Here, we recall, d_j [$d_j = \lambda L_j / 2$] is the size of agglomeration j , θ_j is the unitary commuting cost in agglomeration j , and $n_j q_j$ is the total domestic production of the composite good.

Equilibrium on goods market imposes that all is produced by firms is consumed by households in agglomeration j , at the net of all exports to the pool. The market clearance imposes that the production size $q_j(i)$ of a firm located in region j is:

$$q_j(i) = c_{jj}(i) + \tau c_{jh}(i). \quad (21)$$

Here τc_{jh} represents the volume of shipped goods from production location j to some consumption location k via the pool h . We consider that a share $(1 - \beta)$ of each variety produced is consumed locally, the rest being exported to the pool. Given a j -firm's production size q_j , exports are modeled as a fixed share $c_{jh} = \beta q_j$ of that output volume.

For the sake of simplicity and without loss of generality we consider that all the varieties are identical. This allows us to drop the notation i for the variety in the reminding of the analysis. In particular, the price index in (10) can be re-written as: $P_j = \left(n_j p_{jj}^{1-\epsilon} + n_h p_{hj}^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}}$. By plugging (14.a) and above condition on exports into (21), the equilibrium production q_j of a firm located in region j is defined as follows:

$$q_j = \frac{L_j \Upsilon_j}{1 - \beta} \frac{p_{jj}^{-\epsilon}}{n_j p_{jj}^{1-\epsilon} + n_h p_{hj}^{1-\epsilon}}. \quad (22)$$

As a consequence of the profit maximization behavior, in the agglomerations firms will enter and exit the manufacturing sector until the point at which profits are zero, as an equilibrium condition of monopolistic competition. Therefore, by substituting (22) into (18) and setting $\pi_j = 0$, the return to capital r_j at the equilibrium is:

$$r_j = \frac{q_j}{\chi} [p_j - (l_j w_j + p^Z Z_j)]. \quad (23)$$

Recalling that p_j is the price of a variety i that is both produced and sold in agglomeration j , under Dixit-Stiglitz monopolistic market we have that a profit-maximizing firm sets its price as a constant mark-up on variable cost by assuming a constant elasticity of substitution (CES), $\epsilon > 1$:

$$p_j = \frac{\epsilon}{\epsilon - 1} \frac{\partial TC_j}{\partial q_j} = \frac{\epsilon}{\epsilon - 1} (l_j w_j + p^Z Z_j). \quad (24)$$

All varieties are sold in the agglomeration at the same price and no shopping cost occurs to spatially differentiate the market value of a given variety. Given a firm's export volume in fixed share of the production (βq_j) and the identity of all varieties coming from a certain agglomeration, it turns out that $\beta \int_{k=0}^J n_k q_k dk$ varieties are sent to the pool. We treat them as a single additional variety of pool price $p_{hj} = \frac{\int_{k=0}^J p_{kh} n_k q_k dk}{\int_{k=0}^J n_k q_k dk}$.

It is now worth spending a few words in order to make clear what we consider as the wage rate w_j . In our core-periphery economy, a fraction of the whole available land hosts city activities. Letting l_j the labor productivity within the j -urban area, for a given wage rate discounted from the external cost the nominal income of agglomeration j per *unit* of output associated to (7) is: $l_j \Upsilon_j = l_j w_j |1 - 2\theta_j d_j|$.

Workers decide to enter the agglomeration only if the purchase power they perceive in the urban area is at least identical. In doing so, they are expected to react to differences in real income, as this adequately measures the disposable purchase power.

For a given price index P_j and a certain labor productivity level, we define a *unitary* real income in agglomeration j :

$$y_j = l_j \Upsilon_j (P_j)^{-1}. \quad (25)$$

Workers join the urban agglomeration j if condition on unitary real income $y_j \geq y^*$ is verified, with y^* representing the reference unitary real income for workers that is not augmented to include the urban costs.

To minimize the cost of labor in (17) firms are available to compensate workers with a wage rate that guarantees the minimum unitary real income:

$$y_j = y^* \quad (26)$$

By combining (26) and (25), the equilibrium wage rate for a laborer in agglomeration j is formed as follows:

$$w_j = \frac{y^*}{1 - 2\theta_j d_j} \frac{P_j}{l_j}. \quad (27)$$

This concludes the short-run model.

B The dynamic model: integration in IMACLIM-R

Here we extend the short-run model so as to address dynamics and ensure analytical consistency for its inclusion in the IMACLIM-R framework as a specific module accounting for the spatial organization of the economy at the urban scale.

Spatial disaggregation We consider the IMACLIM-R static equilibrium time t . At this time the information from the macro-economy at the country

level are disaggregated into a combination of local urban economies where the interactions between economic agents take place in the form developed in the previous sub-sections.

In each agglomeration j at time t , a *fixed* number of profit-maximizing firms $n_j(t)$ sets prices $p_j(t)$ and quantities $q_j(t)$ to meet households' demand for the composite good D , according to (24) and (22). Workers requirements for production drive population distribution $L_j(t)$ and agglomeration size $d_j(t)$ through (20) and (5).

Consistency between the description of the economy at the agglomeration scale and that at the country scale requires ensuring that the average value of each spatially disaggregate variable equals the value of the corresponding aggregate variable resulting from the IMACLIM-R equilibrium.

Firm mobility The second step of the module describes firms' location decisions and induced changes in the spatial distribution of firms and productive capital in the national economy.

Agglomerations differ in labor force and infrastructure endowment that, in the urban model, are captured by labor productivity l_j and unitary commuting costs θ_j , respectively. These j -specificities act as constraints on production (through (17)) and expected returns to capital (through (23)), and influence the attractiveness of agglomerations for productive investment. The attractiveness of agglomerations ultimately affects the migration decisions of firms.

Location preferences over the different agglomerations at time t are taken by firms on the basis of an index of attractiveness that accounts for the maximum return to capital investors expect to make in a certain agglomeration and its market potential.

