



A TIMES model of the Reunion Island for analysing the reliability of electricity supply

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International Energy Workshop (Stanford, July 5th to 8th 2011)

Future power mix : a major issue for the next decades

- **Huge investments** are forecasted in power sector ▶ Jump to IEA prediction.

- **Electricity environmental impact** are consequent: power generation stands for more than 40% of Carbon Dioxide emissions.

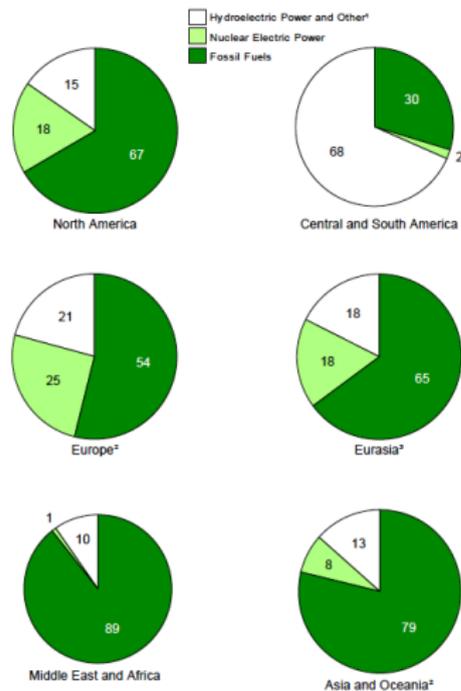


Figure: Power generation by region Source: AER 2009.

Future Power System : generation mix

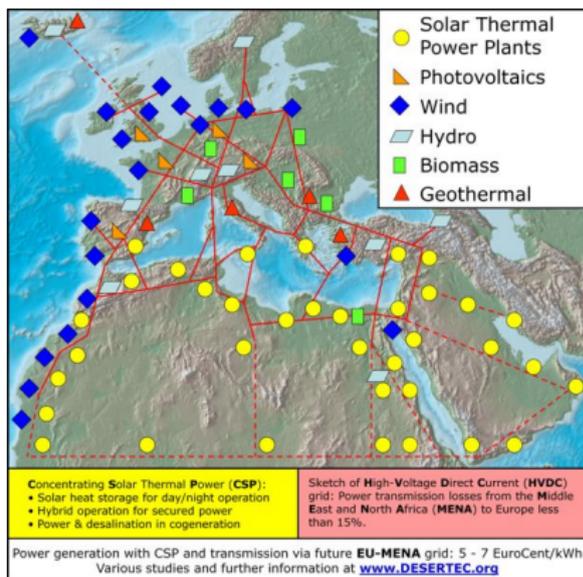


Figure: All-Renewable Electricity Generation in 2050. Source: DESERTEC.

Renewable and distributed energy sources are attractive alternatives for power generation

👉 Major Technical and Economics challenges

- ① Intermittency: complexification of operation issues.
- ② Costs: infrastructures and devices.

Future Power System : Reliability of electricity supply



Figure: Europe from orbit during the Italian blackout (Sept. 28th, 2003). Source: French TSO.

Technical constraints binding the operation of the future power system are related to:

- the given **level and spatial distribution** of loads and capacities;
 - the expected **level of reliability** to prevent from power outages.
- ☞ Where **reliability** is the capability of the power system to withstand sudden disturbances

Transient Stability and Reliability

Definition: Ability of a Power System **after a Transient Period** to lock back into **Steady-State** conditions, maintaining **Synchronism**.

During the Transient Period:

- **Frequency and voltages** change;
- The operator can't modify the production plan;
- The system relies on the **inertia** (kinetic and magnetic) of its transmission and production capacities;
- The power system must remain stable.

Transient Stability Studies assess the level of Reliability of power systems.

Assesing future power systems : dynamics issues

Stability studies

involve time scales ranging from a few milliseconds to a few hours

Long-term planning models

deal with several years or decades

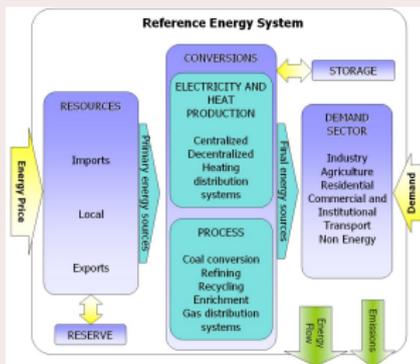
- This gap is the main reason why reliability requirements are often ignored or not accurately implemented in long-term planning models.

Assessment of reliable future power systems

- ➔ This study proposes an approach combining these dynamics issues to assess future power mixes where

Future power mix are assessed through a long-term model

TIMES, a bottom up technological model realizing the minimization of the global discounted cost of the RES



A reliability criteria

is established to handle the **dynamic management** (frequency and voltage controls)

- depending on:
 - the level of reliability required,
 - the **dynamic properties** of capacities,
 - the load profile.
- avoiding *time-consuming* methods relying on Kirchhoff laws.

