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Working paper

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Abstract

In 1881, two electricians built the world's first power system in England. It supplied seven arc lamps at 250 volts and 34 incandescent lamps at 40 volts. However, supply to the lamps was intermittent and in 1882 Thomas Edison and his company, The Edison Electric Light Company, developed the first steam-powered electric power station on Pearl Street in New York City. From this first attempt, several systems started to spread across the United States and Europe. and power companies had built thousands of power systems (both direct and alternating current) in the United States and Europe. Years after, it has become possible to transport electricity over long distances. Power distribution then started to expand throughout the world, propelling the second industrial revolution, and becoming progressively a major source of energy supply. Global electricity consumption has increased by around 70% since 2000, and it accounts for 19% of total final consumption today compared to just over 15% in 2000. The steady rise in demand for electricity means that it is now the second largest fuel by end-use, but the level of electricity consumption remains less than half the level of oil consumption. The emergence of renewable power sources over the last twenty years alongside the further digitalization of power grids are perceived to play a major role if carbon emissions are to decrease significantly. The purpose of this paper is to investigate the efficiency of an 'all electric world' to decarbonize energy systems. It finds that an 'all electric' world scenario, with 4 times more electricity in final energy consumption would require an inevitable climate policy response to support the migration of uses towards clean electricity. The steady decreasing costs of renewables would not be enough to switch to clean power systems. Furthermore, 5.3 GtCO2eq of CCS is to be installed between 2040 and 2050 to compensate CO2 emissions (2.5 GtCO2eq if electricity is to reach 49% in total final energy consumption by 2050). Our analyses come up with massive breakthroughs in power generation, USA would see ¾ of its dispatchable power capacities switched into intermittent renewable sources. a complete redesign of the grid power system towards one that is more decentralized and more digitized is then required to accompany the transition

Keywords

Energy system decarbonization; Electric systems; Prospective study

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1 Introduction

Electricity is the base of modern development. It is used to provide all modern services that economies reaching maturity daily consume. In buildings, electricity serves lighting, heating and cooling, and it provides energy to all appliances daily used such as cooking, washing, etc. In industries, electricity provides energy to many complex process applications via electric motors, beyond powering the facility itself. In transportation, beyond trains, tramways, and other electricity fueled transportation, the recent development of electric vehicles is standing as an alternative to traditional combustion engine technologies. On top of this, electricity is the sole source of energy that enables connectivity, the key development accelerator of our digital era. It powers data centers, telecom infrastructures, computers and other devices. The development of electricity as a source of energy is a relevant indicator of economic development.

In 2017, global electricity demand grew by 3%, more than any other major fuel, reaching 22 200 terawatt-hours (TWh). Global electricity consumption has increased by around 70% since 2000, and it accounts for 19% of total final consumption today compared to just over 15% in 2000. The steady rise in demand for electricity means that it is now the second largest fuel by end-use, but the level of electricity consumption remains less than half the level of oil consumption.

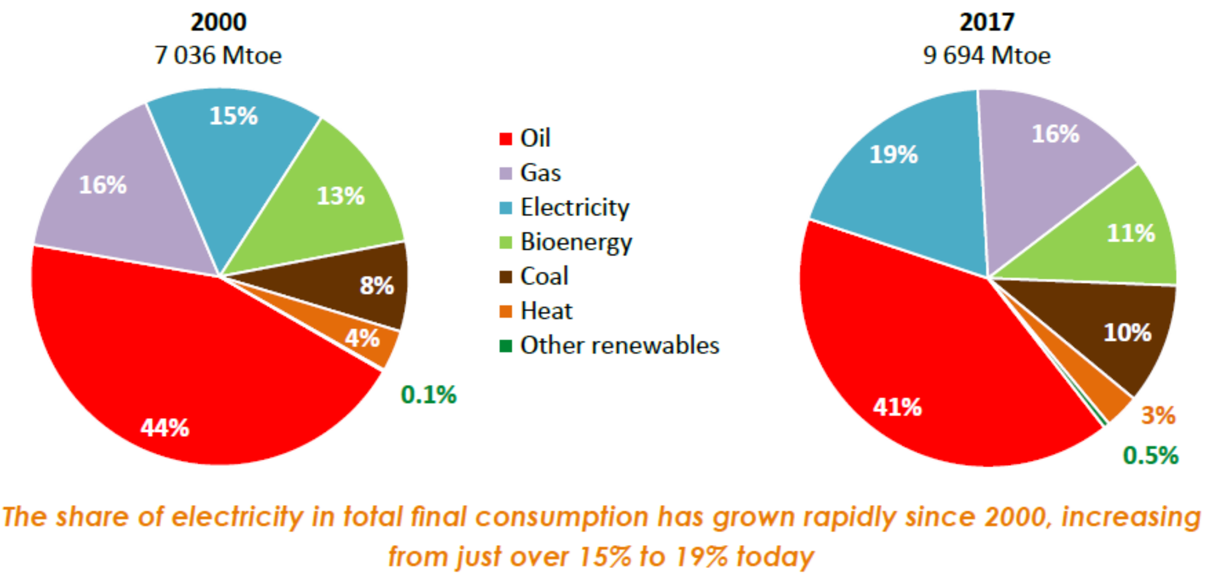

Figure 1: total final consumption, 2000 and 2017 [1]

The steady decrease in renewable based power generation alongside with the considerable electrification potential of end-use sectors is perceived at Schneider Electric as an opportunity to decarbonize energy systems. The purpose of this work is then to investigate the feasibility of an 'all electric' world and its pertinence to help fighting against climate change. Using an optimization tool, TIAM-FR, we analyze technical economic implications of different electrification pathways.

2 Thermodynamic description of power systems

The safety of electricity supply calls for a robust power grid capable of facing to disturbances (brutal over-consumption, device faults, etc) before automatic controls (primary and secondary controls) and the manual control (tertiary control) in order to circumvent grids outages. However, it is difficult to reconcile the transient behavior of the power grid (voltage, frequency, etc. typically some ms to a few mn) with the long-term prospective studies (typically 50 years).

This section deals with the condition of power stability by introducing two indicators representing the synchronism and the inertia of power grids. The indicator related to the power grid's inertia will be calculated in section 10.2.

Past works [2] [3] demonstrated a relevant method to integrate power-systems short-term dynamics associated with transient regimes into prospective modeling.

A variational formulation of electromagnetism is presented through a thermodynamic presentation of power systems. It gives an understanding of power exchanges occurring through a power system.

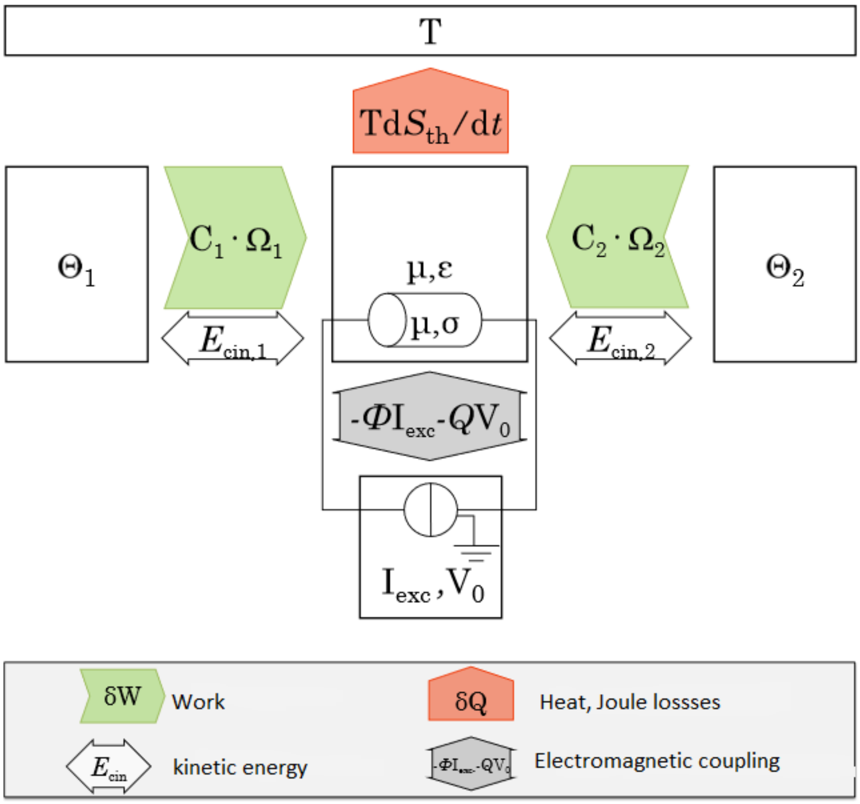

Figure 2: Chart of the energy exchanges between the subsystems involved in the thermodynamic representation of a power system[3] [4], (μ, ε) and (μ, σ) respectively describe conductors and dielectrics immersed in the electromagnetic field conveying power between the subsystems. Arrows illustrate the power exchanges.

As shown in Figure 2, the electrical machines Θ_i exchange mechanical power $P_{mech-ext} = \sum_i T_i \Omega_i$ through the electrical network, where:

- $\Omega_i = \frac{d\Theta_i}{dt}$ is the angular velocity of the machine experiencing the external torque T_i ;
- $\phi I_{exc} + QV_0$ represents the coupling energy between the electromagnetic field and its source (ground connection at voltage V_0, current excitation I_{exc};
- All subsystems exchange heat with the thermostat at the temperature T and electrical charges with the mass at the potential V_0.

The excitation I_{exc} and $P_{mech-ext}$ can be adjusted directly by the system operator. The first principle of thermodynamics conveys the energy conservation:

$$\frac{dE}{dt} = P_{mech-int} - T\frac{dS_{th}}{dt} \tag{1}$$

Where:

- $P_{mech-int}$denotes the electrodynamical power acting on the electromagnetic field which differs from the mechanical power $P_{mech-ext}$ supplied to the system because of the variation of the kinetic energy E_{kin}:

$$P_{mech-ext} - P_{mech-int} = \frac{dE_{kin}}{dt} \tag{2}$$

- S_{th} is the thermostat's entropy at temperature T.

The evolution of the system coupled with the thermostat can be discussed from its Helmholtz free-energy $F = E - TS$:

$$P_{mech-ext} - \frac{dF}{dt} = T\left(\frac{dS}{dt} + \frac{dS_{th}}{dt}\right) = P_{Joule} > 0 \tag{3}$$

Where S describes the entropy of the whole electrical system. The right hand-side represents the power lowered in heat, known as the Joule losses:

$$P_{mech-int} - \frac{dF}{dt} = \min\left(P_{Joule}\right) \tag{4}$$

However, to fully describe the inertial behavior of the electromagnetic coupling (Lenz's law), the Gibbs free energy $G = F - \phi \mathrm{I}_{\mathrm{exc}} - QV_0$ needs to be introduced. Following (3)another evolution assignment reads:

$$P_{mech-int} - \frac{dG}{dt} = P_{Joule} + \frac{d\phi \mathrm{I}_{\mathrm{exc}}}{dt} + \frac{dQV_0}{dt} \tag{5}$$

This leads to a new optimality condition within the assumption of reversibility trend:

$$P_{mech-int} - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d\phi \mathrm{I}_{\mathrm{exc}}}{dt} + \frac{dQV_0}{dt}\right) \tag{6}$$

In (6), the RHS of the functional exhibits ϕ and Q which are the derivates of the Gibbs free-energy G:

$$\phi = -\frac{\partial \mathrm{G}}{\partial \mathrm{I}_{\mathrm{exc}}};\ \mathrm{Q} = -\frac{\partial \mathrm{G}}{\partial \mathrm{V}_0};\ \mathrm{S} = -\frac{\partial \mathrm{G}}{\partial \mathrm{T}} \tag{7}$$

Hence, the RHS in (6) provides the Maxwell Faraday's equation in conductors [5] which can be understood as the local expression of a global tendency towards reversibility [6] whereas the LHS balances it thanks to the variations with time of the Gibbs free-energy G and the electrodynamical power supplied to the field.

The above approach provides an understanding of power transaction that can be applied at different length scales, *i.e.* from materials involved in electrical engineering to grid management. To describe a given subsystem θ it is convenient to introduce the electrical power $P_{elec}(\theta)$ which measures the local deviation of θ from the equilibrium. The global balance of the system provides:

$$\sum_{\theta} P_{elec}(\theta)=0 \tag{8}$$

Hence from (2) and (8), (6) becomes:

$$P_{mech-ext}(\theta) + P_{elec}(\theta) - \frac{dE_{kin}}{dt}(\theta) - \frac{dG}{dt}(\theta) = \min\left(P_{Joule}(\theta) + \frac{d\phi I_{exc}}{dt}(\theta) + \frac{dQV_0}{dt}(\theta)\right) \quad (9)$$

Equation (9) explains power system behavior during transient regimes, namely how a power fluctuation (positive or negative) occurring on any θ is balanced by the energy stocks embedded within the whole system, which fall into two categories; field type $\frac{d\phi I_{exc}}{dt}$ andE_{kin}, and matter-type $P_{mech-ext}$ and $\frac{dQV_0}{dt}$ (electrostatic energy), each of one acting In one hand-side of (9). A power system relies then on its rapidly mobilizable field energy stocks variations which are respectively the electromagnetic coupling ϕI_{exc} and E_{kin}.

As time is uniform [6] [7], (9) provides naturally two-time invariants which are embedded kinetic and magnetic free-energies (references). Using relevant aggregated quantities, it is possible studying the system globally considering local behavior.

Here below, Figure 3 describes two possible evolutions of a power system exposed to a sudden load fluctuation, namely an unbalance between withdrawn and injected powers:

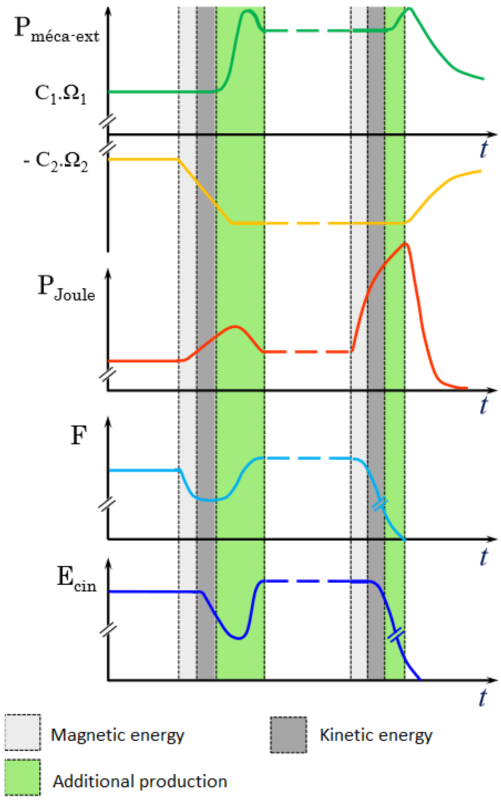

Figure 3: Effect of a load fluctuation on the electric system. $P_{mech-ext} = C_1\Omega_1 + C_2\Omega_2$ Ω_2 represents the mechanical power supplied by the actuators Θ1 and Θ2 to the system, in the case where the actuator Θ1 provides mechanical power to the system and the actuator Θ2 consumes. On the left: the magnetic energy at F and the electrical energy E_{cin} compensate momentarily the power demand and the Joule losses P_{Joule} generated by the variable fluctuation, pending adjustment of additional production $P_{mech-ext}$ and reconstitution of stocks. On the right: in the case of network failure, the magnetic and

kinetic energy stocks are degraded by the Joule effect without the production being able to adjust. The three succeeding times load fluctuation occur at different time scales (a few milliseconds for F, few seconds for $\mathbf{E}_{cin}$, a few minutes for additional production), but they were artificially reduced to the same value for the readability of the scheme

Following subparts handle the development of the aggregated quantities essential to power systems dynamics into prospective models.

2.1 Kinetic reserve

The construction of the kinetic indicator is based on the quantification of the inertial stock embedded in the network. Kinetic energy of all the machines can be aggregated only under the condition of synchronism. In other words, a synchronous functioning of the rotating machine is necessary to take advantage from the maximum available kinetic reserves.

The kinetic energy acting as dynamic reserve for the whole power grid obeys the set of inequalities:

$$\min E_{kin}(i) \leq E_{kin}(i) \leq \sum_{\in\{synchronus\ machines\}} E_{kin}(i) \tag{10}$$

Where the upper bound is reached only if the synchronism is achieved over the whole power grid during the transient regime. In other words, some locally available kinetic energy has been lowered in Joule losses by the inrush currents during the transient regime. In order to maintain the kinetic energy as high as possible in case of a sudden disturbance, it appears critical to enforce the synchronism in order to discuss power system reliability.

Using the aggregated one-loop representation of the system, one can express the total kinetic energy [3]:

$$E_{kin,tot} = \sum_{\in\{synchronus\ machines\}} E_{kin}(i) = \sum_{\in\{synchronus\ machines\}} \frac{1}{2}\frac{J_i}{p_i^2}(2\pi f_0)^2 \tag{11}$$

With:

- J_i, the inertia moment of the alternator I, sum of the inertia moment of the rotor and the turbine;
- p_i, the number of pairs of the rotor poles of the alternator I;
- f_0, the synchronous frequency of the power grid (50 Hz in Europe).

If all generation means are suddenly disconnected or, conversely, if the final consumption rushes to its peak P_{peak}, then the required time to recover steady state condition thanks to a relevant management of the reserves before the transmission collapses may roughly be assessed by the kinetic reserve indicator [7]:

$$H_{kin} = \frac{E_{kin}}{\max\left(S(t), P_{peak} - S(t)\right)} \tag{12}$$

where S stands for the apparent power supplied by the generators just before the disturbance. By forcing H_{kin} to be higher than a critical value – typically derived from the current conditions – It is conversely possible to provide a reliability condition to operate the system and then reconcile the power grid management time-scale with long-term planning issues. This indicator, expressed in seconds, may be interpreted as the time available for an operator to activate regulations when generation and consumption are unbalanced on the power system.

3 Previous works

Between 2013 and 2018, many studies applied the concept developed above to investigate reliable technological paths towards power systems decarbonization. A TIMES model was designed to explore the possibility of reaching 100% renewable energy penetration by 2030 in La Reunion island [3]. System reliability was evaluated through a post-process calculation providing kinetic reserves of the mix proposed by the model. Supplementary works [8] [2] helped endogenizing kinetic reserves indicator as a constraint in the TIMES optimization model to prevent the user from looping the calculation until a sufficient level of kinetic reserves is achieved. This was integrated to La Reunion Island model to provide a reliable scenario to reach a fully decarbonized grid. Further works [9] led to the formulation of the synchronism indicator as part of thinking on the integration of power network stability into prospective studies. In [9], a post-processing study was conducted on La Reunion Island TIMES model results as a proof-of-concept. This approach provided the framework to plan necessary network strengthening so that it remains sufficiently sized during the transition towards a fully decarbonized future.

A reliability study was conducted on the French electric system. The associated TIMES model was formulated to study renewable integration into the grid [10]. Finally, a spatiality study was done and consisted in designing generating mix distribution scenarios over the French aggregated grid [11].

4 Present work

Although their operation is governed by reversibility (as we can see in section 2 of this report), electrical systems exhibit, globally, a low efficiency (around 30%) and are the first CO2 emitters in the world (about 45%). Energy efficiency on demand side and the massive introduction of highly dispersed renewable energies (generation side) is often considered as a means of improvement. Therefore, it is a conceptual and technological breakthrough since:

- electrical energy has so far been considered non-storable, at least on a large scale, forcing the regulator to adapt generation and consumption in the real time (power constraint) ;
- centralized systems, specifically favored for their ability to be piloted in power, would be progressively transformed to allow a more or less large part of intermittent generation (non dispatchable).

We now have some roadmaps for electrical systems implementation – even some experiments in isolated contexts (islands) or demonstrators – including a large proportion of intermittent renewable energy without any focus on spatiality, cost (including aging) or compatibility with climate objectives, are not fully evaluated on the prospective horizon they purport to serve (typically 2050). Furthermore, these scenarios are elaborated considering a trend of the electrical uses where the competition between energy vectors is not taken into account. Finally, the results are not sensitive to the requirement of reliability and adequacy that are imposed on the electrical systems as the share of renewable energy increases.

While electrical uses represent nowadays around 20% of the final energy consumption but exhibit stronger growth than any other vectors, this mission aims at forcing:

- for a limited period, the migration of uses towards electricity, for example by giving priority to electric mobility use in transport sector or heat pumps uses in the residential and tertiary sectors or to systematically electrify industrial processes. A focus on the adequacy of some regional power grids was conducted.
- a low carbon generation use under a reliability constraint power-systems short-term dynamics.

Our methodology consists of analyzing different electrification and decarbonization scenarios[1] under TIAM-FR, which is a Bottom-up optimization model. TIAM-FR's results provide, inter alia, the power generation mix for the milestone year of the study (2050 in this study). The resulting power systems do not take into account neither uncertainties on the load curve nor on the availability of power generation facilities. The intermittency of variable renewable energy sources is particularly not considered. Hence ANTARES, a probabilistic tool for electric systems, enables us to analyze the adequacy of some regional power mixes obtained by TIAM-FR. ANTARES and TIAM-FR formalisms are described in sections 5 and 6.

5 Markal TIMES and TIAM, a prospective tool for our study

All the prospective optimization works related to the electrification pathways in this report are done with TIAM-FR, a TIMES-built model. Markal-TIMES is a bottom up representation of the energy system at a world-scale with highly disaggregated technologies, both for technical and geographical distributions. It is a model generator which defines coherent linear links between all data uploaded, then resolved by a mathematical solver. The solution is the lowest discounted cumulative costs over the studied time horizon that maximizes societal welfare with its technical and investments repartition, the energy flows and the emissions levels [12].

TIAM-FR is the French development of the TIAM model by the CMA, which means "TIMES Integrated Assessment Model". It is based on a recent approach Markal-TIMES with climate module integration and data from ETSAP. This model describes the whole world by dividing it into 15 global structurally close regions as illustrated in Figure 4, for further information about the countries of each region, please refer to Annex 13.2.

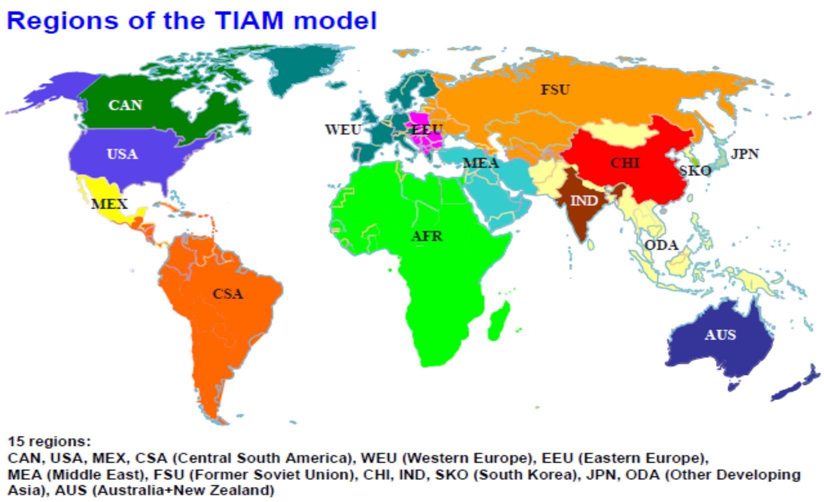

Figure 4: geographical disaggregation in TIAM models

Every region has its own end-use demands for each sector. Energy service demands are projected from year 2010(beginning of the horizon) to 2100 using general economic and demographic drivers, like population, GDP and GDP per capita[12]. In other words, we know the starting point and the global tendencies and the prospective tool gives us an overview of possible long-term evolutions, in order to conduct sensitivity analysis. The model has been calibrated to IEA extended energy balance data, divided by expert judgment to

[1] the description of our scenarios is given in section 9

define the split of fuel consumption between end-use energy service demands. Something essential to remain is that all costs are given in current US$ of year 2000[2].