Let $n_j(t)$ be the number of existing firms in agglomeration j , $r_j^{\text{ant}}(t+1, \widehat{n}_j(t+1))$ the return to capital an investor expects to maximize at time $t+1$ in agglomeration j , and $\widehat{n}_j(t+1)$ the optimal number of firms that maximizes that anticipated return, such that:

$$\frac{\partial r_j^{\text{ant}}(t+1)}{\partial n_j(t+1)} = 0 \Rightarrow \left| \begin{array}{l} \widehat{n}_j(t+1) \\ \widehat{r}_j(t+1) = r_j^{\text{ant}}(\widehat{n}_j(t+1)) \end{array} \right. \quad (28)$$

The attractiveness $A_j(t)$ of a given agglomeration j at the equilibrium time t is then defined as follows:

$$\begin{aligned} A_j(t) = & \phi_1 \frac{r_j^{\text{ant}}(t+1) - \min_k r_k^{\text{ant}}(t+1)}{\max_k r_k^{\text{ant}}(t+1) - \min_k r_k^{\text{ant}}(t+1)} + \\ & + \phi_2 \frac{(\widehat{n}_j(t+1) - n_j(t)) - \min_k (\widehat{n}_k(t+1) - n_k(t))}{\max_k (\widehat{n}_k(t+1) - n_k(t)) - \min_k (\widehat{n}_k(t+1) - n_k(t))}, \end{aligned} \quad (29)$$

with $j, k = (1, J); j \neq k; 0 \leq \phi_1, \phi_2 \leq 1, \phi_1 + \phi_2 = 1$.

The two terms on the right-hand side of (29) represent the two determinants of the attractiveness of agglomeration j . The first term captures the absolute level of future anticipated revenues from investment opportunities as the main economic driver of firms' location decisions in the short run. This reflects the active role of shareholders who want to maximize the return to capital, which is a priori a cost for firms. The second term embeds long-run trends of market potential. More precisely, the second term posits that the larger and positive (negative) the gap between optimal and current number of firms, the higher the incentive to enter (exit) agglomeration j . The parameters $0 \leq (\phi_1, \phi_2) \leq 1$ measure the relative importance of the two determinants of the attractiveness in (29): for $\phi_2 = 1$, only market potentials are accounted for, whereas expected short-run returns to capital play the dominant role when $\phi_1 > 0.5$. We study the case $\phi_1 = \phi_2 = 0.5$, which attaches identical weight to the determinants.

The agglomeration attractiveness $A_j(t)$ helps determine the stable spatial distribution of firms across the available agglomerations at equilibrium time $t + 1$, $n_j(t + 1)$. Two types of firms base their location decisions on $A_j(t)$, namely the existing firms at previous equilibrium time and the newly created firms. For each of the two groups of firms we are able to build an indicator that establishes the stable number of firms at a given equilibrium time.

- i. Consider the case of two agglomerations j and k , with $j, k = (1, 2); j \neq k$. For a generic 'old' j -firm – that is a firm coming from previous equilibrium time and settled in agglomeration j – the magnitude of the incentive to migrate to a given agglomeration k depends on the absolute attractiveness of agglomeration j :

$$m_{j \rightarrow k}(t) = [\pm |A_k(t) - A_j(t)|]^{\gamma_1} \left(\frac{1}{\delta_{jk}} \right)^{\gamma_2} \left[\left| \frac{1}{l_k(t) - l_j(t)} \right| \right]^{\gamma_3}, \quad (30)$$

with $j, k = (1, 2); j \neq k$.

Here δ_{jk} is the distance between the agglomerations j and k , $l_k(t)$ measures the productivity of labor in region k and $\gamma_1, \gamma_2, \gamma_3$ represents the measurement of the relative migration incentive of, respectively, attractiveness, distance, and labor productivity, with $\gamma_1, \gamma_2, \gamma_3 > 0$ and $\gamma_1 + \gamma_2 + \gamma_3 = 1$.

Equation (30) writes that a generic j -firm is encouraged to move from agglomeration j to k if condition: $A_k(t) \geq A_j(t)$ is verified (as this ensures $m_{j \rightarrow k}(t) > 0$). The magnitude of this incentive is a function of: a) the absolute difference in attractiveness between agglomerations k and j ; b) the distance δ_{jk} between the two agglomerations; iii) and the absolute difference between agglomerations in the structure of production, captured by the labor productivity $l(t)$.

Extending (30) to a more generic multi-agglomeration picture, the incentive to move to an agglomeration j from any other k agglomeration

(with $j, k = (1, J)$ and $k \neq j$) is derived as follows:

$$M_j(t) = \mu^M \int_{k=0}^J m_{k \rightarrow j}(t) dk, \quad (31)$$

with $j, k = (1, J); k \neq j$.

Here μ^M is a parameter that homogenizes the units of measurement.

- ii. Consider now the case of new firms that are created at the equilibrium time t . They spatially sort out themselves across the J agglomerations according to the agglomeration attractiveness. The number of firms created in agglomeration j is proportional to the emerging force E_j :

$$E_j(t) = \mu^E \left[A_j(t) - \min_k A_k(t) \right]. \quad (32)$$

Here μ^E is a parameter that homogenizes the units of measurement.

Given the economy size at the time t , the total number of firms in agglomeration j at the equilibrium time $t+1$ results from the interplay between firms' migration decisions from other agglomerations and entry of new firms:

$$n_j(t+1) = n_j(t) + M_j(t) + E_j(t). \quad (33)$$

The relation between the number of firms at play in agglomeration j at equilibrium time $(t+1)$ and the anticipated production in agglomeration j is ensured by the value of parameters μ^M in (31) and μ^E in (32). They in fact are calculated so as to ensure condition: $\overline{Q_C^{\text{ant}}} = \int_{j=0}^J n_j(t+1) q_j^{\text{ant}} dj$ on anticipated production volume at IMACLIM-R equilibrium time $t+1$.

