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Macroeconomic modelling of electrified mobility systems in 2030 European Union

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Abstract

This working paper details in 3 sections (*i*) the data collection and treatment that were necessary to apply IMACLIM-P to a 28-country European Union (EU); (*ii*) the particulars of a version of IMACLIM-P dedicated to a prospective outlook on the penetration of electric passenger cars in the EU, including how results of the PAN-EU TIMES model of energy systems can be imported in IMACLIM-P, together with the complete set of equations of the model; (*iii*) model implementation.

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1 Introduction

This working paper details in 3 sections (*i*) the data collection and treatment that were necessary to apply IMACLIM-P to a 28-country European Union (EU); (*ii*) the particulars of the version of IMACLIM-P that will be applied to a prospective outlook on the penetration of electric passenger cars in the EU, including how results of the PAN-EU TIMES model of energy systems will be imported in IMACLIM-P, together with the complete set of equations of the model; (*iii*) model implementation.

2 Data mining and data treatment: a hybrid energy-economy description of EU28

Energy-economy-environment (E3) prospective modelling strongly developed in the early 1990's, when increasing evidence of the role of carbon emissions on global warming prompted looking into the mid- to long-term future of economic activity and its energy and carbon intensities. Among other modelling tools, computable general equilibrium models were applied to the task, in standard form, *i.e.* calibrated mainly if not solely on national accounting data. Early on, some modellers expressed concerns about manifest discrepancies between national accounting data and detailed price and quantity data of energy vectors (Rutherford and Paltsev, 2000; Sands, 2005): the numerous, ill-documented data treatment processes that are necessary to produce balanced macro-economic accounts can substantially distort raw data, particularly that concerning relatively small economic sectors as the energy sectors, if these are not specifically controlled. What is more, the economic activity of such sectors does not limit itself to the production, transport and distribution of energy but extends to numerous service activities within and indeed beyond the energy markets. Using such uncontrolled data as the basis of prospective analysis comes at the risk of biasing modelling results. This accounts for the effort devoted to data collection and treatment as presented in the following subsections. These in turn address the macroeconomic and energy dimensions of the problem, then their 'hybridising' into one consistent model-oriented dataset.

2.1 Macroeconomic data

Most of the macroeconomic data necessary to computable general equilibrium modelling is handily summarised in an input-output table completed with details on the end-uses of the different products and the value-added embedded in them. When devoting particular attention to trade issues, as our research programme requires, specific information on the split between consumptions of the domestic and imported varieties of goods for each use of each good, is also welcome. Our main source for this information about the European Union is the EUROSTAT database. EUROSTAT compiles aggregate EU27 input-output tables detailing over 60 products and extending to the split between domestic and imported consumptions for all uses, for years ranging from 2000 to 2011. We eventually retained the year 2007 as calibration year considering the availability of both macroeconomic and energy balance data (*cf. infra*).

In the collection of macroeconomic data, a first unexpected difficulty stemmed from the shift by EUROSTAT from CPA 2002 to CPA 2008 nomenclature between years 2007 and 2008. In the process, the coal and the oil and gas mining industries were merged into a mining and quarrying sector extending to non-energy minerals. This, together with the availability of a 2007 input-output table for Croatia in the GTAP database, prompted us to settle on a 2007 calibration year.[1]

A second unexpected difficulty (and a major cause of delay in our research programme) is that the EU27 input-output table provided by EUROSTAT reports transactions “at basic prices”, *i.e.* at production prices net of both trade and transport margins and taxes or subsidies on products. Modelling of the producers’ and the consumers’ trade-offs rather requires tracking transactions “at purchasers’ prices” by aggregating such margins and taxes to each intermediate or final consumption. But EUROSTAT does not provide the “valuation matrix” that would allow switching from one valuation to the other, at the aggregate EU27 level. Member State (MS) data, however, provide use matrixes at purchasers’ prices. We thus had to add up the use matrixes at purchasers’ prices of 24 MSs to approach an aggregate EU27 use matrix.[2] We then adjusted the resulting matrix,

- Scaling up or down each column to match the total consumptions at purchasers’ prices of each production as reported in the available EU27 matrix at basic prices.[3]
- If required, scaling up or down lines of the matrix, to guarantee that the total uses at purchaser’s prices of each good exceed the sum of their total uses at basic prices, as reported in the available EU27 matrix, and the sum of their MS-specific trade and transport margins, as available for 24 MSs.[4]
- For all productions other than trade or transport, if required, substituting uses at basic prices to the computed uses at purchaser’s prices, to guarantee that uses at purchaser’s prices are systematically equal or greater than uses at basic prices—i.e. that all non-transport non-trade uses support a positive net sum of trade & transport margins and product taxation.

These 3 sets of corrections were enforced iteratively until the 3 underlying sets of conditions (on lines, columns and individual cells) were simultaneously observed. This corrected discrepancies (between the sum of MS data and the EU27 aggregate) ranging from -4% to +5% for intermediate uses, from -0.3% to +1.6% for final uses. Lastly, we crossed the resulting EU27 use matrix at

[1] Another advantage of calibration on 2007 rather than on later years is to avoid embarking any statistical bias linked to the global financial crisis erupting in 2008.

[2] The missing data is that of Bulgaria, Malta and Portugal.

[3] A matrix “at basic prices” measures the uses (outputs) of each good at basic prices, but the resources, or inputs of each production, at purchaser’s prices. The sum of such resources, if not their distribution between productions, can be used to reconstruct a full matrix at purchasers’ prices.

[4] Again, the missing data is that of Bulgaria, Malta and Portugal.

purchasers' prices with the available EU27 supply table at basic prices, to compute the required EU27 symmetric input-output table at purchaser's prices.

On July 1st, 2013, Croatia joined the European Union as its 28th Member State. With a population and GDP less than respectively 1% and 0.4% those of EU27, Croatia weighs little in the ensemble. The impact of extending our analysis to it is presumably marginal. For the sake of comprehensiveness we nevertheless devoted extra effort to such an extension. Regretfully indeed, at the time of our data collection EUROSTAT did not yet propose tables for its latest Member State (MS). We thus had to combine its EU27 data with data from another source, namely the GTAP world input-output table dataset.[5] The 8th version of this dataset provides harmonised 2007 57-sector tables for 134 countries and regions, among which Croatia. We only had to change its 2007 dollar monetary unit to 2007 Euros. Rather than resorting to supplementary exogenous data on average exchange rates, we did this in the simplest possible way, *prorata* the 2007 Croatian GDP as reported by EUROSTAT.

We could then combine the EU27 and Croatian tables to produce our original EU28 table. The process, operated on sectors aggregated enough to bridge the 2 slightly different nomenclatures (*cf. infra*), is a simple addition for most components of the table. Trade however requires particular attention. Summing up the imports and exports of both accounts must indeed be corrected by whatever bilateral trade is happening between EU27 and Croatia: from an EU28 perspective this trade is merely domestic consumption and should be depicted as such. To avoid a tedious compilation of bilateral trade statistics at MS level, we approximated the correction needed by considering how the share of imports evolves for each good and use from an EU27 to an EU28 aggregate according to GTAP;[6] we applied the correction factor specific to each good and use to the shares of our EUROSTAT EU27 table, to define the shares applying to our aggregate EU28 table. These we could apply to the straightforward addition of our EU27 and Croatian tables for all goods and uses but exports—which we indeed needed to reassess. To do so:

- For each good, we summed up the consumptions of its imported variety across all uses except exports, correcting for consumption taxes when appropriate *i.e.* for the final consumptions by households, public administrations and investment. For each product this provided us with a value for total imports, 're-exportations' excluded (both GTAP and EUROSTAT indicate that non-negligible shares of the imported varieties of most products end up being exported).
- From the use/resource balance of each good, on which re-exportations do not play, we deduced the amount of exports net of re-exportations.
- From this latter amount and the targeted shares of the imported varieties in exports we deduced re-exportations.

This whole processing was conducted on tables with a **sectoral aggregation** matching our modelling needs—which were agreed upon after discussion with the consortium: from the 61 sectors of our original EUROSTAT tables, we retained

[5] *Cf.* https://www.gtap.agecon.purdue.edu/default.asp.

[6] The correct treatment of bilateral trade in GTAP aggregations is a development that was performed at CIRED (Hamdi-Cherif and Ghersi, 2011).