Power systems through a Thermodynamic framework

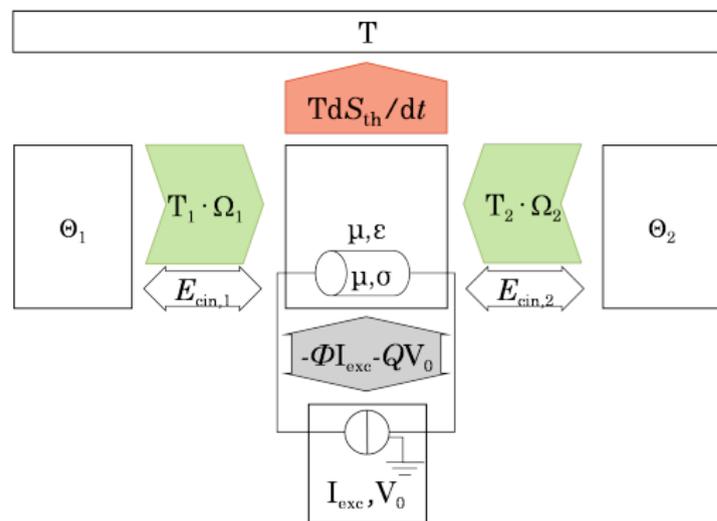


Figure: energy exchanges between the subsystems involved in the Thermodynamic Framework. Source: V. Mazauric

- The electromagnetic field is the studied system. It is seen as a **power conveyor**.
- Generators Θ_1 exchange work with motors Θ_2 through the field.
- T the thermostat.
- I_{exc} is the current exciting the field and V_0 the earth voltage. [▶ Jump to I](#).
- $(\Phi I_{exc} + QV_0)$ is the **coupling energy** between the field and the machines.

Basic principles: Condition of Reversibility I

- ① The **First Principle** conveys the Energy Conservation:

$$\frac{dU}{dt} = P_{\text{mech}_{\text{int}}} - T \frac{dS_{\text{th}}}{dt} \quad (1)$$

- U is the internal energy of the **isolated system**,
 - $P_{\text{mech}_{\text{int}}}$ is the **mechanical power** delivered by the alternator,
 - S_{th} is the entropy of the thermostat, and $T \frac{dS_{\text{th}}}{dt}$ is the heat exchanged with the thermostat. [▶ Jump to II](#).
- ② For an **isothermal evolution**, we introduce the Helmoltz free-energy, $F = U - TS$, to take into account the **coupling with the thermostat** T :

$$P_{\text{mech}_{\text{int}}} - \frac{dF}{dt} = T \left(\frac{dS}{dt} + \frac{dS_{\text{th}}}{dt} \right) = P_{\text{Joule}} \quad (2)$$

The RHS stands for the **Joule losses**, the heat dissipated by the whole system.

Basic principles: Condition of Reversibility II

- ③ To take into account the electromagnetic coupling, we introduce the Gibbs free-energy, $G = F - \Phi I_{\text{exc}} - QV_0$.
- ④ The **Second Principle** conveys the Reversibility Condition stating that Joule losses are always ≥ 0

$$P_{\text{mech}_{\text{int}}}^* - \frac{dG^*}{dt} = \min \left(P_{\text{Joule}} + \frac{d(\Phi I_{\text{exc}})}{dt} + \frac{d(QV_0)}{dt} \right) \quad (3)$$

The **condition of reversibility** for power systems expresses that the evolution of the system minimizing the Joule losses is more reversible. This system have been proven to satisfy Maxwell equations (source V. Mazauric)

Best power transactions

The reversibility condition (3) derives to :

$$\begin{aligned} P_{\text{mech}_{\text{int}}}^* &= P_{\text{Joule}}^* + \frac{dG^*}{dt} + \frac{d(\Phi^* I_{\text{exc}})}{dt} \\ &= P_{\text{Joule}}^* + \frac{dF^*}{dt} \end{aligned} \quad (4)$$

where * stands for the argument of the minimum and QV_0 is neglected.
From the **fundamental equations of dynamics**, $\sum F = m\gamma$, we derive

$$P_{\text{mech}_{\text{ext}}} - P_{\text{mech}_{\text{int}}}^* = \frac{dE_{\text{cin}}^*}{dt} \quad (5)$$

Eventually

$$\underline{P_{\text{mech}_{\text{ext}}} = P_{\text{Joule}}^* + \frac{dE_{\text{cin}}^*}{dt} + \frac{dF^*}{dt}} \quad (6)$$

From the reversibility condition to network management

The best power transaction achieves :

$$\underbrace{\text{tertiary \& secondary control}}_{P_{\text{mech}_{\text{ext}}} \sim mn} = P_{\text{Joule}}^* + \underbrace{\frac{dE_{\text{cin}}^*}{dt}}_{\sim s} + \underbrace{\frac{dF^*}{dt}}_{\sim ms} \quad (7)$$

primary control

where time response is related to dynamic management of a sudden imbalance involving the three control levels needed for network operations :