IV Results

The study aims at providing information on the impact of spatial policies at the city scale on the climate change issue. The US is the geographical context for this study. We consider long-run general equilibrium paths for the US 20 largest cities. Table 2 summarizes the main spatial and economic features of the cities. We show model findings for two types of analysis concerning the interaction mechanisms between local (urban), regional (country) and global (world) economies and investigate those mechanisms in as many alternative policy scenarios. The base year used for policy scenario analysis is the 2001, and the overall study covers the period 2001-2100, in one year steps.

The first analysis considers a Business-As-Usual (BAU) scenario of the world economy and look at the spatial and economic patterns of US urban development when cities are let be part of the global system. In turn, the global system is both economically and environmentally influenced by those patterns. In the BAU scenario, the major drivers of the (both US and world)

macroeconomy (e.g., population, labor productivity, oil price, primary energy mix, CO₂ emissions) follow some conservative trend that are set in IMACLIM-R.

Next, local spatial policies are considered that affect the urban spatial structure through augmented public expenditure in the local infrastructure sector. The direct effect of infrastructure policy takes the form of increased urban density due to increased investments in the building sector and is analyzed in a specific infrastructure scenario. The effect of such a spatial densification policy on global carbon emissions is also isolated, so as to assess its complementary city-scale effect in reducing the cost of a broader international climate policy that aims at setting a market price for carbon. The cost off-setting effect of the two types of policy is addressed by comparing two low carbon scenarios in which an identical cap on carbon emissions is envisaged. The ambitious climate policy requires a mix of carbon pricing (and other economic incentives) and specific “policies and measures”, among which densification policies at the urban scale can either be planned or not.

A Long-run patterns of urban development

In the BAU scenario, the conservative assumption of a constant average density (as defined by: $\frac{L_j}{2d_j}$) in each agglomeration holds throughout the time path considered. For the sake of presentation, we narrow the study of long-run (spatial and economic) patterns of urban development and present results for the ten largest US urban agglomerations.

The dynamic mechanisms of urban development are driven by the attractiveness index A_j affecting firm migration decisions (see figure 1). The number of active firms n_j in turn influences the supply side of the market, as measured by a variation in the production size of each agglomeration, $n_j q_j$ as the amount of locally available firms varies. In particular, our model shows that given the general trend of continuous domestic growth of the production predicted by IMACLIM-R, the share of this production borne by the available agglomerations is expected to be positively related to the number of firms operating in each agglomeration (see figure 2). *Note:* Data source: US Census Bureau, 2000.

Changes in the size of production bring about modifications of the consumption behavior of individuals located in the agglomeration j . In particular, changes in the consumption behavior occur via a modification of the purchase power of households, as defined by $\frac{\Upsilon_j}{P_j}$, which in turn results from a combination of overall increasing households’ disposable income Υ_j (conveyed by labor productivity gains) and the cost of living in each agglomeration as captured by the price index P_j , which remains almost homogenous across the agglomerations at each point in time (see figure 3).

Finally, dynamic feedback mechanisms between the local and aggregate dimensions of the economy affect the spatial structure of urban economies over the time. This effect is captured through the study of the city size

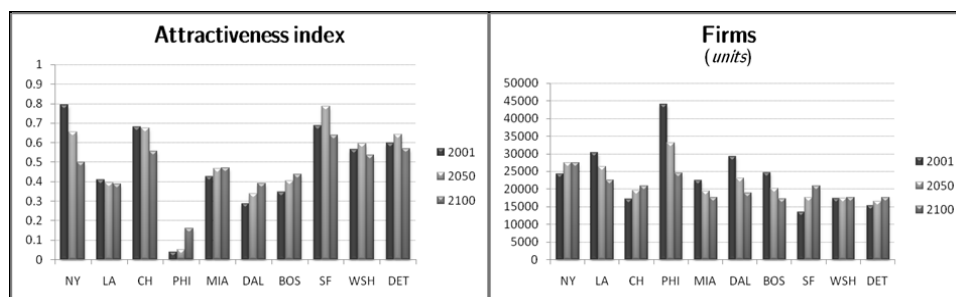


Figure 1: *Dynamic mechanisms of the urban market in terms of agglomeration attractiveness (left) and firm migration (right).* [Source: IMACLIM-R modeling outcome based on US Census Bureau (2000) data]

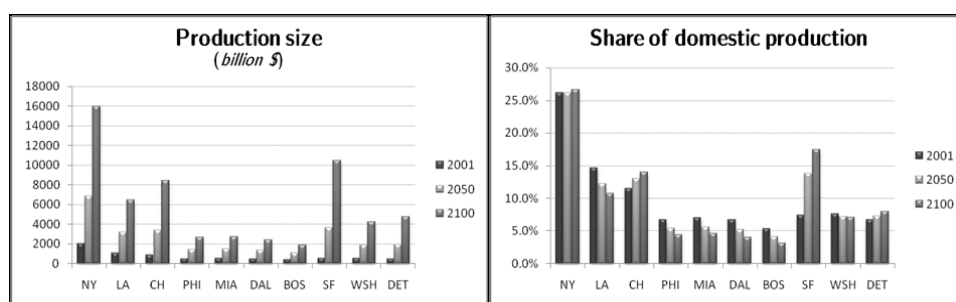


Figure 2: *Long-run domestic production size and pathways of production share allocation across cities.* [Source: IMACLIM-R modeling outcome based on US Census Bureau (2000) data]

