Supplementary Material

1. Methods

1.1. Imaclim-R modeling framework

The Imaclim-R model (Sassi et al., 2010; Waisman et al., 2012a) is a multi-region and multi-sector model of the world economy. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. Furthermore, it describes growth patterns in second best worlds with market imperfections, partial uses of production factors and imperfect expectations. An extended description of the model is available at http://www.imaclim.centre-cired.fr/IMG/pdf/imaclim_v1.0.pdf; and details about the model structure and results, with respect to various aspects: energy technologies, energy efficiency, fossil fuels, macroeconomy, can be found in the publications listed in table 1.

The model is calibrated on the 2001 base year by modifying the input-output tables provided by the GTAP-6 dataset (Dimaranan and McDougall, 2006) to make them compatible with 2001 IEA energy balances (in Mtoe) and data on passengers' mobility (in passenger.km) from Schafer and Victor (2000). Technically, the model can be labelled as a recursive dynamic simulation framework, since it generates an energy-economy trajectory by solving a sequence of yearly static equilibria of the economy, interlinked by dynamic modules. The recursive structure organizes a systematic exchange of information between a top-down annual static equilibrium providing a snapshot of the economy, and bottom-up dynamic modules providing information on the evolution of technical parameters between each annual equilibria

The static equilibrium represents short-run macroeconomic interactions at each date t under technology and capacity constraints. It is calculated assuming Leontief production functions with fixed intermediate consumption and labor inputs, decreasing static returns caused by higher labor costs at a high utilization rate of production capacities (Corrado and Mattey, 1997) and a fixed mark-up in non-energy sectors. Households maximize their current utility through a trade-off between consumption goods, mobility services, and residential energy uses considering fixed end-use equipment. Market clearing conditions can lead to partial utilization of production capacities given the mark-up pricing and the stickiness of labor markets. This equilibrium provides a snapshot of the economy at date t in terms of relative prices, wages, employment, production levels, and trade flows. Dynamic sub-modules are reduced forms of bottom-up models that represent the evolutions of household equipment and technical characteristics of productive capacities between t and t+1. They include technology explicit descriptions of the energy system (power generation, vehicles, etc.) and endogenous technical change mechanisms (learning-by-doing, induced energy efficiency). A description of these sub-modules is available in Waisman et al. (2012a).

In the Imaclim-R model, GDP is endogenous. The growth engine is composed of exogenous demographic trends (total population growth and active population growth) and exogenous trends of labor productivity, as in Solow's neoclassical model of economic growth (Solow, 1956). To build these labor productivity trends we draw on stylized facts from the literature, in particular

	Description of Imaclim-R structure and results	Models comparison (including Imaclim-R)
Technologies	Bibas and Mejean (2014) (bioenergy)	Kim et al. (2014) (nuclear) Koelbl et al. (2014) (CCS) Krey et al. (2014) Kriegler et al. (2014) Luderer et al. (2014) (renewables) Rose et al. (2014) (bioenergy) Tavoni et al. (2012)
Energy efficiency	Bibas et al. (2015)	Sugiyama et al. (2013)
Fossil fuels	Rozenberg et al. (2010) Waisman et al. (2012b) Waisman et al. (2013a)	Bauer et al. (2015) McCollum et al. (2014)
Transport	Waisman et al. (2013b)	
Macroeconomy	Crassous et al. (2006) (endogenous structural change) Guivarch et al. (2011) (labor markets)	
Evaluation of model	Guivarch et al. (2009) (backcasting)	Kriegler et al. (2015a) (diagnostics)
Scenarios	Guivarch and Mathy (2012) Hamdi-Cherif et al. (2011) Mathy and Guivarch (2010) Rozenberg et al. (2014) Waisman et al. (2014)	Blanford et al. (2014) Kriegler et al. (2015b) Luderer et al. (2012b) Luderer et al. (2012a) Riahi et al. (2015)