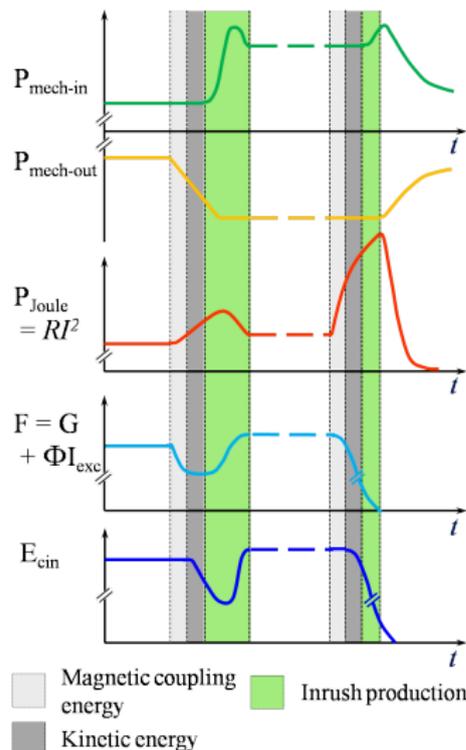
- **primary** : automatic devices re-establishes the balance between demand and generation at a system frequency other than the frequency set-point value (50 Hz). It causes a deviation in power exchanges between control areas from the scheduled values.
- **secondary** : automatic devices restore the system frequency to its set-point and restore the power exchanges between the control areas.
- **tertiary** : TSO manual action to activate reactive compensation equipment.

Load fluctuation and stability

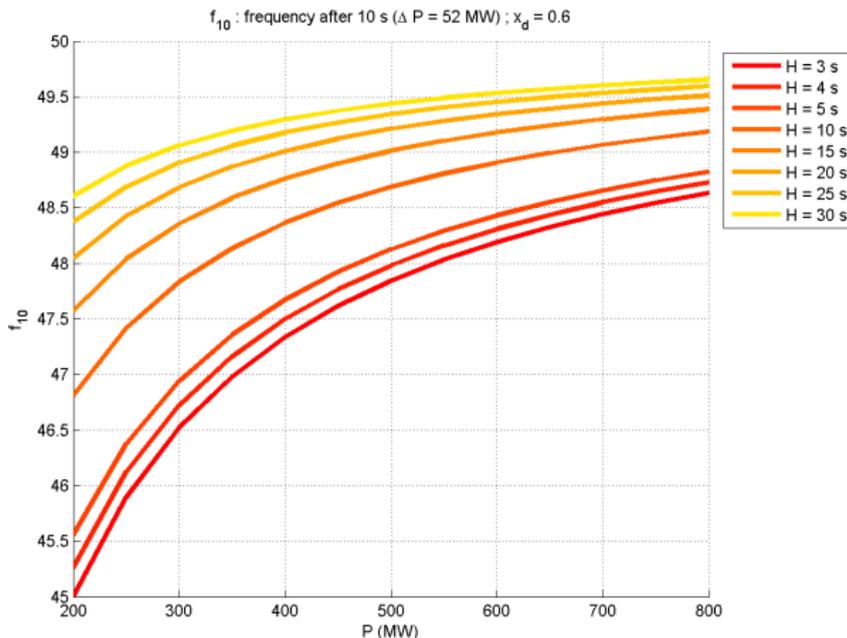
energy exchanges between the subsystems involved in the Thermodynamic Framework

Source: V. Mazauric

Two events experienced by a power system:
 an admissible load fluctuation is lifted by the electromagnetic coupling energy (Φ_{exc}), the kinetic reserve (E_{cin}) and the generation realignment during a load fluctuation (left) ;
 conversely, a short circuit lowers the coupling energy and the kinetic reserve leading to a collapse of power transmission (right).



Frequency response 10s after a load fluctuation of 52 MW



H is the time you have to recover the stability of the system by monitoring it.

Steps of the approach

- 1 A power mix is delivered through the prospective horizon using TIMES
- 2 The level of reliability of the power system can be derived from
 - the **dynamic properties** of the installed capacities
 - the associated inertia of the system (kinetic and magnetic)
 - the load profile.

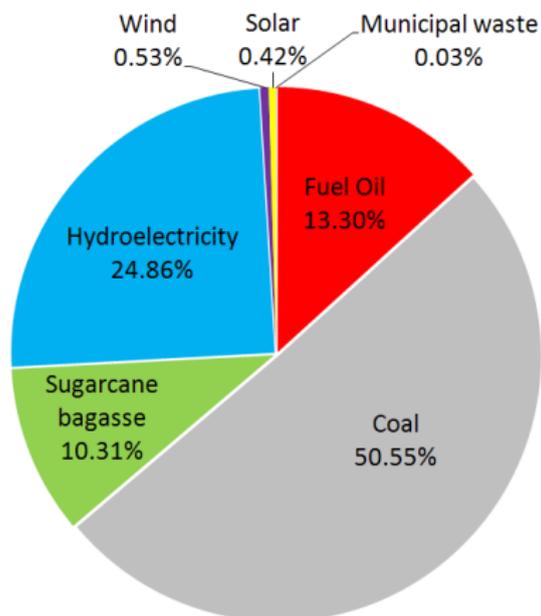
characterized by H as a measure of the kinetic energy inertia

Why focusing on the Reunion Island ?