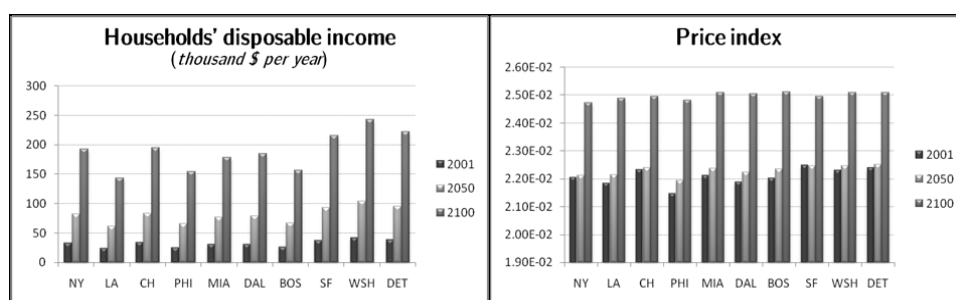


Figure 3: *Impact of urban development on onsumption behavior through households' income (left) and price index (right).* [Source: IMACLIM-R modeling outcome based on US Census Bureau (2000) data]

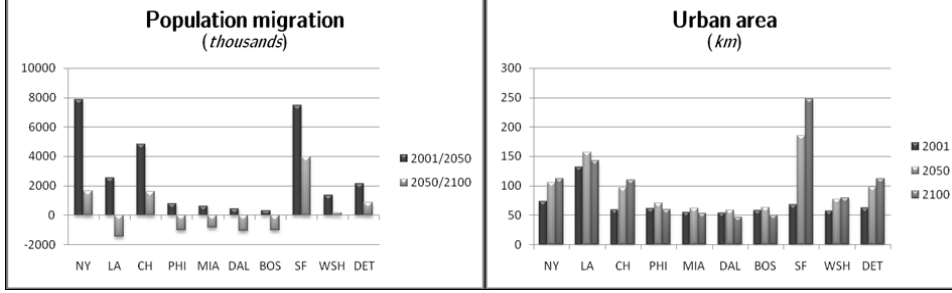


Figure 4: *Spatial development patterns of cities through population dynamics (left) and urban land area (right).* [Source: IMACLIM-R modeling outcome based on US Census Bureau (2000) data]

d_j , which is a proxy for the extension of the urban land area. The size of a given city evolves proportionally to the urban population L_j in this BAU scenario. This is due to the assumption of constant average density in each agglomeration throughout the time period considered. Analyzing population migration flows shows that on the one hand constant population growth path occurs for certain cities (New York, Chicago, San Francisco and Detroit); on the other hand, long-term population is found to decrease for the remaining ones (see figure 4). This last result makes sense as the first group of cities experience a strong increase in the share of domestic production and therefore in their labor force requirement. Given our assumption on homogeneous density of the BAU agglomerations, New York, Chicago, San Francisco, and Detroit turn out to grow proportionally more than the others.

B *Macroeconomic effect of urban policies*

The US government decides to support densification policies at the city scale that have the goal of reducing domestic dependence on energy import through lowering the need of transport. This type of policy takes the form of increased urban density in the 20 largest US cities. We test the effect of the densification policy strategy on domestic and global macroeconomic setting through studying its impact on US national income and on global CO₂ emissions, respectively. From a modeling standpoint, this exercise is carried out by forcing an increasing trend on average urban density instead of assuming it constant as it is the case in the BAU scenario (see previous sub-section). Increased urban density influences the general equilibrium through reduced travel demand. For the sake of simplicity, we consider a 25% increase of density for all agglomerations between 2010 and 2060, which corresponds to a moderate densification rate of 0.45% per year. We abstract from any welfare effect of increasing density. This is no shortcoming as we focus on carbon emissions that create external costs, which in turn harm social welfare.

Investments that are necessary to implement the densification policy enter

the general equilibrium computation as the reduced external costs the policy induces. A five-year delay is assumed between the time at which investments are set in operation and their actual effect on the urban structure.

First we focus on the impact of increasing density on the use of automobile, which with its 90% of modal share represents the most important travel mode used for commuting purpose in US. Our findings reveal a beneficial action of the policy measure in that it induces a reduction of carbon emissions by automobile displayed in figure 5. Our model predicts that the overall effect of a 25% densification leads to 2% reduction of global CO₂ emissions from car use in 2100, passing through a 2.7% reduction in 2060.

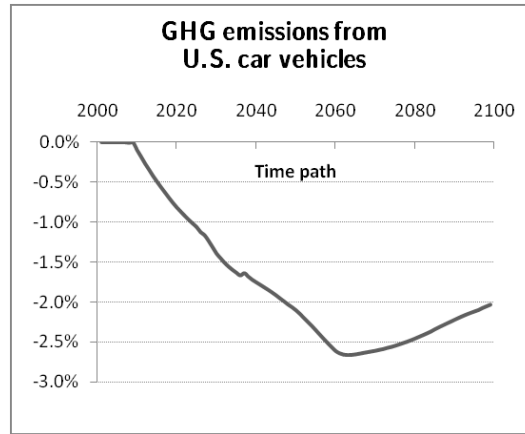


Figure 5: *Reduction of CO₂ emissions from the automobile sector due to infrastructure policy at the urban scale.* [Source: IMACLIM-R scenario analysis]

The drivers of a variation in carbon emissions from the transportation sector can be analyzed through what in the climate change literature is known as the “Kaya identity”:

$$\text{Emissions} = \frac{\text{Emissions}}{\text{Energy}} \cdot \frac{\text{Energy}}{\text{Transport volume}} \cdot \text{Transport volume}$$

The above relation decomposes emission changes into components related to carbon intensity (in turn associated to the primary energy mix of liquid fuel production by oil, biomass, and coal), energy efficiency of vehicles (resulting from technical change) and transport volume (measured in physical quantities, namely passenger-km).

