ENERGY SYSTEMS PLANNING AND THE INTERACTIONS WITH THE ELECTRICITY SYSTEM PLANNING – AN EUROPEAN MODEL –

MIGUEL LOPEZ-BOTET ZULUETA, VERA SILVA

EDF R&D

2015
EDF at a glance

- Electricity: covering the entire chain, from generation to transmission, distribution and supply.
- Solidly anchored in Europe: France, the UK, Poland, Italy, etc.
- Industrial operations in Asia and United States
- Natural gas: a major player

Key figures

- 37.9 million customers worldwide
- 169,139 employees worldwide
- €66.3 billion in sales, of which 49% outside France
- 618.5 TWh of energy generated worldwide
- 117.1 g of CO₂ per kWh generated
- 2009 sales %
  - 49 Outside France o/w the UK 17
  - Germany 11
  - Italy 7.5
  - France 51

2009 Group generation mix %
- 75.4 Nuclear
- 11.2 Fossil-fired
- 4.3 Gas
- 8.1 Hydro
- 1.1 Other energies
- Total: 618.5 TWh
EDF R&D – AREAS OF ACTIVITY AND KEY FIGURES

Areas of activity

2 110 PERSONS
including
370 PhDs
150 PhD students
200 Researchers teaching in universities

€523 million
2012 Budget
of which 25% for environmental projects

Information technologies
Generation: nuclear and fossil-fired power
Energy management
Sales and marketing development
Transmission and distribution networks
Renewable energies, including hydropower
RESEARCH CENTERS AROUND THE WORLD

ÉTATS-UNIS
PALO ALTO
Electric Power Research Institute (EPRI), dont EDF est membre

ROYAUME-UNI
LONDRES
UK Centre

FRANCE
CHATOU
CLAMART
LES RENARDIÈRES

ALLEMAGNE
KARLSRUHE
European Institute for Energy Research (ElfER)

POLOGNE
CRACOVIE
EDF R&D Polska

CHINE
PÉKIN
Centre de R&D inauguré en 2011

LOS ALTOS
R&D Team
Wind capacity = 120 GW
7% of demand covered in 2013

Wind + PV = 202 GW in 2013

PV capacity = 82 GW => 3% of demand covered

Source: ENTSO-E

Hydro generation is still the largest RES (Norway, Sweden, Italy, France, Switzerland)

<table>
<thead>
<tr>
<th>Countries</th>
<th>TSO’s</th>
<th>Peak</th>
<th>Capacity</th>
<th>Energy demand</th>
<th>Synchronous systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>41</td>
<td>530 GW</td>
<td>930 GW</td>
<td>3340 TWh</td>
<td>5</td>
</tr>
</tbody>
</table>
WHAT IS OUR INTEREST ON MULTI-ENERGY SYSTEMS ANALYSIS

- Evaluate the impact of energy policies:
  - Renewable deployment, EU ETS

- Anticipate evolutions on the energy/electricity demand and adapt business/investment strategies

- Analyze business opportunities
  - Evaluate the benefits of new use of electricity, for the system and for new business development

- Contribute to the public debate
The interaction between energy vectors needs to be taken into account when studying the power system.

- **Energy prospective**
  - Hypothesis on demand, fuel prices, RES potential...

- **Market design**
  - Power and gaz market design
  - Technical and economical rules

- **Power system planning**
  - Power system economic planning
  - Demand, network, generation and storage coordination
  - Multi-energy usages optimization

- **Power systems operations**
  - **Mid-term**
    - Maintenance
    - Fuels
    - Market coverage
  - **Short term**
    - Unit commitment
    - Economic dispatch
    - Flexibility and reserves
    - Dynamic stability
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1 : USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES

   EXAMPLE 2 : USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS
   
   EXAMPLE 3 : USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1: USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES

   EXAMPLE 2: USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS

   EXAMPLE 3: USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
Basic Concepts:

What is adequacy? What is flexibility?

Adequacy is connected with the issues of investment decisions and is used as a measure of long term ability of a system to match demand and supply with an accepted level of risk. This is a measure that internalizes the stochastic fluctuations of the aggregate demand and supply.

Flexibility is mostly connected with operation decisions and represents the ability of a system to adapt its to both predictable and unpredictable fluctuating conditions, either on the demand or generation side, at different time scales, within economical boundaries.
INTEGRATION OF THE MULTI-ENERGY VISION IN THE AND ELECTRICITY PLANNING MODELS

Goal: to obtain an a long term electricity system expansion solution that ensures a flexible system the problem needs to include: 1) the interaction between the energy and the electricity systems 2) the long term uncertainties and 3) the relevant short term operation constraints and uncertainties.
Option 1) Representation of electricity system flexibility in the Times model by increasing the simulation granularity and including additional constraints=> MADONE

Option 2) Coupling energy system models with electricity system models using a chain of simulation tools with the possibility of back feeding relevant information

- Energy system optimization : Madone
- Electricity system planning : Continental Model with Investment loop
- Detailed near term flexibility assessment : Continental with FlexAssessment
MADONE performs a multi-annual and multi-energy simulation of each of the 29 interconnected European countries

