TIMES bottom-up techno-economic modeling for China and India in the global context (KANLO)

Introduction

This document describes briefly the TIAM model used for TOCSIN, and focuses more particularly on changes made to the model for the purpose of the project. Much more details are available in the two reports written in 2008 for deliverables D.2.1 and D.2.2 titled respectively, 'Bottom-up models for China and India' and 'Fully integrated 15 region TIMES model'. In addition, a full documentation on the TIMES model's generic equations, variables, and parameters, as well as its economic significance, is available from www.etsap.org. A more condensed and more approachable description of TIAM is contained in two articles by Loulou (2007) and by Loulou and Labriet (2007).

Two types of modifications were performed during the TOCSIN project:

- Structural modifications to the equations of the TIMES model itself;
- Modifications to the database of the TIAM implementation, consisting of:
    - Full re-calibration to the 2005 national statistics for all TIAM regions, with particular detail on the China and India regions;
    - Update of the assumptions concerning the demands for energy services in the Base Case for India and China. The GEMINI-E3 model had been used to compute driver trajectories for all regions simultaneously in the base case;
    - Technological data improvements made for the entire TIAM model (all regions) in 2007. Indeed, one of the most important considerations presiding to any Base Case revision is to maintain *coherence of assumptions* across all regions.

In the following section, we provide a brief description of the TIMES paradigm, of which TIAM is a global instance. In the next section we explain succinctly the changes made to TIAM during the early phases of the project. That section is split in three subsections, dealing respectively with structural changes to the model, data updates and enhancements affecting the entire model, and data enhancements more specific to the China and India regions as a result of the collaboration with the India and China partners.

General description of TIAM

ETSAP-TIAM is an instance of the TIMES (The Integrated Markal-Efom System) model generator, developed by ETSAP members over the last decade (ETSAP website, www.etsap.org/documentation).

TIMES is a technology based, technology-rich bottom-up model of the third generation, that integrates the entire energy/emission system of a country/region or set of regions, into a single model, including the procurement, transformation, trade, and consumption of a large number of energy forms. TIMES' economic paradigm is the computation of a dynamic inter-temporal partial equilibrium on energy/emission markets based on the maximization of total surplus, defined as the sum of suppliers and consumers surpluses. In the Base (or Reference) case, the model is driven by user provided demands for a detailed set of energy services in all sectors of the economy. The demands are provided over the entire time horizon of the instance. In Alternate (or Policy) scenarios, the demands are elastic to their own prices, and are thus endogenously re-computed by the model as a result of an endogenous increase or decrease in demand prices. The price elasticities are set to 0 at the initial (usually past) period, and at low values for the few initial years of the horizon.

Figure-1 illustrates the equilibrium in the simplified case of a single commodity. For each demand segment, the inverse supply curve is *implicitly* constructed within TIMES, whereas the inverse demand curve is provided by the modeler via an explicit own price elasticity. In multi-commodity cases, the inverse supply curve is a multi-dimensional surface with as many dimensions as there is demand categories multiplied by time periods and by number of regions. The equilibrium point lies at the intersection of the increasing inverse supply curve (or surface) and the decreasing inverse demand curve(s).

The equilibrium is computed via Linear Programming, using the GAMS matrix generation language and the CPLEX or XPRESS optimizers. The GAMS program that contains all TIMES equations and variables is owned by ETSAP and is available only from that organization. The optimization is conducted as the minimization of the negative of the surplus, which is usually called the system 'cost'.