Figure 6 shows relative variations of the three components of the Kaya identity when an densification policy aimed at increasing urban density is set in place. Expectedly, the major impact of such a policy measure occurs through a reduction of the total volume of transport (measured in passenger-km) due to a decrease in average commuting distance by individuals in denser

agglomerations (around 2.6% reduction with respect to BAU case). However, indirect effects also simultaneously occur that affect carbon intensity and vehicle unitary fuel consumption in the long run. In particular, the decrease of liquid fuel demand due to a decrease in the average commuting distance, endogenously generates a fall of liquid fuel prices. This in turn slows down technical change towards more energy-efficient vehicles (modeling findings show that automobile vehicles are 0.40% less efficient in 2100), which ultimately causes the CO₂ emissions from car to raise of another 0.6% in the period 2030-2100 up to the final level of 2%.

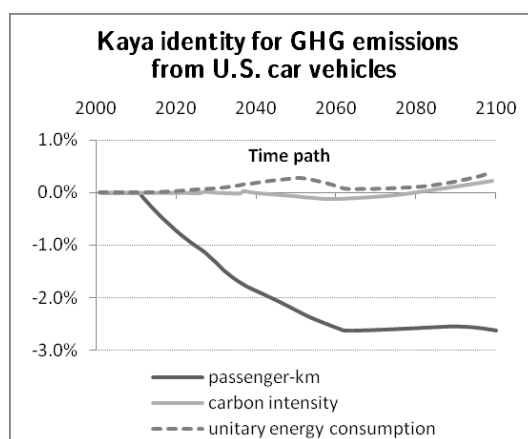


Figure 6: *Kaya decomposition of CO₂ emissions from U.S. car vehicles.* [Source: IMACLIM-R scenario analysis]

The positive net effect of density on carbon emissions from cars is only partially offset by a simultaneous increase of emissions from other transport modes that is due to modal shift. In particular, our findings show that increasing density stimulates modal shift towards less energy-intensive travel modes. As a consequence, carbon emissions from public transport means are found to increase by 4% in 2100 (results for this analysis are not included here).

Results for the role of spatial policy measures on carbon emissions from the transportation sector and from all sectors of the US economy are reported in figure 7, left and right panels, respectively. As a general insight, it is found that long-run emissions from transport may be higher if a densification policy is implemented. This counter-intuitive outcome is a consequence of underlying general equilibrium mechanisms. Indeed, the reduced travel demand by automobile pushes down the consumption of liquid fuels and, hence, their price due to release of market tensions. The associated fall of transport cost finally stimulates a rise in transport activity, which in turn tends to offset the direct reduction of emissions from automobile induced by a 25% increase in urban density (see figure 5). Figure 7 (right panel) shows that this indirect effect may be dominant in the long run and induce an overall increase of emissions.

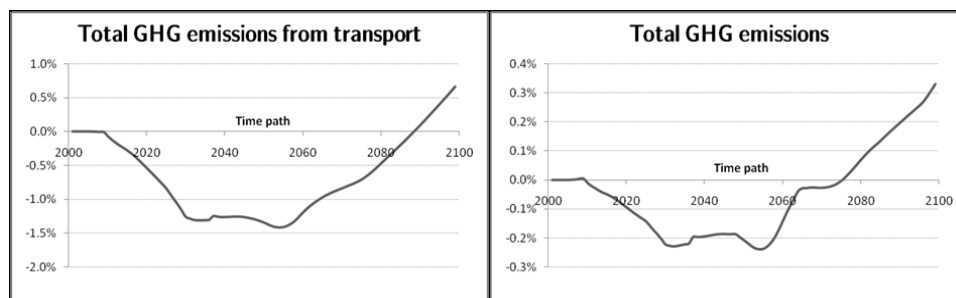


Figure 7: *US trend for CO₂ emission from the transportation sector (left) and all sectors of the economy (right).* [Source: IMACLIM-R scenario analysis]

The trend for global total emissions (figure 7, right panel) is of course similar but generally more diluted. This is due to the effect of other energy-intensive economic sectors which are affected but indirectly (i.e. through prices rather than quantities) by a spatial policy at the urban scale.

Next, the macroeconomic impact of setting in operation the densification policy is studied. This is done through analyzing the long-run path of US total and sectoral GDP. The trend for US total domestic income under densification policy scenario is studied with respect to the baseline one. Figure 8 reports results for this analysis.

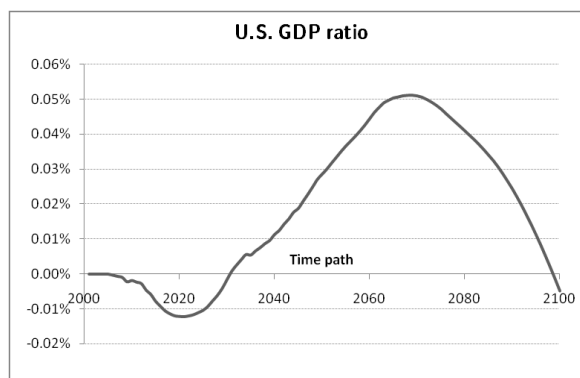


Figure 8: *Ratio of US GDP under infrastructure policy scenario to baseline US GDP.* [Source: IMACLIM-R scenario analysis]

As it is shown, in the first 30 years of the set in operation of the densification policy, early investments are responsible for losses in the overall economic activity, especially since a five-year delay is assumed before investments start to operate effectively on urban density.

In 2060, the densification process is ultimated, no additional investment is required, and the economy starts benefiting from the full advantages of the densification policy through a reduction of urban external costs. This

gives rise to a 65-year period during which the US GDP increases because of the beneficial effect of increased urban density in reducing national energy demand. In particular, up to the year 2060 and increasing-rate growth is envisaged for the US economy. In the last five years of our time period simulation, this positive trend is expected to reverse. Main reason to that is the over-time decreasing trend of the price of energy due to fall in the energy demand, which is expected to slow down technical change and raise significantly the energy intensity. This indirect effect of the densification policy becomes dominant in the last time period of the simulation, jeopardizing the initially beneficial economic impact. Additional measures (like e.g., direct regulation for carbon emissions from vehicles) may be envisaged that can correct for the negative effect of a rapid fall in energy efficiency due to low energy demand.