- 1 Blessed with high renewable energy potentials
- 2 Small, weakly-meshed and remoted power system
- 3 Binding target in 2030: 100% renewable sources in power generation

The electricity sector in 2008



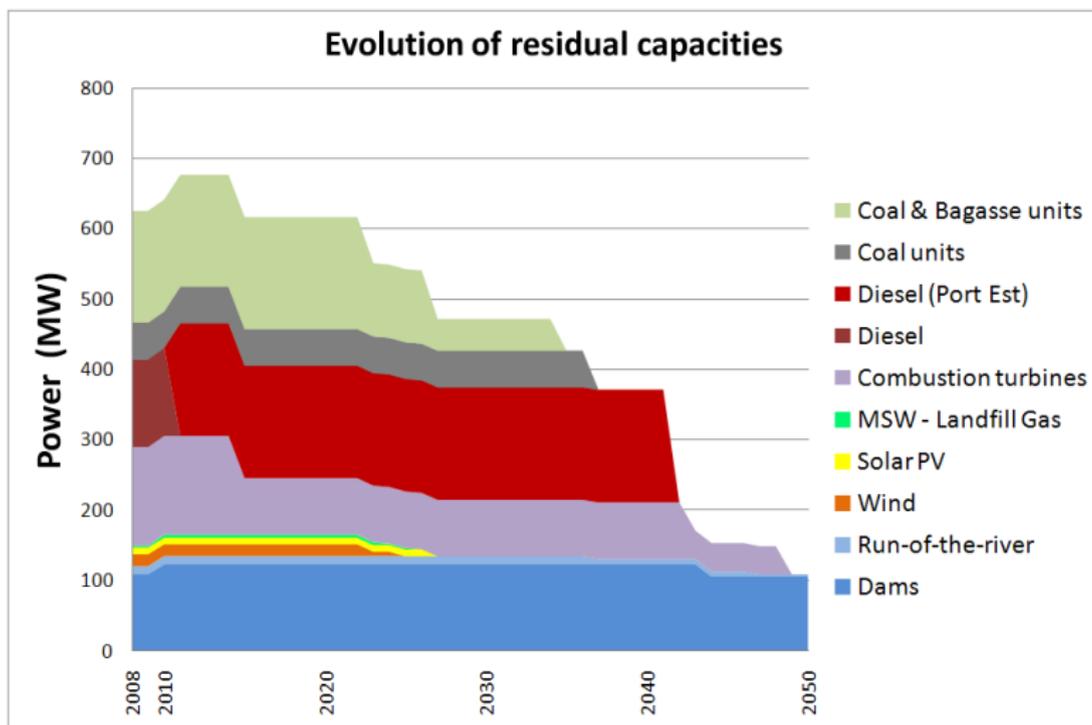
Source : BPPI - EDF SEI 2009

Electricity production: 2 546 GWh

Installed capacities

- **Thermal units (76%):**
 - 476 MW
 - Fuels: coal, fuel oil, sugarcane bagasse
- **Hydroelectricity (20%):**
 - Dams: 109,4 MW
 - Run-of-the-river: 11,6 MW
- **Others (4%):**
 - Wind: 16,8 MW
 - Solar PV: 10 MW
 - Municipal Waste: 2 MW

Existing power plants



Assessment of two contrasted scenarios

- 1 BASE** (with fossil) scenario, reflecting Business as Usual trends where imports levels in 2008 :
 - coal (COA) = 16 395 TJ
 - distillate fuel oil (OILFOD) = 408 TJ
 - heavy fuel oil (OILHFO) = 3122 TJ
- 2 noFOS** (no fossil) scenario, 100% Renewable Energy in 2030 where fossil fuel imports levels are constrained as follows :
 - 25 000 TJ in 2010.
 - 10 000 TJ in 2020.
 - 0 TJ in 2030.

General hypotheses

	Unit	2000	2008	2015	2020	2025	2030
Energy Prices¹:							
Steam Coal	\$2008/t	41.22	120.59	91.05	104.16	107.12	109.4
Crude Oil	\$2008/bbl	34.3	97.19	86.67	100.00	107.50	115.00
Heavy fuel oil	€2008/t	-	196	174	201	216	231
Distillate fuel oil	€2008/hl	-	47	42	48	51	55
Electricity:							
Growth rate	%		3.4	2.6	2.4	1.5	1.5
Consumption	GWh		2 546	3 110	3 500	3 805	4100
Peak power	MW		408	520	595	670	720