Table 1: Selection of peer-reviewed articles with Imaclim-R

the convergence assumption (Barro and Sala-i Martin, 1992) and two empirical analyses on economic convergence, one investigating past trends by Maddison (1995), and another one by Martins et al. (2005) looking at future trends. We retain a leader economy, the US, whose labor productivity growth trend is exogenous and for which alternatives can be investigated (see next section). The trends in labor productivity of the other regions catch up with the leader's over time, i.e. their growth in labor productivity is higher the further their level of absolute labor productivity is from the leader's. All sectors within one region exhibit the same growth in labor productivity, while the respective initial levels are sector and region specific. The two sets of assumptions on active population growth and labor productivity growth describe natural growth, i.e. the growth rate that an aggregated one-sector economy would follow under full employment of factors of production. In the multi-sectoral framework of Imaclim-R, with partial use of factors of production, the effective economic growth rate may depart from the exogenous natural growth rate trend. The structure and rate of realized growth are endogenously determined by: (i) the allocation of labor force across sectors, which is itself governed by the final demand of these sectors, and (ii) the evolution in unemployment rates, which also results from the final demand of these sectors and the constraints of installed productive capacities and their technical characteristics.

In the model, structural change and technical change are also endogenous, and induced by relative price movements. It can be influenced exogenously by the potentials for new technologies (e.g. maximum market share, learning rates...) and the potentials for energy efficiency (e.g. the reaction of energy input consumption to energy prices).

Households' consumption is determined by a utility function that includes basic needs. The evolution of these basic needs (e.g. housing, transportation) over time represents lifestyle evolutions.

1.2. Methodology to build an ensemble of scenarios

To construct an ensemble of scenarios, we identify the uncertain parameters that can have an impact *a priori* on scenarios outcomes, in terms of emissions and GDP in particular. We group them into seven parameter sets. The methodology is similar to that used in Rozenberg et al. (2014), with slightly different parameter sets (described in Table 2).

For each parameter sets, two or three alternatives are built with contrasted parameter values, as described below.

1.2.1. Productivity growth in the USA

In line with the SSP (Shared Socioeconomic Pathways, Nakicenovic et al. (2014))quantifications, we build three alternatives combining hypotheses on population growth and productivity growth for the leading region, US (see Table 3).

Exogenous population growth can take the values from either ssp5 (low population growth), ssp2 (medium population growth) or spp3 (high population growth), as quantified in the SSP database (https://secure.iiasa.ac.at/web-apps/ene/SspDb). Labor productivity growth can follow three alternative trends, all starting from a 2.3% growth in 2010 and decreasing to 1.65%, 1.4% or 1.2% in 2050, respectively in the high growth, medium growth or low growth assumptions.

- Productivity growth in the USA: evolutions of labor productivity growth and population growth in the USA - Productivity catch-up in other regions: catch-up speed towards the leader's labor productivity level and population growth in other regions - Rigidities in the labor markets: degree of rigidity in the labor markets - Energy demand behaviors: households' preferences and basic needs for transportation and living surfaces, freight content of the economy (a proxy for location choices) - End-use energy efficiency: parameters governing the evolution of energy input per unit of goods and services produced and its reaction to energy prices - Availability of low-carbon technologies: maximum potentials and learning rates for new generation of nuclear plants, renewables, CCS and electric vehicles - Availability of unconventional fossil fuels: costs and potentials of unconventional fossil fuels, such as shale oil and gas and coal-to-liquids

Table 2: Parameter sets

Productivity growth in the USA	Low	Medium	Fast
labor productivity growth	low	medium	high
population growth	ssp_3	ssp_2	ssp_5

Table 3: Parameters assumptions for leading region growth.

Productivity catch-up in other regions	Low	Medium	Fast
catch-up time (τ_2 in eq. 1, in years)	300	200	150
population growth	ssp_3	ssp_2	ssp_5

Table 4: Parameters assumptions for other regions growth.

End-use energy efficiency	High	Low	Mixed
Maximum annual improvement in the leader energy efficiency (%)	1.5	0.7	1.5 for OECD countries 0.7 for other countries
Other countries speed of convergence (% of the initial gap after 50 years)	10	50	10 for OECD countries 50 for other countries
Asymptotic level of catch-up (% of the leader's energy efficiency)	95	60	95 for OECD countries 60 for other countries

Table 5: Parameters assumptions for end-use energy efficiency.