A sectoral analysis of the impact of densification enables further insights for the comprehension of the underlying mechanisms through which the macro-economy is affected. We consider the IMACLIM-R 12 sectors of the world economy. Figure 9 presents results for the impact of the spatial policy on four sectors of the US economy, the remaining 8 being affected only marginally (within 0 and 0.5% of a variation in the GDP between the two scenarios has been found). These are all related to the US transportation sector.

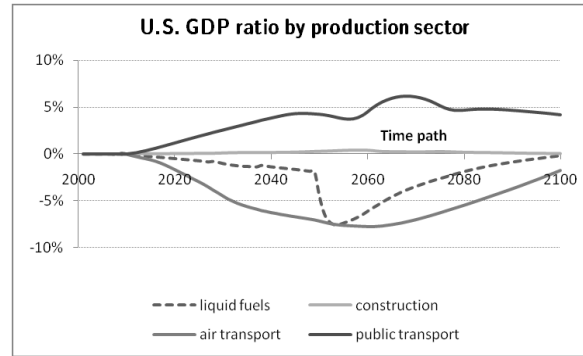


Figure 9: *Ratio of US GDP under infrastructure policy regime to baseline US GDP for four sensitive IMACLIM-R sectors.* [Source: IMACLIM-R scenario analysis]

As it is shown, production of liquid fuels is negatively affected by a change in the spatial structure. This is logic consequence of the decrease in the use of car when density increases. Public transport and air transport show opposite trends. The increasing trend of the public transport is due to individuals' preference towards cheaper and slower transport modes when car use drops and travel distances (and time) are shorter. The sharp increase of air transport in the second part of the period is stimulated by the overall lower price of liquid fuels under the densification scenario than in the BAU one, which acts as a strong incentive for this energy-intensive mode.

Finally, the implementation of the spatial policy at the urban scale requires

additional public investments on buildings and transport. Hence, it stimulates the activity of sectors involved in densification supply, among which construction plays a major role. This justifies the higher sectoral GDP for the construction sector.

C Cost off-setting effect of urban policies in the context of international climate policy

As we have demonstrated in the previous sub-section, a densification policy aimed at increasing urban density produces the net effect of reducing carbon emissions. Therefore, we can expect to act as a valuable complementary measure to carbon pricing schemes in the context of an ambitious climate policy. In this sub-section we test this. To investigate the role of urban densification policies in a carbon constrained world, we assume that an international climate policy is decided. For the sake of simplicity, we further assume that an agreement is reached among all countries to pursue the objective of a stabilization of CO₂ atmospheric concentration at 450ppm, which corresponds to a carbon budget of 520GtC for the period 2001-2100. Burden-sharing across countries is based on a “contraction-and-convergence” principle, which aims at homogenous emissions per capita in 2100. Two alternative climate policy scenarios are considered with identical goal in terms of carbon emissions. Scenarios differ regarding the implementation of a specific densification policy at the urban scale as part of the “policies and measures” adopted to complement carbon pricing. We are interested in investigating whether a densification policy is beneficial in this context. Results of the simulation show that this is globally the case (Figure 10).

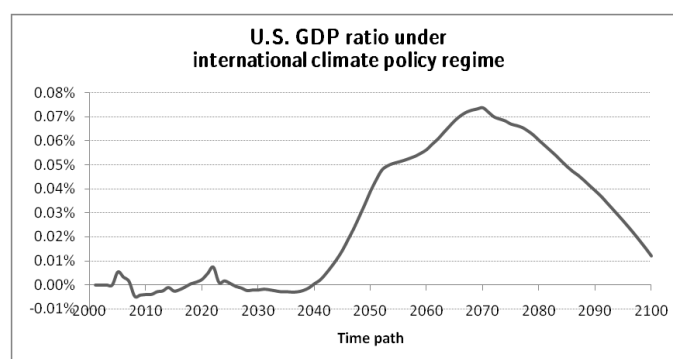


Figure 10: *Ratio of US GDP under infrastructure policy regime to US GDP under climate policy regime (e.g., carbon tax).* [Source: IMACLIM-R scenario analysis]

During the thirty-five first years, the densification policy has hardly any effect on the economic activity, early investments costs being compensated by the benefits of the densification process. This policy at the urban scale is

specifically important in a climate policy context, since it induces a decrease of commuting emissions and then makes a lower carbon price compatible with the threshold on emissions. This effect is dominant during the next 40 years and leads to a significant increase of the economic activity when a densification policy is carried out in urban areas as a complement of carbon pricing (around a 0.07% gain). In the last period, the densification policy becomes less beneficial in terms of economic activity as a result of its indirect effect on energy intensity of the economy.

V Conclusions

To summarize, this paper has presented a theoretical model in the light of the new economic geography (NEG) to explain the international policy community's claim of involvement of local governments (cities) in taking action against the global climate change. To provide better understanding of the feedback mechanism between urban, regional (country) and global (world) economies in the context of climate change, the model has been conceived to be driven in IMACLIM-R, a dynamic, multi-region, computable general-equilibrium model for international climate policy analysis. It differs from earlier work, which focused on a globally aggregated approach, by introducing production, consumption, trade and urban-related external costs for multiple cities within regions. Our study has allowed for regional economies where multiple urban agglomerations dynamically evolve and alternative configurations of city growth potentially emerge. This has been done in a simple analytical framework that enables to account for external (costs) benefits of land use and transport that reflect the (dis)economies arising from agglomeration. The spatial disaggregation of national into city economies is a major outcome of our research that goes beyond the scope of climate change analysis. Possible applications concern the field of public economics and finance, to analyze the macroeconomic consequences of interjurisdictional mobility under some jurisdiction-specific land-use versus income tax. This line of research is not pursued here but may prove fruitful in future studies.