- Fully disaggregated energy sectors, to allow tracking the substitution of electricity to conventional car fuels and its feedback effects. Regretfully enough, the CPA 2002 nomenclature used by EUROSTAT for 2007 accounts distinguishes 4 energy sectors only: “coal and lignite; peat” (sector 10); “crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying” (sector 11); “coke, refined petroleum products and nuclear fuels” (sector 23); “electrical energy, gas, steam and hot water” (sector 40). Section 2.3 below details how we used energy balance data to modify this aggregation into one more in line with our needs of interfacing with PAN-EU TIMES modelling.
- The “Electrical machinery and apparatus n.e.c. (not elsewhere counted)” sector (numbered 31), for the reason that it entails the manufacturing of car batteries. It obviously embraces much equipment other than car batteries, even if only considering its particular sales to the automobile industry. We however single it out to use its cost structure as an arguably acceptable proxy of that of car batteries—which we do want to specifically model, as they are the main source of discrepancy between the cost of the conventional and the electric car.
- The “Motor vehicles, trailers and semi-trailers” sector (numbered 34), obviously required considering our focus on automobile production. Similarly to the electrical machinery sector, it covers productions other than personal vehicles strictly speaking, but our intent is to use its cost structure as a proxy of that of conventional personal vehicles.
- Fully disaggregated transport sectors, to allow calibration on the PAN-EU TIMES model results in this regard, for the consistency of our joint prospective effort. This means the “land transport; transport via pipeline services” sector (numbered 60), the “water transport services” sector (numbered 61) and the “Air transport services” sector (numbered 62) are disaggregated from the composite remainder of economic activity.

Annex 1 reproduces the EU28 macroeconomic table to which we eventually arrived at this level of sectoral aggregation.

2.2 Energy volumes and prices

For energy volumes our main sources are detailed International Energy Agency (IEA) balances, which cover 63 products across 65 uses. The IEA provides tables for EU27 and Croatia, which we had to combine to produce one aggregate EU28 table. Similarly to the macroeconomic tables, the summing up of the two tables is a straightforward operation except as regards trade and international bunkers. While investigating the matter we discovered that the imports and exports of the EU27 aggregate by the IEA indeed do not correct for movements between MSs. Considering the small statistical weight of Croatia we opted for correcting the summed-up aggregates (imports, exports, marine and aviation bunkers) based on available EU27 data used in relative terms.

As regards genuine **imports and exports**, we first used EUROSTAT statistics on the shares of intra versus extra-EU27 imports and exports of energy products at a fairly disaggregate level.[7] Discrepancies arising from comparing intra-EU imports and exports of the same products, which by definition should match, were settled by evenly splitting the correction required between the 2 aggregates. For some products this rule could not apply because the correction thus computed superseded one of the non-corrected amounts; in this latter case the smaller of the two amounts was retained. However, a few months after implementing this method, and in the search of import and export price estimates, we discovered that the COMEXT database of EUROSTAT provides first-hand information on energy import and export flows; we thus decided to abandon the previous computations in favour of raw COMEXT data for the volumes of energy imports and exports. Our only amendment to COMEXT was a ventilation of the 5% of non-specified imports *pro-rata* the 95% specified ones; more precisely, we ventilated monetary imports in this way, then used the average prices of the explicit imports to derive volumes.

International bunkers posed a different, more complex problem. Contrary to energy statistics, national accounts do not treat fuelling operations geographically, *i.e.* depending on the destination of the transport operation that required fuelling. They rather consider the nationality of the transporter, *i.e.* treat the consumptions of EU-registered companies as intermediate consumptions of the transportation sector, and those of foreign companies as exports. The data to bridge the gap between those quite orthogonal logics is hard to find. We ended up treating air and sea transport differently. For air transport, we crossed an estimate by the European Commission of 4 litres kerosene per passenger kilometre (pkm) with pkm data from the Association of European Airlines (AEA) to compute total kerosene consumption for passenger transport by European airlines; then we crossed another AEA statistics on tonne-kilometres (tkm) of airborne freight with an average energy intensity of air freight established by the US. For water transport the lack of statistics forced us to an even cruder estimation: (*i*) we retained as average fuel price the average of the industrial price of heavy fuel oil and light fuel oil as reported by ENERDATA, weighted by the IEA share of heavy fuel and gasoil consumption in total (domestic navigation and international marine bunkers) water transport consumption; (*ii*) we acknowledged the 8.081 billion euro (coke and) petroleum products expenses of the water transport sector reported by EUROSTAT; this, crossed with our average price, produces a consumption volume that we split between gasoil and fuel oil according (again) to the observed share of each fuel in total water transport consumption.

Beyond these corrections linked to international trade, we performed a series of modifications of the resulting EU28 table:

- For each energy product, **statistical errors** were corrected by adjusting total uses and resources by the same amount—half of the reported statistical error; this amount was distributed between uses and resources *pro rata* the *ex ante* structures of uses and resources. In rare instances, this method could not be implemented because it would have brought total uses or resources below 0. In such cases the correction was entirely passed on the higher of the two totals.

[7] We also had to resort to data of the United States Department of Agriculture on biofuels.

- Similarly, **stock changes** were systematically absorbed, to bring the table in consistency with the exclusive flow approach of standard economic modelling. For the sake of simplicity, only the primary production and imports were modified, *pro rata* their *ex ante* weight in the available resource, to absorb stocks (increased to absorb positive stocks contribution, decreased to absorb stocks build up).[8]

- The **autoproduction of heat and electricity** does not appear in national accounts, where energy flows are only measured between firms, not within them. It consequently was "vertically integrated" by transferring the inputs of these autoproductions to the industrial sectors *pro-rata* their *ex-ante* final uses of such inputs—*i.e.* autoproduction of heat and electricity from some energy vector is assumed to be limited to the industrial users of this vector. The total heat and electricity consumptions of these sectors were cut down by the amount generated by autoproduction; this amount was distributed among sectors to replicate the distribution of the inputs to autoproduction (*i.e.* reflecting the *ex-ante* consumptions of the autoproduction inputs).

- The **transfers between refined petroleum products and primary hydrocarbons** resulting from the refining process are also outside the scope of national accounts. They were vertically integrated by a direct correction of the inputs and outputs of refineries.

- Finally, the **fuel consumptions of road transports** were disaggregated between households and firms consumptions—a distinction quite necessary to our economic modelling—based on 2010 shares of personal cars and two-wheelers in total fuel consumption by fuel type.[9]

The matrix derived from these procedures is a tentative energy balance of EU28 in a format compatible with national accounting, for disaggregated energy industries and 13 non-energy industrial aggregates including machinery, transport equipments, land, sea and air transport. It is only tentative because of one supplementary difficulty that required further data treatment through confrontation with the EUROSTAT national accounts data of section 2.1. This difficulty stems from the quite different notions of "transportation activities" in the energy balance *vs.* the national accounting framework.

From a fuel consumption point-of-view the "transport" end-uses of the energy balances embrace all fuel consumptions for public road, air and water transport, regardless of the economic agent involved. The corresponding consumptions thus range far beyond the consumptions of the transport services sectors in national accounts—notwithstanding households consumptions, which, as we already indicated, were separated from land transport consumptions by resorting to data from the Odyssee database (*cf.* footnote 9). The amounts at stakes are arguably negligible for air and sea transportation, for which energy consumptions are quite concentrated on those firms that provide

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[8] We thus shunned the difficulty of adjusting the production (transformation process) of refineries, which would have required a simultaneous adjustment of refineries inputs. For most refined products the ratio of stocks over imports is below 6% anyway, the only exceptions being gasoline type jet fuels (a quite marginal product) and non-specified oil products.

[9] Data from the Odyssee database, http://www.indicators.odyssee-mure.eu/energy-efficiency-database.html.

the corresponding transportation services.[10] But they cannot be ignored for land transportation, whose consumptions are spread across all production sectors. Crossing the reported (coke and) petroleum products expenses of the land transport sector of EUROSTAT with the average price of automotive diesel for commercial uses given by ENERDATA reveals indeed a fuel consumption of about 40% only of the total fuel consumption of land transportation. For lack of information, we affect the 60% remaining land transport consumptions to our aggregate composite sector, with the exception of a few MTOE attributed to the coal sector and the transport equipment sector following their EUROSTAT petroleum products expenses, which hint at much larger consumptions than the non-transport volumes reported by IEA (when priced as industrial light fuel oil following ENERDATA). Note that this massive correction in favour of our composite sector is partially validated by the fact that the consecutive, significant 60% increase of the petroleum products consumption of the composite sector (compared to uncorrected IEA data for the corresponding aggregate end-uses) brings the average price of this consumption, considering EUROSTAT expenses, much closer to the price of diesel for commercial use—prior to this correction the average price thus computed is much too high to make sense.

Conversely, from a sectoral point-of-view the “transport” end-uses of the energy balances are limited to vehicle fuel consumption strictly speaking, *i.e.* do not extend to the energy consumptions of all the commercial buildings mobilised to deliver transportation services. Such consumptions are rather aggregated in a “commercial and public services” end-use. Contrary to the question of fuel consumptions for transport purposes by non-transport sectors the amounts at stake are quite negligible. Still, for the sake of consistency we transfer some electricity, gas and coal products consumptions of our composite sectoral aggregate (which aggregates commercial end-uses) to the air and water transportation sectors at least. For these two sectors indeed, EUROSTAT reports electricity and gas expenses that can safely be assumed to cover commercial uses, which we end up estimating by acknowledging said expenses and crossing them with pricing estimates (*cf. infra*). For the land transportation sector, large consumptions of all vectors (including gas and electricity) for transportation proper forbids applying a similar method and we eventually shun from any form of correction.