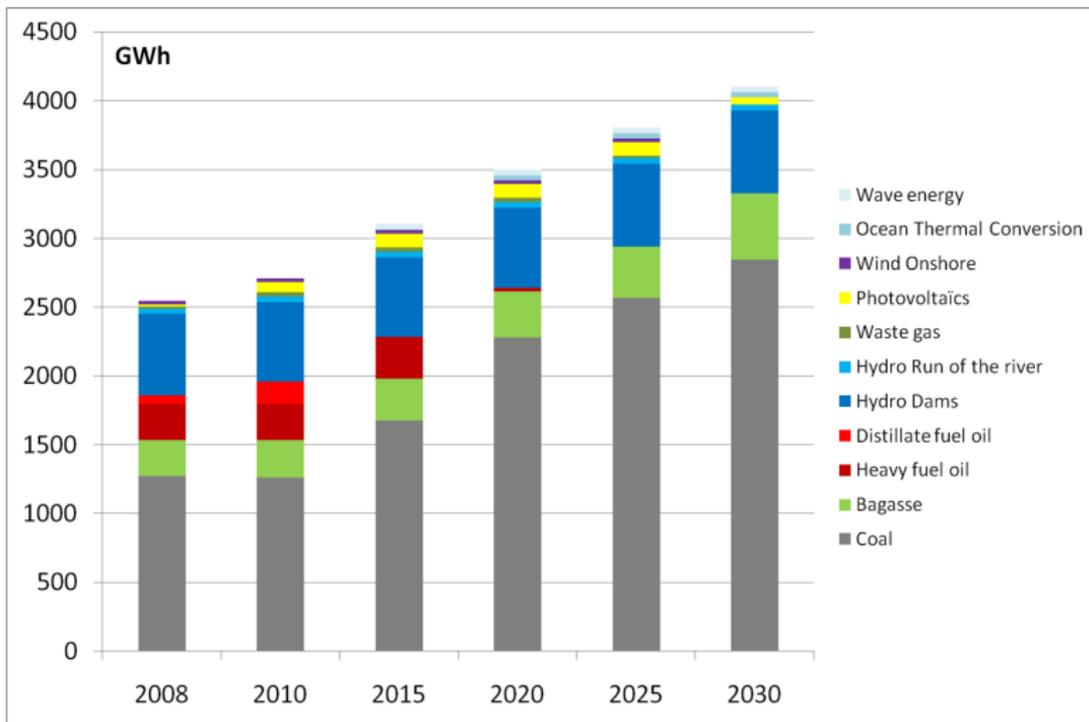
Sources : International Energy Agency, Electricité de France

¹2008 real term prices

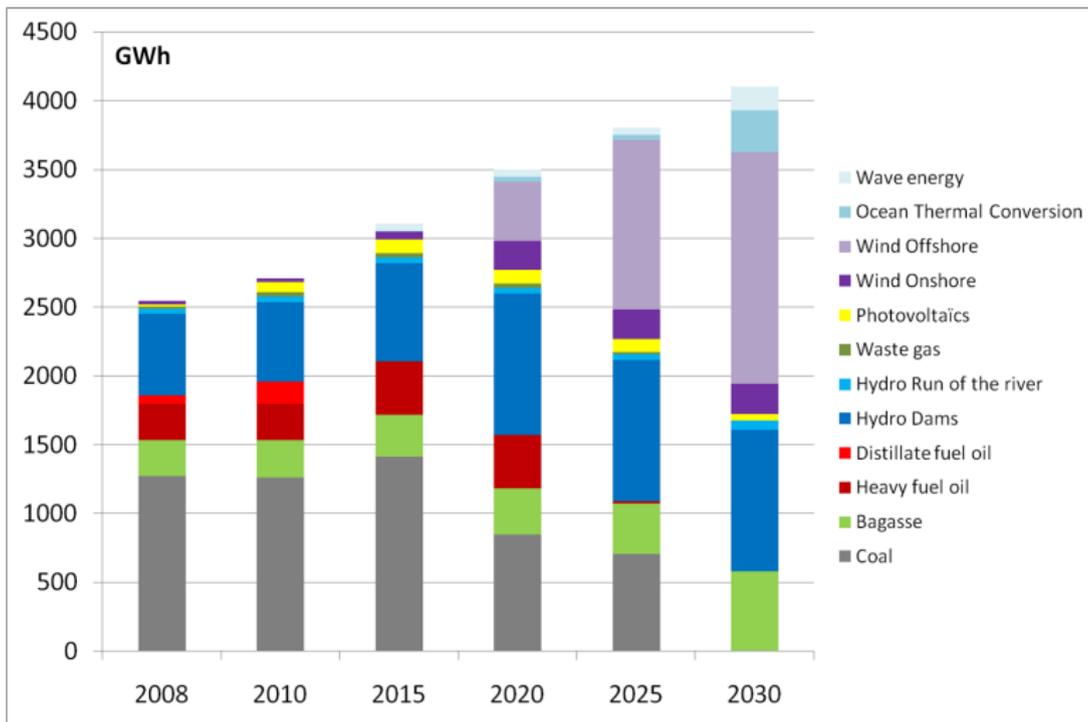
Renewable energy potentials

Energy sources	2008 levels	2030 potentials
Biomass (SIDECE)	260 GWh	400 GWh
Hydropower (SDAGE)	121 MW (\approx 633 GWh)	268 MW (\approx 1093 GWh)
Wind Onshore (PETREL)	16,8 MW	100 MW (only 50 MW according to Aéro watt)
Wind Offshore	–	600 MW
Solar PV (PETREL)	10 MW	250 MW (BT) 500 MW (HT)
Ocean Thermal Energy Conversion (ETM) (PETREL)	–	= 1 MW in 2012 \geq 10 MW in 2020
Wave Energy (COREX)	–	= 3 MW in 2012 \geq 10 MW in 2015
Geothermy	–	100 MW (only 30 MW according to PETREL)
Biogas	4 MW	(Life = 15 y)

BASE Scenario : production (GWh)