The Reference Energy System (RES), or topology of the model, represents the entire energy chain and contains all transformations of fossil fuels, nuclear, biomass and renewable from potential states until the final demands. Each conversion process is a brick with commodities in and commodities out linearly linked by a yield, investment, operation and maintenance costs and a lifetime. In the TIAM-FR model, there are more than 3000 processes and 500 commodities, which provide a glimpse of its complexity. The final demand is finally divided into 42 final demands corresponding to Agriculture, Commercial, Residential, Transport and Industrial services (See annex 13.1).

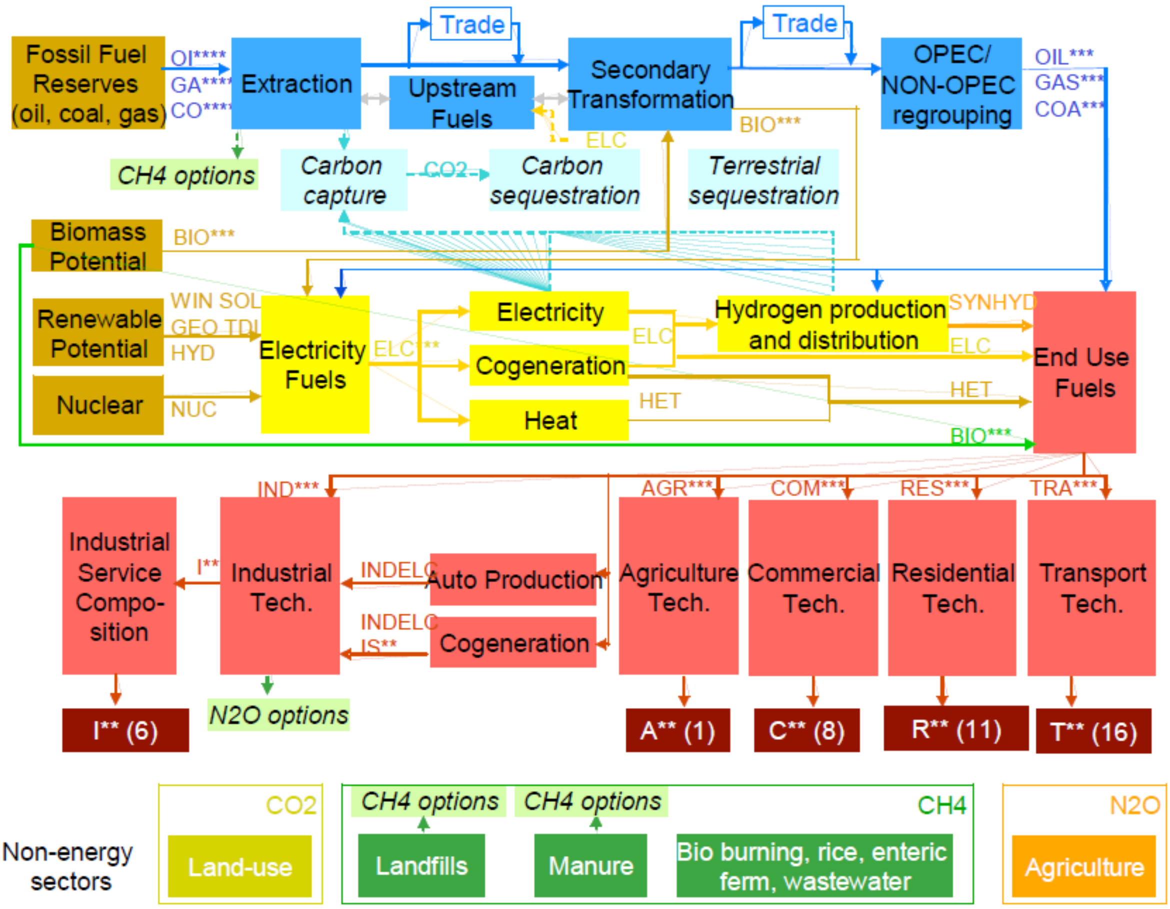

Figure 5: Representation of the reference energy system of TIAM

The GAMS solver is then called to optimize the repartition between all the identified processes in order to minimize the actualized cumulative costs under linear constraints, which represent physical constraints and various scenarii. Each new run of TIAM simultaneously recalculates the equilibrium with energy produced and consumed, energy prices, technologies adoption and abandonment, emissions and emissions prices, climate variables and demand for energy services [12].

[2] Starting from now, each "$" sign refers to "2000US$".

VEDA is an interface that translates TIMES language into readable files. VEDA_FE (Front End) converts Excel documents gathering all data into .dd files and launches the solver Gams. VEDA_BE (Back End) allows the modeler to interpret its results through interactive tables.

6 ANTARES, a probabilistic tool for electric systems

ANTARES is a Monte-Carlo software designed for power systems analysis[3] that was set open source since July 2018[4] [13].

In terms of power studies, the different fields of application Antares has been designed for are the following:

- **Generation adequacy problems:** assessment of the need for new generating plants so as to keep the security of supply above a given critical threshold. What is most important in these studies is to survey a great number of scenarios that represent well enough the random factors that may affect the balance between load and generation. Economic parameters do not play as much a critical role as they do in the other kinds of studies, since the stakes are mainly to know if and when supply security is likely to be jeopardized (detailed costs incurred in more ordinary conditions are of comparatively lower importance). In these studies, the default Antares option to use is the "Adequacy" simulation mode, or the"Draft" simulation mode (which is extremely fast but which produces crude results).
- **Transmission project profitability:** assessment of the savings brought by a specific reinforcement of the grid, in terms of decrease of the overall system generation cost (using an assumption of fair and perfect market) and/or improvement of the security of supply (reduction of the loss-of-load expectation). In these studies, economic parameters and the physical modeling of the dynamic constraints bearing on the generating units are of paramount importance. Though a thorough survey of many bearings on the generating units are of paramount importance. Though a thorough survey of many generation adequacy studies. In these studies, the default Antares option to use is the "Economy" simulation mode.
- **Economic assessment of generation projects:** unlike the adequacy simulation mode, a market modelling is needed to determine which plants are delivering power at a given time. A "perfect market" competition assumption is made under this mode, which is translated into market bids based on short-term marginal costs, yet, other bidding strategies are possible [14].

As illustrated in Figure 6, the simulation scheme consists of 4 steps:

- **Step 1:** for each parameter, generation or retrieval of year-round times-series, with an hourly resolution.
- **Step 2:** creation of a Monte-Carlo scenario, the output of this step is an annual scenario for demand and generation called a "Monte-Carlo year".
- **Step 3:** hydro storage management, the annual or monthly hydro storage energy is broken into weekly amounts through a Heuristic based on the scenario's data, hydro management policy parameters and reservoir rule curves.

[3] ANTARES was developed by RTE, the French transmission system operator. Its main mission is to ensure at all times that there is a balance between supply and demand of electricity.
[4] Link to download the software: https://antares-simulator.org/news/

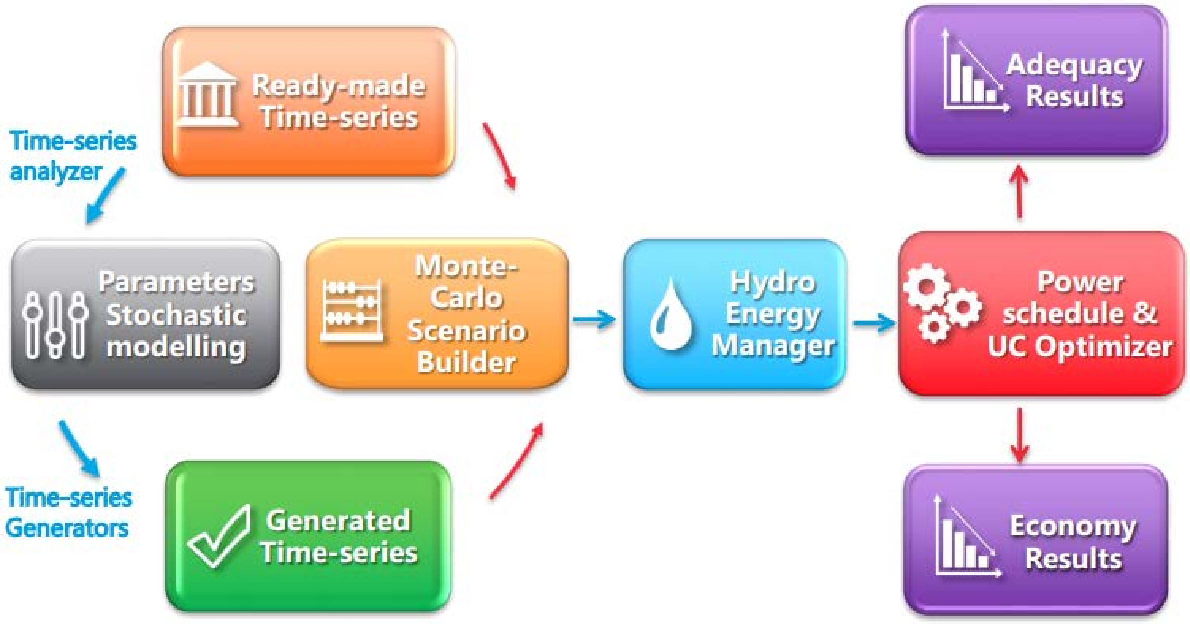

Figure 6: ANTARES in one glance [14]

- **Step 4:** simulating the system using "adequacy" or "economy" mode.

Hereafter, we will give an overview of electricity use by sector and detail shares that electricity could reach by 2050 before describing our scenarios.

7 Electricity use by sector

Today, electricity accounts for 19% of total final consumption [1]. Its high conversion efficiency means that electricity provides more useful energy per unit than other fuels, and as a result it meets 27% of useful energy demand[5]. Electricity powers a multitude of end-uses (Figure 7). The share of electricity is largest in the buildings sector, accounting for 32% of buildings energy demand and 47% of useful energy demand (Figure 8). Appliances alone account for over 20% of total global electricity demand. Cooling accounts for a further 9% and has been propelled higher by 4.3% per year since 2000 by an expanding middle-income population living in hot and humid regions.

End-use applications in industry account for 40% of global electricity demand. Non-energy intensive industries account for around 20%, mostly for motor-driven systems (including fans, compressors and drives). Chemicals, iron and steel, and aluminum production together account for around 15% of electricity use worldwide. Aluminum production grew at 6% per year since 2000, leading to a 5% electricity growth in that sector – the fastest rate among end-uses in industry.

The transport sector only accounts for around 2% of electricity demand. Currently, rail is responsible for more than two-thirds of this. It is the road component, however, that is the fastest growing as the sales of electric vehicles swell, up from a very low base.

[5] Useful energy refers to the energy that is available to end-users to satisfy their needs.

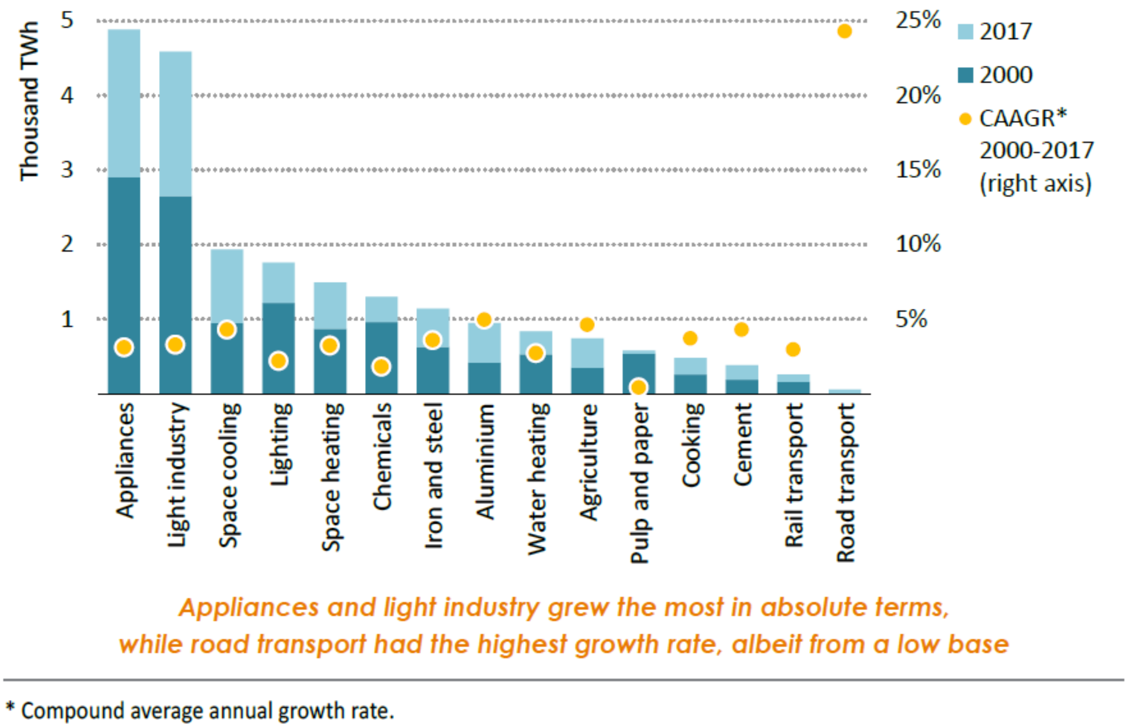

Figure 7: Electricity demand growth by end-use, 2000-2017 [1]

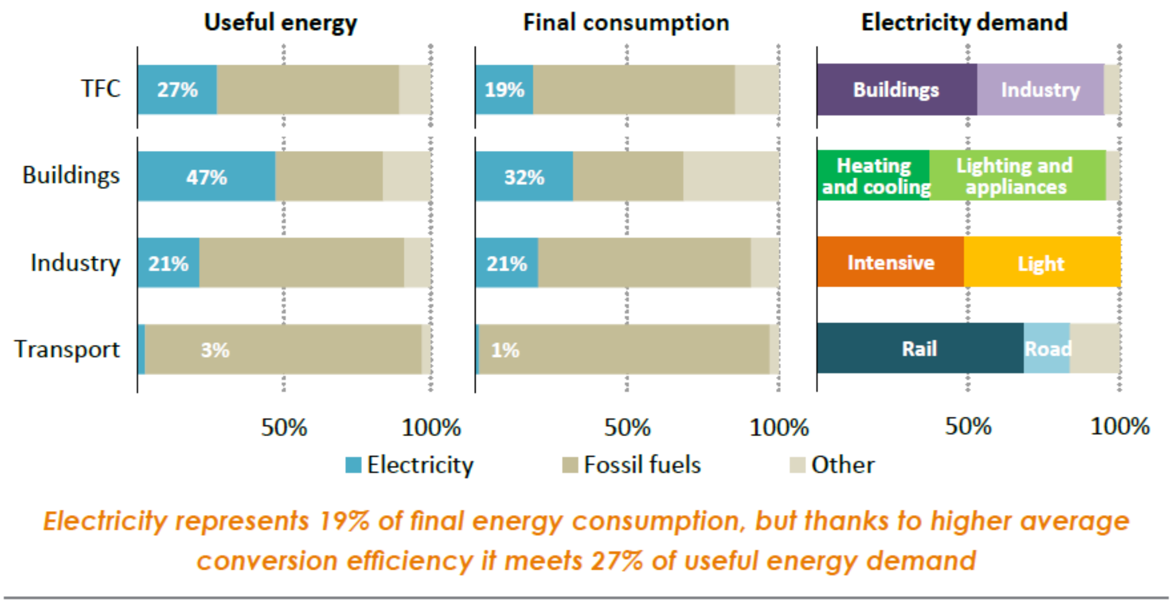

Figure 8: share of electricity measured in terms of useful energy delivered and TFC (total final consumption), 2017 [1]

8 Electrification potential, towards an "all electric" world

In the coming pages, we aim at giving an overview of the actual electrification potentials. We do not intent to give a forecast in this section. Yet, we have analyzed different decarbonization and electrification scenarios which have been done at different scales.

8.1 Buildings electrification

With 71% in advanced economies and 40% in developing economies, buildings were already the highest electricity consumers in 2017[1]. In principle, all buildings energy applications can be electrified, and fossil fuels dependence could be avoided in all buildings uses. In particular, one-third of space heating could be provided by electricity by 2040 [15]. The share of electricity in final energy uses in buildings is set to attempt 68% by 2050 according to IRENA [16]. The possibility of 100% electric buildings relies on the switching of space and water heating and cooking applications to full electric. Indeed, heat pumps achieve energy efficiencies up to five times higher than fossil fueled boilers and can be powered by renewable energy. Under the REmap[6] scenario of IRENA, heat pumps would cover 28% of space heating by 2050, increasing from around 20 million today to around 253 million units in 2050 [16]. The shift in cooking from fossil fuels to electricity would help increase energy efficiency: electric stoves, such can cut energy demand of cooking three to five times.

8.2 Transport electrification

The transport sector shows a high dependency on fossil fuels (more than 90% in 2017 [17]). Furthermore, oil consumption in transportation represents 25% of worldwide energy consumption. 43% of this energy is devoted to small distance light road transportation. Electrification is particularly adapted to such travel modes. An acceleration of electric vehicles penetration in the early 2030s would lead to a disruptive transport electrification scenario. Recent studies have shown that 10-30% of fossil fuels use can be replaced through electrification by 2040 [18]. The potential estimated here thus corresponds to full electrification of small intra-urban light road travels. It is considered that heavy road traffic, maritime and aviation travels would keep relying on fossil fuels. However, technology is only at its beginnings, and it is possible that new discoveries expand the perimeter of application of electric technologies in the decades to come. With these assumptions made, it is possible to evaluate the potential of electrification of the transportation sector. We reuse here a specific study made in another publication [19]. The light road segment shows great diversity across regions. Indeed, the share of light vehicle transportation (among all types of transportation) strongly varies from one country to another. It typically reaches 79% in North America (60% in Europe), but barely tops 7% in India. The REmap analysis of IRENA shows that an accelerated uptake of renewables could raise the number of light duty vehicles to over 1 billion by 2050.

8.3 Industry electrification

The technical opportunity for electrification is hard to estimate in the industry sector because of the variety of its applications. According to the Energy Transition Commission [15], electro-thermal technologies could enable significant process energy electrification: 85% in the pulp and paper industry using induction and electric arcs, 80% in cement production (mainly for clinker calcination) using electro-thermal dryers, 65% in chemicals and petrochemical segments using electro-thermal furnaces and 25% Alumina production. Under the REmap scenario of IRENA, electricity would meet 42% of industry's energy needs by 2050 [16].

At the best of our knowledge, the share of electricity in total final consumption achieved by 2050 in the REmap scenario by IRENA [16] is the highest share announced in a long-term planning exercise. Hence, we use the results of this study to build our intermediate scenario as explained in the following section.

[6] Renewable energy roadmap analysis by IRENA

9 Scenarios description

As was stated before, this study aims at analyzing technical economic implications of electrifying transportation, commercial and residential buildings and industry at a worldwide scale. Thus, scenarios developed in this report can be divided into three families: the business as usual scenario, an intermediate electrification scenario and a voluntarist scenario.

- **The business as usual scenario (BAU):** a basic scenario that only considers existing policies and provides a comparison reference for all other scenarios.
- **The intermediate scenario (INT_DCRB)**: this scenario consists of electrifying end use sectors according to the results of IRENA's REmap scenario. The share of electricity in end use sectors as stated in Annex 13.6 are considered as lower bounds of added constraints to this use case. a climate constraint consisting of global neutral carbon emissions by 2100 is added to this scenario.
- **The voluntarist scenario (ELC_DCRB)**: this scenario studies the theoretical share that electricity could reach in the world by 2050. The only considered barrier to electrification in this scenario is the existence of electric technologies, no matter how expensive they are. Hence, bunkers, domestic navigation and aviation travels are not electrified in this scenario, because, to the best of our knowledge, there are no electric technologies providing costs allowing demand fulfillment for these end-use sectors. The share of electricity in end use sectors as stated in Annex 13.7 are considered as lower bounds of added constraints to this use case.

For all the stated scenarios, power facilities installation and maintenance costs are extracted from the New Policies scenario (NPS) of the international energy agency [20], which is coherent with the decarbonization scenarios since the costs of NPS scenario incorporate the nationally determined contributions to deliver the Paris agreement. An excel sheet of CapEX and OpEX costs as well as efficiencies according to the NPS scenario are stated in Annex 13.5.

10 Global results

10.1 BAU vs. the electrification scenarios

10.1.1 Final energy consumption

As illustrated in Figure 9, the share of electricity in total final energy consumption would increase from 19% today to 49%, 76% under the intermediate scenario, the voluntarist scenario, respectively, while it would reach 24% under the BAU scenario. Furthermore, total final energy consumption falls as the share of electricity increases, which is an immediate result of the high conversion efficiency of electricity as the it would be mainly be produced using renewable sources. Coal is the biggest loser under clean electrification scenarios. Mainly used for power generation and steel production, steam coal (used as fuel in power facilities) decrease to almost 0 as a coal phase-out is observed worldwide in the power sector (see section 10.1.2). As a result, the share of coal in total final consumption drops to 2%, down from 14% today [16].

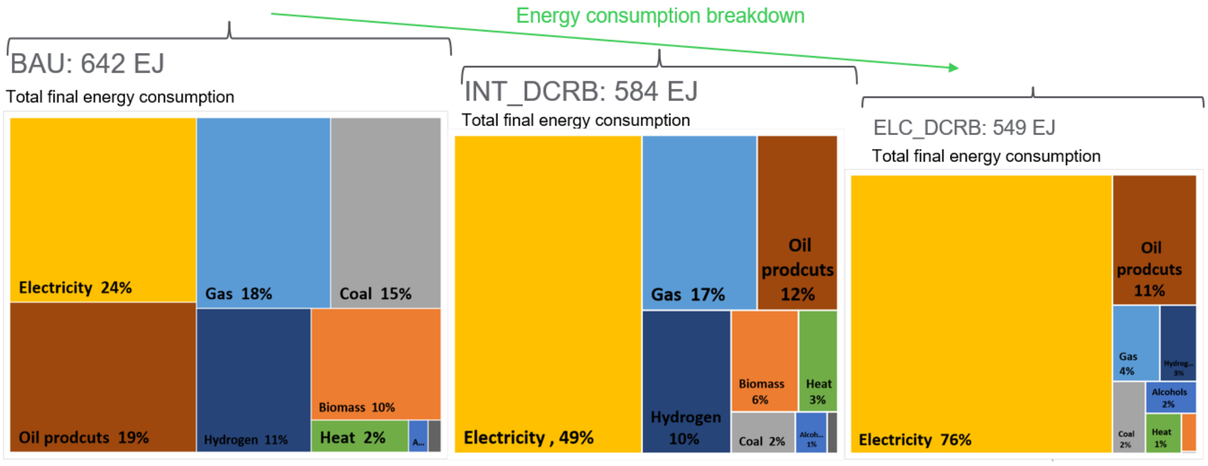

Figure 9: Total final energy consumption by 2050

Under the intermediate scenario, the share of electricity consumed in industry and buildings would double to reach 42% and 68% by 2050, under the intermediate scenario, the voluntarist scenario, respectively. In transportation, the share of electricity would increase from only 1% to 26%. Likewise, almost all transportation sectors apart from aviation and navigation would see increases in the share of electricity use. The largest growth in electricity consumption would be seen in the buildings sector for space heating and cooking, and in the transport sector for passenger and road freight.