Turning to **prices**, we draw estimates or information to build estimates from 3 additional sources: ENERDATA, EUROSTAT and COMEXT. We already hinted at how COMEXT data stands out as it is detailed enough both in monetary and volume terms to allow a precise reconstruction of the average prices of the 6 energy imports and exports we disaggregate at this stage: crude oil, coal, coal products (including coke), petroleum products & biomass & waste, electricity, gas & heat. In 4 instances of intermediate consumption of our crude oil aggregate we also use COMEXT data, thereby acknowledging the high probability that the corresponding sectors are (mainly) direct importers. We more specifically use:

- The import price of our crude oil aggregate as the price of crude oil consumption by our petroleum products—and accessorily by our electricity and gas, heat & steam sectors, although their consumptions are quite negligible.

[10] Although we lack precise data to estimate the share of such fuel consumptions that accrue e.g. to households (private planes and motorboats).

- The import price of natural gas condensates as the price of crude oil consumption by our composite sector, following a close scrutiny of our detailed IEA balance;

ENERDATA and EUROSTAT data are of a different nature, of a less straightforward use. ENERDATA provides a handful of prices for the more common energy types and for a few generic end-users that seldom match our sectoral decomposition. EUROSTAT provides natural gas and electricity prices only, for different ranges of consumption of sectorally unspecified businesses and households. We thus end up directly drawing 13 prices only from either one of the two sources. Altogether the 3 databases therefore only provide 29 of the 90 prices theoretically required to complete our hybridation.[11] 12 more prices are simply not required because the corresponding energy consumptions are nil (*e.g.* the crude oil consumption of households). The 49 remaining prices are derived as follows:

- We assume 4 nil prices for the self-consumptions of the crude oil, coal, petroleum products and electricity sectors, considering the integrated nature of these sectors in most Member States in 2007. In the case of the electricity sector this however means that we ignore commodity trading between the producers and the distributors of electricity, which had already picked up in some important MSs in 2007.

- Similarly, we assume a nil price for the consumption of natural gas by the crude oil sector: the gas used in the exploitation of oil fields is assumed to be mainly the by-product of oil extraction.

- We extrapolate the ratio of coal products export prices to coal export prices, as reported by COMEXT, to derive the coal products prices of the composite sector and of households (two more prices) from their respective coal prices, which we infer from total expenses reported by EUROSTAT (*cf. infra*). We use the resulting composite sector price for all other production sectors (all other non-nil intermediate consumptions of coal products), thereby defining 7 more prices.

- We infer 23 more prices by acknowledging the total expenses reported by EUROSTAT. In the particular case of the electricity and gas consumptions, to split EUROSTAT aggregated expenses we resort to EUROSTAT data on the gap between electricity and gas prices for (*i*) energy and non-energy industries and land transport (using net-of-VAT data for the higher industrial consumptions), (*ii*) the composite sector and air and water transport (using net-of-VAT data for the lower industrial consumptions) and (*iii*) households (using all-tax-included data for the residential sector).

- The 12 remaining prices, exclusively intermediate prices applying to small volumes, are generalisations of the composite sector prices, with the exception of the electricity prices of the crude oil, the coal products and the gas, steam & heat sectors, for which the electricity price of the coal sector is preferred (as a sort of 'heavy industry' price).

[11] The prices of 6 energy products for 6 energy productions, 6 aforementioned non-energy sectors, households, imports and exports.

Annex 1 reproduces the energy volumes and prices we thus determine.

2.3 Aggregation into a hybrid input-output matrix and disaggregation of the electric vehicle good

We cross our EU28 input-output matrix at purchasers' prices and our EU28 energy balance in national-accounting format, together with the complementary price information, to produce what we call a hybrid input-output matrix.

To do so, we systematically substitute our reconstructed energy expenses to the expenses appearing in the EUROSTAT tables for each of the 11 sectors we detail at this stage (5 energy sectors—we merge coal and coal products including coke—, electrical machinery, motor vehicles and parts, 3 types of transport services and the composite remainder of economic activity). Then, to re-balance uses and resources of each good,

- For the 5 energy sectors we homothetically scale up or down all non-energy resources to match the adjusted values of their total uses.
- For the 6 non-energy sectors except the composite remainder, we adjust the sole intermediate consumption of the composite good to compensate the increase or decrease of energy expenses—intermediate consumptions of other non-energy goods, imports, value-added, taxes and margins on products remain unchanged.
- For all lines of the input matrix the composite good is systematically reconstructed as the remainder of economic flows: all totals of the initial EU28 matrix are maintained but the reassessed weight of energy productions and consumptions is acknowledged.

Once our hybrid input-output table thus balanced, one last step of our data collection and treatment consists in **disaggregating the electric vehicle from the generic production of motor vehicles**. This is done using exogenous information or assumptions on

- The number of electric vehicle (EV) units sold in EU28 in the year 2007,
- The average price, subvention included, of these vehicles,
- The average subsidy (or the rate thereof), on vehicle purchase,
- The detailed EV market, *i.e.* to which economic agent the vehicles are sold,
- The share of total EV sales imported from extra-EU producers,
- For the EU production, the share of the battery cost in the total vehicle cost.

The product of the average price and the number of vehicles sold yields the total sales, or total uses (in national accounting terms), of the electric vehicle. These uses are distributed among economic agents (11 pre-existing productions and the 12th production of electric vehicles, households, exports) based on the assumed market structure. On the resources side, leaning on the balance between total uses and total resources, (*i*) the cost shares of conventional vehicles net of "electrical machinery" expenses are reproduced; (*ii*) the share of "electrical machinery" costs in the conventional vehicle cost is augmented by the assumed share of the battery in the total cost of the EV, then applied; (*iii*) imports are the product of total uses and the share of imported sales;[12] (*iv*) subsidies are the product of the number of units sold and the average subsidy per vehicle (or of the rate of subsidy and of total vehicle sales); (*v*) trade and transport margins are assumed to mobilise the same share of total sales as they do for the conventional vehicle. Conventional motor vehicle production uses and resources are of course systematically cut down to conserve the total uses and resources of vehicle production.

The final hybrid matrix reproduced in Annex 1 tentatively retains the following numerical assumptions: the sales of 25 thousand EV units at the subsidised price of 25k€, with the subsidy amounting to 33% of the production cost for domestic production; a market structure identical to that of conventional motor vehicles barring sales to EV production itself (for the sake of clarity) and exports; a 50% share of imports in total sales; a 40% cost share for the battery in domestic production.

These assumptions, loosely based on information gleaned from various industrial and institutional reports if not purely exogenous, are to be confirmed by discussion with experts. A first obvious point to be confirmed is the exact perimeter of our EV good (if only purely electric vehicles are targeted then 2007 sales are nil, say statistics of the International Council on Clean Transportation). Another point is the probable dominance of institutional buyers on the EV market, which would require modifying the assumption of a market structure identical to that of the conventional vehicle.

3 The IMACLIM-P model

3.1 Model overview

The version of IMACLIM-P developed to serve the requirements of an electric-vehicle prospective outlook is based on a Solow-Swann growth model: a recursive, discrete model where economic growth mainly derives from exogenous assumptions on demography, the productivity of primary inputs, and an exogenous savings rate that drives the accumulation of capital through time.

Essentially, for each disaggregated production, Y_t the volume of output at time t is a function of the mobilised capital stock K_t, labour L_t, aggregate volume of energy E_t and of an aggregate of non-energy goods ("materials", although services are encompassed) M_t:

$$Y_t = f_t\left(K_t, L_t, E_t, M_t\right). \tag{1}$$

The main driver to growth hides in the t index to the f function: each time period the productivity of labour is specifically increased based on exogenous data from either the short-run projections of the IMF or the World Bank, or long-term analysis, *e.g.* by the late Angus Maddison (OECD). Besides, the

[12] Note that this computation does not preclude differentiated pricing for the imported and the domestic varieties of EVs.

trajectory of L_t derives from an estimate of the International Labour Organisation up to 2020; then the labour force participation rate of 2020 is maintained to the projection horizon and applied to UN median population projections. L_t boils down to the exogenous data unless it is required that unemployment trajectories should be endogenised.[13] The aggregate (across productions) trajectory of K_t is solved through a standard accumulation rule:

$$K_{t+1} = (1-\delta)K_t + I_t, \tag{2}$$

with δ_t an exogenous depreciation rate (usually constant through time, but that could be time dependent) and I_t the investment decision. Investment is a proportion of households' income R_t based on an exogenous savings rate:

$$\sum p_{It} I_t = s_t R_t, \tag{3}$$

R_t being defined as the sum of payments of primary factors plus social transfers (the sum of the taxes levied on the different consumptions net of public expenditures *G*) minus the trade deficit, which in this simple framework must be compensated to balance current accounts.