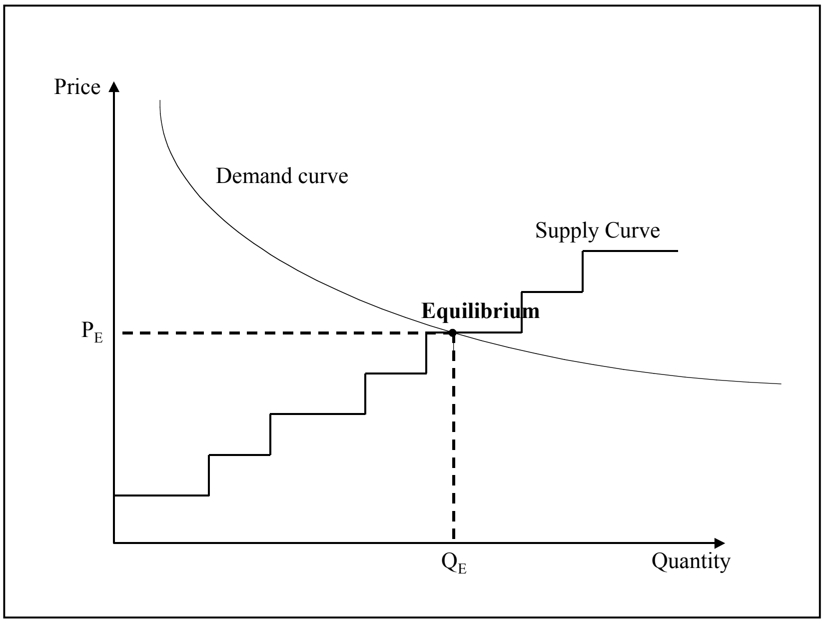

Figure0-1: Illustration of the TIMES equilibrium in the one-dimensional case

The TIAM instance of the TIMES paradigm was constructed by several researchers who are members of ETSAP and partners in TOCSIN (ETSAP website, www.etsap.org/documentation). TIAM is a global model with 15 regions covering the entire planet. Figure-2 contains a list of the regions. TIAM was meant from the beginning to cover a rather long horizon, extending up to 2100. In TOCSIN, the relevant horizon extends to 2050.