Figure 10 details the part of energy to save per sector by electrifying end use sectors. In the industry and buildings sectors, electric heating devices are announced with an efficiency of 100%, which means that there are virtually no losses in converting electric energy into heat, while fossil fuels-based systems have their efficiency ratios lower than 85% in the best cases[21]. Furthermore, heat pumps can yield up to 3 or 4 units of heat for one unit of energy effectively consumed. In the transport sector, the efficiency of combustion engines cannot top 40, electric motors have typically efficiency ratios of 80% or above [22]. Under the INT_DCRB scenario, this is translated into 10 000 Petajoule savings in the commercial sector comparing to the BAU scenario, 35 000 Petajoule in industry, 15 000 Petajoule in residential buildings and 32 000 Petajoule in transportation. a higher electrification rate coupled with climate constraints means more energy savings, 35 000 Petajoule is to be avoided if the share of electricity in final energy consumption is to reach 76% by 2050 (ELC_DCRB), up from 49% (INT_DCRB scenario).

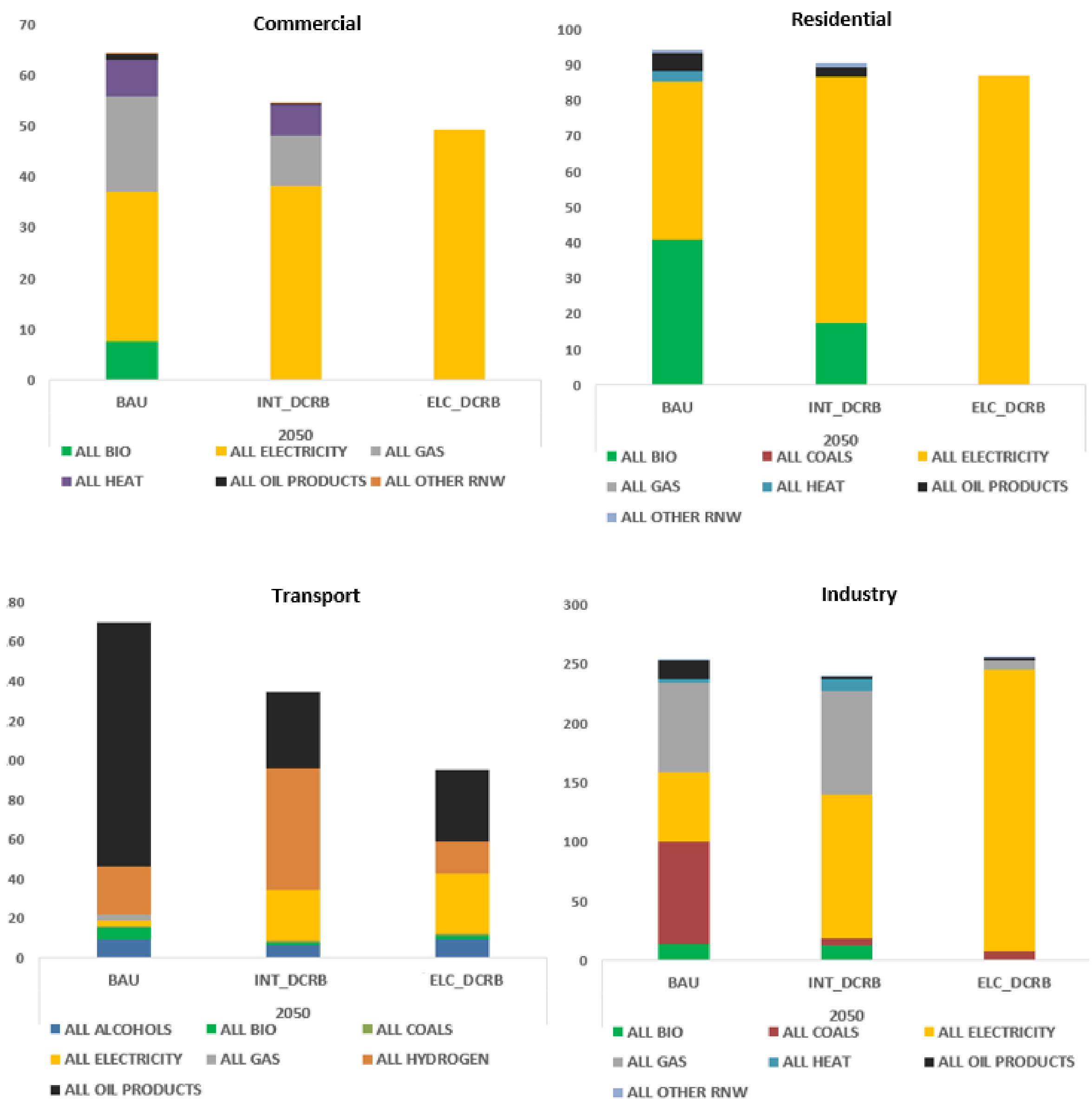

Figure 10: Total final energy consumption per sector by 2050

10.1.2 Power generation

Fossils fuels have accounting for 60-70% share of the global power generation mix since the 1970s. This trend would stop under INT_DCRB scenario. Coal, oil and gas plants would deliver 66% of the global power generation by 2050. learning rates of investment costs related to solar farms would change the renewable power generation mix, centralized solar generation would represent more than 60% of clean power generation.

Under this intermediate electrification scenario, wind and solar technologies would provide 50% of total electricity, with hydro, nuclear and other renewable sources providing further 21% (see Figure 12), only 27% of power generation would result from burning fossil fuels by 2050, down from 63% today.

As stated before, coal is biggest loser under INT_DCRB scenario. Indeed, a coal phase would be inevitable by 2050 if global carbon neutrality is to achieve by 2100 and the share of electricity is to increase by 2050. Today coal make up 37% of global power generation with China and India running 65% and 75% on coal, respectively. Pushing coal to phase-out would call for accelerated investment rates in power generation sources.

Solar sees the most growth, rising from less than 3% today to 37% by 2050, an annual average growth of 19.3%, of which 11% is deployed "behind-the-meter". Wind sees slower growth comparing to solar, its part rises from 5% today to 18% by 2050.

Hydro's share sees a moderate decrease and nuclear part stay flat because of solar and wind decreasing investment costs. These two technologies become globally cheaper then hydro and nuclear by early 2030s according to the New Policies Scenario of IEA.

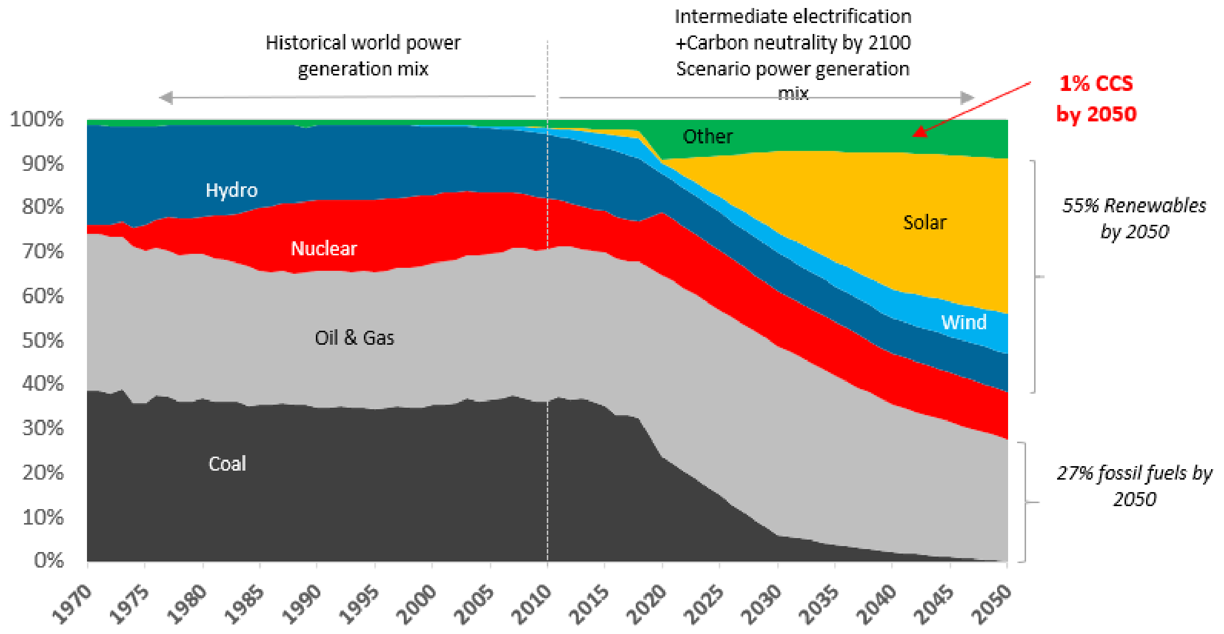

Figure 11: global power mix between 1970 and 2050, INT scenario

Electrifying at 49% the end use sectors would require an additional 70 613 TWh of power generation across the world. The increase in power generation requires 21 066 GW to be commissioned between now and 2050 under the INT_DCRB scenario.

Many changes on the power generation mix are observed between the intermediate scenario (Figure 11) and the voluntarist scenario (Figure 12). Under ELC_DCRB scenario, coal phase-out would be done at a slower rate, a slight increase in coal-based generation would take place in 2020 before coal's share drops to 1% by 2050 at an annual rate of 30%. Furthermore, oil and gas-based generation would peak by 2030. By 2050, 34% fossil fuels would be used to generate electricity against 27% for the intermediate scenario. Power generation would rise to 196 261 TWh, 8 times higher than 2018's global power generation and double the generation that would be reached under the intermediate scenario. About 64% of this generation would be fuel-free, exposing many countries to less primary energy dependency and to volatile commodity prices. Moreover, 6% of CCS would have been implemented under the voluntarist scenario, to fully satisfy the climate constraint, against 1% under the intermediate scenario. the of oil and gas-based generation by 2030 is owed to the high electrification ratio in this year compared to the electrification ratio reached the same year under the intermediate scenario.

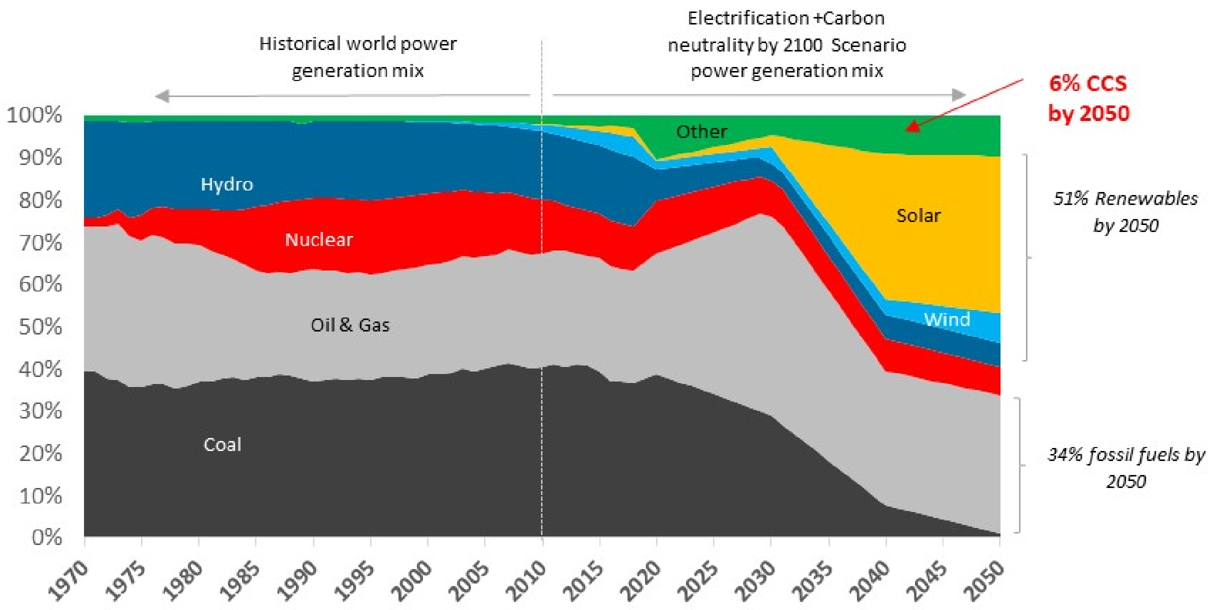

Figure 12: global power mix by 2050, ELC_DCRB scenario

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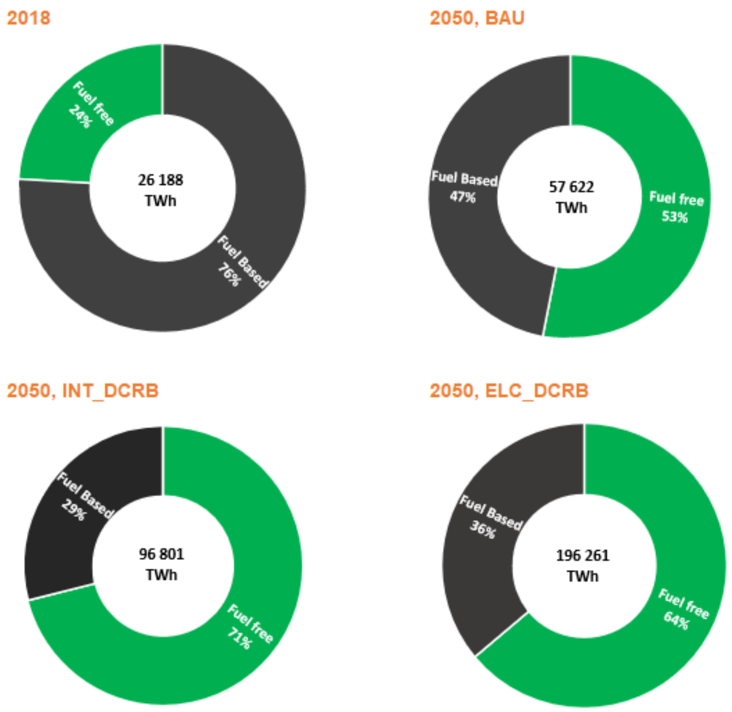


Figure 13: global power generation, while electricity stand for 19 % of final energy in 2018, it rises up in 2050 respectively to 24%, 49%, 76% for BAU, INT_DCRB and ELC_DCRB, respectively.

Electrifying at 76% (ELC_DCRB scenario) would be translated into a global capacity generation 10 times bigger than 2018's power generation capacity. Variable renewables sources and oil and gas facilities would account for more than 80% of the global capacity (Figure 14).

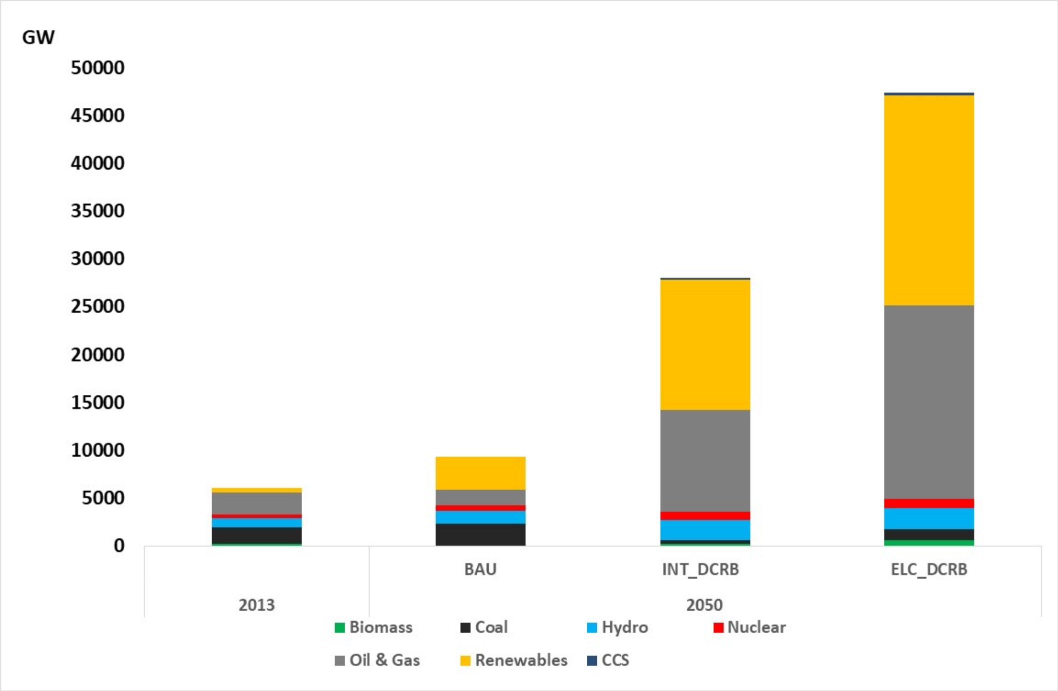


Figure 14: global generation capacity mix by 2050

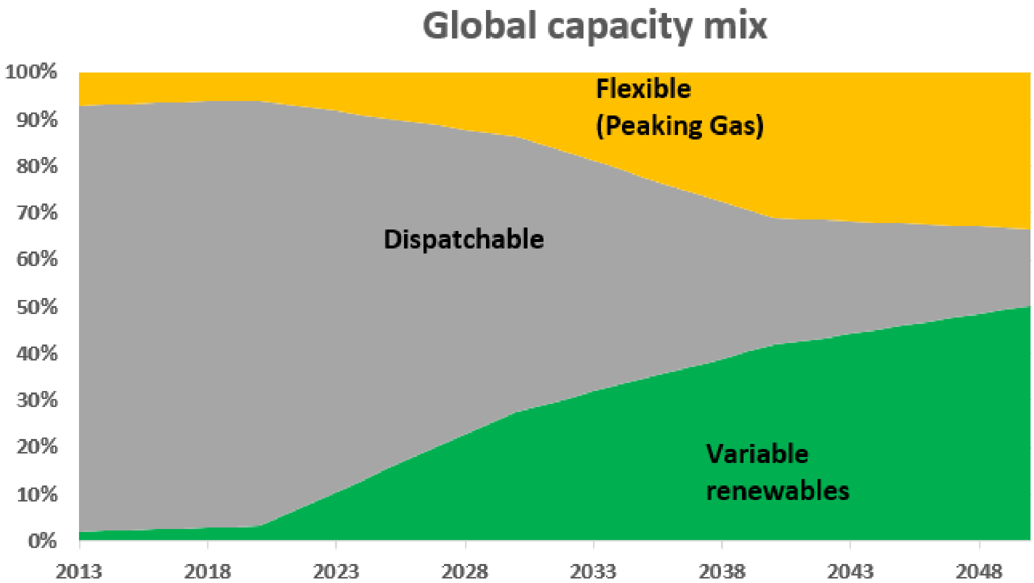


Figure 15: global capacity by category, INT_DCRB scenario

By 2050, the world's electricity system would have been remade almost around solar and wind as bulk generation and peaking gas plants that provide flexibility. These two groups of technologies together would make up 81% of installed capacity in 2050 up from 23% today (Figure 15).

The overall result here is that variables renewables supported by an important capacity of flexible gas can help decarbonize almost 50% of power generation. This result should be strengthened by including different type of batteries: pumped hydro (PHES), compressed air energy storage (CAES), small-scale and utility-scale batteries, as well as demand-side flexibility. For this purpose, the number of Times Slices in TIAM-FR model must be increased to capture the inertia of these storage assets.

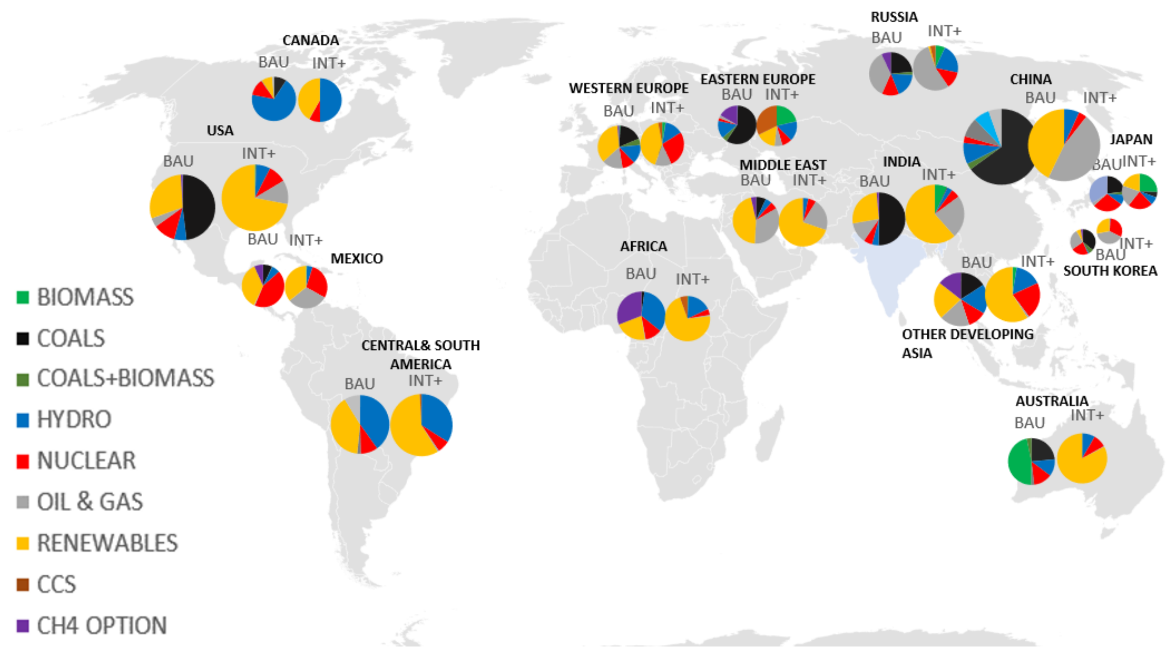


Figure 16: regional power generation mix by 2050 under BAU and INT+, INT+ refers to INT_DCRB scenario, The size of circles is the same for BAU and INT+, which does not reflect the ratio of production between the two scenarios. In fact, since we electrify in INT+ Scen, power generation is higher compared to BAU (see Figure 13).