Concerning international trade, the setting is that of an open economy: imports and exports are represented but the foreign economy is left unspecified and its price vector is assumed independent from the conditions of the domestic economy. The deformation of the international price vector through time induced by changes of energy prices is one of the main inputs required from the bottom-up modelling of PAN-EU TIMES. The ratio of foreign to domestic prices drives both the 'import intensity' of the economy in each of the disaggregated products (following the Armington (1969) assumption of imperfect substitutability), and the absolute exports of each product. Some complementary assumption must be made on the development of exports outside any change in domestic prices relative to international prices (*i.e.* an assumption on the growth of EU export markets).

3.2 Choice of behavioural specifications

The model standardly disaggregates 2 primary factors of production, capital *K* and labour *L*.[14] Considering the focus of our application on electric vehicles penetration, it disaggregate economic activity in 12 goods (*cf.* supra):

- 5 energy vectors: oil; coal; gas; petroleum products, biofuels and waste (*PPBW*) and electricity (*ELEC*);
- 2 types of personal vehicles: the average conventional vehicle (*ICE*) and the electric vehicle (*EV*);

[13] L_t is thus more precisely the occupied labour force. Unemployment trajectories bridge the gap to total labour force. If required, an imperfect labour market can be introduced in the form of a 'wage curve' connecting unemployment to real wages.

[14] Considering the expected soft-linking with PAN-EU TIMES we shun from representing a natural resources factor, which raises serious calibration issues.

- 1 electric equipments good (*ELEQ*), which encompasses the batteries of electric vehicles;
- 3 transportation services: air (*AIRT*), water (*WTT*) and land (*LDT*) transportation.
- 1 composite good (*COMP*) that aggregates all other economic products and services.

Final demand is disaggregated in 3 uses of the 12 goods: household consumption *C*, consumption of public administrations *G* and immobilisation into capital *I*.

Concerning the **behaviour of producers**, goods are produced in a quantity that is a function of intermediate consumptions of the primary factors *K* and *L*, an energy aggregate *E* and an aggregate of all other secondary inputs *M*. The primary and secondary factors combine in a nested structure (Figure 1).

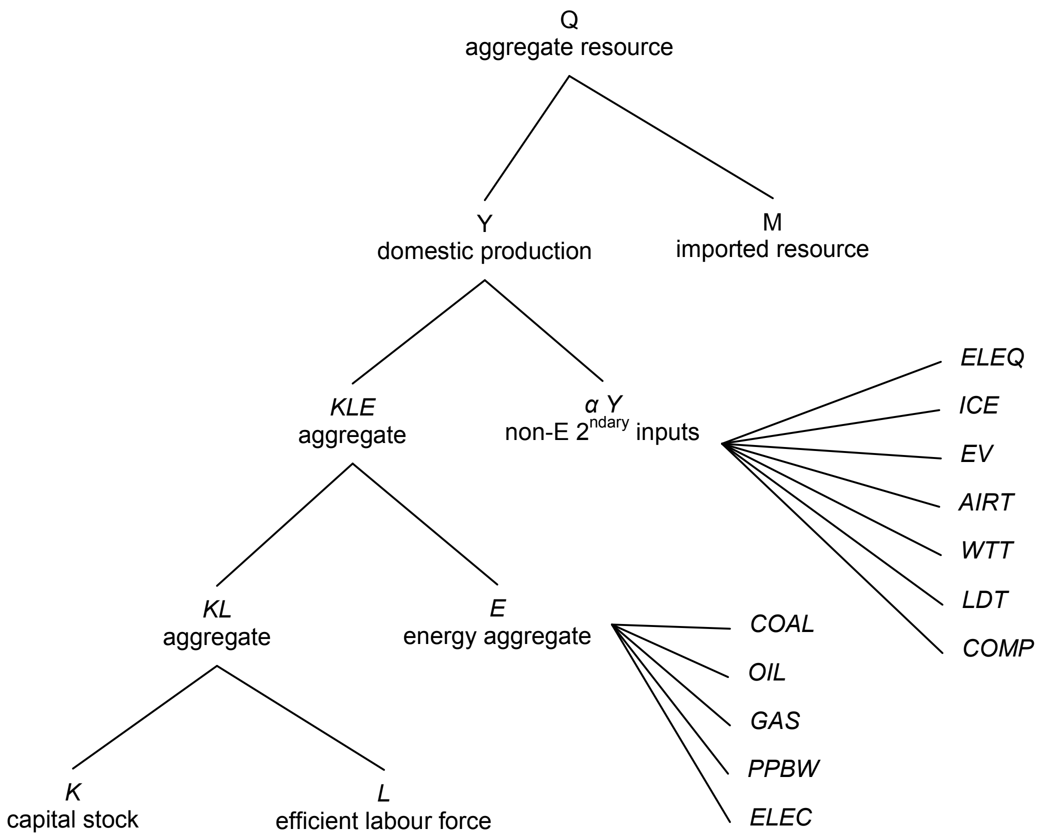

Figure 1 Nested production structure

At the bottom of the structure:

- Capital *K* and Labour *L* are traded off through a Constant Elasticity of Substitution (CES) function to produce a *KL* aggregate. Annex 2 details our sources for the core σ_{KL} elasticity parameter.
- Energy inputs, expressed in physical units, sum up to *E* the Energy aggregate. Their substitutabilities do not have to be modelled as they will be imported from PAN-EU TIMES.

- Non-energy consumptions combine in fixed proportions into *M* (the Leontief assumption). If required, information on the transportation intensities of *M*, or indeed *Y* (total output of each good in volume), either from exogenous scenarios or from PAN-EU TIMES, can be fed into the model.

At the second tier of the input structure the *KL* and *E* aggregates combine into a *KLE* aggregate through a CES function of elasticity σ_{KLE} (*cf.* Annex 2). The CES production function linking *KL* and *E* inputs to a *KLE* output is assumed to hold for those sectors whose energy intensity is imported from PAN-EU TIMES.

At the 3rd tier of the input structure, the *KLE* and *M* aggregates combine into output *Y* (for each of the 12 products) through a CES function of elasticity σ_Y (*cf.* Annex 2).

Turning to **households** and beyond the assumption of an exogenous savings rate, the model departs from the pre-existing versions of IMACLIM-P by fully exogenising final consumption trade-offs. Volumes of energy consumptions, conventional and electric vehicle consumptions together with transportation services will be imported from PAN-EU TIMES:

- Energy consumptions and vehicle purchases can be imported as volumes, provided the 2007 volumes (our calibration year, presumably one of PAN-EU TIMES simulation years) match. Alternatively their respective growths can be matched.

- For transportation services the growth of the macro model volumes will be matched to relevant indicators of PAN-EU TIMES—presumably, growth in (public modes) pkm for land, air and sea transportation.

- Electrical equipment, for lack of a better hypothesis, is assumed to be devoted a budget share constant through time.

- The remainder of households' consumption budget fuels expenses on the composite good.

Lastly, unless relevant information can be imported from PAN-EU TIMES **the goods-structures of *G* and *I* remain fix** (a form of Leontief assumption). The trajectory of *I* is defined by the exogenous savings rate assumption, while *G* is devoted a constant share of GDP through time.

3.3 Articulation with the PAN-EU TIMES model

As pervades the two preceding sub-sections, the version of IMACLIM-P focused on electric vehicle penetration is built with the purpose of articulating with the PAN-EU TIMES model of energy markets.

At the core of this articulation, both the producers' trade-offs between primary factors and energy and the consumer's trade-off between energy and other consumption and energy are imported from PAN-EU TIMES. For both agents, the competition between energy vectors, or energy mix, is also taken from PAN-EU TIMES. To be more specific, for each prospective run of IMACLIM-P the energy intensities of all productions and the household consumptions of all energy vectors follow an exogenous trajectory drawn from PAN-EU TIMES.

A second major import from PAN-EU TIMES to IMACLIM-P is the vector of import prices of the model's 5 energy aggregates. These are forced into IMACLIM-P, keeping other import prices constant. This implies that the probable hike in energy prices of prospective runs is measured against non-energy imports, which therefore collectively define the *numéraire* of the model.[15]

A third major set of imports from PAN-EU TIMES to IMACLIM-P regards transportation. It entails, at the very least, the number of electric and conventional passenger vehicles sold both to the various producers and to households. Depending on availability in the PAN-EU TIMES model, it shall also extend to indexes of variations of the consumption of the 3 transportation services by sectors and households. Also, assumptions or results of the PAN-EU TIMES model on the cost structure of the electric vehicle could be translated in IMACLIM. This could require abandoning the CES production function for some of the nests of the *EV* production structure, similarly to what is already implemented for all energy trade-offs. Alternatively, matching cost trajectories could be obtained by implementing one or several exogenous technical progress coefficients in the EV cost structure.