In addition to allowing for spatial disaggregation of the national economy, our model has departed from the standard NEG approach in at least two ways: i) dynamics of cities is allowed through migration decisions of firms, whose location preferences go towards those urban agglomeration markets that offer the best investment opportunities. This in turn introduces a conceptual innovation of our model that better fits the modern structure of the production sector, where decisions are taken as a result of trade-offs between firms' profits and managers' and shareholders' interests; ii) the agglomeration spillover effect is endogenously modeled by breaking the duality of the production sector through inclusion of a third input factor of production, namely the intermediate consumption of goods. We consider intermediate consumption as subject to external economies of scale resulting from improved production process through some agglomeration-specific technology spillovers. This allows for

analytically capturing the Marshallian-Chamberlanian set of positive spatial externalities, whose formalization in the broad literature of urban economics and trade theory has proved to be difficult and controversial.

A specific study was carried out that accounts for the overall impact of the disaggregated US economy on the climate change. The study has considered the U.S. first 20 largest cities in terms of population. We have compared three different strategies for the control of global warming through spatial policy mechanisms: a market approach in which no climate change policies are taken; a domestic approach in which US country takes urban infrastructure (e.g., urban densification) policies to raise its own national income through switching from high- to low-intensive carbon economy; and a global international approach in which all countries choose climate-change policy action and the US only fosters additional densification policy that levies the burden of a carbon policy action. In the first baseline scenario, we assume that condition of constant average density in each urban agglomeration holds throughout the time path considered. In the last two scenario analyses, the densification policy is thought as one that increases actual degree of density by 25% in 50 years (until 2060), which is moderate.

We have provided some guiding intuitions as well as evidence from calibrated general equilibrium simulations that indicate that the spatial dimension of the economy matters in the climate change debate. General equilibrium results have shown that, first, in the business as usual (BAU) economy (market or uncontrolled scenario), the share of increasing-over-time production size is expected to be spread across the agglomeration proportionally to the number of firms operating in each agglomeration. This in turn provokes modifications in the consumption behavior of individuals. In particular, purchase power of households increases as their disposable income increases, whereas the cost of living in each agglomeration proves not to vary significantly over the time period considered.

Second, we have studied the effect of the densification policy strategy on domestic macroeconomic setting through studying the impact of increasing urban density on US national income. We have found that the major impact of such a policy occurs through up to 2.8% reduction of the total carbon emissions from transport due to a decrease in average commuting distance by individuals in denser agglomerations with respect to BAU case. Because of modal shift, the net benefit of increasing density amounts to a total of 1.8% of carbon emission reduction. When looking at the total benefit of a 25% increase in density in 2060, it is found that 0.35% reduction of cumulative CO₂ emissions from the overall US economy is reached. Next, we have studied the impact of setting in operation the densification policy on long-run path of U.S. GDP. In the first 30 years of the set in operation of the densification policy, early investments are responsible for losses in the overall economic activity, especially since a five-year delay is assumed before investments start to operate effectively on urban density. From 2030 to 2095 the economy is expected to benefit from the advantages of the densification policy via a

decrease of national demand to energy import. In the last five years of our time period simulation, this positive trend is reversed because of a fall in energy efficiency due to low energy demand. As a consequence, households consume less of the differentiated good and production falls, dragging down domestic income.

Third, we have investigated the cost-offsetting role of the urban densification policy in the context of a carbon constrained world where countries are committed to stabilization goal of CO₂ atmospheric concentration at 450ppm, which corresponds to a carbon budget of 520GtC for the period 2001-2100. Results have suggested a slow initial effect of urban density on the economic activity. Subsequently, the spatial policy becomes effective in decreasing commuting carbon emissions and thus making a lower carbon price compatible with the threshold on CO₂ emissions (around a 0.07% net gain in GDP). In the last period of the policy, the densification policy becomes less beneficial in terms of economic activity as a result of its indirect effect on energy intensity. More direct regulations of energy efficiency may prevent long-run decreasing (yet positive) trend of national income. These findings have indicated that there will be substantial efficiency in an densification policy that intervenes to complement emissions control policies by reducing its total cost, when a market price for carbon is available.

In sum, the results of this integrated modeling analysis of climate and the spatial economy have emphasized the implications of the fact that while climate change is a global externality, the decision makers can be local and relatively small. The inherent difficulties involved in planning over a horizon of a century about so uncertain and complex a phenomenon like climate change may be avoided by integrating the international with the regional and urban dimensions of climate change policy, where externalities that lie at the origin of the phenomenon arise. This would allow in turn curtailing the risk of free-riding by non-participants or outdrawing in any global agreement due to the high cost of the carbon price policy.

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Appendix

Here we provide the details of data calibration for the integrated modeling framework that has been developed in the paper. The twofold representation adopted in IMACLIM-R, both in money and physical flows, creates some important constraints on calibration. Indeed, it makes necessary to use a so-called ‘hybrid matrix’ including consistent economic input–output tables and physical quantities (Sands *et al.*, 2005). In the current version of the model, energy and transport sectors are described in explicit physical quantities (MToe and p-km, respectively). At the calibration date 2001, the equilibrium is obtained by combining macroeconomic data from GTAP 6, energy balances from ENERDATA 4.1 and the International Energy Agency (IEA) and data on passenger transport from (Schäfer and Victor, 2000). For each region, a set of macroeconomic variables corresponding to country-level averages in 2001 are obtained as a result of this calibration process. Among those variables, we find domestic production size $\overline{Q_C}$, production price $\overline{p_C}$, labor requirements for production $\overline{\Omega_C l_C}$, aggregate wage $\overline{w_C}$, price of intermediate consumption goods $\overline{p_C^Z}$, intermediate consumption requirements for production $\overline{Z_C}$ and total production capacity $\overline{K K_C}$. The model presented in this paper is calibrated to US data; since USA is a specific region of IMACLIM-R, national averages at the USA level are directly given for all those macroeconomic variables.