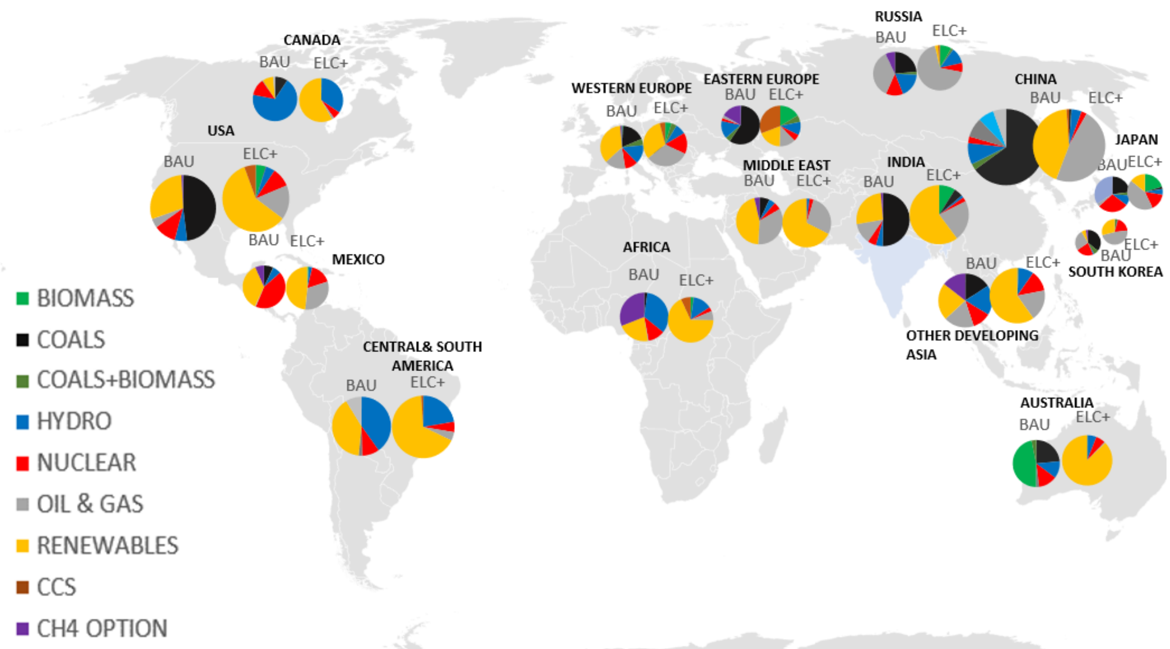


Figure 17:Figure 17: regional power generation mix by 2050 under BAU and ELC+, ELC+ refers to ELC_DCRB scenario, The size of circles is the same for BAU and ELC+, which does not reflect the ratio of production between the two scenarios. In fact, since we electrify in ELC+ Scen, power generation is higher compared to BAU (see Figure 13).

The power generation mixes showed in Figure 14 conceal many regional disparities as illustrated in Figure 16 and 18. China would rely on variable renewables supported by a considerable oil and gas-based production (About 48% of China's power generation by 2050) under the electrification scenarios against more than 70%

of coal-based generation under the BAU. The United States of America would see 75% of its dispatchable generation switched into intermittent renewable sources.

Therefore, the question of transient stability is particularly relevant for the electrical mix in the USA (see section 2.1). The adequacy of the power system in this region is not analyzed in this report because of a lack of data. We then decided to analyze the adequacy of the western European power mix later in this report (see section 10.2).

10.1.3 Emissions

Combining electrification with global carbon neutrality by 2100 would have a positive impact on electricity related emissions under the intermediate scenario. Under the intermediate electrification scenario, global power sector emissions may have peaked in 2018 at 13 780Mt. Between 2020 and 2030 emissions fall by around 5.1% per year to 4 770Mt, half than today's value (Figure 18). Under the voluntarist electrification scenario, the considerable use of Oil & gas-based generation starting from 2040 results in a continous rise in power sector-related CO2 emissions until 2050. These emissions would have reached 11 371 Mt by 2050, 4 727 Mt less than the value that would have been reached under the BAU scenario (Figure 18).

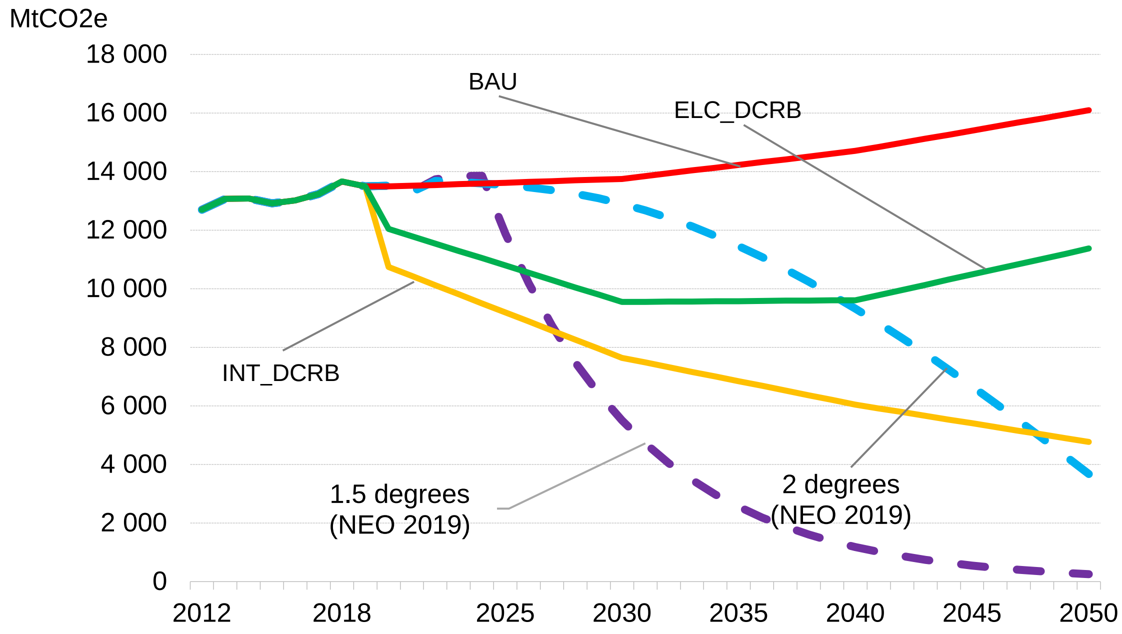


Figure 18: trajectories for CO2 emissions related to power generation, comparison to New Energy Outlook of Bloomberg (NEO2019)

Trajectories of emissions illustrated in Figure 18 conceal considerable country-level variation. In Europe, the decline of coal and high penetration of free CO2 technologies drives down emissions quickly, at around 5% per year. This allows achieving carbon neutrality in the power sector for Europe by 2050. Emissions peak in India in 2030 before a slight reduction takes places at a rate of 0.5% until 2100. Southeast Asia (ODA in Figure 19) is one the fattest growing economies in the world [1]. Despites, this region would have divided its power-related emissions by 2 in the next thirty-one years.

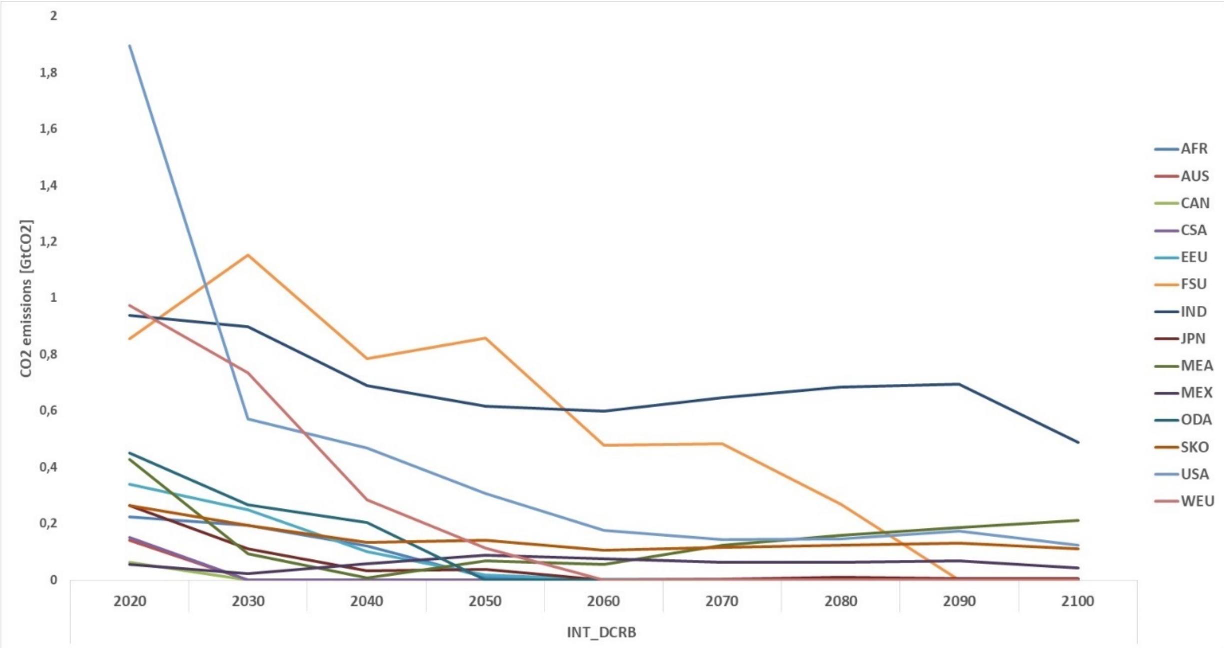


Figure 19: trajectories for CO2 emissions by region under INT_DCRB scenario

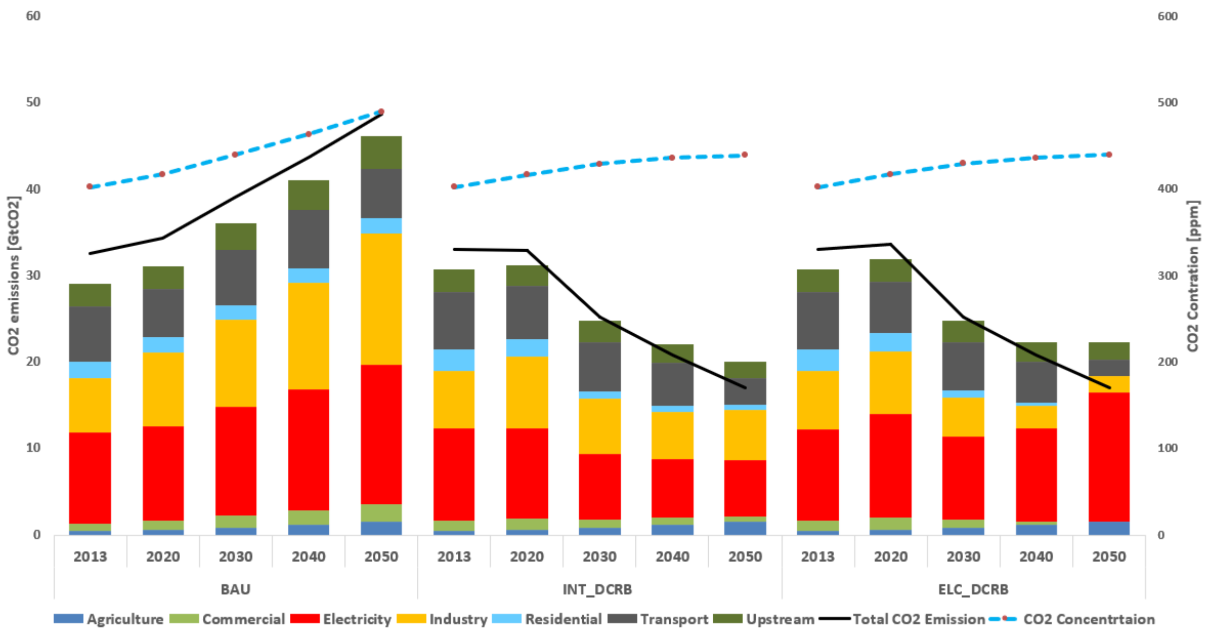


Figure 20: Overall CO2 emissions between 2013 and 2050

Figure 20 shows the overall CO2 emission between 2013 and 2050. Under the BAU scenario, the power sector would remain the 1st emitter of CO2 with 16 059 Mt by 2050. Industry-related CO2 emissions would rise to 15 290 Mt by 2050 up from 6 204 Mt in 2013. Under the electrification scenarios, Industry would see its emissions peak by 2020 respectively at 8 281 Mt, 7 215 Mt under INT_DCRB, EL_DCRB. By 2050, the industry would emit less CO2 than 2013's unregistered value, these emissions would notably reduce to 1 925 Mt under the voluntarist scenario. The same conclusions are noticed for the transport sector, which would reduce its CO2 emissions to, respectively, 3 026 Mt, 1 955 Mt by 2050 as the share of electricity increase in transportation.

It is notable that, under the electrification scenarios, the net CO2 emissions (the black curve in Figure 20) are not equal to the CO2 emissions resulting from all the sectors in Figure 20 starting from 2040. The net differential corresponds to the amount of carbon capture and sequestration needed to compensate CO2 emissions as shown in Figure 21. We have tested scenarios of electrifications without activating CCS over the horizon of optimization. None of these scenarios converged, which translates the bumpy journey that represents the electrification scenarios.

By 2050, a total amount of 1 695 MtCO2e, 3 503 MtCO2e would have to be sequestrated worldwide under the intermediate, the voluntarist scenario, respectively. 62 % (respectively 59%) of which would have to be achieved by enhanced coal bed methanation removal under the intermediate scenario (respectively under voluntarist scenario). The United States, the first country in the world to number of storage tanks [23], would see the largest CCS installation. Some of the Petroleum Exporting Countries, especially the middle east countries, Mexico and some African countries would have to increase enhanced oil recovery to attempt 215 MtCO2e (respectively 437 MtCO2e) under INT_DCRB scenario (respectively ELC_DCRB scenario). Yet, carbon capture and sequestration would require advanced research and development for the next few years to make it cost-effective and to answer some opened questions particularly with regard to the risks related to short-term CO2 leakage (acidification of surface or groundwater bodies) or long-term (lack of efficiency in the fight against climate change) [24].

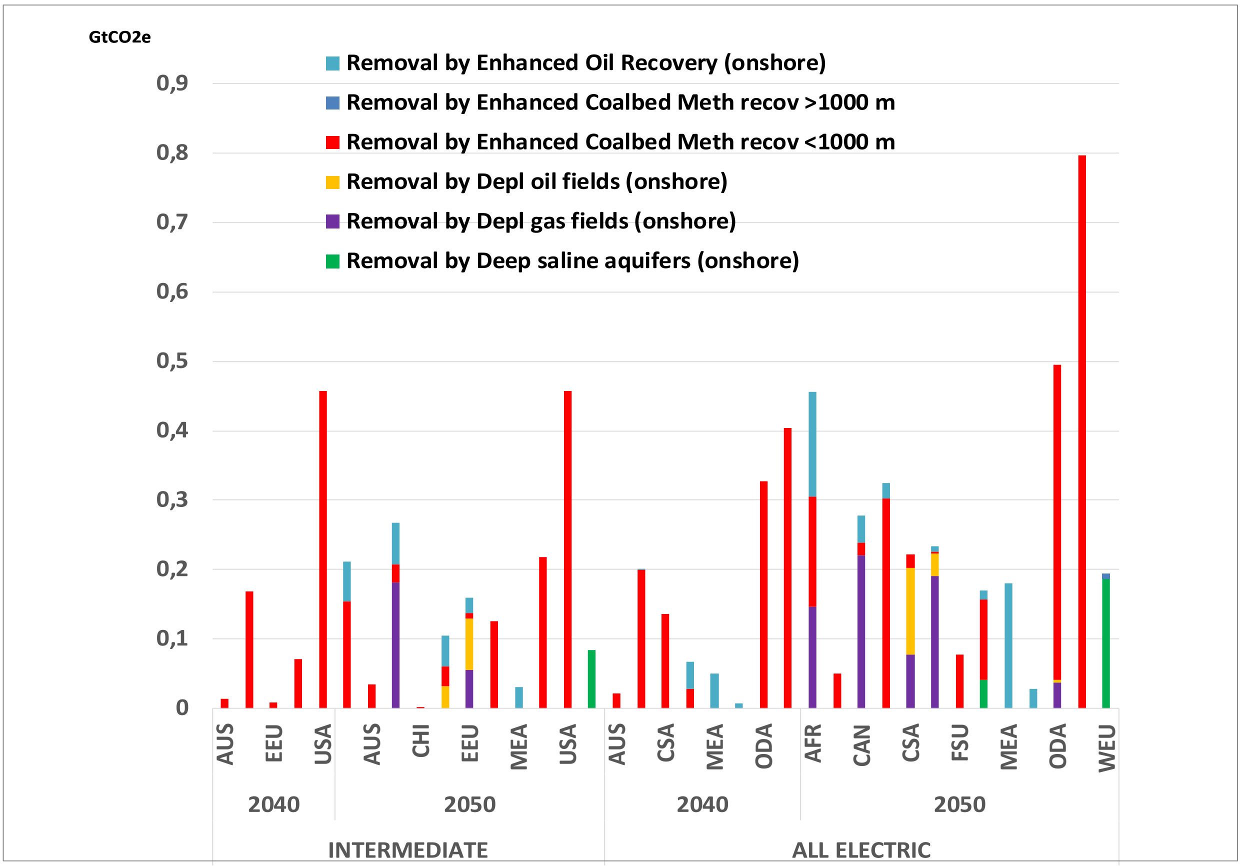


Figure 21: Total avoided CO2 emissions between 2040 and 2050

10.1.4 Investments

A total amount of 6.76 trillion $[7], 9.14 trillion $ would have to be invested up to 2050 in the power sector respectively for INT_DCB scenario, and for ELC_DCRB scenario. China sees by far the most new investment (Figure 22), at 1.80 trillion $ under INT_DCRB and 2.69 trillion $ under ELC_DCRB, China accounts for almost one-third of the world investments in the power sector. India and U.S.A come in the second place. Africa, Australia and Western Europe would require about 0.76 trillion $ (respectively 0.97 trillion $), 0.05 trillion $ (respectively US$0.07 trillion) and 0.48 $ trillion (respectively 0.57 trillion $), to support new power generating capacity coming online over the next thirty-one years, respectively. Nevertheless, investments in the power sector would barely represent 9% of the total investments worldwide between 2019 and 2050. 41.5% of total investments goes to transportation, 54.1% for buildings, of which 76% for residential buildings under LEC_DCRB.

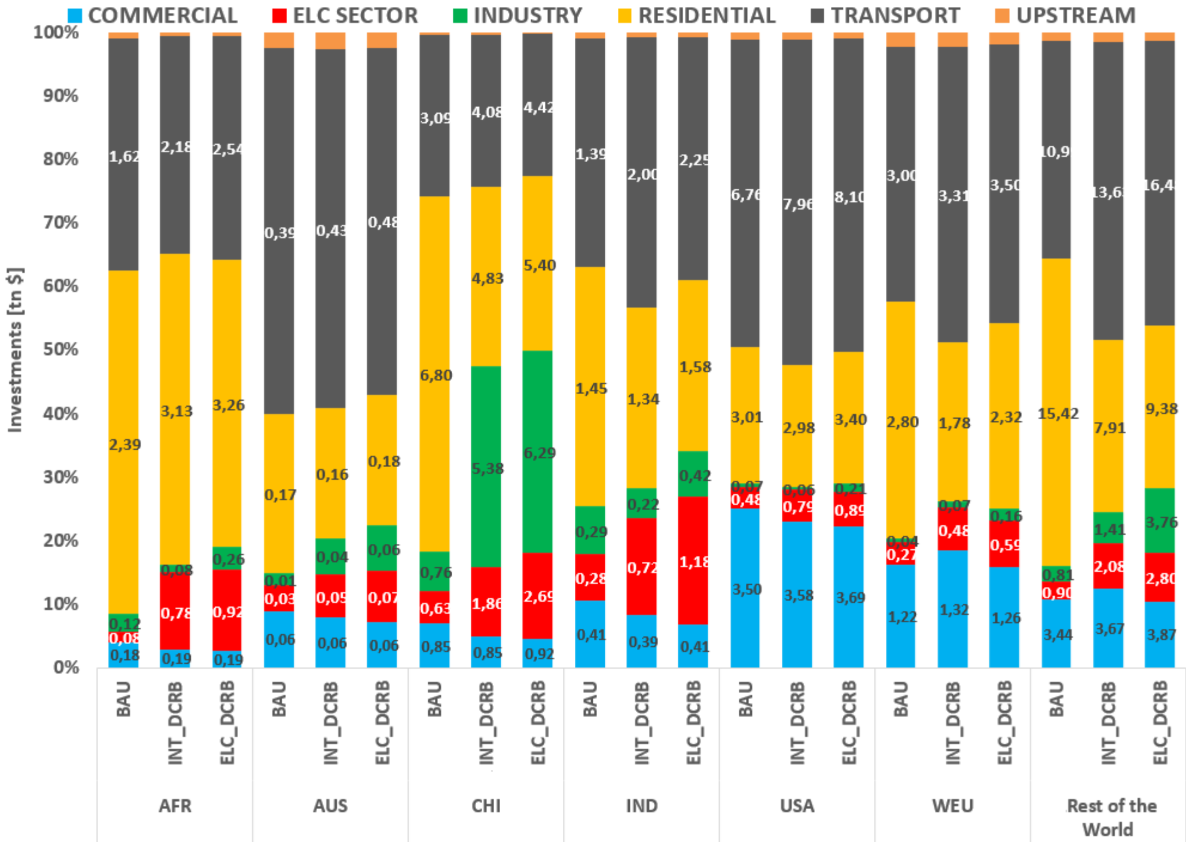


Figure 22: Overall investment costs (US$2000) between 2020 and 2050, Rest of the world englobes Canada, central and south America, Mexico, eastern Europe, Russia, other developing Asian countries (ODA), the middle east, Japan and south Korea.

The high investment in transportation could be explained by the high cost of lithium-Ion batteries, which represents the biggest barrier to mass adoption of electric vehicles, other are standardization and manufacturability. Currently, commercial Li-ion automotive-grade cells for electric vehicles cost about 350€/kWh. With an average cost for active materials of about 75€/kWh for EVs, depending on chemistry and

[7] For the following of this paragraph, $ refers to US$2000.

cell architecture, and requiring about 6kg active materials per kWh, the US Advanced Battery Consortium's once ambitious cost goal of about 200US$/kWh is indeed an achievable target [25].

10.1.5 Regional incentives options to enhance migration toward electricity: the case study of electric heat pumps in space heating

Figure 23 illustrates regional space heating by 2050 under ELC_DCRB scenario. Conventional electric equipments would dominate the market worldwide except in Japan, where electric heat pumps become cost-effective by 2040. Nevertheless, electric heat pumps can reach higher efficiency ratio; these heating devices can yield up to 3 or 4 units of heat for one unit of energy effectively consumed as shown in Figure 24. Hence, we have decided to conduct a study on the incentives to be done by governments to make electric heat pumps cost-effective in residential space heating.