A last tentative set of imports from PAN-EU TIMES to IMACLIM-P regards the cost structure of domestic (EU) energy productions. Beyond the drivers of international primary energy prices, PAN-EU TIMES indeed elaborately settles the competition between alternative techniques to produce secondary energies (refined petroleum products, electricity); it also presumably tracks quite relevant information on the investment requirements on networks, which age and expand differently in the various Member States. This information could be aggregated to be passed on to the capital intensity of the energy productions of IMACLIM-P, particularly that of refined products and electricity. The decision to extend the articulation in that direction will lie in a comparison of the two models' domestic cost trajectories—if too contrasted, these will have to be reconciled for the sake of consistency. Whether the CESs governing the capital-labour substitutions would be maintained remains to be settled—similarly to EV costs, an exogenous trend of technical progress could alternatively be applied to the CES structure.

3.4 Formulary of the static core of IMACLIM-P

The model formulary mostly deals with the static equations that define the price and quantity equilibria at each time step; equation (19) is the only equation linking time t variables to time $t + 1$ variables—section 3.1 explains how time steps are interconnected by capital dynamics; section 4 further details model implementation. In its static core the model boils down to a set of simultaneous equations:

[15] Price homogeneity holds in IMACLIM-P as in any standard CGE model. Keeping constant non-energy import prices amounts to (*i*) selecting one of the import goods, *e.g.* the composite aggregate, as *numéraire*, and (*ii*) assuming that the prices of non-energy imports relative to the price of this *numéraire* are constant.

$$\begin{cases} f_1 (x_1,\ldots, x_n, z_1,\ldots, z_m) = 0 \\ f_2 (x_1,\ldots, x_n, z_1,\ldots, z_m) = 0 \\ \ldots \\ f_n (x_1,\ldots, x_n, z_1,\ldots, z_m) = 0 \end{cases}$$

with:

- x_i, $i \in [1, n]$, a set of variables (as many as equations),
- z_i, $i \in [1, m]$, a set of parameters,
- f_i, $i \in [1, n]$, a set of functions, some of which are non-linear in x_i.

The f_i constraints are of two quite different natures: one subset of equations describes accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced; the other subset translates various behavioural constraints, written either in a simple linear manner (*e.g.* households consume a fixed proportion of their income) or in a more complex non-linear way (*e.g.* the producers' trade-offs). It is these behavioural constraints that ultimately reflect, in the flexible architecture of the model, a certain economic 'worldview'.

The presentation of the equations successively details production, final consumption and investment, international trade, the market clearing conditions and the build-up of producer and consumer prices. Any variable name indexed with a '0' designates the specific value taken by the variable in the 2007 equilibrium (*i.e.* the value calibrated on the 2007 hybrid IOT); it thus indicates a parameter of the equation system. Although most equations are written for unspecified production/good *i*, some are specific to the energy goods *COAL, GAS, OIL, PPBW, ELEC*, which for short are indexed by a general *E*.

3.4.1 Production

At the bottom of the production tree (*cf.* Figure 1 above) capital and labour are traded off with a constant σ_{KL} elasticity of substitution (*cf.* Annex 2) to form a *KL* aggregate. Facing prices p_K and p_L, cost minimisation canonically induces

$$L_i = \left(\frac{\beta_{KLi}}{p_{Li}}\right)^{\sigma_{KLi}} \left(\alpha_{KLi}{}^{\sigma_{KLi}}\, p_{Ki}{}^{1-\sigma_{KLi}} + \beta_{KLi}{}^{\sigma_{KLi}}\, p_{Li}{}^{1-\sigma_{KLi}}\right)^{-\frac{1}{\rho_{KLi}}} KL_i \tag{1}$$

$$K_i = \left(\frac{\alpha_{KLi}}{p_{Ki}}\right)^{\sigma_{KLi}} \left(\alpha_{KLi}{}^{\sigma_{KLi}}\, p_{Ki}{}^{1-\sigma_{KLi}} + \beta_{KLi}{}^{\sigma_{KLi}}\, p_{Li}{}^{1-\sigma_{KLi}}\right)^{-\frac{1}{\rho_{KLi}}} KL_i \tag{2}$$

On the tier immediately above, with the energy consumption α_{Ei} exogenous (a sum of the energy intensities inferred from PAN-EU TIMES results) the cost-minimisation programme is truncated. KLE_i is still assumed to be a CES production of KL_i and $\alpha_{Ei}\, Y_i$ though, following

$$KLE_i = \left(\alpha_{KLEi}\, KL_i^{\rho_{KLEi}} + \beta_{KLEi}\,(\alpha_{Ei}\, Y_i)^{\rho_{KLEi}}\right)^{\frac{1}{\rho_{KLEi}}}, \tag{3}$$

where for convenience $\rho_{KLEi} = \frac{\sigma_{KLEi}-1}{\sigma_{KLEi}}$ (*cf.* Annex 2 for the sectoral values of σ_{KLE}).

Still higher on the production tree, the KLE_i aggregate and composite input $\alpha_{Ci}\, Y_i$ (a Leontief aggregate of non-energy goods) are traded off with a constant σ_{Yi} elasticity of substitution (*cf.* Annex 2) to form domestic production Y_i. Facing prices p_{KLE} and p_{Ci}, cost minimisation induces

$$KLE_i = \left(\frac{\alpha_{Yi}}{p_{KLEi}}\right)^{\sigma_{Yi}} \left(\alpha_{Yi}^{\ \sigma_{Yi}}\, p_{KLEi}^{\ 1-\sigma_{Yi}} + \beta_{Yi}^{\ \sigma_{Yi}}\, p_{Ci}^{\ 1-\sigma_{Yi}}\right)^{\frac{\sigma_{Yi}}{1-\sigma_{Yi}}} Y_i\,. \tag{4}$$

$$\alpha_{Ci}\, Y_i = \left(\frac{\beta_{Yi}}{p_{Ci}}\right)^{\sigma_{Yi}} \left(\alpha_{Yi}^{\ \sigma_{Yi}}\, p_{KLEi}^{\ 1-\sigma_{Yi}} + \beta_{Yi}^{\ \sigma_{Yi}}\, p_{Ci}^{\ 1-\sigma_{Yi}}\right)^{\frac{\sigma_{Yi}}{1-\sigma_{Yi}}} Y_i\,. \tag{5}$$

3.4.2 Final consumption and investment

The consumed income of households R is defined as the sum of factor incomes and of tax revenues, net of public spending, investment and the trade balance:

$$R = \sum_{i=1}^{n} p_{Li}\, L_i + \sum_{i=1}^{n} p_{Ki}\, K_i + T - \sum_{i=1}^{n} p_{Gi}\, G_i - \sum_{i=1}^{n} p_{Ii}\, I_i - \left(\sum_{i=1}^{n} p_{Xi}\, X_i - \sum_{i=1}^{n} p_{Mi}\, M_i\right) \tag{6}$$

Tax revenues T sum up the series of taxes and subsidies identified by the model:

$$T = \sum_{i=1}^{n} w_i\, \tau_{CSi}\, L_i + \sum_{i=1}^{n} \tau_{Yi}\, p_{Yi}\, Y_i + \sum_{A=H,G,I,X} \sum_{i=1}^{n} \frac{\tau_{Ai}}{1+\tau_{Ai}}\, p_{Ai}\, A_i + \sum_{A=H,G,I,X} \sum_{i=1}^{n} t_{Ai}\, A_i \tag{7}$$

Household consumptions of energy C_{COAL}, C_{OIL}, C_{GAS}, C_{PPBW}, C_{ELEC} are exogenous (to be imported from PAN-EU TIMES). Household consumptions of air, water and land transport (C_{AIRT}, C_{WTT}, C_{LDT}) are indexed on the billions passenger-kilometres projected by PAN-EU TIMES. Household consumptions of conventional and electric vehicles (C_{ICE}, C_{EV}) are directly imported from PAN-EU TIMES. Electrical equipment (C_{ELEQ}) is devoted a constant budget share. The remaining budget, spent on the composite good (C_{COMP}) derives from the saturation of the budget constraint:

$$\sum_{i=1}^{n} p_{Hi}\, C_i = R \tag{8}$$

Public spending G_i is a constant share s_{Gi} of GDP (traditionally nil for energy goods)

$$p_{Gi}\, G_i = s_{Gi}\, GDP \tag{9}$$

with GDP defined on the expenditure side as

$$GDP = \sum_{i=1}^{n} p_{Hi}\, C_i + \sum_{i=1}^{n} p_{Gi}\, G_i + \sum_{i=1}^{n} p_{Ii}\, I_i + \sum_{i=1}^{n} p_{Xi}\, X_i - \sum_{i=1}^{n} p_{Mi}\, M_i \tag{10}$$