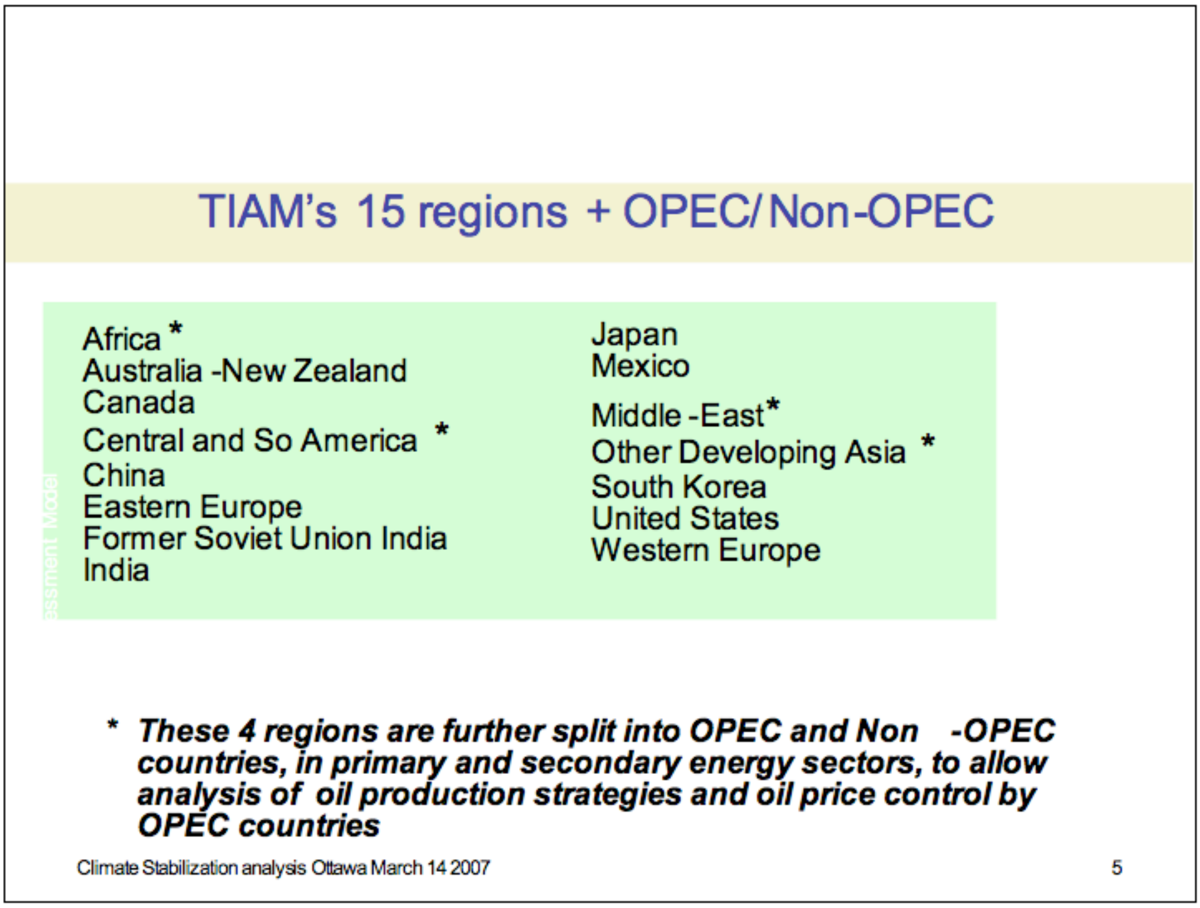

Figure-2: The 15 TIAM regions

Improvements to the ETSAP-TIAM model

Improvements to Model structure and equations

Three types of structural improvements were made over the first period of TOCSIN. Two of these were directly or indirectly motivated by the objectives of TOCSIN. The implementation of the new or improved features was greatly helped by the collaborative effort of other members of ETSAP (who are not all TOCSIN partners). We outline below the two new features of interest to TOCSIN.

New constraints on costs

This new feature enables the modeler to define constraints (usually upper bounds) based on cost elements of TIAM. For instance, it is now possible to impose upper bounds on total investments in a given subset of technologies for a given subset of regions and at specified periods. This feature is very useful in scenarios where capital is rationed, a situation that may be an important cause of the failure to adopt some new technologies by developing countries (Loulou et al. 2007).

We have already applied this feature to analyze the pattern of energy investments in Developing Countries (DC's) in Climate scenario, when capital is rationed at various levels. The findings were presented at two conferences in May 2007 (IAEE-EU, Firenze) and June 2007 (IEW, Stanford), and show a striking contrast in investments when capital is rationed as compared to the unrationed case. This is a strong indication that capital availability plays a major role in the adoption of GHG benign technologies by DC's.

New features of the TIMES climate module

The TIAM climate module was restructured in order to model the life cycle as well as the radiative forcings of the three gases separately. This allows a more precise tracking of the CO2, N2O and CH4 atmospheric cycles. Details are available in deliverable D.2.1.

More recently, the computation of GHG emissions was also modified in order to be closer to the coverage in the WITCH model. They now include CO2 emissions from land-use and full N2O emissions from agriculture. As a consequence, the exogenous forcing trajectory was also adjusted to cover the impact of emissions from the Montreal gases. In this way, WITCH and TIAM have coherent radiative forcings. This exogenous forcing is taken from the current values indicated in the AR4 (IPCC 2007, vol 1, ch 2) and extended to 2100 using the assumptions from Prinn *et al.* (2008): it varies from 0.337 W/m2 in 2005 to 0.1 W/m2 in 2100

Changes made to the entire database

The changes listed below are reported in some detail in deliverable D.2.2, and, of course, in the complete TIAM database.

Improvements of the technology database

A general review and revision of the technological data in most sectors was conducted during 2007 and early 2008. Although such data reviews are an ongoing process with models such as TIAM, the review and revision accomplished during 2007 was a particularly intensive one that affected several sectors of crucial importance for energy production and consumption. We briefly outline the main changes.

Electric Power Generation (EPG) sector

This sector was almost completely updated. New data emphasize even more than before new technologies that are likely to play a large role in Climate scenarios, for instance : solar, geothermal, and carbon capture. The potentials for renewables such as hydro, geothermal, solar and wind have been revised.

It should be noted that the technological parameters of the electricity plants are further adapted to each world region (in particular, operating costs are adapted to labor costs in each region).