1.2.2. Productivity catch-up in other regions

The trends in labor productivity of the other regions catch up with the leader's over time, i.e. their growth in labor productivity is higher the further their level of absolute labor productivity is from the leader's. All sectors within one region exhibit the same growth in labor productivity, while the respective initial levels are sector and region specific.

Equation 1 represents labor productivity catch-up:

$$\dot{l}_{t,j} = e^{-\frac{t}{\tau_1}} \cdot l_{t_0,j} + \left(1 - e^{-\frac{t}{\tau_1}}\right) \cdot \left[\frac{t}{\tau_2}\left(l_{t,j} - l_{t,leader} + \dot{l}_{t,leader}\right)\right] \tag{1}$$

where $l_{t,j}$ is the unitary labor input in each region j and at each time step t, $l_{t_0,j}$ is the unitary labor input in each region j at calibration year, $l_{t,leader}$ is the unitary labor input in the leading region and $\dot{l}_{t,leader}$ the decrease of labor input in the leading region.

Labor productivity catch-up assumptions are combined with assumptions on population growth (see Table 4).

1.2.3. End-use energy efficiency

In each sector, the country with the lowest energy intensity is the leader and its energy efficiency is triggered by energy prices. The other countries catch-up with the leader after a delay. We build three hypotheses (see Table 5) using the following parameters: maximum annual improvement in the leader's energy efficiency, other countries' speed of convergence (% of the initial gap after 50 years) and asymptotic level of catch-up (% of the leader's energy efficiency).

1.2.4. Energy demand behavior

For energy demand behaviors, we build two assumptions using parameters that describe (a) development patterns in transport, housing and industrial goods consumption and (b) location patterns.

Development patterns

Transport

In each region, the motorization rates increase with per capita income through variable income-elasticity η_{mot}: (a) low for poor households whose access to mobility relies on non-motorized and public modes; (b) high for households with a medium per capita income (c) low again, because of saturation effects, for per capita income level comparable to that of the OECD. We make two hypotheses on these parameters, representing the evolution of preferences (see Table 6).

Buildings

Housing surface per capita has an income elasticity of η_H, and region-specific asymptotes for the floor area per capita, h_{max}. This limit reflects spatial constraints, cultural habits as well as assumptions about future development styles. To account for different development patterns, we make two hypotheses on η_H and h_{max} (see Table 6).

Industrial goods

The progressive switch from industry to services is controlled by saturation levels of per capita consumption of industrial goods (in physical terms, not necessarily in value terms), via asymptotes at levels equal to $\kappa_{ind,i}$ multiplied by 2001 consumption levels in each region i. We make two hypotheses on these parameters to represent alternative assumptions about the evolutions in consumption preferences (see Table 6).

Location patterns: freight content of economic growth

In the freight sector, total energy demand is driven by freight activity, in turn depending on the level of economic activities and their freight content. This freight content correspond to the freight requirement to produce goods and services, which depend on the location of activities and supply-chains organizations. In the model, it is represented by the input-output coefficient of freight sector intermediate consumption by productive sectors. We build two alternative evolutions of the input-output coefficient representing the transportation requirement per unit of good produced (see Table 6).

1.2.5. Availability of low carbon technologies

In the IMACLIM-R model, technologies penetrate the markets according to their profitability, but are constrained by a maximum market share which follows a 'S-shaped curve' (Grubler et al., 1999). We consider two alternatives for each group of technologies. The high availability assumption corresponds to a higher maximum market share, and faster diffusion than under the low availability assumption. Moreover, for some new technologies, there is an endogenous learning mechanism: the cost of the technology is reduced with the cumulative investment in that technology. This mechanism is governed by a learning rate,