Investment has an exogenous ratio s_I to consumed income (this amounts to an exogenous savings rate; of course immobilisation in energy goods is nil)

$$\sum_{i=1}^{n} p_{Ii} I_i = s_I R \tag{11}$$

The good-structure of investment is supposed constant through time

$$\forall i,j \quad \frac{I_i}{I_{i0}} = \frac{I_j}{I_{j0}} \tag{12}$$

3.4.3 International trade

For goods other than energy and personal vehicles the domestic and foreign varieties of products are imperfect substitutes that are traded off following the Armington specification of international trade (Armington, 1969) with a σ_Q elasticity. Domestic production Y and imports M are thus

$$\forall i \neq E, ICE, EV \quad Y_i = \left(\frac{\alpha_{Qi}}{p_{Yi}}\right)^{\sigma_{Qi}} \left(\alpha_{Qi}^{\sigma_{Qi}}\, p_{Yi}^{1-\sigma_{Qi}} + \beta_{Qi}^{\sigma_{Qi}}\, p_{Mi}^{1-\sigma_{Qi}}\right)^{\frac{\sigma_{Qi}}{1-\sigma_{Qi}}} Q_i\,, \tag{13}$$

$$\forall i \neq E, ICE, EV \quad M_i = \left(\frac{\beta_{Qi}}{p_{Mi}}\right)^{\sigma_{Qi}} \left(\alpha_{Qi}^{\sigma_{Qi}}\, p_{Yi}^{1-\sigma_{Qi}} + \beta_{Qi}^{\sigma_{Qi}}\, p_{Mi}^{1-\sigma_{Qi}}\right)^{\frac{\sigma_{Qi}}{1-\sigma_{Qi}}} Q_i\,. \tag{14}$$

For the energy and vehicle goods, which must be accounted for in concrete physical units (TOE, number of vehicles) the Armington specification is dropped to avoid introducing a quantity index specific to aggregate resources Q. Rather, the ratio of the imported volume M to aggregate resource Q is deemed price-elastic:

$$\forall i \in E, ICE, EV \quad \frac{M_i}{Q_i} = \frac{M_{i0}}{Q_{i0}} \left(\frac{p_{Mi0}}{p_{Yi0}} \frac{p_{Yi}}{p_{Mi}}\right)^{\sigma_{Mpi}} \tag{15}$$

and M and Y simply add up to Q, to warrant commensurability

$$\forall i \in E, ICE, EV \quad M_i + Y_i = Q_i \tag{16}$$

Then, indistinctly for all goods, exports X_i are elastic to terms of trade around an exogenous trend (to be harmonised with PAN-EU TIMES based on the average growth of main current export markets)

$$X_i = \left(1+\overline{\delta_{Xi}}\right) X_{i0} \left(\frac{p_{Xi}}{p_{Mi}} \frac{p_{Mi0}}{p_{Xi0}}\right)^{\sigma_{Xi}}, \tag{17}$$

3.4.4 Market clearings

Market balance for each good *i* is

$$Q_i = \sum_{j=1}^{n} \alpha_{ij} Y_j + C_i + G_i + I_i + X_i \tag{18}$$

Labour demand by the 12 productions matches labour supply (through homothetic adjustments of wages w_i), which grows at a combination of exogenous rates reflecting active population growth δ_N, and an assumption on labour productivity growth δ_g.

$$\sum_{i=1}^{n} L_i = L = \left(1+\overline{\delta_N}\right)\left(1+\overline{\delta_g}\right)L_0, \tag{19}$$

Similarly capital markets clear (through the adjustment of p_K), but the trajectory of the capital stock follows the traditional accumulation rule—for this unique dynamic equation we add *t* subscripts to variables to mark time periods.

$$\sum_{i=1}^{n} K_{i,t} = K_t = \left(1-\overline{\delta_K}\right) K_{t-1} + I_{t-1} \tag{20}$$

3.4.5 Producer and Consumer Prices

At the bottom of the nested production structure (Figure 1), labour costs in the sector *i* are equal to net wage w_i plus payroll taxes that are levied at a constant rate τ_{CS}:

$$p_{Li} = \left(1+\overline{\tau_{CSi}}\right) w_i \tag{21}$$

w_i adjust homothetically to clear the labour market (*cf. supra*). Similarly, p_K the price of capital rental common to both sectors adjusts to clear the capital market.

One tier higher in the production structure, p_{KLi} is the price of the *KL* aggregate in sector *i* , a canonical function (considering that *KL* is a CES product of *K* and *L*) of prices p_K and p_{Li} and of the elasticity of substitution of the two inputs σ_{KLi}

$$p_{KLi} = \left(\alpha_{KLi}^{\ \sigma_{KLi}}\, p_{Ki}^{\ 1-\sigma_{KLi}} + \beta_{KLi}\, p_{Li}^{\ 1-\sigma_{KLi}}\right)^{\frac{1}{1-\sigma_{KLi}}} \tag{22}$$

Still one tier higher, contrary to p_{KLi}, p_{KLEi} the price of the *KLE* aggregate in sector *i* cannot be defined as a function of prices p_{KLi} and p_{Ei} and of the elasticity of substitution of the two inputs σ_{KLEi}, because exogenously setting *E* in the *KLE* aggregate (importing it from PAN-EU TIMES) truncates the underlying cost-minimisation programme. Consequently, p_{KLEi} is rather inferred from the simple accounting equation[16]

$$p_{KLEi}\, KLE_i = p_{KLi}\, KL_i + p_{Ei}\, \alpha_{Ei}\, Y_i \tag{23}$$

At the tier of domestic production *Y*, p_{Yi} the producer price of good *i* is again the canonical CES price of the *KLE* aggregate and the composite input to production $\alpha_{Ci}\, Y_i$, to which a constant *ad valorem* output tax is added:

$$p_{Yi} = \left({\alpha_{Yi}}^{\sigma_{Yi}}\, {p_{KLEi}}^{1-\sigma_{Yi}} + {\beta_{Yi}}^{\sigma_{Yi}}\, {p_{Ci}}^{1-\sigma_{Yi}} \right)^{\frac{1}{1-\sigma_{Yi}}} + \overline{\tau_{Yi}}\, p_{Yi} \tag{24}$$

Then p_{Mi} the price of imported good *i* is good-specific: the international composite good is the *numéraire* of the model; its price is consequently assumed constant. The prices of imported non-energy goods (electrical equipment, conventional and electric vehicles, transport services) are assumed constant relative to the price of the international composite good. Then the prices of imported energy goods relative to the price of the international composite good are directly imported from PAN-EU TIMES—if the calibration of year 2007 produces perfect matches they can be imported as such; if it does not their growth is replicated.

Because of the difference in aggregation of *Y* and *M* into total resource *Q* (CES *vs.* simple sum), p_{Qi} the price of the resource of good *i* is good-specific. For the non-energy goods it is the Armington price of the imported and domestic varieties:

$$p_{QC} = \left({\alpha_{QC}}^{\sigma_{QC}}\, {p_{YC}}^{1-\sigma_{QC}} + \beta_{QC}\, {p_{MC}}^{1-\sigma_{QC}} \right)^{\frac{1}{1-\sigma_{QC}}} \tag{25}$$

For the energy good, considering that the Armington specification is dropped lest a specific quantity index is introduced, the price of the resource is simply inferred from

$$p_{QE}\, Q_E = p_{YE}\, Y_E + p_{ME}\, M_E \tag{26}$$

Turning to purchasers' prices, the price of good *i* consumed in the production of good *j* p_{ij} is equal to the resource price of good *i* plus a constant-through-time agent-specific margin (allowing the price differentiation of energy goods, cf. the matrix of energy prices Annex 2) and an aggregate of other excise taxes; this is all multiplied by an *ad valorem* sales tax.

$$p_{ij} = \left[p_{Qi} \left(1 + \overline{\tau_{MSij}} \right) + \overline{t_{ICi}} \right] \left(1 + \overline{\tau_{ICi}} \right) \tag{27}$$

The consumer price of good *i* for households (p_{Hi}), public administrations (p_{Gi}) and investment (p_{Ii}), and the export price of good *i* (p_{Xi}), are constructed similarly.

$$p_{Hi} = \left[p_{Qi} \left(1 + \overline{\tau_{MSHi}} \right) + \overline{t_{Hi}} \right] \left(1 + \overline{\tau_{Hi}} \right) \tag{28}$$

$$p_{Gi} = \left[p_{Qi} \left(1 + \overline{\tau_{MSGi}} \right) + \overline{t_{Gi}} \right] \left(1 + \overline{\tau_{Gi}} \right) \tag{29}$$

[16] For the sake of simplicity this accounting equation is substituted to the canonical price definition for p_{KLEC} too, although the canonical CES price definition could have been retained. When the CES optimisation is respected the 2 equations can be substituted freely.

$$p_{Ii} = \left[p_i \left(1 + \overline{\tau_{MSIi}}\right) + \overline{t_{Ii}} \right] \left(1 + \overline{\tau_{Ii}}\right) \quad (30)$$

$$p_{Xi} = \left[p_i \left(1 + \overline{\tau_{MSXi}}\right) + \overline{t_{Xi}} \right] \left(1 + \overline{\tau_{Xi}}\right) \quad (31)$$

4 Model implementation

The IMACLIM-P model is implemented in Microsoft Excel leaning on Excel's built-in solver, which adequately addresses non-linear equation systems.