Alternative energy production

In this sector, the database was augmented by 8 technologies for diesel production (from coal, biomass, and natural gas, with or without carbon capture), methanol and ethanol production, and hydrogen production. These technologies were added to the existing database or replaced others.

Carbon sequestration

We have added 5 carbon capture (CC) technologies as follows:

Hydrogen production from coal with CC (2 technologies),
Hydrogen production from Natural Gas with CC (2 technologies),
Diesel production with CC,
Methanol production from Natural Gas with CC.

Transportation sector

The road transportation subsector was entirely revised. Some old technological data were superseded by new assessments, leading to an almost entirely new set of future technologies. This subsector includes 8 separate segments, each with its own demand, and with its own set of technologies :

- Cars,
- Light trucks (SUV's, minivans),
- Commercial (delivery) trucks,
- Medium trucks,
- Heavy trucks,
- Buses
- Three-wheelers
- Two-wheelers

The first six segments (four wheels or more) were revised as follows:

- New costs or cost adjustments, especially for alternative vehicles (hybrids, fuel cells, biofuels)
- Vintaging of all vehicles (in 2008, 2018, 2028, 2038, 2048)

Trade links

The 15 TIAM regions form a fully integrated single energy system thanks to the definition of trade variables that link the regions in pair-wise fashion. Table-1 is the list of commodities currently traded among regions, which increased from 6 to 11 recently. We have added the trading of 4 refined petroleum products and of natural gas liquids to the existing list.

Table-1: Tradable commodities in TIAM

Energy trading	Crude oil
	Gasoline
	Diesel
	Fuel oil
	Naphtha
	Natural Gas Liquids
	Natural gas
	Liquefied Natural Gas
	Coal
Emission trading	CO2 permits
	GHG permits

Interface improvement

The KANLO team uses the VEDA suit of softwares to develop, maintain, and operate the TIMES family of models. VEDA was created by KanORS Inc., a sister company to KANLO. The development of VEDA is supported by KanORS and KANLO, independently of the TOCSIN project. However, the objectives of TOCSIN have served as a guide for the development of new features and capabilities. The new version 4.0 of VEDA concretizes these advances, and was used for the remainder of the project.

Specific modifications of the China and India TIAM regions

Base year calibration

The input data and results initially submitted to the India and China teams in 2007 were those pertaining to the TIAM model as of Summer 2007, with 2000 as Base Year. Since then, a new base year of 2005 was adopted, and the model has been re-calibrated to the IEA and other available statistics for that year. For this reason, the partners examining the 2005 results of the old model noted some discrepancies between 2005 energy balances and those actually observed in their respective countries for that same year. These discrepancies have now been removed by re-calibration to the 2005 energy balances. The new 2005 data are now consistent with the recommendations by the partners.

In addition to the Base Year energy balances, the TIAM model requires the selection of some 'splits' of energy consumptions that are not covered by the usually published statistics. Examples of such splits are: the split of some end-uses between rural and urban sub-regions in the Residential sector, or the split of natural gas consumption between several end-uses in a given sector, etc. These splits have been reviewed and corrected where needed.

This task was one of the most time-consuming one in the adaptation of the TIAM model to the TOCSIN project, and has received additional support from external sources for its completion.

The many aspects of the base year calibration cannot be reproduced in this report. They have become an integral part of the TIAM model.

<u>Remark</u>: As a final comment, let us re-iterate that the calibration task need not be a very precise exercise, since the model is to be used over a fairly long horizon (to 2050), so that any small discrepancies occurring in 2005 will rapidly be made irrelevant after a suitably long period of time. This is especially true in fast growing economies such as those of India and China, where all energy numbers change at a fast rate, making the initial conditions quickly irrelevant for the future behavior of the energy system.

Service demands

As explained in detail in the previously distributed deliverables D.2.1 and D.2.2, the TIMES model is 'drawn' by a set of demands for 42 energy services. These exogenously determined demands must be satisfied in the base case, but may be altered by the model itself in alternate policy scenarios, since each demand is elastic to its own price. In the Base Case, each demand is associated to one socioeconomic driver (table 6 shows the list of drivers). The values of the drivers are determined by runs of the GEMINI-E3 general equilibrium model, and then the demands are calculated assuming an elasticity of each demand to its associated driver.