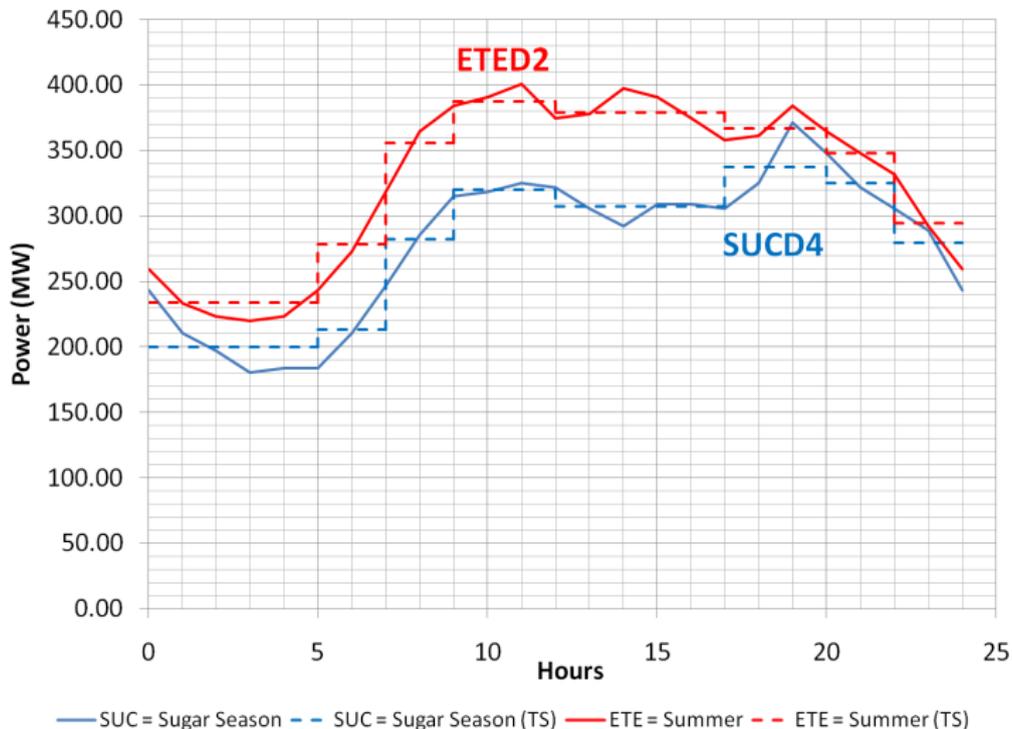


noFOS Scenario : production (GWh)