The dynamics of the model develop stepwise by changing, at each time step:

- Labour endowment *L*, which is adjusted through active population growth δ_N, and an assumption on labour productivity growth δ_g. Active population growth δ_N is drawn from the EAPEP database of the International Labour Office up to 2020, then it will be derived from the total population projections used by PAN-EU TIMES by continuingly applying the labour force participation rate attained by EAPEP in 2020. Labour productivity growth will be calibrated on observed trends up to 2013, then exogenously postulated—sensitivity analysis on this central parameter will be performed.

- Capital endowment *K*, following the accumulation rule of equation (19). The rate of capital depreciation δ_K, constant through time, will be adjusted to minimise discrepancy with observed growth up to 2013.

- The size of export markets X_i, following equation (16). The rate of growth of the volumes exported *ex ante* variations of the terms of trade is set at that of global non-EU GDP growth based on the long term forecasts used by PAN-EU TIMES.

- The savings rate s_I, *i.e.* the gross fixed capital formation ratio to GDP. Historical EUROSTAT series are used until 2013. For further years, our preliminary intent is to have the rate linearly catch up its average 1995 to 2007 level between 2013 and 2018, then to keep it constant. The Solow growth model underlying this version of IMACLIM-P is notoriously sensitive to this assumption, which will accordingly be devoted some sensitivity analysis.

These 4 central growth drivers are completed by the energy-related changes imported from PAN-EU TIMES following section 3.3, including the penetration rate of the electric vehicle.

Note that with the exception of capital accumulation, which is by definition recursive, the entire set of dynamic changes is exogenous to IMACLIM-P's trajectory (not impacted by it). After a first run there is no guarantee that the GDP variations computed by IMACLIM-P match the exogenous GDP trajectory underlying PAN-EU TIMES's projection—although the Solow-based representation of growth and the use of internationally recognised datasets are features probably common to IMACLIM-P and whatever model is at the source of PAN-EU TIMES growth estimates. A natural way of improving the consistency of the IMACLIM-P and PAN-EU TIMES trajectories would be by iterating exchanges of GDP and other growth drivers versus energy sector details between IMACLIM and PAN-

EU TIMES, each time re-running the models to compute revised trajectories. IMACLIM's experience with other energy sector models is that convergence (stable GDP and energy sector trajectories) is obtained after few iterations.

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Annex 1

EU28 input-output matrix, year 2007 (million Euros)

Source: EUROSTAT (EU27), GTAP (Croatia)

		COMP	10	11	23	31	34	40	60	61	62	IC	C	G	I	X	USES
Composite good	**COMP**	9 340 373	7 080	14 791	69 664	124 170	275 528	99 053	173 040	62 798	69 211	**10 235 708**	6 134 530	2 517 774	2 378 870	1 342 745	**22 609 626**
Coal & lignite; peat	**10**	8 777	594	48	3 960	55	28	17 170	113	2	0	**30 746**	2 499	22	68	292	**33 627**
Crude oil & natural gas	**11**	41 568	64	7 614	188 335	403	495	73 314	995	115	2	**312 905**	13 150	67	1 221	9 461	**336 804**
Coke, ref. petroleum pdts and nuclear fuels	**23**	241 699	378	560	48 160	1 377	2 301	19 516	55 003	11 428	26 524	**406 945**	273 539	182	376	54 615	**735 657**
Electrical machinery and apparatus n.e.c.	**31**	145 183	228	333	616	52 565	24 702	8 723	2 155	87	164	**234 755**	23 813	211	56 274	63 265	**378 318**
Motor vehicles, trailers and semi-trailers	**34**	95 638	61	28	244	1 857	226 879	318	9 045	67	136	**334 274**	299 559	115	197 295	144 515	**975 757**
Electrical energy, gas, steam and hot water	**40**	256 221	1 461	2 965	4 028	3 444	6 013	128 673	6 941	206	387	**410 337**	193 681	1 400	144	5 375	**610 937**
Land transport; pipeline services	**60**	236 862	373	1 112	4 469	1 915	6 383	4 019	28 594	518	373	**284 619**	104 426	10 437	1 011	14 317	**414 811**
Water transport services	**61**	18 918	14	559	872	219	1 145	433	1 540	8 937	86	**32 721**	13 181	1 113	559	75 761	**123 336**
Air transport services	**62**	52 916	17	298	294	477	946	232	1 090	226	6 045	**62 541**	59 702	396	0	24 649	**147 288**
Total intermediate consumption	**IC**	**10 438 154**	**10 271**	**28 309**	**320 640**	**186 481**	**544 419**	**351 450**	**278 516**	**84 384**	**102 927**	**12 345 551**	**7 118 081**	**2 531 718**	**2 635 819**	**1 734 994**	**26 366 163**
Compensation of employees	L	5 527 707	6 631	5 595	12 710	58 055	99 140	53 677	151 422	11 444	22 969	**5 949 349**					
Consumption of fixed capital	K1	1 518 312	1 857	7 770	10 838	12 136	29 566	52 801	50 881	7 795	7 520	**1 699 476**					
Operating surplus, net	K2	2 897 144	653	50 761	21 191	19 837	29 171	77 751	52 912	16 767	4 434	**3 170 622**					
Other net taxes on production	T1	153 009	-3 664	-3 790	-2 246	284	-4 089	16 712	32 126	2 262	-10 973	**179 632**					
Domestic output	**Y**	**20 534 327**	**15 749**	**88 644**	**363 133**	**276 794**	**698 207**	**552 392**	**565 857**	**122 652**	**126 877**	**23 344 631**					
Imports	**M**	1 243 556	13 302	204 042	60 444	46 699	62 959	8 042	7 305	5 196	15 477	**1 667 024**					
Taxes less subsidies on products	**T2**	1 000 636	220	13 033	230 126	6 544	61 790	60 282	-23 714	-298	5 891	**1 354 508**					
Trade and transport margins	**TTM**	-168 892	4 357	31 085	81 955	48 282	152 802	-9 780	-134 637	-4 214	-958	**-0**					
RESOURCES		**22 609 626**	**33 627**	**336 804**	**735 657**	**378 318**	**975 757**	**610 937**	**414 811**	**123 336**	**147 288**	**26 366 163**					

EU28 energy balance in national accounts format, year 2007 (million TOE)

		A	B	C	D	E	F	Electrical mach. [a]	Motor vehic. [a]	Land transp.	Air transp.	Water transp.	COMP	C	X	*USES*	Y	M	*RES*
Crude oil	A	0.0	-	-	710.0	0.0	0.0	-	-	-	-	-	2.6	-	15.9	***728.5***	119.0	609.6	***728.5***
Coal, lignite, peat	B	0.5	12.5	39.6	0.1	204.8	33.6	0.1	0.1	0.5	0.0	0.0	38.7	8.8	1.2	***341.1***	196.1	145.0	***341.1***
Coke	C	-	0.0	0.2	-	0.0	0.0	0.0	0.0	0.0	-	-	35.6	0.2	1.2	***37.3***	34.2	3.1	***37.3***
Petroleum products, biomass, waste	D	0.1	0.574	0.5	43.3	35.0	10.6	2.2	3.6	54.0	39.6	22.6	215.1	247.7	136.3	***811.1***	676.0	135.1	***811.1***
Electricity	E	0.2	1.6	0.1	2.8	13.9	2.2	0.9	1.0	6.3	0.2	0.2	149.7	70.2	4.2	***253.9***	247.5	6.4	***253.9***
Gas, heat, steam	F	3.9	0.3	0.2	5.9	94.0	26.4	7.3	8.6	1.6	0.2	0.1	167.5	133.9	0.1	***450.1***	272.7	177.4	***450.1***

[a] The energy consumptions of the electrical machinery and motor vehicle sectors are derived from EUROSTAT expenses using the prices obtained/computed for the Transport vehicle and Machinery end-uses of the detailed IEA energy balances.