An important contribution of the partners was to send detailed comments on the values of the drivers' growths (Table-2 and 4) and to a lesser extent on some of the elasticities. Note that data in some of the following tables are shown until 2090, but that the relevant horizon for TOCSIN is 2050.

Demands for China

Table-2: New driver growth rates for China

Driver	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
GDP	11.8%	9.0%	6.4%	6.0%	6.0%	6.0%	5.4%	4.5%	4.9%	4.0%
GDPP	11.0%	8.3%	5.8%	5.6%	5.8%	5.7%	5.0%	4.0%	4.9%	4.0%
GDPPHOU	11.0%	8.3%	5.8%	5.6%	5.8%	5.7%	5.0%	4.0%	4.9%	4.0%
HOU	1.1%	1.0%	0.9%	0.8%	0.6%	0.7%	0.8%	0.8%	0.9%	0.7%
PAGR	5.9%	3.5%	3.4%	2.3%	3.2%	2.6%	3.8%	2.9%	3.7%	2.8%
PCHEM	8.2%	5.7%	5.7%	3.2%	4.1%	3.8%	3.9%	2.9%	3.5%	2.6%
PISNF	8.1%	6.9%	6.3%	4.5%	4.7%	3.7%	3.9%	3.0%	3.4%	2.5%
POEI	7.3%	5.1%	4.2%	2.8%	3.4%	2.3%	3.6%	2.7%	3.6%	2.6%
POI	7.2%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	5.0%	5.0%	5.0%
POP	0.7%	0.6%	0.5%	0.4%	0.2%	0.3%	0.4%	0.4%	0.05%	0.0%
PSER	6.0%	6.0%	7.0%	7.0%	7.0%	7.0%	7.0%	6.0%	6.0%	4.0%

These new drivers' values led to the demands for energy services shown in Table -3.

Table -3: Energy Service demands for China (2005-2050)

Demand segment	2005	2010	2020	2030	2040	2050
AGR [Agricultural demand]	1712	2033	2693	3592	5009	6888
CC1 [Commercial Cooling - Region 1]	2	2	4	7	12	18
CC2 [Commercial Cooling - Region 2]	44	55	97	169	284	423
CCK [Commercial Cooking]	592	752	1315	2298	3861	5756
CH1 [Commercial Space Heat - Region 1]	29	34	49	71	100	129
CH2 [Commercial Space Heat - Region 2]	211	247	356	514	722	936
CHW [Commercial Hot Water]	260	330	577	1009	1694	2526
CLA [Commercial Lighting]	839	1066	1863	3257	5471	8156
COE [Commercial Office Equipment]	84	107	187	326	548	817
CRF [Commercial Refrigeration]	34	43	75	131	219	327
ICH [Chemicals]	4045	5338	8238	12139	16954	22877
IIS [Iron and Steel]	116	162	275	414	582	780
ILP [Pulp and Paper]	33	43	61	80	109	149
INF [Non-ferrous metals]	2	3	6	9	12	16
INM [Non Metals]	4389	5632	7973	10568	14417	19612
IOI [Other Industries]	4588	6140	10995	19690	33630	54780
NEO [Industrial and Other Non Energy Uses]	2019	2889	4741	7653	11338	16173
ONO [Other non-specified consumption]	696	996	1635	2640	3911	5578
RC1 [Residential Cooling - Region 1]	45	67	117	204	317	489
RC2 [Residential Cooling - Region 2]	405	603	1052	1836	2852	4394
RCW [Residential Clothes Washing]	51	81	155	297	499	830
REA [Residential Other Electric]	153	242	465	892	1497	2489
RH1 [Residential Space Heat - Region 1]	1194	1238	1316	1379	1459	1547
RH2 [Residential Space Heat - Region 2]	734	762	810	848	898	952
RHW [Residential Hot Water]	883	914	962	989	1033	1036
RK1 [Residential Cooking - Region 1]	3842	3941	4090	4174	4310	4319
RK2 [Residential Cooking - Region 2]	1044	1070	1111	1134	1171	1173
RL1 [Residential Lighting - Region 1]	105	167	320	614	1030	1713
RL2 [Residential Lighting - Region 2]	522	830	1591	3055	5125	8522
RRF [Residential Refrigeration]	305	485	929	1784	2994	4978
TAD [Domestic Aviation]	322	565	1258	2607	4771	7370
TAI [International Aviation]	77	135	301	624	1143	1765
TRB [Road Bus Demand]	135	138	143	146	151	151
TRC [Road Commercial Trucks Demand]	65	96	166	283	438	650