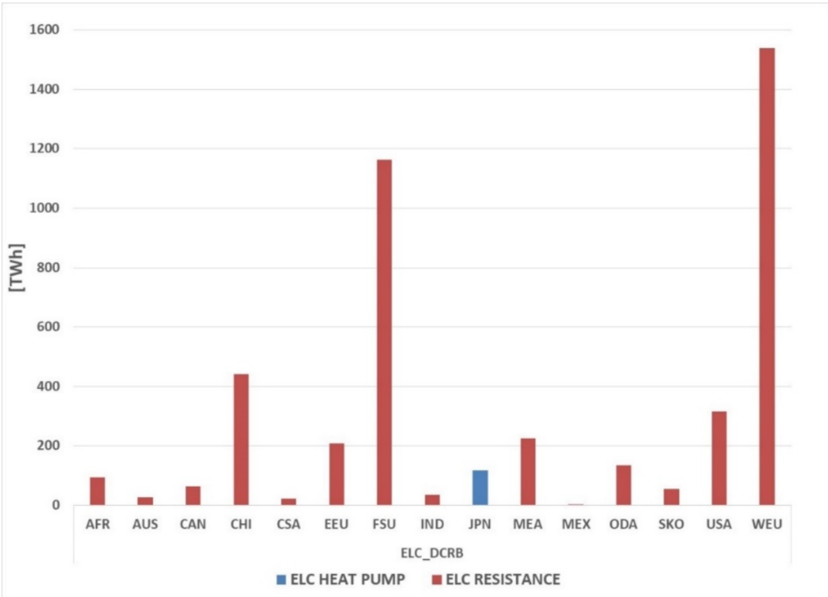


Figure 23: residential space heating consumption by 2050

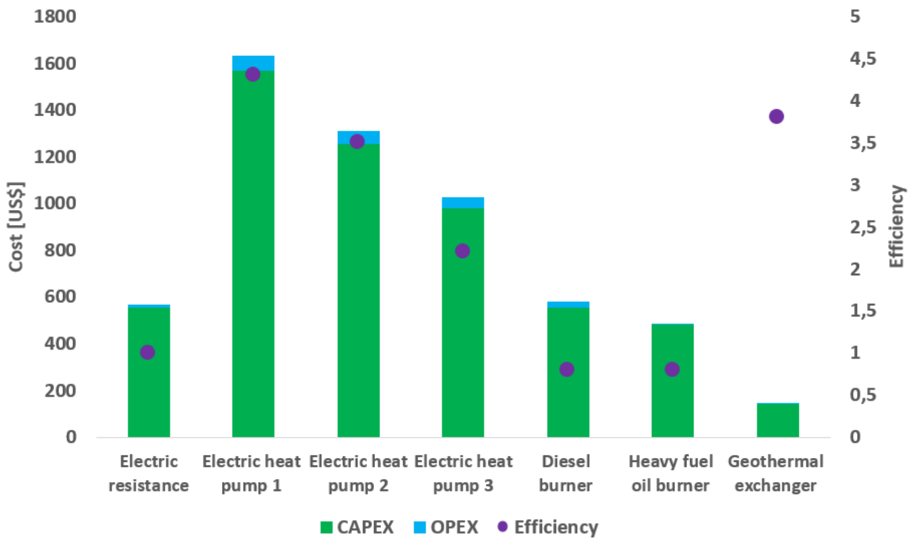


Figure 24: average costs[8] and efficiencies for different residential heating technologies

[8] The cost of a heating technology varies from a region to another in our model

For this purpose, we based our study on the reduced cost notion. For more details about our methodology, please refer to Annex 13.8.2.2.

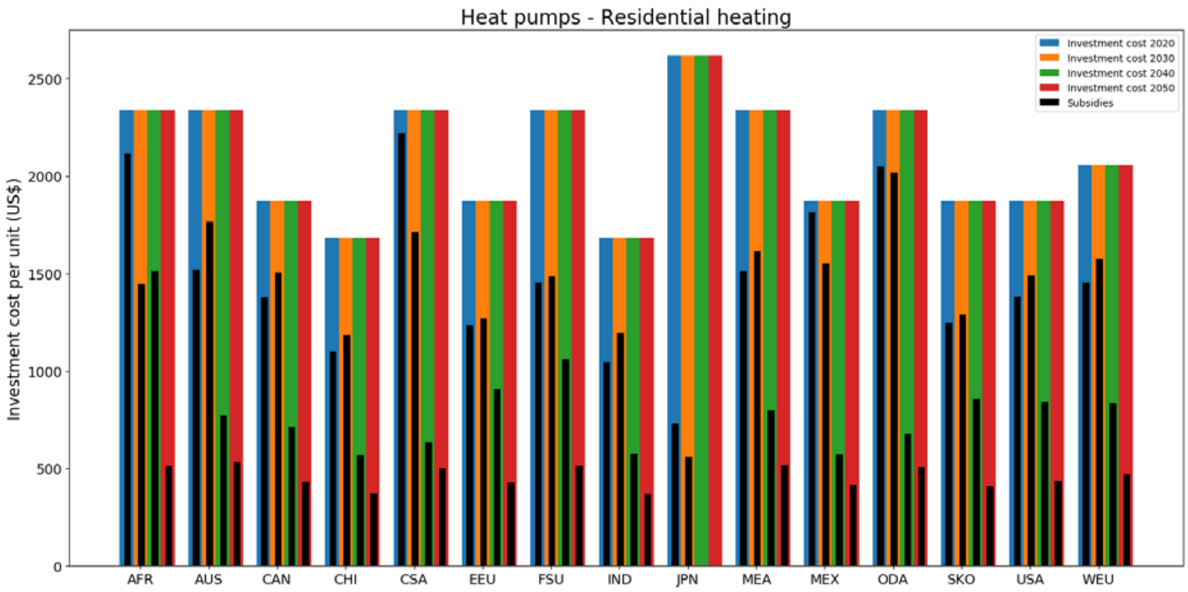


Figure 25: Investment cost per an electric heat pump (of type1) unit, for more details about this technology, refer to figure 26, the black bars correspond to the subsidies to be done to enhance the migration tword heat pumps in residential space heating

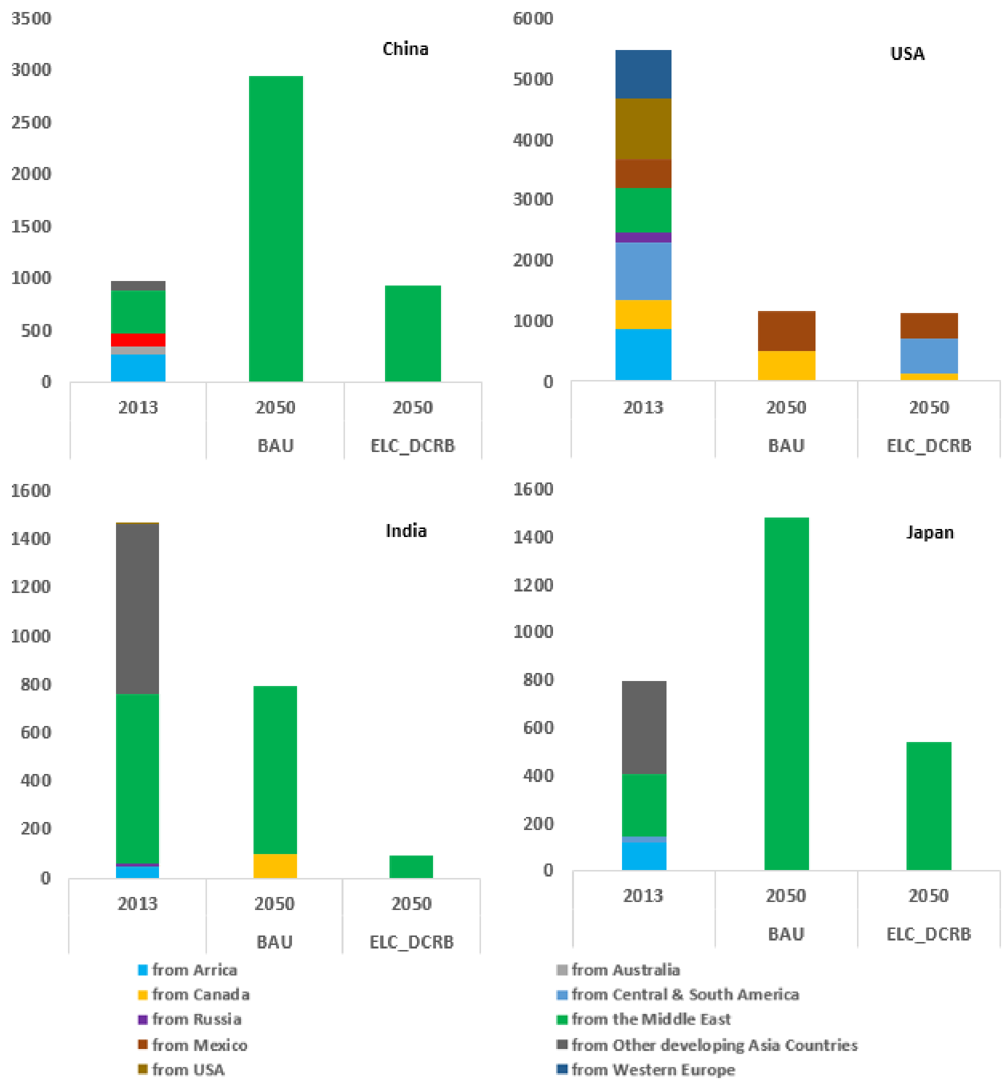
The highest subsidies would have to be put in place in developing countries; Africa, south and central America and developing Asian countries. Subsidies in Japan would have to be done only between 2020 and 2030. Starting from this year, electric heat pumps would become competitive in this region.

10.1.6 Oil imports dependency

The structural conditions in a country's economy influence correlation between oil prices and economic growth. In developing countries, a higher ratio of the economy comprised manufacturing industries, which are more energy intensive than services. Although the amount of oil used for transportation usually represents a smaller share in the total oil consumption in non-OECD countries, it tends to increase rapidly, as expanding economies increase the need to move goods and people. The per capita vehicle ownership also correlates highly with rising incomes and has considerable room to grow in non-OECD countries. For these reasons, non-OECD economic growth rates tend to be an important factor affecting oil prices. As a result of China's strong economic growth, it has become the largest energy consumer and the second largest oil consumer in the world. In addition, China's rising oil consumption has been a major contributor to incremental growth in worldwide oil consumption.

While oil consumption is primarily related to the global economic activity and thus to the worldwide total final consumption breakthrough, changes in the economic outlook (and thus of energy outlook since energy is the major fuel of economy) could have impacts on oil prices. In particular, our analyses of the electrification pathways show that by electrifying end-use sectors, the four biggest oil consumers in the world in 2018, China, USA, India and Japan, would see their oil consumption reduces significantly comparing to the Business as usual case. China's crude oil importation would multiply by 2.5 between 2013 and 2050 under the BAU scenario while a decrease is observed if green electrification takes places in the coming thirty-one years. Assumptions made on oil reserves per region lead to a more oil dependent china by 2050 under both scenarios since oil imports would be mainly from the middle East. the same trends are observed for the three other regions; oil importations would decrease if end use sectors are electrified. However, two main assumptions were taken into account:

- A perfect market competition for all the commodities including crude oil, which does not reflect the complex reality of crude oil trades around the world. Indeed, up until the middle of the 20th century, the United States was the largest producer of oil and controlled oil prices. In the years to follow, OPEC controlled the oil markets and prices for most of the latter part of the 20th century.
- The economically accessible American shale oil reserve is supposed limited in our model. This assumption does not stick with the EIA's latest records [26].



- **Figure 26: oil imports**

10.2 Power systems adequacy analyses

As highlighted before, the massive penetration of intermittent renewable sources particularly in the United States, Africa, India and Australia could have a negative impact on power supply for these regions by 2050. Two questions arise particularly: is the power grid capable of overcoming transient instabilities that could be related to a brutal increase in power demand or to an unexpected outage of a power plant? Are the regulators capable of delivering the right amount of power without a high annual loss of load duration?

To answer these questions, we chose to study the adequacy of the power mix of Western Europe in 2050. This choice is linked to the availability of data related to the load curve in this region. More details about our methodology are given below:

10.2.1 Load

As output from TIAM-FR, one gets the sum of power load over the six time slices of one year as shown in Table 1. Yet, ANTARES only takes as input "ready-made" 8760 hours Time-Series available for the simulation[9].

Day	Night	Day	Night	Day	Night
Summer		intra-season		Winter	

Table 1: Time-Slices in TIAM-FR

To generate a load curve compatible with ANTARES inputs. We assumed that the western European load seasonal profile would not change between 2019 and 2050[10]. Hence, we have scaled the European curve load of 2018 by the expected values of load curve by 2050 (The red curve in Figure 27). The blue curve is then obtained.

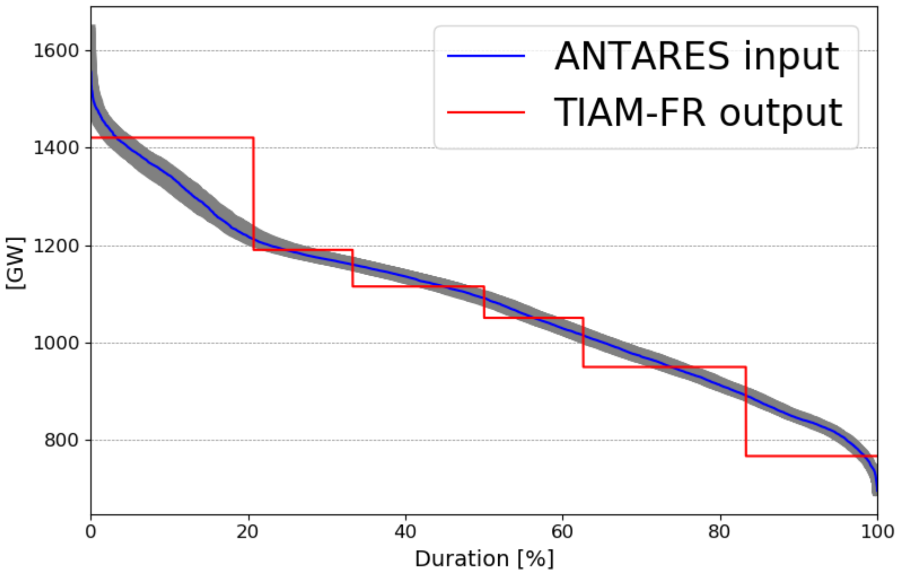


Figure 27: Load duration curve for Western Europe by 2050, the red curve represents the load duration curve obtained by TIAM, the blue curve represents the 8760 Time-Serie of LDC that will be taken as input in ANTARES, the grey surface corresponds to the dispersion considered around load duration curve, this surface compiles 100 Time-series generated on ANTARES using the Time-Series generator. Consistency is enforced by the equality of the energies below the two curves.

[9] There are different ways of generating load time-series under ANTARES as explained in [14], but the only way to consider data from any other origin outside ANTARES is to dispose of one 8760 hours times series at least.

[10] This is a strong assumption, as this region has been experiencing high temperatures for the last few years and cooling demand has increased since 2010 as a result. Henceforth, he steady increasing cooling demand could change the load curve by 2050 if the trend continuous.

The load is modelled by the blue curve in "mean climatic conditions" to which is added a climatic deviation process simply modelled by a normal process whose standard deviation ranges from: 0*3GW = 0 GW in June to 1.5*3GW = 4.5 GW in January[11]. The autocorrelation function of this process is such that the climatic deviation at any given time is 50% correlated with that obtained a week before. This method seems pertinent since the European power load shows high sensitivity to temperature. In France for instance, this sensitivity was unregistered at 2.4 GW/°C in 2018 [27].

10.2.2 Thermal

Thermal generation englobes all available dispatchable power generation. One must adapt TIAM-FR's output to a considered format by ANTARES. Indeed, TIAM-FR provides the total installed capacity and the total thermal generation over periods. By 2050, the installed thermal capacity is shown in Table 2:

Fuel	biomass	Coal	Nuclear	Oil and Gas
Installed capacity [MW]	32 424	14 692	156 730	617 563

Table 2: installed thermal power capacity in western Europe by 2050

Many assumptions and considerations have been made to derive an ANTRES-compatible input for thermal generation:

- From a political point of Vue, only third generation pressurized water reactors (EPR) of 1450 MW could be installed in Western Europe for the next thirty-one years. This assumption seems pertinent as all nuclear reactors being constructed in thus western Europe concern 1450 MW EPRs [28].
- To dispose of flexible dispatchable units and as only the adequacy of the electrical system is analyzed[12], we decided to divide the coal-based and the oil and gas-based generation into units of 300 MW and the biomass-based generation into units of 150 MW.
- We suppose that all thermal units have a forced outage rate of 5% during the year and a planned outage rate of 10% from June to September. Hence the available power is:
    - **available power = installed power*(1-FOR)*(1-POR)/(1-POR*FOR),** where FOR stands for forced outage rate and POR stands for planned outage rate.

10.2.3 Hydro

It is possible to generate hourly time-series of hydro generation by specifying as input in ANTARES the monthly generation profile and defining the hydro management mode. For this purpose, the same method used to generate 2050's load curve was adopted; monthly hydro generation in western Europe in 2018 was extracted from ENTSO-E's free database. This monthly generation was scaled based on the 2050's hydro generation obtained from TIAM-FR. As a result, one gets the expected monthly generation presented in Table 3. The hydro generation fleet is then characterized by an average monthly energy ranging from 45 TWh to 72 TWh, out of which 37% of run of the river and 15% to 65%. Standard deviation are comprised between 5 and 14 TWh, successive monthly energies are 65% correlated.

The maximum available hydro storage generating power ranges from 60 GW to 86 GW.

[11] 3GW is the primary reserve in Western Europe, it corresponds to 2 of the biggest installed power capacities and consequently to 2 nuclear reactors of 1 500 MW each.

[12] In this study, we do not analyze the system's cost (cost of the loss of load, etc)

	Expectation (MWh)	Std Deviation (MWh)	Min. (MWh)	Max. (MWh)	ROR[13] Share
January	67629540	14345660	0	143456600	0.37
February	66604850	13320970	0	143456600	0.37
March	65580160	12296280	0	143456600	0.37
April	64555470	12296280	0	143456600	0.37
May	71728300	11271590	0	143456600	0.37
June	69678920	10246900	0	143456600	0.37
July	60456710	10246900	0	143456600	0.37
August	46111050	5123450	0	143456600	0.37
September	45086360	6148140	0	143456600	0.37
October	56357950	11271590	0	143456600	0.37
November	60456710	14345660	0	143456600	0.37
December	64555470	12296280	0	143456600	0.37

Table 3: Hydro monthly generation in western Europe by 2050

10.2.4 Solar

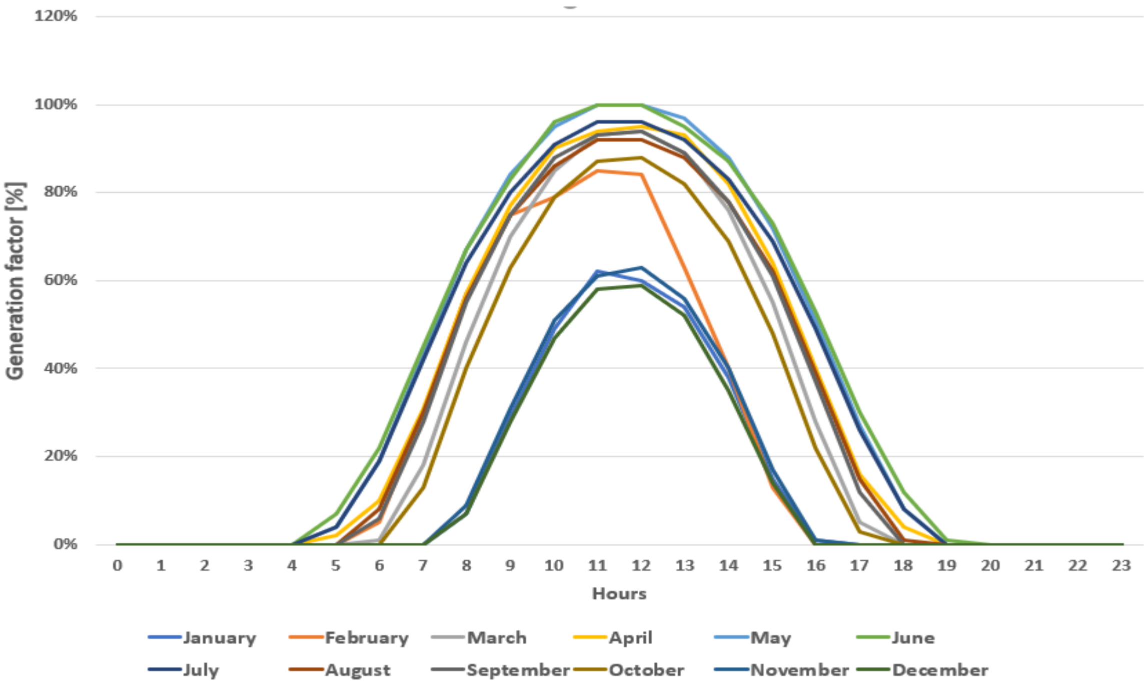


Figure 28: capacity factor of the considered solar farm

A total installed capacity of 1 098 777 MW in western Europe is obtained by TIAM-FR under ELC_DCRB. To model the production of this capacity, the maximum theoretical generation factors (Figure 28) were

[13] Run of river

considered according to RTE [29]. Nebulosity is modelled by monthly Beta processes whose parameters are specified in Annex 13.9.2.

The wind generation (expressed in percentage of power installed) is modelled by : 12 monthly Beta variables, a 12*24 hourly average profile, and 12*2 autocorrelation parameters.

10.2.5 Results

Figure 29 and Figure 30 illustrate the power dispatch decisions made by ANTRAES. Apart from Solar, oil and gas generation, the assumptions we made allow us to reproduce the same availability factors used in TIAM-FR. For solar, it is notable that even if we suppose that the generation factor is constant over the year and is equal to June's generation factor (Which does not reflect the physical reality of the solar flux received by earth), we do not reach the Solar's availability factor used in TIAM-FR. As a result, TIAM-FR's availability factor for solar should be scaled down. As market bid prices for gas-based generation are supposed to be the highest in our ANTARES simulation, oil and gas plants produce mainly at night to replace solar capacities.

When consumption reaches its peak value, about 1400 GW would have to be mobilized according to our simulation, almost 140 bigger than the highest power demand ever registered in France for example (102 GW in 2012).