The disaggregate microeconomies at the urban scale and the aggregate macroeconomy of the IMACLIM-R equilibrium at the country scale are consistent if each variable appearing in both the scale description satisfies the condition: “the aggregation of microeconomic variables must equal the corresponding aggregate macroeconomic variable given in IMACLIM-R”. Given J agglomerations represented in USA, the condition on consistency sets that the set of equations listed in Table A1 must be verified.

TABLE A1: CONSISTENCY EQUATIONS WITH IMACLIM-R CALIBRATION DATA		
$\int_{j=0}^J n_j q_j dj = \overline{Q}_{US}$	\rightsquigarrow	Domestic production size
$\int_{j=0}^J X_j dj = \overline{K} \overline{K}_{US}$	\rightsquigarrow	Domestic production capacity
$\frac{\int_{j=0}^J p_j n_j q_j dj}{\int_{j=0}^J n_j q_j dj} = \overline{p}_{US}$	\rightsquigarrow	Market price of the composite good
$\frac{\int_{j=0}^J l_j n_j q_j dj}{\int_{j=0}^J n_j q_j dj} = \overline{l}_{US} \overline{\Omega}_{US}$	\rightsquigarrow	Labor requirement for production
$\frac{\int_{j=0}^J w_j l_j n_j q_j dj}{\int_{j=0}^J l_j n_j q_j dj} = \overline{w}_{US}$	\rightsquigarrow	Return to labor (aggregate wage)
$\frac{\int_{j=0}^J w_j l_j n_j q_j dj}{\int_{j=0}^J l_j n_j q_j dj} = \overline{Z}_{US}$	\rightsquigarrow	Intermediate good requirement for production
$p^Z = \overline{p}_{US}^Z$	\rightsquigarrow	Price of the intermediate consumption good

Next, we turn to detail the calibration process adopted for the urban module. Agglomerations correspond to the standard Metropolitan Statistical Area (MSA) classification as defined by the U.S. Office of Management and Budget (OMB). We restrict our analysis to the twenty largest agglomerations in terms of population: $J = 20$.⁴ The purpose of carrying out the calibration is to provide all the variables described in the urban model (see Section 3) with numerical values that may enable the economy at the baseline year to be representative of the reality, as required in CGE exercise. To do that, a set of empirical equations defining the main economic and spatial characteristics of the agglomerations considered is imposed. More precisely, each agglomeration is characterized by its population, size, production and wage. Population $\overleftrightarrow{Pop}_j$ and size \overleftrightarrow{d}_j are given by US Census Bureau (US Census Bureau, 2000). For production, the share of national output that is actually produced in agglomeration j , $\overleftrightarrow{\sigma}_j$ is derived from GDP at the metropolitan level provided by the Bureau of Economic Analysis (BEA, 2001). This ensures a distribution of economic activity coherent with empirical facts. Finally, wages play a central role in driving the urban economies, since it represents both households'

⁴ A Metropolitan Statistical Area is a geographic unit comprised of one or more counties around a central city or urbanized area with 50,000 or more population. However, since the urban module developed in this paper is relevant for large agglomerations in which the agglomeration effect is strong, we restrict our analysis to the largest agglomerations. In this sense, we are in line with the definition of OECD 'metropolitan regions', setting in particular a lower threshold at 1.5 million inhabitants (OECD, 2006). Restricting the analysis to the 20 largest agglomerations is not limiting since it is enough to capture more than half the total national production in terms of GDP.

income and a production cost for firms. In order to represent realistically the differences in terms of wealth and labor costs, wages in agglomeration j are derived from personal income data in (BEA, 2007). Since the average wage value is imposed by IMACLIM-R, as it is made clear in the fourth equation in Table A1, only relative wages \overleftrightarrow{w}_j across agglomerations are imposed (without loss of generality, we consider the largest agglomeration, namely New York, as the reference agglomeration).

Table A2 gives the numerical value of those four variables for the first ten agglomerations. To ensure that the empirical values listed in table A2 actually correspond to the calibration values of the associated variables, the equations listed in Table A3 must be satisfied for each agglomeration j .

TABLE A2:
EMPIRICAL CHARACTERISTICS OF THE TEN BIGGEST US AGGLOMERATIONS

MSA	Label	Population (<i>thousands</i>)	City size (<i>km</i>)	Production share (%)	Relative wage (<i>index</i>)
New York	NY	21199	73	19.0%	1
Los Angeles	LA	16374	132	10.7%	0.81
Chicago	CH	9157	59	8.4%	0.85
San Francisco	SF	7039	61	4.9%	1.17
Philadelphia	PHI	6188	55	5.1%	0.89
Boston	BOS	5819	54	4.9%	1.03
Detroit	DET	5456	58	3.9%	0.80
Dallas	DAL	5221	68	5.4%	0.82
Washington	WSH	4923	57	5.6%	1.07
Miami	MIA	3876	40	3.8%	0.83

Note: Data source: US Census Bureau, 2000.

TABLE A3:
EMPIRICAL EQUATIONS ON CITY CHARACTERISTICS

$Pop_j = \overleftrightarrow{Pop}_j$	\rightsquigarrow	Population
$d_j = \overleftrightarrow{d}_j$	\rightsquigarrow	City size
$\frac{n_j \overleftrightarrow{q}_j}{\int_{j=0}^J n_j \overleftrightarrow{q}_j dj} = \overleftrightarrow{\sigma}_j$	\rightsquigarrow	Production share
$\frac{w_j}{w_1} = \overleftrightarrow{w}_j, j \neq 1$	\rightsquigarrow	Relative wage

The calibration of the urban model is then obtained by simultaneously satisfying the equations characterizing the urban economies as described in section 3, and equations listed in Table A1 and Table A3, ensuring respectively consistency with the macroeconomic equilibrium and a reliable representation of major empirical characteristics of the agglomerations.