Demand segment	2005	2010	2020	2030	2040	2050
TRE [Road Three Wheels Demand]	19	20	21	21	21	22
TRH [Road Heavy Trucks Demand]	23	34	60	101	157	233
TRL [Road Light Vehicle Demand]	32	47	82	140	216	321
TRM [Road Medium Trucks Demand]	27	40	69	117	181	269
TRT [Road Auto Demand]	65	114	249	547	1025	1901
TRW [Road Two Wheels Demand]	106	108	112	114	117	117
TTF [Rail-Freight]	372	612	1237	2445	4296	6402
TTP [Rail-Passengers]	254	260	270	276	285	285
TWD [Domestic Internal Navigation]	388	597	1090	1951	3031	4086
TWI [International Navigation]	320	492	899	1610	2501	3371

Demands for India

Table-4 shows the new annual growth rates of the India drivers.

Table-4: New driver growth rates for India

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
GDP	6.7%	8.0%	8.0%	8.0%	8.0%	8.0%	7.0%	6.0%	5.0%	5.0%
GDPP	5.1%	6.5%	6.7%	6.9%	7.1%	7.2%	6.3%	5.4%	4.5%	4.6%
GDPPHOU	4.7%	6.1%	6.3%	6.5%	6.7%	6.7%	5.8%	4.9%	4.0%	4.2%
HOU	1.9%	1.8%	1.6%	1.4%	1.3%	1.2%	1.1%	1.0%	0.9%	0.7%
PAGR	6.2%	5.2%	5.5%	4.6%	5.4%	4.5%	4.8%	4.0%	4.3%	3.4%
PCHEM	7.3%	8.0%	8.0%	8.0%	8.0%	8.0%	7.0%	6.0%	5.0%	5.0%
PISNF	6.6%	7.5%	7.5%	7.5%	7.5%	7.5%	6.5%	5.5%	4.5%	4.5%
POEI	6.6%	7.7%	7.7%	7.7%	7.7%	7.7%	6.7%	5.7%	4.7%	4.7%
POI	6.2%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
POP	1.5%	1.4%	1.2%	1.0%	0.9%	0.8%	0.7%	0.6%	0.5%	0.3%
PSER	5.5%	8.4%	8.4%	8.4%	8.4%	8.4%	7.4%	6.4%	5.4%	5.4%

These new drivers' values led to the demands for energy services shown in Table-5.

Table-5 : Energy service demands for India (2005-2050)