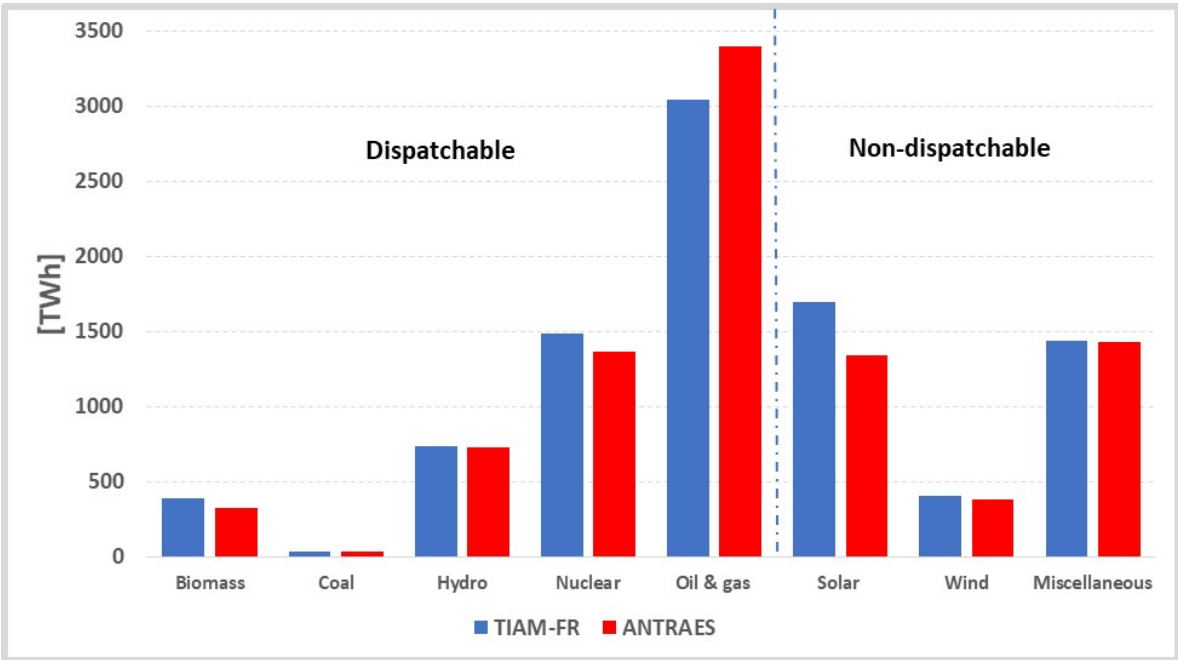


Figure 29:Power dispatch decisions made by ANTARES, Miscellaneous represent geothermal and tidal generation, only the expected values of generation are represented in this figure

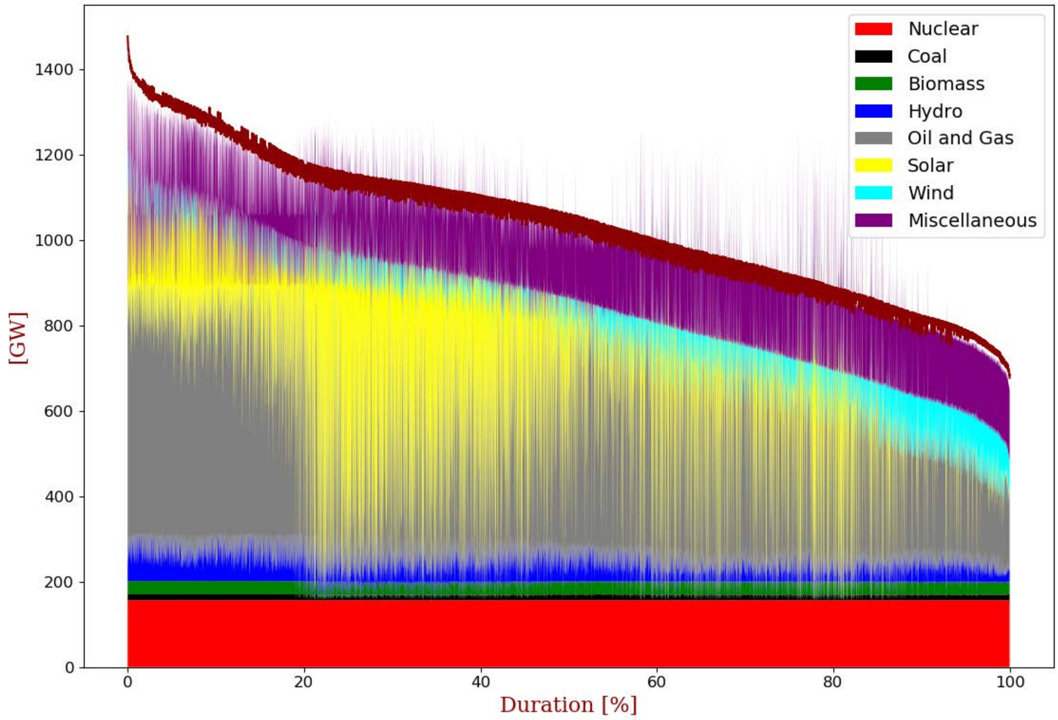


Figure 30: Power dispatch decisions made by ANTARES and fatal generation, Miscellaneous represent geothermal and tidal generation, only the expected values of generation are represented in this figure, the dark red curve corresponds to the expected value of LDC adjusted by its standard deviation

As a result of our simulation, power supply in western Europe would be cut almost 20% of the year. Indeed, loss of load would last 1806 hours on average by 2050. The standard deviation of this value is 196 hours. In the best-case scenario, the duration of loss of load would be 1430 hours.

We have also calculated the hourly variation of the kinetic reserve H_{kin} (defined in section 2.1). A mean value of 8.3 seconds is observed. This value is lower than the minimum time needed by the operators to activate the primary control if a sudden disruption takes place.

Hence the considerable share of renewables in western Europe's power system in 2050 would require more digitized grids capable of supplying power under extreme situations.

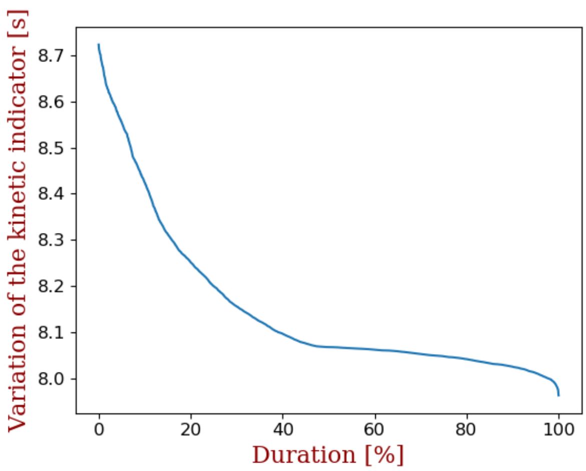


Figure 31: Kinetic reserve duration

11 Conclusion

Prospective modelling is a precious tool in the service of long-term planning. Our models, TIAM-FR and ANTARES allow us to shed light on the technical economic impacts of an 'all electric' world. TIAM-FR provides information on the possible pathways for electrification. ANATRES allows to analyze the adequacy of the power systems obtained under TIAM-FR.

First, we calibrated TIAM-FR by changing costs and efficiencies of power generation facilities accordingly with the New Policies scenario of the international Energy Agency. We then defined three scenarios, the BAU, the intermediate scenario and the voluntarist scenario. Second, we conducted a study on ANTARES to analyze the adequacy and the reliability of western Europe under the voluntarist scenario. The choice of this region is due to the availability of free data.

The realization of the "all electric" world is likely to be a bumpy journey. We found that an 'all electric' world scenario, with 4 times more electricity in final energy consumption (the voluntarist scenario) would require an inevitable climate policy response to support the migration of uses toward **clean** electricity. The steady decreasing costs of renewables would not be enough to switch to clean power systems. Significant shifts need to occur on investments; respectively, additional investments of 6.2 trillion $, 20.4 trillion $, are to add up comparing to the BAU if electricity is to reach 49%, 76%, in total final energy consumption (intermediate scenario). Furthermore, 5.3 GtCO2eq of CCS is to be installed between 2040 and 2050 to compensate CO2 emissions (2.5 GtCO2eq under the intermediate scenario. Our analyses come up with massive breakthroughs in power generation, USA would see ¾ of its dispatchable power capacities switched into intermittent renewable generation. Moreover, adequacy analyses we conducted under ANATRES show that the western European power grid would see 1806 hours of loss of load by 2050 under the voluntarist scenario. A complete redesign of the grid power system toward one that is more decentralized and more digitized is then required to accompany the transition. In the end, the "all electric" world represents a complete reconfiguration of the energy system balance which has prevailed for the last 100 years.

Hence, this study allows us to identify trends and changes that could occur by electrifying end-uses. Nevertheless, it could be refined by calibrating TIAM-FR according to ETSAP's improvements. The adequacy study conducted on western Europe should be transposed to USA (strategic region for the business of Schneider Electric) since the power system of this region seems to raise the question of reliability more than any other region. Finally, since variable renewables would occupy a greater share in power generation, it seems pertinent to study the shifts to occur on power grids to support the decentralization of power generation.

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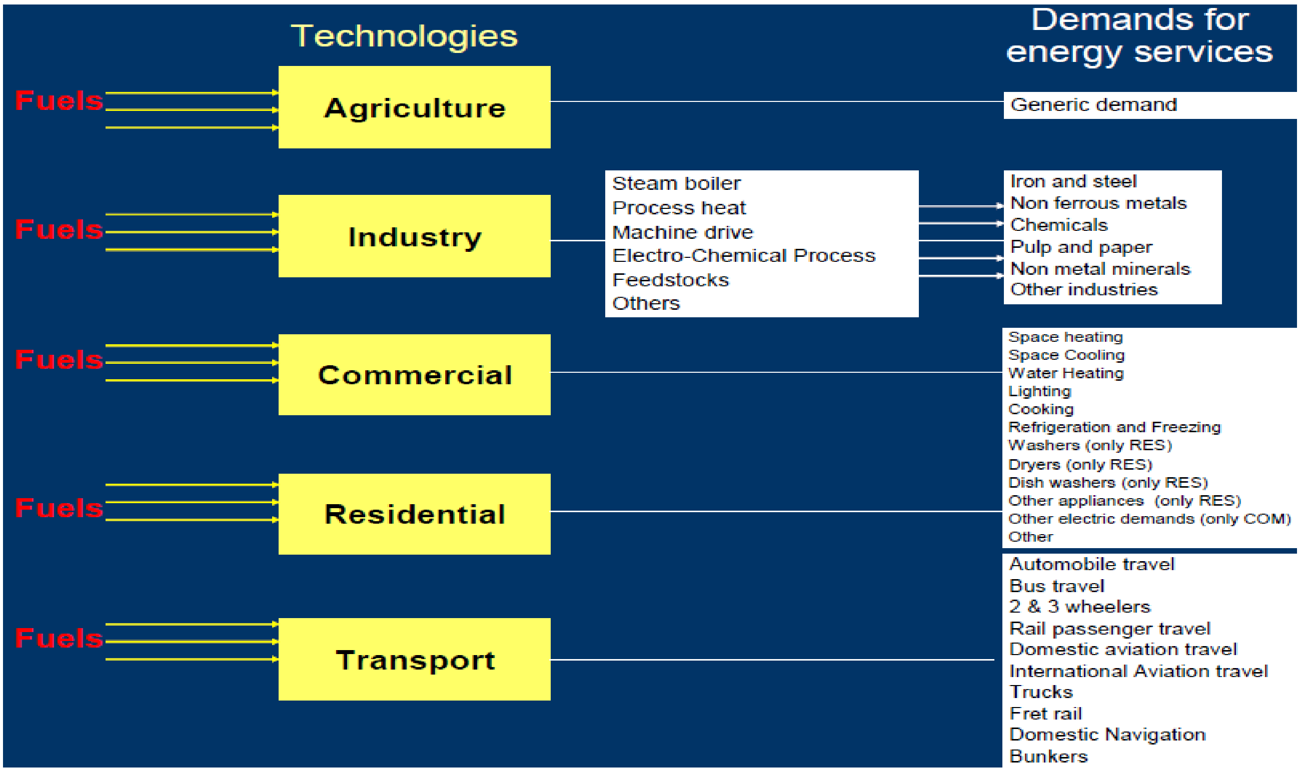
13 Appendices

13.1 Appendix 1: End use sectors in TIAM-FR

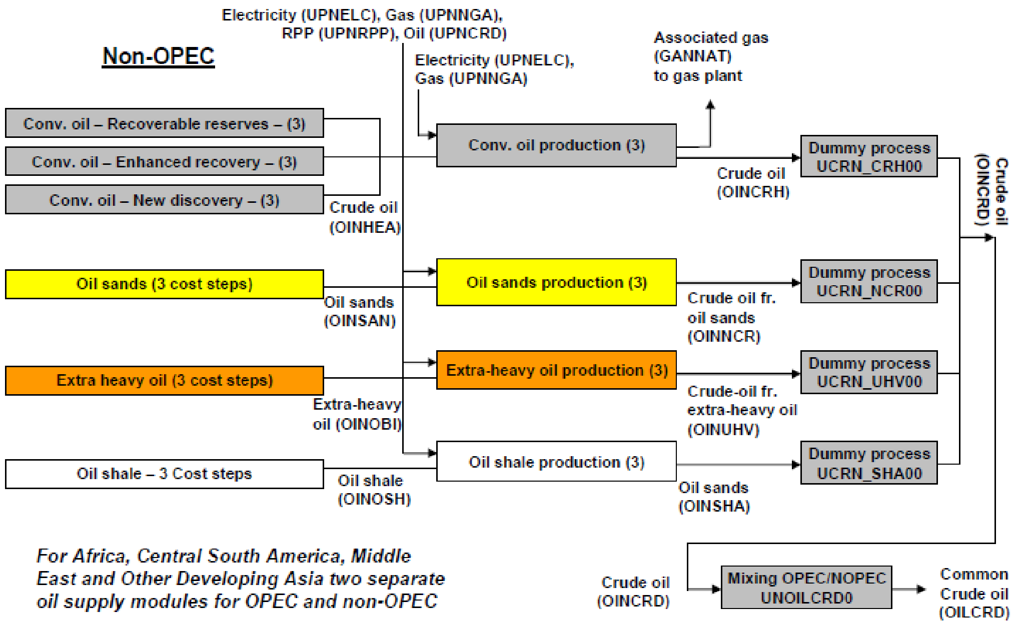


13.2 Appendix 2: Countries and regions in TIAM models

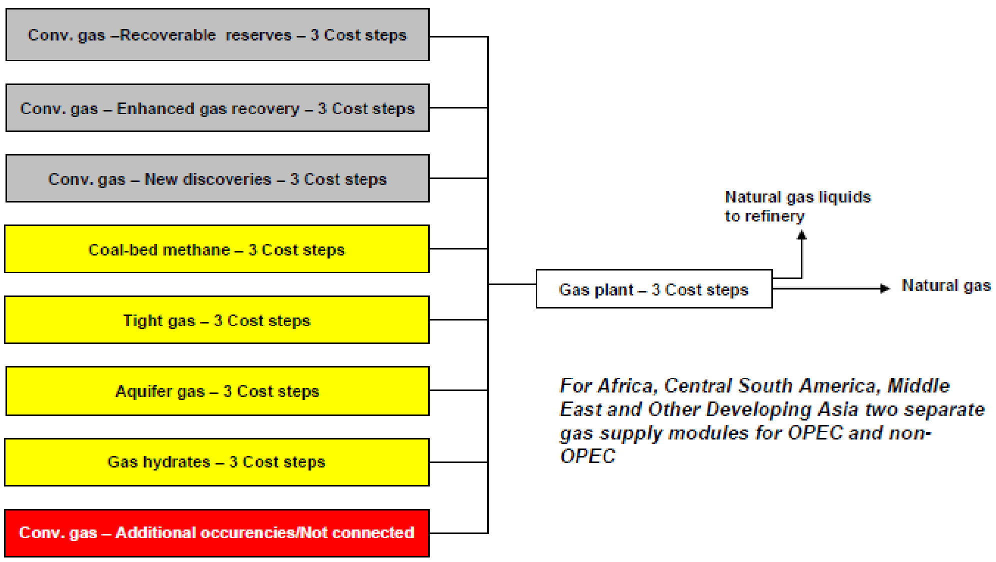
Region	Countries
Africa (AFR)	Algeria, Angola, Benin, Cameroon, Congo, Congo Republic, Egypt, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Libya, Morocco, Mozambique, Nigeria, Other Africa, Senegal, South Africa, Sudan, Tanzania, Tunisia, Zambia, Zimbabwe
Australia (AUS)	Australia and New Zealand
Canada (CAN)	Canada
Central and South America (CSA)	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Other Latin America, Panama, Paraguay, Peru, Trinidad-Tobago, Uruguay, Venezuela
China (CHI)	China
Eastern Europe (EEU)	Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
Former Soviet Union (FSU)	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
India (IND)	India
Japan (JAP)	Japan
Mexico (MEX)	Mexico
Middle-east (MEA)	Bahrain, Cyprus, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, Yemen
Other Developing Asia (ODA)	Bangladesh, Brunei, Chinese Taipei, Indonesia, North Korea, Malaysia, Myanmar, Nepal, Other Asia, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam
South Korea (SKO)	South Korea
USA (USA)	United States of America
Western Europe (WEU)	Austria, Belgium, Denmark, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland

13.3 Appendix 3: Modeling of fossil fuels supply

Modeling of oil supply in TIAM



Modeling of gas supply in TIAM



- Addition of new unconventional resources coal-bed methane, CBM, tight gas and aquifer gas

Mining technologies convert the reserve into primary fuels as oil, gas or coal; whereas secondary transformation processes change those into secondary fuels like oil products, coke oven gas or blast furnace gas (Anandarajah, et al., 2011). World is shared into OPEC and Non-OPEC zones that do not act the same regarding oil extraction. For the world regions containing OPEC member countries, the fossil fuel supply and further fuel processing are divided into the two sub-regions OPEC and NOPEC.

13.4 Appendix 4: BAU scenario list

Scenario Name	Description
BASE	Composition of regional templates, all technologies and resources, base year 2005
ALTFUEL	New alternative fuel technologies
B-NEWTECHS	New technology repository
CH4MEASURESC	CH4 abatement options
HYDROGEN	H2 production and vehicle technologies
N2OMEASURES	N20 abatement solutions
NONCO2	Nitric acid, CH4 from agriculture, bio-burning, waste water…
SEQUESTRATIOND	CO2 capture and storage options
BASE15R	Modification demand
TRADE_PARMS	Trade descriptions
BASE_BIOMASS	Modification of biomass resources
BASE_ELCTDCOST	Avoided transport and distribution costs for distributed compared to grid-connected electricity
BASE_EMIAGGREGATION	Definition of TOTCO2, TOTCH4, TOTN2O, NONCO2
BASE_EXTRA	Modification of data in SubRES and Templates
BASE_EXTRACTION	Modification of fossil resources
CLIMODULE	Climatic module
SYSSETTINGS	Interpolation options
UC-ELC	User's constraints, Electricity
UC-IND	User's constraints, Industry
UC-TRA	User's constraints, Transport
UC-UPS	User's constraints, Upstream

13.5 Appendix 5: Excel Sheet for power generation facilities costs and efficiencies

13.5.1 Oil and Gas

~TFM_INS

TimeSlice	Attribute	Year	WEU	USA	JPN	FSU	CHI	IND	MEA	AFR	CSA	MEX	ODA	SKO	EEU	CAN	AUS	Pset_Set	Pset_PN
	INVCOM	2015	735	735	809	588	404	515	588	515	515	515	588	809	588	735	515		EGOICCA105
	INVCOM	2020	735	735	809	588	404	515	588	515	515	515	588	809	588	735	515		EGOICCA105
	INVCOM	2030	735	735	809	588	404	515	588	515	515	515	588	809	588	735	515		EGOICCA105
	INVCOM	2040	735	735	809	588	404	515	588	515	515	515	588	809	588	735	515		EGOICCA105
	INVCOM	2050	735	735	809	588	404	515	588	515	515	515	588	809	588	735	515		EGOICCA105
	Fixom	2015	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOICCA105
	Fixom	2020	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOICCA105
	Fixom	2030	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOICCA105
	Fixom	2040	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOICCA105
	Fixom	2050	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOICCA105
	INVCOM	2015	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676		EGASFCE105
	INVCOM	2020	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676	3 676		EGASFCE105
	INVCOM	2030	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838		EGASFCE105
	INVCOM	2040	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838		EGASFCE105
	INVCOM	2050	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838	1 838		EGASFCE105
	Fixom	2015	74	74	74	110	110	110	110	110	110	110	110	74	110	74	110		EGASFCE105
	Fixom	2020	74	74	74	110	110	110	110	110	110	110	110	74	110	74	110		EGASFCE105
	Fixom	2030	37	37	37	55	55	55	55	55	55	55	55	37	55	37	55		EGASFCE105
	Fixom	2040	37	37	37	55	55	55	55	55	55	55	55	37	55	37	55		EGASFCE105
	Fixom	2050	18	18	18	28	28	28	28	28	28	28	28	18	28	18	28		EGASFCE105
	INVCOM	2015	368	368	368	331	257	294	331	294	294	294	331	368	331	368	294		EGOITUA105
	INVCOM	2020	368	368	368	331	257	294	331	294	294	294	331	368	331	368	294		EGOITUA105
	INVCOM	2030	368	368	368	331	257	294	331	294	294	294	331	368	331	368	294		EGOITUA105
	INVCOM	2040	368	368	368	331	257	294	331	294	294	294	331	368	331	368	294		EGOITUA105
	INVCOM	2050	368	368	368	331	257	294	331	294	294	294	331	368	331	368	294		EGOITUA105
	Fixom	2015	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOITUA105
	Fixom	2020	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOITUA105
	Fixom	2030	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOITUA105
	Fixom	2040	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOITUA105
	Fixom	2050	18	18	22	22	15	18	22	18	18	18	22	22	22	18	18		EGOITUA105

13.5.2 Coal

~TFM_INS																		
TimeSlice	Attribute	Year	WEU	USA	JPN	FSU	CHI	IND	MEA	AFR	CSA	MEX	ODA	SKO	EEU	CAN	AUS	Pset_Set	Pset_PN
	INVCOM	2015	1 250	1 324	1 544	1 250	441	735	956	956	956	956	956	1 544	1 250	1 324	956		ECOAPUL105
	INVCOM	2020	1 250	1 324	1 544	1 250	441	735	956	956	956	956	956	1 544	1 250	1 324	956		ECOAPUL105
	INVCOM	2030	1 250	1 324	1 544	1 250	441	735	956	956	956	956	956	1 544	1 250	1 324	956		ECOAPUL105
	INVCOM	2040	1 250	1 324	1 544	1 250	441	735	956	956	956	956	956	1 544	1 250	1 324	956		ECOAPUL105
	INVCOM	2050	1 250	1 324	1 544	1 250	441	735	956	956	956	956	956	1 544	1 250	1 324	956		ECOAPUL105
	Fixom	2015	33	33	40	37	15	26	33	33	33	33	33	40	37	33	33		ECOAPUL105
	Fixom	2020	33	33	40	37	15	26	33	33	33	33	33	40	37	33	33		ECOAPUL105
	Fixom	2030	33	33	40	37	15	26	33	33	33	33	33	40	37	33	33		ECOAPUL105
	Fixom	2040	33	33	40	37	15	26	33	33	33	33	33	40	37	33	33		ECOAPUL105
	Fixom	2050	33	33	40	37	15	26	33	33	33	33	33	40	37	33	33		ECOAPUL105
	INVCOM	2015	1 471	1 544	1 765	1 471	515	882	1 176	1 176	1 176	1 176	1 176	1 765	1 471	1 544	1 176		ECOACCO105
	INVCOM	2020	1 471	1 544	1 765	1 471	515	882	1 176	1 176	1 176	1 176	1 176	1 765	1 471	1 544	1 176		ECOACCO105
	INVCOM	2030	1 471	1 544	1 765	1 471	515	882	1 176	1 176	1 176	1 176	1 176	1 765	1 471	1 544	1 176		ECOACCO105
	INVCOM	2040	1 471	1 544	1 765	1 471	515	882	1 176	1 176	1 176	1 176	1 176	1 765	1 471	1 544	1 176		ECOACCO105
	INVCOM	2050	1 471	1 544	1 765	1 471	515	882	1 176	1 176	1 176	1 176	1 176	1 765	1 471	1 544	1 176		ECOACCO105
	Fixom	2015	44	48	51	51	22	37	48	48	48	48	48	51	51	48	48		ECOACCO105
	Fixom	2020	44	48	51	51	22	37	48	48	48	48	48	51	51	48	48		ECOACCO105
	Fixom	2030	44	48	51	51	22	37	48	48	48	48	48	51	51	48	48		ECOACCO105
	Fixom	2040	44	48	51	51	22	37	48	48	48	48	48	51	51	48	48		ECOACCO105
	Fixom	2050	44	48	51	51	22	37	48	48	48	48	48	51	51	48	48		ECOACCO105
	INVCOM	2015	1 838	1 912	2 132	1 838	809	1 176	1 471	1 544	1 471	1 471	1 471	2 132	1 838	1 912	1 544		ECOAAFB105
	INVCOM	2020	1 838	1 912	2 132	1 838	809	1 176	1 471	1 544	1 471	1 471	1 471	2 132	1 838	1 912	1 544		ECOAAFB105
	INVCOM	2030	1 728	1 801	2 022	1 728	735	1 103	1 397	1 471	1 397	1 397	1 397	2 022	1 728	1 801	1 471		ECOAAFB105
	INVCOM	2040	1 691	1 765	1 985	1 691	662	1 103	1 397	1 471	1 397	1 397	1 397	1 985	1 691	1 765	1 471		ECOAAFB105
	INVCOM	2050	1 691	1 765	1 985	1 691	662	1 103	1 397	1 471	1 397	1 397	1 397	1 985	1 691	1 765	1 471		ECOAAFB105
	Fixom	2015	66	66	74	66	37	51	66	70	66	66	66	74	66	66	70		ECOAAFB105
	Fixom	2020	66	66	74	66	37	51	66	70	66	66	66	74	66	66	70		ECOAAFB105
	Fixom	2030	59	63	70	59	33	51	63	66	63	63	63	70	59	63	66		ECOAAFB105
	Fixom	2040	59	63	70	59	29	51	63	66	63	63	63	70	59	63	66		ECOAAFB105
	Fixom	2050	59	63	70	59	29	51	63	66	63	63	63	70	59	63	66		ECOAAFB105