Life styles	energy-frugal	energy-intensive
Transport	Option 1	Option 2
Motorization rate growth with GDP per capita (η_{mot})	Values from IEA data (Fulton and Eads, 2004)	50% increase w.r.t Option 1 value
Buildings	Option 1	Option 2
Income elasticity of buildings stock growth (η_H)	0.7	1
Asymptote to surface per capita(h_{max}) (m^2)	40	60
Industrial goods	Option 1	Option 2
Households industrial goods consumption saturation level [min-max] (κ_{ind})	[1-2]	[1.5-3]
Freight content of economic growth	Option 1	Option 2
Input-output coefficient of transportation requirement per unit of good produced	decreases along with labor productivity growth in the composite sector and along with energy efficiency in the industry sector	Constant in all sectors

Table 6: Parameters assumptions for energy demand behaviors

Availability of low carbon technologies	High	Low
Nuclear (new generation)	Option 1	Option 2
Bottleneck phase (years)	15	
Growth phase (years)	75	
Maturation phase (years)	25	
Maximum market share at the end of the maturation phase (%)	30	0
Renewables	Option 1	Option 2
Bottleneck phase (years)	2	3
Growth phase (years)	20	65
Maturation phase (years)	15	25
Maximum market share at the end of the maturation phase (%)	60	50
Learning rate (%)	7	5
CCS	Option 1	Option 2
Bottleneck phase (years)	13	17
Growth phase (years)	8	8
Maturation phase (years)	8	8
Maximum market share at the end of the maturation phase (%)	80	30
Learning rate (%)	10	5
Electric vehicles	Option 1	Option 2
Bottleneck phase (years)	6	6
Growth phase (years)	40	40
Maturation phase (years)	16	16
Maximum market share at the end of the maturation phase (%)	80	25
Learning rate (%)	20	10

Table 7: Parameters assumptions for low carbon technologies

and two alternative values are considered for this learning rate. The values of parameters are given in Table 7.

1.2.6. Availability of unconventional fossil fuels

We describe price formation on the world coal market in a reduced functional form linking variations in price to variations in production. This choice allows to capture the cyclic behaviour of this commodity market. Coal prices then depend on current production through an elasticity coefficient η_{coal}: tight coal markets exhibit a high value of η_{coal} (i.e the coal price increases if production rises). We make two hypotheses for η_{coal} (see Table 8).

The unconventional liquid fuels (gas to liquids, coal to liquids, heavy oils, etc.) enter the markets when they become competitive compared to conventional liquid fuels. Their prices results from the sum of the associated non-refined energy carrier price plus a capital cost (given as a ratio to the non-refined

Availability of unconventional fossil fuels	Low	High
Coal	Option 1	Option 2
Price growth elasticity to production variations (η_{coal})	2	1.5
Unconventional liquid fuels	Option 1	Option 2
margin applied to the production cost	0.4	0.3
ratio between capital cost and energy cost	1.5	1
ratio OM cost and energy cost	1.7	1.5

Table 8: Parameters assumption for unconventional fossil fuels

energy price) and an operation and maintenance cost (given as a ratio to the non-refined energy price), with a margin applied to all costs. We make two hypotheses for the costs ratios and margins (see Table 8).

1.3. Discussion of limitations

All modeling exercises imply simplifications and assumptions, this one is no exception to this rule. The main limitation of the Imaclim-R model is that it does not account for damages caused by climate change. Including damages would make the point made in this paper no longer valid, since a balancing of mitigation costs with benefits would then be represented. But the possibility of doing so is precisely what is increasing called into question, because estimates of damages than can be caused by climate change are highly uncertain and possibly in the realm of the unknowable (Dietz, 2012; Koomey, 2013; Pindyck, 2013).

The choice of parameters sets and the alternative values also imply some limitations. Other sets or combinations might be relevant to investigate. Obviously, the impact of an uncertain driver on the results depends on the numerical assumptions behind each state of the driver. The more contrasted the alternative assumptions on a parameter, the more variance the parameter set creates on the results. Also, the bigger the parameter set (the more parameters in the set) the more variance it is likely to create on the results. The results may also be specific to the model used, in which there are strong feedbacks between energy systems and economic growth.

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