Demand segment	2005	2010	2020	2030	2040	2050
AGR [Agricultural demand]	598	772	1267	2059	3168	4624
CC1 [Commercial Cooling - Region 1]	0	1	1	2	3	5
CC2 [Commercial Cooling - Region 2]	19	26	51	99	171	264
CCK [Commercial Cooking]	241	337	658	1285	2228	3429
CH1 [Commercial Space Heat - Region 1]	6	7	11	18	26	34
CH2 [Commercial Space Heat - Region 2]	18	23	35	55	79	105
CHW [Commercial Hot Water]	37	52	102	199	345	531
CLA [Commercial Lighting]	205	287	560	1094	1896	2918
COE [Commercial Office Equipment]	40	56	109	213	370	569
CRF [Commercial Refrigeration]	21	30	58	113	197	303
ICH [Chemicals]	955	1404	3030	6542	12278	20000
IIS [Iron and Steel]	19	27	55	113	203	316
ILP [Pulp and Paper]	3	5	10	22	40	63
INF [Non-ferrous metals]	1	1	2	4	6	10
INM [Non Metals]	461	669	1404	2948	5379	8515
IOI [Other Industries]	2425	3245	5811	10407	18637	33376
NEO [Industrial and Other Non Energy Uses]	560	771	1458	2759	4634	6909
ONO [Other non-specified consumption]	211	290	548	1037	1743	2598
RC1 [Residential Cooling - Region 1]	3	4	8	15	26	34
RC2 [Residential Cooling - Region 2]	53	74	143	285	501	648
RCD [Residential Clothes Drying]	2	3	6	13	26	35
RCW [Residential Clothes Washing]	4	6	12	26	51	69
RDW [Residential Dishwashing]	2	3	6	13	26	35
REA [Residential Other Electric]	112	165	356	794	1540	2082
RH1 [Residential Space Heat - Region 1]	84	89	99	108	116	123
RH2 [Residential Space Heat - Region 2]	76	80	90	98	105	111
RHW [Residential Hot Water]	468	504	569	622	667	699
RK1 [Residential Cooking - Region 1]	2686	2837	3103	3312	3486	3607
RK2 [Residential Cooking - Region 2]	848	896	980	1046	1101	1139
RL1 [Residential Lighting - Region 1]	135	195	420	936	1814	3061
RL2 [Residential Lighting - Region 2]	601	870	1873	4177	8096	13666
RRF [Residential Refrigeration]	63	94	202	450	873	1180
TAD [Domestic Aviation]	59	97	267	693	1520	2476
TAI [International Aviation]	88	146	401	1040	2280	3715
TRB [Road Bus Demand]	17	18	20	21	22	23
TRC [Road Commercial Trucks	24	35	70	142	253	394

Demand segment	2005	2010	2020	2030	2040	2050
Demand]						
TRE [Road Three Wheels Demand]	25	26	28	30	31	32
TRH [Road Heavy Trucks Demand]	10	15	29	59	106	164
TRL [Road Light Vehicle Demand]	24	34	69	140	249	388
TRM [Road Medium Trucks Demand]	12	17	34	69	123	191
TRT [Road Auto Demand]	50	78	196	512	1138	2149
TRW [Road Two Wheels Demand]	50	53	57	60	63	65
TTF [Rail-Freight]	45	70	171	418	872	1360
TTP [Rail-Passengers]	60	63	69	74	78	80
TWD [Domestic Internal Navigation]	27	40	87	188	334	464
TWI [International Navigation]	1	2	4	8	15	21

The two initial test scenarios

Two contrasted scenarios, one reference (or base) case and one climate scenario, were defined and run in order to provide a first validation of the model changes. This allowed us to test the model's response to a severe climate constraint. The results were reported in deliverables D.2.1 and D.2.2, and discussed collectively, leading to some additional minor adjustments. The TIAM runs made in view of Work Packages 5 and 6 were made with the fully updated and validated model.

We give below a brief description of the two initial validation runs, and direct the reader to the earlier deliverables for a full presentation of their results. In the "Policy Insight" section of this web report we present and comment the TIAM results obtained for the Policy scenarios of WP5 and 6. Note that in spite of the fact that the TOCSIN project's horizon is 2050, we will usually run TIAM for a longer horizon, perhaps extending up to 2090. This will avoid any undesirable boundary effects.

Base Case: this is the Base Case described in Deliverable 2.1, which assumes a moderately high level of development worldwide, especially in India and China, moderate oil prices, and global GHG emissions that reach 18 GtC in 2050 and 27 GtC-eq in 2090. As already mentioned, a common set of base case assumptions will be adopted by all TOCSIN researchers in order to conduct policy runs and analyses.

Climate scenario: we chose to impose a constraint on total forcing in the later periods of the century. The upper limit allowed for total forcing is 3 W/m2 starting in 2040 and extending to 2090. This scenario offers several advantages:

- it imposes a global constraint on all GHG's rather that separate ones on each;
- it is in line with one of the climate scenarios recommended by the IPCC special New Scenarios Working Group (IPCC 2007);
- It allows us to test not only the response of the energy system but also the newly improved climate module.