13.5.3 Renewables

~TFM_INS																		
TimeSlice	Attribute	Year	WEU	USA	JPN	FSU	CHI	IND	MEA	AFR	CSA	MEX	ODA	SKO	EEU	CAN	AUS	Pset_Set	Pset_PN
	INVCOM	2015	1 765	1 838	1 765	1 691	1 176	1 581	1 691	1 581	1 654	1 654	1 691	1 765	1 294	1 838	1 691		EBIOSLC105
	INVCOM	2020	1 728	1 801	1 728	1 654	1 176	1 581	1 618	1 581	1 618	1 618	1 618	1 728	1 294	1 801	1 618		EBIOSLC105
	INVCOM	2030	1 691	1 765	1 691	1 654	1 176	1 544	1 581	1 544	1 581	1 581	1 581	1 691	1 294	1 765	1 581		EBIOSLC105
	INVCOM	2040	1 654	1 728	1 654	1 618	1 176	1 544	1 544	1 507	1 581	1 581	1 544	1 654	1 294	1 728	1 544		EBIOSLC105
	INVCOM	2050	1 654	1 728	1 654	1 618	1 176	1 544	1 544	1 507	1 581	1 581	1 544	1 654	1 294	1 728	1 544		EBIOSLC105
	Fixom	2015	63	66	63	59	40	55	59	55	59	59	59	63	44	66	59		EBIOSLC105
	Fixom	2020	59	63	59	59	40	55	55	55	55	55	55	59	44	63	55		EBIOSLC105
	Fixom	2030	59	63	59	59	40	55	55	55	55	55	55	59	44	63	55		EBIOSLC105
	Fixom	2040	59	63	59	55	40	55	55	51	55	55	55	59	44	63	55		EBIOSLC105
	Fixom	2050	59	63	59	55	40	55	55	51	55	55	55	59	44	63	55		EBIOSLC105
	INVCOM	2015	1 875	2 059	1 985	1 985	1 360	1 618	1 949	1 838	1 728	1 728	1 949	1 875	1 496	2 059	1 949		EBIOMSW105
	INVCOM	2020	1 838	2 059	1 949	1 949	1 360	1 581	1 875	1 801	1 728	1 728	1 875	1 838	1 496	2 059	1 875		EBIOMSW105
	INVCOM	2030	1 801	1 985	1 912	1 949	1 360	1 581	1 838	1 765	1 691	1 691	1 838	1 801	1 496	1 985	1 838		EBIOMSW105
	INVCOM	2040	1 765	1 949	1 875	1 912	1 324	1 581	1 801	1 728	1 654	1 654	1 801	1 765	1 456	1 949	1 801		EBIOMSW105
	INVCOM	2050	1 765	1 949	1 875	1 912	1 324	1 581	1 801	1 728	1 654	1 654	1 801	1 765	1 456	1 949	1 801		EBIOMSW105
	Fixom	2015	70	77	77	77	51	63	74	70	66	66	74	70	57	77	74		EBIOMSW105
	Fixom	2020	70	77	74	74	51	59	74	70	66	66	74	70	57	77	74		EBIOMSW105
	Fixom	2030	70	77	74	74	51	59	70	66	66	66	70	70	57	77	70		EBIOMSW105
	Fixom	2040	66	74	70	74	51	59	70	66	63	63	70	66	57	74	70		EBIOMSW105
	Fixom	2050	66	74	70	74	51	59	70	66	63	63	70	66	57	74	70		EBIOMSW105
	INVCOM	2015	2 757	2 978	2 868	2 574	1 838	2 059	2 206	2 096	2 132	2 132	2 206	2 757	2 022	2 978	2 206		ECHPBIOP105
	INVCOM	2020	2 721	2 941	2 831	2 537	1 838	2 059	2 096	2 059	2 096	2 096	2 096	2 721	2 022	2 941	2 096		ECHPBIOP105
	INVCOM	2030	2 684	2 868	2 757	2 500	1 838	2 022	2 059	2 022	2 059	2 059	2 059	2 684	2 022	2 868	2 059		ECHPBIOP105
	INVCOM	2040	2 610	2 831	2 684	2 463	1 801	2 022	2 022	1 985	2 059	2 059	2 022	2 610	1 982	2 831	2 022		ECHPBIOP105
	INVCOM	2050	2 610	2 831	2 684	2 463	1 801	2 022	2 022	1 985	2 059	2 059	2 022	2 610	1 982	2 831	2 022		ECHPBIOP105
	Fixom	2015	103	110	107	96	70	77	81	77	81	81	81	103	77	110	81		ECHPBIOP105
	Fixom	2020	103	110	107	96	70	77	81	77	77	77	81	103	77	110	81		ECHPBIOP105
	Fixom	2030	99	107	103	96	70	77	77	77	77	77	77	99	77	107	77		ECHPBIOP105
	Fixom	2040	99	107	103	92	70	77	77	74	77	77	77	99	77	107	77		ECHPBIOP105
	Fixom	2050	99	107	103	92	70	77	77	74	77	77	77	99	77	107	77		ECHPBIOP105
	INVCOM	2015	2 132	1 618	2 096	1 654	1 691	2 647	1 618	2 279	2 279	2 279	1 618	2 132	1 860	1 618	1 618		EGEOT105
	INVCOM	2020	2 059	1 581	2 022	1 581	1 691	2 610	1 581	2 206	2 206	2 206	1 581	2 059	1 860	1 581	1 581		EGEOT105
	INVCOM	2030	1 985	1 507	1 949	1 544	1 618	2 500	1 544	2 132	2 132	2 132	1 544	1 985	1 779	1 507	1 544		EGEOT105
	INVCOM	2040	1 912	1 434	1 838	1 507	1 581	2 426	1 471	2 059	2 059	2 059	1 471	1 912	1 739	1 434	1 471		EGEOT105
	INVCOM	2050	1 912	1 434	1 838	1 507	1 581	2 426	1 471	2 059	2 059	2 059	1 471	1 912	1 739	1 434	1 471		EGEOT105
	Fixom	2015	44	33	40	33	33	51	33	44	44	44	33	44	36	33	33		EGEOT105
	Fixom	2020	40	33	40	33	33	51	33	44	44	44	33	40	36	33	33		EGEOT105
	Fixom	2030	40	29	40	29	33	51	29	44	44	44	29	40	36	29	29		EGEOT105
	Fixom	2040	37	29	37	29	33	48	29	40	40	40	29	37	36	29	29		EGEOT105
	Fixom	2050	37	29	37	29	33	48	29	40	40	40	29	37	36	29	29		EGEOT105
	INVCOM	2015	971	1 632	1 485	1 897	1 000	985	1 735	1 765	1 456	1 456	1 735	971	1 100	1 632	1 735		ESOPV105
	INVCOM	2020	765	1 191	1 103	1 294	750	735	1 206	1 294	1 000	1 000	1 206	765	825	1 191	1 206		ESOPV105
	INVCOM	2030	632	941	912	1 044	618	588	926	1 029	794	794	926	632	679	941	926		ESOPV105
	INVCOM	2040	574	824	809	926	559	529	809	912	706	706	809	574	615	824	809		ESOPV105
	INVCOM	2050	574	824	809	926	559	529	809	912	706	706	809	574	615	824	809		ESOPV105
	Fixom	2015	10	16	15	19	10	10	18	18	18	18	18	10	11	16	18		ESOPV105
	Fixom	2020	9	15	13	18	9	9	16	16	16	16	16	9	10	15	16		ESOPV105
	Fixom	2030	9	15	13	16	9	9	15	16	15	15	15	9	10	15	15		ESOPV105
	Fixom	2040	9	15	13	16	9	9	15	16	15	15	15	9	10	15	15		ESOPV105
	Fixom	2050	9	15	13	16	9	9	15	16	15	15	15	9	10	15	15		ESOPV105
	INVCOM	2015	1 176	2 559	2 118	2 559	1 088	1 074	2 206	2 088	1 971	1 971	2 206	1 176	1 197	2 559	2 206		ESOPVD105
	INVCOM	2020	941	1 853	1 559	1 691	824	794	1 471	1 515	1 309	1 309	1 471	941	906	1 853	1 471		ESOPVD105
	INVCOM	2030	794	1 456	1 309	1 353	691	647	1 132	1 206	1 029	1 029	1 132	794	760	1 456	1 132		ESOPVD105
	INVCOM	2040	721	1 294	1 176	1 206	632	574	985	1 059	912	912	985	721	696	1 294	985		ESOPVD105
	INVCOM	2050	721	1 294	1 176	1 206	632	574	985	1 059	912	912	985	721	696	1 294	985		ESOPVD105
	Fixom	2015	12	25	21	25	10	10	22	21	22	22	22	12	11	25	22		ESOPVD105
	Fixom	2020	12	24	21	24	10	10	21	19	21	21	21	12	11	24	21		ESOPVD105
	Fixom	2030	10	22	19	22	10	10	19	19	19	19	19	10	11	22	19		ESOPVD105
	Fixom	2040	10	22	19	22	10	9	19	19	19	19	19	10	11	22	19		ESOPVD105
	Fixom	2050	10	22	19	22	10	9	19	19	19	19	19	10	11	22	19		ESOPVD105
	INVCOM	2015	4 191	4 816	4 191	4 816	3 603	4 191	3 860	3 713	3 934	3 934	3 860	4 191	3 963	4 816	3 860		ESOTH105
	INVCOM	2020	3 750	4 375	3 750	4 375	3 199	3 787	3 456	3 346	3 566	3 566	3 456	3 750	3 518	4 375	3 456		ESOTH105
	INVCOM	2030	3 125	3 713	3 125	3 713	2 684	3 199	2 868	2 794	2 978	2 978	2 868	3 125	2 952	3 713	2 868		ESOTH105
	INVCOM	2040	2 757	3 309	2 757	3 309	2 390	2 831	2 537	2 463	2 610	2 610	2 537	2 757	2 629	3 309	2 537		ESOTH105
	INVCOM	2050	2 757	3 309	2 757	3 309	2 390	2 831	2 537	2 463	2 610	2 610	2 537	2 757	2 629	3 309	2 537		ESOTH105
	Fixom	2015	169	191	169	191	147	169	154	147	154	154	154	169	162	191	154		ESOTH105
	Fixom	2020	147	176	147	176	125	154	140	132	140	140	140	147	138	176	140		ESOTH105
	Fixom	2030	125	147	125	147	110	125	118	110	118	118	118	125	121	147	118		ESOTH105
	Fixom	2040	110	132	110	132	96	110	103	96	103	103	103	110	105	132	103		ESOTH105
	Fixom	2050	110	132	110	132	96	110	103	96	103	103	103	110	105	132	103		ESOTH105
	INVCOM	2015	1 353	1 265	1 632	1 574	912	1 000	1 485	1 382	1 015	1 015	1 485	1 353	1 003	1 265	1 485		EWIND305
	INVCOM	2020	1 309	1 221	1 559	1 500	882	971	1 412	1 338	971	971	1 412	1 309	971	1 221	1 412		EWIND305
	INVCOM	2030	1 265	1 176	1 500	1 456	882	956	1 353	1 294	941	941	1 353	1 265	971	1 176	1 353		EWIND305
	INVCOM	2040	1 235	1 162	1 456	1 441	882	941	1 324	1 265	941	941	1 324	1 235	971	1 162	1 324		EWIND305
	INVCOM	2050	1 235	1 162	1 456	1 441	882	941	1 324	1 265	941	941	1 324	1 235	971	1 162	1 324		EWIND305
	Fixom	2015	34	32	41	40	22	25	37	35	28	28	37	34	24	32	37		EWIND305
	Fixom	2020	32	31	40	38	22	25	35	34	28	28	35	32	24	31	35		EWIND305
	Fixom	2030	32	29	38	37	22	24	35	32	26	26	35	32	24	29	35		EWIND305
	Fixom	2040	32	29	38	37	22	24	34	32	26	26	34	32	24	29	34		EWIND305
	Fixom	2050	32	29	38	37	22	24	34	32	26	26	34	32	24	29	34		EWIND305
	INVCOM	2015	3 382	3 824	3 971	3 750	3 235	3 419	3 566	3 456	3 566	3 566	3 566	3 382	3 559	3 824	3 566		EWIND205
	INVCOM	2020	2 831	3 272	3 272	3 125	2 721	2 868	2 978	2 868	3 015	3 015	2 978	2 831	2 993	3 272	2 978		EWIND205
	INVCOM	2030	2 353	2 610	2 684	2 574	2 279	2 353	2 426	2 353	2 463	2 463	2 426	2 353	2 507	2 610	2 426		EWIND205
	INVCOM	2040	2 132	2 390	2 426	2 353	2 059	2 169	2 206	2 132	2 243	2 243	2 206	2 132	2 265	2 390	2 206		EWIND205
	INVCOM	2050	2 132	2 390	2 426	2 353	2 059	2 169	2 206	2 132	2 243	2 243	2 206	2 132	2 265	2 390	2 206		EWIND205
	Fixom	2015	118	132	140	129	114	121	125	121	125	125	125	118	125	132	125		EWIND205
	Fixom	2020	103	118	118	114	99	103	107	107	107	107	107	103	109	118	107		EWIND205
	Fixom	2030	88	99	103	99	85	92	92	92	92	92	92	88	93	99	92		EWIND205
	Fixom	2040	85	92	96	92	81	85	85	85	85	85	85	85	89	92	85		EWIND205
	Fixom	2050	85	92	96	92	81	85	85	85	85	85	85	85	89	92	85		EWIND205

13.5.4 Nuclear

~TFM_INS

TimeSlice	Attribute	Year	WEU	USA	JPN	FSU	CHI	IND	MEA	AFR	CSA	MEX	ODA	SKO	EEU	CAN	AUS	Pset_Set	Pset_PN
	INVCOM	2015	4 853	3 676	2 941	2 794	1 471	2 059	2 574	2 941	2 941	2 941	2 574	2 941	2 794	3 676	2 941		ENUCADV105
	INVCOM	2020	4 412	3 676	2 941	2 794	2 059	2 059	2 574	2 941	2 941	2 941	2 574	2 941	2 794	3 676	2 941		ENUCADV105
	INVCOM	2030	3 750	3 529	2 941	2 794	2 022	2 059	2 574	2 941	2 941	2 941	2 574	2 941	2 794	3 529	2 941		ENUCADV105
	INVCOM	2040	3 309	3 309	2 941	2 794	1 838	2 059	2 574	2 941	2 941	2 941	2 574	2 941	2 794	3 309	2 941		ENUCADV105
	INVCOM	2050	3 309	3 309	2 941	2 794	1 838	2 059	2 574	2 941	2 941	2 941	2 574	2 941	2 794	3 309	2 941		ENUCADV105
	Fixom	2015	125	132	154	118	88	103	118	125	125	125	118	154	118	132	125		ENUCADV105
	Fixom	2020	121	132	154	118	88	103	118	125	125	125	118	154	118	132	125		ENUCADV105
	Fixom	2030	121	132	154	118	88	103	118	125	125	125	118	154	118	132	125		ENUCADV105
	Fixom	2040	121	132	154	118	88	103	118	125	125	125	118	154	118	132	125		ENUCADV105
	Fixom	2050	121	132	154	118	88	103	118	125	125	125	118	154	118	132	125		ENUCADV105

13.6 Appendix 6: Share of electricity in final end use sectors by 2050 in the REmap Scenario, IRENA

Regions	Years	Share of electricity use in TFEC %	Share of electricity use in Industry %	Share of electricity use in Transport %	Share of electricity use in Buildings %
North Amercia	2016	20%	20%	0%	48%
	2030	28%	21%	13%	54%
	2050	52%	29%	57%	78%
Latin America	2016	18%	22%	0%	44%
	2030	26%	27%	9%	61%
	2050	39%	33%	24%	78%
Sub Sahara Africa	2016	6%	23%	0%	4%
	2030	23%	31%	2%	57%
	2050	48%	29%	47%	89%
Oceania	2016	23%	28%	1%	57%
	2030	22%	20%	6%	64%
	2050	45%	67%	31%	34%
EU 28	2016	23%	33%	2%	33%
	2030	30%	40%	7%	42%
	2050	49%	54%	32%	55%
Rest of Europe	2016	17%	25%	7%	22%
	2030	23%	34%	12%	28%
	2050	38%	44%	37%	42%
MENA	2016	17%	11%	0%	41%
	2030	20%	12%	2%	48%
	2050	38%	20%	15%	77%
Souheast Asia	2016	18%	22%	0%	29%
	2030	20%	16%	3%	63%
	2050	42%	27%	23%	91%
East Asia	2016	24%	30%	3%	32%
	2030	37%	42%	14%	45%
	2050	58%	66%	46%	57%
Rest of Asia	2016	18%	22%	1%	20%
	2030	26%	20%	18%	51%
	2050	47%	32%	51%	75%

13.7 Appendix 7: Excel sheets for the electrification scenarios

13.7.1 INT_DCRB scenario:

13.7.1.1 Industry

						~UC_T: UC_COMPRD																
UC_N	Pset_SET	PSET_CO	PSET_CI	Cset_CN	LimType	Year	UC_FLO	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU
TUC-L_SHR_IM__-ELC	PRE	IM__	INDELC	IM__	LO	2010	1	-100,0%	-99,9%	-100,0%	-99,8%	-100,0%	-99,9%	-99,9%	-100,0%	-100,0%	-99,8%	-100,0%	-99,7%	-99,9%	-99,2%	-99,9%
				IM__		2050		-75,0%	-74,9%	-75,0%	-74,8%	-75,0%	-74,9%	-75,0%	-75,0%	-75,0%	-74,8%	-75,0%	-74,7%	-75,0%	-74,4%	-74,9%
				IM__		2100		-50,0%	-49,9%	-50,0%	-49,9%	-50,0%	-50,0%	-50,0%	-50,0%	-50,0%	-49,9%	-50,0%	-49,8%	-50,0%	-49,6%	-49,9%
\I: constraining shares on "Other Industry" production - All uses (ISOI, IPOI, ...)																						
TUC-L_SHR___OI-HFO	PRE,HPL	__OI,-IMOI,-IOI	INDHFO	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR___OI-OIL	PRE,HPL	__OI,-IMOI,-IOI	INDOIL	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR___OI-NGA	PRE,HPL	__OI,-IMOI,-IOI	INDNGA	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-U_SHR___OI-COA	PRE,HPL	__OI,-IMOI,-IOI	INDCOA	__OI,-IMOI,-IOI	UP	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR___OI-ELC	PRE,HPL	__OI,-IMOI,-IOI	INDELC	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR___OI-LPG	PRE,HPL	__OI,-IMOI,-IOI	INDLPG	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR___OI-BIO	PRE,HPL	__OI,-IMOI,-IOI	INDBIO	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR___OI-HET	PRE,HPL	__OI,-IMOI,-IOI	INDHET	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
\I: constraining shares on "Other uses" production - All Industries (IO-MN, IO-LP, ...)								0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-HFO	PRE,HPL	IO__,-IOOI, -IOI	INDHFO	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-OIL	PRE,HPL	IO__,-IOOI, -IOI	INDOIL	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-NGA	PRE,HPL	IO__,-IOOI, -IOI	INDNGA	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-COA	PRE,HPL	IO__,-IOOI, -IOI	INDCOA	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-ELC	PRE,HPL	IO__,IM__,IP__,IS__,-I(	INDELC	IO__,IM__,IP__,IS__,-IOI,-ILP,-INF,-INM,-ICH,-INF	LO	2010	1	-18,0%	-21,0%	-24,2%	-45,2%	-8,8%	-19,7%	-18,9%	0,0%	-19,3%	-4,1%	-13,4%	-16,5%	-45,0%	-14,1%	-27,4%
				IO__,IM__,IP__,IS__,-IOI,-ILP,-INF,-INM,-ICH,-INF		2050		-29,0%	-67,0%	-29,0%	-66,0%	-33,0%	-44,0%	-44,0%	-32,0%	-66,0%	-20,0%	-29,0%	-27,0%	-66,0%	-29,0%	-54,0%
				IO__,IM__,IP__,IS__,-IOI,-ILP,-INF,-INM,-ICH,-INF		2100		-29,0%	-67,0%	-29,0%	-66,0%	-33,0%	-44,0%	-44,0%	-32,0%	-66,0%	-20,0%	-29,0%	-27,0%	-66,0%	-29,0%	-54,0%
TUC-L_SHR_IO__-HET	PRE,HPL	IO__,-IOOI, -IOI	INDHET	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-LPG	PRE,HPL	IO__,-IOOI, -IOI	INDLPG	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-BIO	PRE,HPL	IO__,-IOOI, -IOI	INDBIO	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
TUC-L_SHR_IO__-HET	PRE,HPL	IO__,-IOOI, -IOI	INDHET	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%