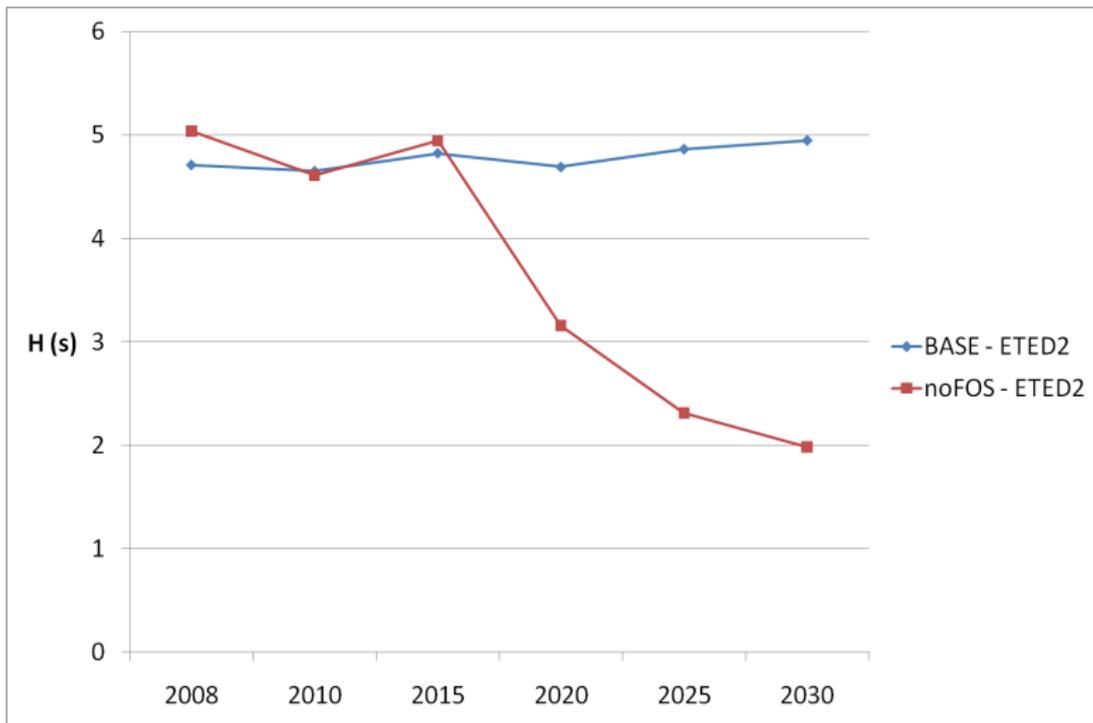


The Reunion Island Load curve

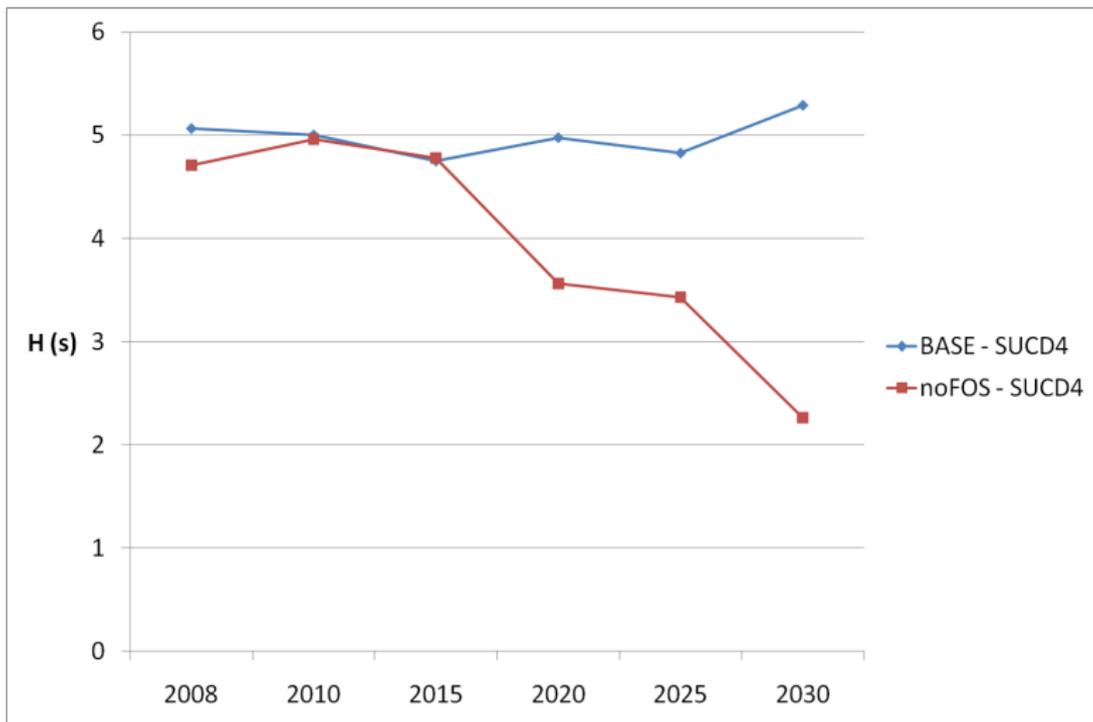
Two distinct seasons: Summer (ETE) / Sugar season (SUC)



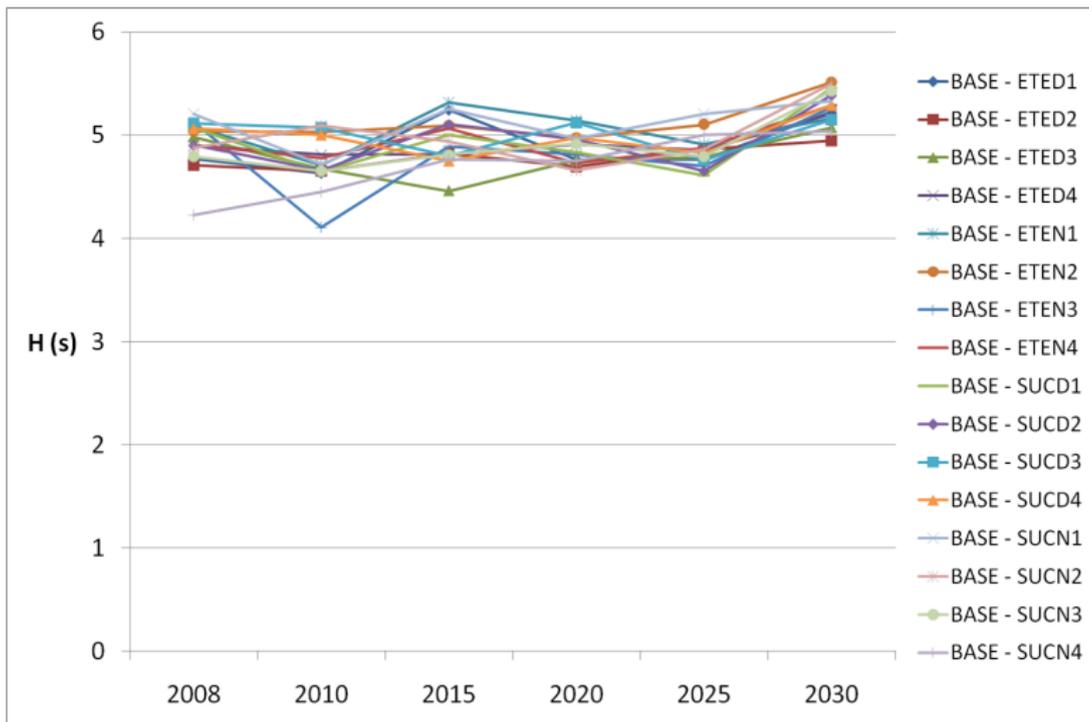
Kinetic response for Summer season peak hour (ETED2)