EU28 average prices of energy goods, year 2007 (Euros *per* TOE)

		A	B	C	D	E	F	Electrical mach.	Motor vehicles	Land transp.	Air transp.	Water transp.	COMP	C	X	M
Crude oil	A	-	-	-	375	375	375	-	-	-	-	-	448	-	391	375
Coal, lignite, peat	B	225	-	99	225	100	100	306	576	225	225	225	225	285	203	104
Coke	C	-	276	276	-	276	276	276	276	276	-	-	276	350	250	252
Petroleum products, biomass, waste	D	383	635	635	-	428	428	635	635	1018	670	506	1104	1104	395	386
Electricity	E	913	913	913	834	-	913	1677	1163	1170	1511	1511	1511	1856	513	514
Gas, heat, steam	F	-	306	279	279	279	279	562	390	392	456	456	456	571	1530	200

Hybrid EU28 input-output matrix, year 2007

	COMP	COAL	OIL	RPBW	ELEC	GAS+	31	34a	34b	60	61	62	TOTAL	C	G	I	X	USES

Composite good	**COMP**	9 461 907	11 013	5 447	58 071	84 367	39 196	124 170	275 443	85	173 040	62 798	69 211	**10 364 748**	6 134 530	2 519 445	2 380 680	1 349 504	**22 748 908**
Coal, coke, coal products	**COAL**	18 539	3 997	110	23	20 559	3 377	61	38	0	113	2	0	**46 819**	2 552	-	-	552	**49 924**
Crude petroleum	**OIL**	1 184	-	-	266 480	7	6	-	-	-	-	-	-	**267 678**	-	-	-	6 214	**273 892**
Ref. pet. products, biomass and waste	**RPBW**	237 528	679	28	-	14 958	4 552	1 371	2 290	1	55 002	11 428	26 524	**354 361**	273 486	-	-	53 913	**681 759**
Electricity	**ELEC**	226 117	1 522	191	2 358	-	1 992	1 003	1 697	1	7 325	263	318	**242 786**	130 348	-	-	2 178	**375 312**
Gas, heat, steam	**GAZ+**	76 446	138	-	1 637	26 263	7 373	2 843	4 808	1	611	58	71	**120 250**	76 483	-	-	126	**196 858**
Electrical machinery and apparatus n.e.c.	**31**	143 211	354	123	513	7 429	3 452	52 565	24 542	160	2 155	87	164	**234 755**	23 813	211	56 274	63 265	**378 318**
Motor vehicles, trailers and semi-trailers	**34a**	95 437	95	10	203	271	126	1 854	226 809	70	9 031	67	136	**334 109**	299 099	115	197 295	144 515	**975 132**
Electric vehicles	**34b**	147	0	0	0	0	0	3	-	-	14	0	0	**165**	460			-	**625**
Land transport; pipeline services	**60**	237 107	581	410	3 725	3 423	1 590	1 915	6 381	2	28 594	518	373	**284 619**	104 426	10 437	1 011	14 317	**414 811**
Water transport services	**61**	19 301	22	206	727	369	171	219	1 144	0	1 540	8 937	86	**32 721**	13 181	1 113	559	75 761	**123 336**
Air transport services	**62**	53 085	27	110	245	198	92	477	946	0	1 090	226	6 045	**62 541**	59 702	396	0	24 649	**147 288**
TOTAL	**Σ**	**10 570 008**	**18 428**	**6 634**	**333 983**	**157 844**	**61 927**	**186 481**	**544 099**	**319**	**278 516**	**84 384**	**102 927**	**12 345 551**	**7 118 081**	**2 531 718**	**2 635 819**	**1 734 994**	**26 366 163**
Compensation of employees	L	5 516 391	10 314	2 060	10 595	45 719	21 241	58 055	99 110	30	151 422	11 444	22 969	**5 949 349**					
Consumption of fixed capital	K1	1 510 927	2 889	2 861	9 035	44 972	20 894	12 136	29 557	9	50 881	7 795	7 520	**1 699 476**					
Operating surplus, net	K2	2 913 136	1 016	18 694	17 664	66 224	30 767	19 837	29 162	9	52 912	16 767	4 434	**3 170 622**					
Other net taxes on production	T1	148 141	-5 699	-1 396	-1 872	14 235	6 613	284	-4 088	-1	32 126	2 262	-10 973	**179 632**					
Domestic output	**Y**	**20 658 603**	**26 949**	**28 854**	**369 404**	**328 994**	**141 441**	**276 794**	**697 840**	**367**	**565 857**	**122 652**	**126 877**	**23 344 631**					
Imports	**M**	1 193 797	15 857	228 790	52 208	3 303	35 432	46 699	62 592	367	7 305	5 196	15 477	**1 667 024**					
Taxes less subsidies on products	**T2**	1 032 125	342	4 800	191 831	51 345	23 854	6 544	61 996	-206	-23 714	-298	5 891	**1 354 508**					
Trade and transport margins	**TTM**	-135 617	6 777	11 448	68 317	-8 330	-3 870	48 282	152 704	98	-134 637	-4 214	-958	**-0**					
RESOURCES		**22 748 908**	**49 924**	**273 892**	**681 759**	**375 312**	**196 858**	**378 318**	**975 132**	**625**	**414 811**	**123 336**	**147 288**	**26 366 163**					

Annex 2
Behavioural parameters of the IMACLIM-P model

We painstakingly draw the Armington and input substitution elasticities of IMACLIM-P from two sources: Okagawa and Ban (2008) and Hertel *et al.* (2008)—the latter being part of the documentation of the CGE model maintained by the developers of the GTAP database.[17]

Okagawa and Ban provide σ_{KL}, σ_{KLE} and σ_Y (our notations) substitution elasticities assessed on annual data for 19 sectors covering 14 countries—12 EU countries, Japan and the United-States. We retain their Mining sector estimates for our coal and oil productions; their Chemical sector estimates for our petroleum products production; their Electricity, gas and water sector estimates for our electricity and our gas, heat and steam productions; their Electrical equipment sector for our Electrical machinery production; their Transport equipment sector estimate for our two vehicle productions; their Transport sector estimates for our 3 transport services. For the remaining sectors of their decomposition σ_{KL} estimates vary from 0.023 (Agriculture) to 0.382 (Food industry), with an average of 0.234; for lack of more appropriate sources (and considering the impossibility to recompose fixed elasticities of substitution by any aggregating procedure) we retain this estimate for our composite sector, together with similarly obtained estimates of 0.466 and 0.572 estimates for the σ_{KLE} and σ_Y of the same sector.

Hertel *et al.* provide σ_Q (our notation) *i.e.* Armington elasticity estimates for the 57 goods of the GTAP database. This provides direct coverage of 10 of the 11 productions we disaggregate from our composite good remainder of economic activity. The remaining non-composite production is our Gas, heat and steam sector, which aggregates two distinctive GTAP sectors: that of gas extraction and that of gas distribution. For lack of a better assumption we average the two estimates provided by GTAP. Similarly, we average all the estimates of the sectors aggregated into our composite production to produce its own Armington elasticity.

The remaining behavioural parameter σ_X, the price elasticity of exports, is even harder to pinpoint than the substitution and Armington elasticities. A literature review reveals contrasted country estimates ranging from a few percents (e.g. Hooper et al., 2010) to over 10. Sector-specific estimates could not be obtained except from Crane *et al.* (2007), where, however, many fail standard significance tests or take problematic values, casting doubts on the more acceptable estimates. We consequently rely on assumptions regarding these parameters: a low -0.5 elasticity for the composite good, which is partly composed of non-tradable services; high -5 elasticities for quite homogeneous (hence highly substitutable between different origins) primary energies; -3 for partially homogeneous refined petroleum products; -0.5 for electricity, whose exports rely on costly infrastructure developments; -0.5 for the allegedly product-specific industries of electrical equipment and vehicle production; -0.5 for geographically constrained land transport—although some larger firms operate

[17] Van der Werf (2008) also proposes σ_{KL} and σ_{KLE} estimates but for more aggregated industries or at the scale of entire countries. Hertel et al. (2008) offer σ_{KL} estimates only, also for a limited number of sectors (5 different values cover their 57 sectors). Similar to Okagawa and Ban, all van der Werf estimates are between 0.2 and 0.6; however, 3 out of 5 Hertel *et al.* σ_{KL} estimates reach over 1 (1.12, 1.26 and 1.68).

on international markets; -2 for the more internationally challenged air and water transport services. These crude assumptions are provisional, and will be adjusted if they turn out to induce pathologic developments of the EU trade balance over the simulation horizon. Further reports on modelling results will duly report on any inflexion of this parameter set.

Sector	Code	σ_{KL}	σ_{KLE}	σ_{Y}	σ_{Q}/σ_{Mp}	σ_{X}
Composite good	**COMP**	0.234	0.466	0.572	2.850	-0.500
Coal, coke, coal products	**COAL**	0.139	0.553	0.729	3.050	-5.000
Crude petroleum	**OIL**	0.139	0.553	0.729	5.200	-5.000
Refined petroleum pdcts, biomass and waste	**RPBW**	0.334	0.001	0.848	2.100	-3.000
Electricity	**ELEC**	0.460	0.256	0.001	2.800	-0.500
Gas, heat, steam	**GAZ+**	0.460	0.256	0.001	10.000	-5.000
Electrical machinery and apparatus n.e.c.	**31**	0.163	0.524	0.876	4.050	-0.500
Motor vehicles, trailers and semi-trailers	**34a**	0.144	0.519	0.548	2.800	-0.500
Electric vehicles	**34b**	0.144	0.519	0.548	2.800	-0.500
Land transport; pipeline services	**60**	0.310	0.281	0.252	1.900	-0.500
Water transport services	**61**	0.310	0.281	0.252	1.900	-2.000
Air transport services	**62**	0.310	0.281	0.252	1.900	-2.000

Table 1 **Behavioural parameters of the IMACLIM-P model**