13.7.1.2 Transport

~UC_SETS: R_E: AFR,AUS,CAN,CHI,CSA,EEU,FSU,IND,JPN,MEA,MEX,ODA,SKO,USA,WEU					~UC_T: UC_COMPRD~LO																			
UC_N	Pset_CI	Pset_PN	Pset_CO	Cset_CN	Year	UC_FLO	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	UC_RHSRTS	UC_RHSRTS-
TUC-L_SHAR_ELC-TRT	TRAELC	TRTELC0*	TRT	TRT	2030	1	-2%	-6%	-13%	-14%	-9%	-12%	-12%	-18%	-14%	-2%	-13%	-3%	-14%	-13%	-7%	0	15
				TRT	2050		-47%	-31%	-57%	-46%	-24%	-37%	-37%	-51%	-46%	-15%	-57%	-23%	-46%	-57%	-32%		
				TRT	2100		-47%	-31%	-57%	-46%	-24%	-37%	-37%	-51%	-46%	-15%	-57%	-23%	-46%	-57%	-32%		
TUC-L_SHAR_ELC-TRL	TRAELC		TRL	TRL	2030	1	-10%	-10%	-10%	-10%	-6%	-10%	-10%	-10%	-10%	-2%	-10%	-5%	-10%	-10%	-10%	0	15
				TRL	2050		-47%	-31%	-57%	-46%	-24%	-37%	-37%	-51%	-46%	-15%	-57%	-23%	-46%	-57%	-32%		
				TRL	2100		-47%	-31%	-57%	-46%	-24%	-37%	-37%	-51%	-46%	-15%	-57%	-23%	-46%	-57%	-32%		
TUC-L_SHAR_ELC-TRB	TRAELC		TRB	TRB	2030	1	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	0	15
				TRB	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-58%		
				TRB	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-58%		
TUC-L_SHAR_ELC-TRM	TRAELC		TRM	TRM	2030	1	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	0	15
				TRM	2050		-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%		
				TRM	2100		-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%		
TUC-L_SHAR_ELC-TRW	TRAELC		TRW	TRW	2030	1	0%	0%	0%	-29%	0%	0%	0%	-29%	0%	0%	0%	0%	0%	0%	0%	0	15
				TRW	2050		0%	0%	0%	-59%	0%	0%	0%	-59%	0%	0%	0%	0%	0%	0%	0%		
				TRW	2100		0%	0%	0%	-59%	0%	0%	0%	-59%	0%	0%	0%	0%	0%	0%	0%		
TUC-L_SHAR_ELC-TRH	TRAELC		TRH	TRH	2030	1	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	0	15
				TRH	2050		-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%		
				TRH	2100		-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%		
TUC-L_SHAR_ELC-TTP	TRAELC		TTP	TTP	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TTP	2050		-40%	-96%	-96%	-96%	-50%	-96%	-96%	-96%	-96%	-56%	-96%	-60%	-96%	-96%	-96%		
				TTP	2100		-40%	-96%	-96%	-96%	-50%	-96%	-96%	-96%	-96%	-56%	-96%	-60%	-96%	-96%	-96%		
TUC-L_SHAR_ELC-TTF	TRAELC		TTF	TTF	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TTF	2050		-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%		
				TTF	2100		-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%		
TUC-L_SHAR_ELC-TRC	TRAELC		TRC	TRC	2030	1	-10%	-10%	-10%	-10%	-6%	-10%	-10%	-10%	-10%	-2%	-10%	-5%	-10%	-10%	-10%	0	15
				TRC	2050		-47%	-31%	-57%	-46%	-24%	-37%	-37%	-51%	-46%	-15%	-57%	-23%	-46%	-57%	-32%		
				TRC	2100		-47%	-31%	-57%	-46%	-24%	-37%	-37%	-51%	-46%	-15%	-57%	-23%	-46%	-57%	-32%		
TUC-L_SHAR_ELC-TRE	TRAELC		TRE	TRE	2030	1	0%	0%	0%	-29%	0%	0%	0%	-29%	0%	0%	0%	0%	0%	0%	0%	0	15
				TRE	2050		0%	0%	0%	-59%	0%	0%	0%	-59%	0%	0%	0%	0%	0%	0%	0%		
				TRE	2100		0%	0%	0%	-59%	0%	0%	0%	-59%	0%	0%	0%	0%	0%	0%	0%		

13.7.1.3 Buildings

		~UC_SETS: R_E: CAN, MEX, USA				~UC_T					
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	UC_COMPRD	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_1	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1		0	15	Min electrcity in buildings (residential+commercial) in north America
	NRG	RES*,COM*			2030			-54%			
	NRG	RES*,COM*			2050			-78%			
	NRG	RES*,COM*			2070			-78%			
	NRG	RES*,COM*			2100			-78%			

		~UC_SETS: R_E: CHI, JPN, SKO				~UC_T					
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	UC_COMPRD	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_2	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1		0	15	Min electrcity in buildings (residential+commercial) in the east of Asia (China, Japan and South Korea)
	NRG	RES*,COM*			2030			-45%			
	NRG	RES*,COM*			2050			-57%			
	NRG	RES*,COM*			2070			-57%			
	NRG	RES*,COM*			2100			-57%			

		~UC_SETS: R_E: AFR, AUS, CSA, EEU, FSU, IND, MEA, ODA, WEU				~UC_T : UC_COMPRD											
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	AFR	AUS	CSA	IND	MEA	ODA	WEU	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_3	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1								0	15	Min electrcity in buildings (residential+commercial) in the other regions
	NRG	RES*,COM*			2030			-57%	-64%	-61%	-51%	-48%	-63%	-42%			
	NRG	RES*,COM*			2050			-89%	-64%	-78%	-75%	-77%	-91%	-55%			
	NRG	RES*,COM*			2070			-89%	-64%	-78%	-75%	-77%	-91%	-55%			
	NRG	RES*,COM*			2100			-89%	-64%	-78%	-75%	-77%	-91%	-55%			

		~UC_SETS: R_E: EEU, FSU				~UC_T					
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	UC_COMPRD	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_4	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1		0	15	Min electrcity in buildings (residential+commercial) in the east of Europe
	NRG	RES*,COM*			2030			-28%			
	NRG	RES*,COM*			2050			-42%			
	NRG	RES*,COM*			2070			-42%			
	NRG	RES*,COM*			2100			-42%			

13.7.2 ELC_DCRB scenario

13.7.2.1 Industry

						~UC_T: UC_COMPRD																			
UC_N	Pset_SET	PSET_CO	PSET_CI	Cset_CN	LimType	Year	UC_FLO	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	UC_RHSR'	UC_RHSR'	UC_Desc
TUC-L_SHR_IM__-ELC	PRE	IM__	INDELC	IM__	LO	2010	1	-100,0%	-99,9%	-100,0%	-99,8%	-100,0%	-99,9%	-99,9%	-100,0%	-100,0%	-99,8%	-100,0%	-99,7%	-99,9%	-99,2%	-99,9%	0	15	Min Share of ELC in Machine Drive production
				IM__		2050		-75,0%	-74,9%	-75,0%	-74,8%	-75,0%	-74,9%	-75,0%	-75,0%	-75,0%	-74,8%	-75,0%	-74,7%	-75,0%	-74,4%	-74,9%			
				IM__		2100		-50,0%	-49,9%	-50,0%	-49,9%	-50,0%	-50,0%	-50,0%	-50,0%	-50,0%	-49,9%	-50,0%	-49,8%	-50,0%	-49,6%	-49,9%			
\I: constraining shares on "Other Industry" production - All uses (ISOI, IPOI, …)																									
TUC-L_SHR___OI-HFO	PRE,HPL	__OI,-IMOI,-IOI	INDHFO	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of HFO in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR___OI-OIL	PRE,HPL	__OI,-IMOI,-IOI	INDOIL	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of OIL in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR___OI-NGA	PRE,HPL	__OI,-IMOI,-IOI	INDNGA	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of NGA in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-U_SHR___OI-COA	PRE,HPL	__OI,-IMOI,-IOI	INDCOA	__OI,-IMOI,-IOI	UP	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Max Share of COA in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR___OI-ELC	PRE,HPL	__OI,-IMOI,-IOI	INDELC	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of ELC in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR___OI-LPG	PRE,HPL	__OI,-IMOI,-IOI	INDLPG	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of LPG in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR___OI-BIO	PRE,HPL	__OI,-IMOI,-IOI	INDBIO	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of BIO in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR___OI-HET	PRE,HPL	__OI,-IMOI,-IOI	INDHET	__OI,-IMOI,-IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of HET in *OI production (except IMOI)
				__OI,-IMOI,-IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				__OI,-IMOI,-IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
\I: constraining shares on "Other uses" production - All Industries (IO-MN, IO-LP, …)								0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-HFO	PRE,HPL	IO__,-IOOI, -IOI	INDHFO	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of HFO in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-OIL	PRE,HPL	IO__,-IOOI, -IOI	INDOIL	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of OIL in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-NGA	PRE,HPL	IO__,-IOOI, -IOI	INDNGA	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of NGA in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-COA	PRE,HPL	IO__,-IOOI, -IOI	INDCOA	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Max Share of COA in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-ELC	PRE,HPL	IO__,IM__,IP__,IS__,-I(	INDELC	IO__,IM__,IP__,IS__,-IOI,-ILP,-INF,-INM,-ICH,-INF	LO	2010	1	-18,0%	-21,0%	-24,2%	-45,2%	-8,8%	-19,7%	-18,9%	0,0%	-19,3%	-4,1%	-13,4%	-16,5%	-45,0%	-14,1%	-27,4%	0	15	Min Share of ELC in IO* production (except IOOI)
				IO__,IM__,IP__,IS__,-IOI,-ILP,-INF,-INM,-ICH,-INF		2050		-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%			
				IO__,IM__,IP__,IS__,-IOI,-ILP,-INF,-INM,-ICH,-INF		2100		-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%	-100,0%			
TUC-L_SHR_IO__-HET	PRE,HPL	IO__,-IOOI, -IOI	INDHET	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of ELC in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-LPG	PRE,HPL	IO__,-IOOI, -IOI	INDLPG	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of LPG in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-BIO	PRE,HPL	IO__,-IOOI, -IOI	INDBIO	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of BIO in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
TUC-L_SHR_IO__-HET	PRE,HPL	IO__,-IOOI, -IOI	INDHET	IO__,-IOOI, -IOI	LO	2010	1	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0	15	Min Share of HET in IO* production (except IOOI)
				IO__,-IOOI, -IOI		2050		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
				IO__,-IOOI, -IOI		2100		0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			

13.7.2.2 Transport

~UC_SETS: R_E: AFR,AUS,CAN,CHI,CSA,EEU,FSU,IND,JPN,MEA,MEX,ODA,SKO,USA,WEU					~UC_T: UC_COMPRD~LO																		
UC_N	Pset_CI	Pset_PN	Pset_CO	Cset_CN	Year	UC_FLO	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	UC_RHSRTS	UC_RHSRTS-
TUC-L_SHAR_ELC-TRT	TRAELC	TRTELC0*	TRT	TRT	2030	1	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	0	15
				TRT	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRT	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TRL	TRAELC		TRL	TRL	2030	1	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	0	15
				TRL	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRL	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TRB	TRAELC		TRB	TRB	2030	1	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	0	15
				TRB	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRB	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TRM	TRAELC		TRM	TRM	2030	1	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	0	15
				TRM	2050		-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%		
				TRM	2100		-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%		
TUC-L_SHAR_ELC-TRW	TRAELC		TRW	TRW	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TRW	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRW	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TRH	TRAELC		TRH	TRH	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TRH	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRH	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TTP	TRAELC		TTP	TTP	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TTP	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TTP	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TTF	TRAELC		TTF	TTF	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TTF	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TTF	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TRC	TRAELC		TRC	TRC	2030	1	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%	0	15
				TRC	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRC	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
TUC-L_SHAR_ELC-TRE	TRAELC		TRE	TRE	2030	1	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	-40%	0	15
				TRE	2050		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		
				TRE	2100		-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%		

13.7.2.3 Buildings

		~UC_SETS: R_E: CAN, MEX, USA				~UC_T					
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	UC_COMPRD	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_1	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1		0	15	Min electrcity in buildings (residential+commercial) in north America
	NRG	RES*,COM*			2030			-54%			
	NRG	RES*,COM*			2050			-100%			
	NRG	RES*,COM*			2070			-100%			
	NRG	RES*,COM*			2100			-100%			

		~UC_SETS: R_E: CHI, JPN, SKO				~UC_T					
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	UC_COMPRD	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_2	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1		0	15	Min electrcity in buildings (residential+commercial) in the east of Asia (China, Japan and South Korea)
	NRG	RES*,COM*			2030			-45%			
	NRG	RES*,COM*			2050			-100%			
	NRG	RES*,COM*			2070			-100%			
	NRG	RES*,COM*			2100			-100%			

		~UC_SETS: R_E: AFR, AUS, CSA, EEU, FSU, IND, MEA, ODA, WEU				~UC_T : UC_COMPRD											
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	AFR	AUS	CSA	IND	MEA	ODA	WEU	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_3	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1								0	15	Min electrcity in buildings (residential+commercial) in the other regions
	NRG	RES*,COM*			2030			-57%	-64%	-61%	-51%	-48%	-63%	-42%			
	NRG	RES*,COM*			2050			-100%	-100%	-100%	-100%	-100%	-100%	-100%			
	NRG	RES*,COM*			2070			-100%	-100%	-100%	-100%	-100%	-100%	-100%			
	NRG	RES*,COM*			2100			-100%	-100%	-100%	-100%	-100%	-100%	-100%			

		~UC_SETS: R_E: EEU, FSU				~UC_T					
UC_N	Cset_SET	Cset_CN	PSet_CI	Pset_PN	Year	LimType	UC_FLO	UC_COMPRD	UC_RHSRTS	UC_RHSRTS~0	UC_Desc
TUC_S_BUI_ELC_SHARE_4	NRG	RESELC*,COMELC*	RESELC*,COMELC*	R*,C*	2030	LO	1		0	15	Min electrcity in buildings (residential+commercial) in the east of Europe
	NRG	RES*,COM*			2030			-28%			
	NRG	RES*,COM*			2050			-100%			
	NRG	RES*,COM*			2070			-100%			
	NRG	RES*,COM*			2100			-100%			

13.8 Appendix 8: Linear programming complements

This section is not strictly needed for a basic understanding of the TIMES model and may be skipped a first reading. However, it provides additional insight into the microeconomics of the TIMES equilibrium. In particular, it contains a review of the theoretical foundation of Linear Programming and Duality Theory. This knowledge may help the user to better understand the central role shadow prices and reduced costs play in the economics of the TIMES model

13.8.1 A brief primer on Linear Programming and Duality Theory

13.8.1.1 Basic definitions

In this subsection, the superscript t following a vector or matrix represents the transpose of that vector or matrix. A Linear Program may always be represented as the following Primal Problem in canonical form:

$$\min c^t x \qquad (1)$$

$$\text{s.t} \quad \mathrm{A\,x} \le \mathrm{b} \qquad (2)$$

$$\mathrm{x} \ge 0 \qquad (3)$$

where x is a vector of decision variables, $c^t x$ is a linear function representing the objective to maximize, and Ax ≤ b is a set of inequality constraints. Assume that the LP has a finite optimal solution, x*.

Then each decision variable, x_j^* falls into one of three categories, x_j^* may be:

- equal to its lower bound (as defined in a constraint), or
- equal to its upper bound, or
- strictly between the two bounds

In the last case, the variable x_j^* is called basic. Otherwise it is non-basic.

For each primal problem, there corresponds a Dual problem derived as follows:

$$\min b^t y \qquad (4)$$

$$\text{s.t} \quad A^t\, y \ge c \qquad (5)$$

$$\mathrm{y} \ge 0 \qquad (6)$$

Note that the number of dual variables equals the number of constraints in the primal problem. In fact, each dual variable y_i may be assigned to its corresponding primal constraint, which we represent as: $A_i x \le b_i$ where A_i is the i th row of matrix A.

13.8.1.2 Duality theory

Duality theory consists mainly of three theorems: weak duality, strong duality, and complementary slackness.

Weak duality therorem

If x is any feasible solution to the primal problem and y is any feasible solution to the dual, then the following inequality holds:

$$c^t x \le b^t y \qquad (7)$$

The weak duality theorem states that the value of a feasible dual objective is never smaller than the value of a feasible primal objective. The difference between the two is called the duality gap for the pair of feasible primal and dual solutions (x,y).

Strong duality theorem

If the primal problem has a finite, optimal solution x*, then so does the dual problem (y*), and both problems have the same optimal objective value (their duality gap is zero):

$$c^t x^* = b^t y^* \qquad (7)$$

Note that the optimal values of the dual variables are also called the shadow prices of the primal constraints.

Complementary Slackness theorem

At an optimal solution to an LP problem:

- If y_i^* is > 0 then the corresponding primal constraint is satisfied at equality (i.e. $A_i x^* = b_i$ and the i th primal constraint is called tight. Conversely, if the i th primal constraint is slack (not tight), then $y_i^* = 0$,
- If x_i^* is basic, then the corresponding dual constraint is satisfied at equality, (i.e. . $A_j^t y^* = c_j$, where At j is the j th row of A^t, i.e. the j th column of A. Conversely, if the j th dual constraint is slack, then x_j^* is equal to one of its bounds.

Remark: Note however that a primal constraint may have zero slack and yet have a dual equal to 0. And, a primal variable may be non basic (i.e. be equal to one of its bounds), and yet the corresponding dual slack be still equal to 0. These situations are different cases of the so-called degeneracy of the LP. They often occur when constraints are over specified (a trivial case occurs if a constraint is repeated twice in the LP)

13.8.2 Sensitivity analysis and the economic interpretation of dual variables

It may be shown that if thej^{th} RHS b_j of the primal is changed by an infinitesimal amount d, and if the primal LP is solved again, then its new optimal objective value is equal to the old optimal value plus the quantityy_j^*•d, where y_j^* is the optimal dual variable value.

13.8.2.1 Economic interpretation of dual variables

If the primal problem consists of maximizing the surplus (objective function $c^t x$), by choosing an activity vector x, subject to upper limits on several resources (the b vector) then:

- Each a_{ij} coefficient of the dual problem matrix, A, then represents the consumption of resource b_j by activity x;
- The optimal dual variable value y_j^* is the unit price of resource j, and
- The total optimal surplus derived from the optimal activity vector, x*, is equal to the total value of all resources, b, priced at the optimal dual values y* (strong duality theorem).

Furthermore, each dual constraint $A_j^t y^* \geq c_j$ has an important economic interpretation. Based on the Complementary Slackness theorem, if an LP solution x* is optimal, then for each x_j^* that is not equal to its upper or lower bound (i.e. each basic variable x_j^*), there corresponds a tight dual constraint $y^* A'j = c_j$, which means that the revenue coefficient c_j must be exactly equal to the cost of purchasing the resources needed to produce one unit of x_j. In economists' terms, marginal cost equals marginal revenue, and both are equal to the market price of x_j^*. If a variable is not basic, then by definition it is equal to its lower bound or to its upper bound. In both cases, the unit revenue c_j need not be equal to the cost of the required resources. The technology is then either non-competitive (if it is at its lower bound) or it is super competitive and makes a surplus (if it is at its upper bound).

Example: The optimal dual value attached to the balance constraint of commodity c represents the change in objective function value resulting from one additional unit of the commodity. This is precisely the internal unit price of that commodity.

13.8.2.2 Reduced surplus and reduced cost

In a maximization problem, the difference $y^*A'j - c_j$ is called the reduced surplus of technology j, and is available from the solution of a TIMES problem. It is a useful indicator of the competitiveness of a technology, as follows:

- If x_j^* is at its lower bound, its unit revenue c_j is less than the resource cost (i.e. its reduced surplus is positive). The technology is not competitive (and stays at its lower bound in the equilibrium);
- If x_j^* is at its upper bound, revenue c_j is larger than the cost of resources (i.e. its reduced surplus is negative). The technology is super competitive and produces a surplus; and
- If x_j^* is basic, its reduced surplus is equal to 0. The technology is competitive but does not produce a surplus

We now restate the above summary in the case of a Linear Program that minimizes cost subject to constraints:

$$\min c^t x$$

s.t $\quad \mathrm{A\,x} \leq \mathrm{b}$

$$\mathrm{x} \geq 0$$

In a minimization problem (such as the usual formulation of TIMES), the difference $c_j - y^*A'j$ is called the reduced cost of technology j. The following holds:

- If x_j^* is at its lower bound, its unit cost c_j is larger than the value created (i.e. its reduced cost is positive). The technology is not competitive (and stays at its lower bound in the equilibrium);
- if x_j^* is at its upper bound, its cost cj is less than the value created (i.e. its reduced cost is negative). The technology is super competitive and produces a profit; and
- if x_j^* is basic, its reduced cost is equal to 0. The technology is competitive but does not produce a profit

The reduced costs/surpluses may thus be used to rank all technologies, including those that are not selected by the model.

13.9 Appendix 9: solar and wind parameters for the WEU adequacy simulation under ANTARES

13.9.1 Solar

Nebulosity Is simulated using a Beta law which parameters are grouped in the next table:

	α	β	γ	δ
1 - January	4.342	12.158	0	1
2 - February	5.842	12.658	0	1
3 - March	4.789	8.211	0	1
4 - April	6.632	7.368	0	1
5 - May	8.211	6.423	0	1
6 - June	7.609	2.431	0	1
7 - July	7.609	2.431	0	1
8 - August	7.609	2.431	0	1
9 - September	7.912	5.754	0	1
10 - October	8.842	12.158	0	1
11 - November	5.842	12.658	0	1
12 - December	3.448	11.572	0	1

Table 4: Parameters of the beta law used to model nebulosity

The expectation of the beta law is: $\gamma + \frac{\alpha(\delta-\gamma)}{\alpha+\beta}$

The variance of the beta law is : $\frac{\alpha\beta(\delta-\gamma)^2}{(\alpha+\beta+1)(\alpha+\beta)^2}$

13.9.2 Wind

The daily profile average generation is given in the next table:

	January	February	March	April	May	June	July	August	September	October	November	December
0	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003	92.870003
1	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003	89.870003
2	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998	91.099998
3	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002	90.190002
4	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002	88.190002
5	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996	87.839996
6	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998	76.739998
7	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997	81.269997
8	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002	86.940002
9	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999	89.959999
10	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998	93.059998
11	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004	92.160004
12	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088	1.187088
13	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569	1.2569
14	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764	1.307764
15	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746	1.333746
16	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795	1.330795
17	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919	1.291919
18	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208	1.204208
19	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264	1.053264
20	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948	0.933948
21	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344	0.900344
22	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427	0.902427
23	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719	0.89719

The coefficients of the beta law used to model the 12 variables for wind are given in the next table:

	alpha		beta	gamma	delta
1 - January	0.636502		2.524613	0	92.870003
2 - February	0.615911		2.524613	0	89.870003
3 - March	0.658591		2.514769	0	88.190002
4 - April	0.625074		2.407045	0	90.190002
5 - May	0.658591		2.514769	0	88.190002
6 - June	0.718841		2.524613	0	87.839996
7 - July	0.61699		2.663432	0	92.365791
8 - August	0.645206		2.528729	0	81.269997
9 - September	0.731966		2.334828	0	86.940002
10 - October	0.658591		2.514769	0	88.190002
11 - November	0.658591		2.514769	0	88.190002
12 - December	0.658591		2.514769	0	88.190002

Table 5: parameters of the beta law used to model wind profile production

The expectation of the beta law is: $\gamma + \frac{\alpha(\delta-\gamma)}{\alpha+\beta}$

The variance of the beta law is: $\frac{\alpha\beta(\delta-\gamma)^2}{(\alpha+\beta+1)(\alpha+\beta)^2}$

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