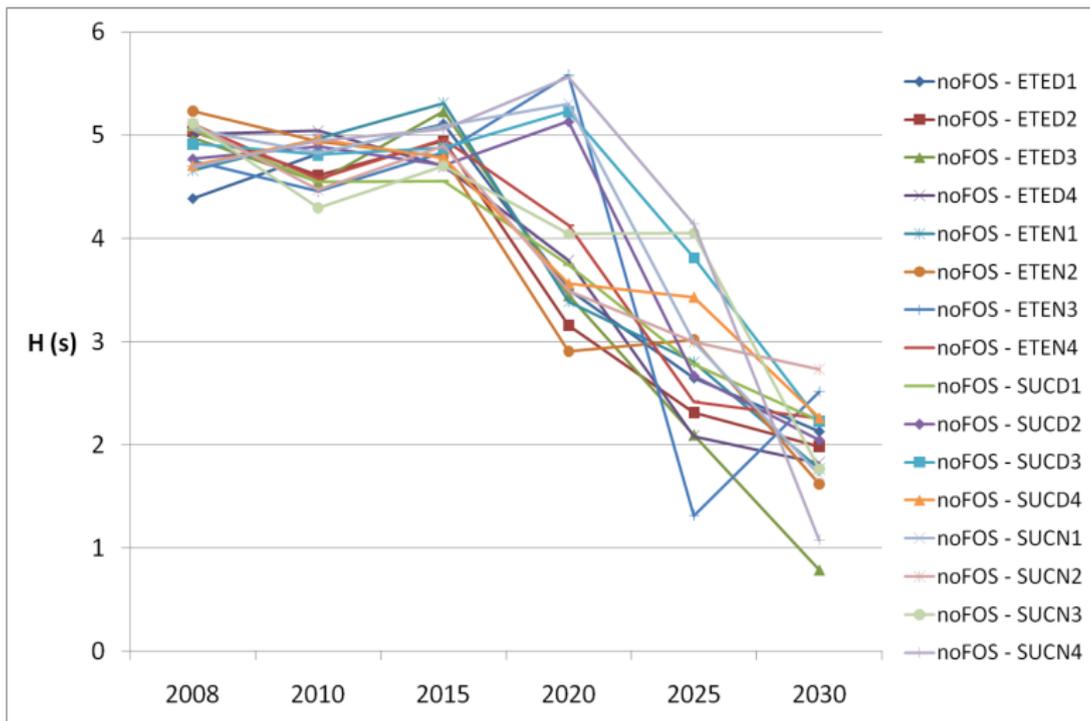
Kinetic response for Sugar season peak hour (SUCD4)



Robustness of the results : BASE (fossil) scenario



Robustness of the results : noFOS (100% renewable) scenario



Summary and perspectives

We have developed an innovative approach enabling to qualify

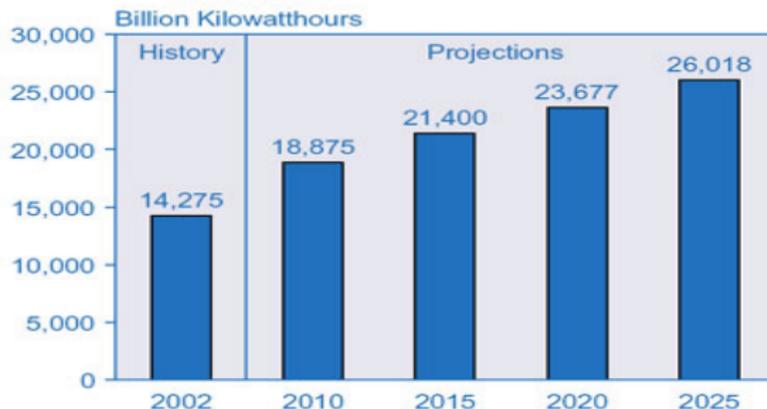
The level of reliability of an assessed power mix system resulting for TIMES assessment derived from

- the **dynamic properties** of the installed capacities
 - the associated inertia of the system (kinetic and magnetic)
 - the load profile.
-
- ☞ the criteria reflecting kinetic energy inertia has been established
 - ☞ the criteria reflecting magnetic energy inertia is under development
 - ☞ the Reunion Island is a first case of application

This approach is dedicated to assess the technical feasibility of future power mix, especially when, in order to cope with environmental issues, the spread of renewable energies is often highly recommended without questioning reliability issues.

Power consumption prediction

Figure 58. World Net Electricity Consumption, 2002-2025



Sources: **2002:** Energy Information Administration (EIA), *International Energy Annual 2002*, DOE/EIA-0219(2002) (Washington, DC, March 2004), web site www.eia.doe.gov/iea/. **Projections:** EIA, System for the Analysis of Global Energy Markets (2005).

Figure: Power consumption for the next decades (2002-2025)

Basic principles: Variational Formulation I

Maximum-entropy Principle

- For complex systems, we use thermodynamics.
- The **entropy** S measures the missing information describing the system.
- Equilibrium conditions are obtained from the **maximum-entropy principle**, while keeping the **macroscopic information**, namely:
 - the positions of the moving parts (Θ for the machines),
 - the internal energy U ,
 - the magnetic flux Φ and the electric charge Q squeezed from the earth.
- The system can also be described with its **state variables**: $\{T, I_{\text{exc}}, V_0\}$.

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Basic principles: Variational Formulation II

Non-equilibrium Evolution

- For non-equilibrium conditions, considering an isothermal evolution, **the entropy of the isolated^a system can only increase.**
- Then, the evolution is said **reversible** when the entropy is not modified.
- Otherwise, the evolution is said **irreversible** and the more reversible evolution is reached when the **variation of entropy is minimised.**

^aThe system is **isolated** thanks to the couplings exhibited in the last picture.

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