- **Perimeter EU27+NO+CH (Europe 29)**
  - with different levels of detail depending on the country

- **Trans-national networks represented**
  - electricity and gaz, CO2

- **Storage capacities**
  - hydro (one lake per country + hydro-pumping), gaz, CO2

- **Pipelines/electricity injections at the frontier of EU29**
  - NordStream, Southstream, Nabucco, DESERTEC…

- **National resource potentials & limits**
  - Wind off-shore: km2(depth, wind speed, distance to coast) X Capacity density; Wind on-shore km2 (area potentially available) X Capacity density; solar PV: area available, roofs surfaces; CO2 storage; biomass resources

- **Period and simulation time step**
  - yearly from 2005 to 2010, every 10 years from 2010 to 2050
  - representation of each year with load curves eg: 24, 288 points

- **Outputs**
  - Technology mix & detailed energy balances, energy dependency, and environmental indicators, balance for electricity (including exchanges), association of energy uses and activities….
In order to represent a “realistic” European electricity system, we require:

- description of different countries generation mix and key transmission corridors
- interconnection capacities between countries
- management of water reservoirs and pump storage
- demand and variable generation across the European system => time-synchronise data with hourly (or lower) resolution and over a large number of climate years

Some key challenges of this problem:

- **Hydro** and **storage** flexibility optimization => **stochastic problem**
- **Generation scheduling** needs to be performed across the whole Europe including interconnection and key transmission constraints (high performance computing)
- Impact of variable generation on static and dynamic security => detailed analysis of system operation in the future is needed (hierarchical approaches)
The objective is to obtain the thermal generation mix that ensures that for every new unit the revenues equals its annuitized fixed costs:
- Fixed costs include investment and O&M
- Variable costs include start-up and fuel costs

The generation mix is optimized in two iterative steps:
- Load duration curve based heuristic to propose a candidate solution
- Validation of the heuristic solution solving the hourly load-generation dispatch => creates a price signal that feeds the investment loop

The generation mix needs to respect an adequacy criterion
- Maximum of 3h/year with market clearing price = VOLL
Scenario based representation of stochastic parameters:
Large number of annual scenarios of demand, wind and PV generation, water inflows, fuel costs, thermal unit availabilities

Minimize global production cost for each zone
Unit commitment and economic dispatch minimizes thermal and hydro generation cost over all the scenarios
Constraints include primary, secondary and tertiary reserve and generation dynamic ratings
Multi area optimization with interconnection constraints represented by NTC
For each dispatch period and for each zone the dispatch solution and the market clearing prices are obtained to access the revenues of generation units

Stochastic hydro-generation scheduling
Maximize the reduction in terms of generation costs using dynamic optimization to obtain the “water value” for each time step
Define a set of strategies of the optimal use of hydro reservoirs in order to minimize the global generation cost

C HAIN OF SIMULATION TOOLS FOR DETAILED FLEXIBILITY ASSESSMENT OF CONTINENTAL MODEL SCHEDULING SOLUTIONS

Madone/TIMES model

Detailed description of VG
- Location of VG
- Load factors (with resolution 1h or lower)
- VG forecast errors

Input data
- Demand time series
- Investment costs
- Generation dynamic constraints
- Fuels costs
- CO2 price
- Network transfer capacities

Investment / hourly dispatch

Investment loop

CONTINENTAL Model

Flex Assessment

Dynamic simulation model

Economical analysis

Generation mix
- Interconnection load factors
- Generation load factors
- VG curtailment
- Market prices and generation costs
- Plant revenues
- Reserves and flexibility adequacy
- Frequency stability

The model coupling can include multi-annual investment trajectories simulated with Times complemented with annual snapshot simulations with Continental Model.
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1: USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES
   
   EXAMPLE 2: USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS
   
   EXAMPLE 3: USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
**MADONE**

- Bottom-up TIMES model: all 29 interconnected European countries
- Renewables national resources potentials & limits detailed: Wind off-shore, wind on-shore, roof for PV etc...
- Horizon = 2005 to 2050 with a perfect foresight of each year
- **Time-slices: 24 or 288**
  - 24 = Peak and Off-Peak for each month
  - 288 = 2 representative day (Week/W-E, bi-hourly)/month
- **Peak equation: additional demand constraint**
  \[ Dem_{max}(t) - Dem(t) \]
- With or without renewable contribution
- **Deterministic**
  - Or multi-scenarios for one chosen year: testing with 4 annual scenarios

**Continental Model with Investment loop**

- EDF R&D’s Elec Production Cost model
- Electricity generation portfolio optimization
- Stochastic simulation of hourly system operation
  - Demand-generation balancing solved for one year with hourly resolution
  - Interconnection constraints included
  - Stochastic parameters: \( T^\circ, \text{hydro, wind, PV and generation outages} \)
Comparing Continental and Madone Optimal Thermal Generation Mix

- Consistency of base capacity needs between the 2 models.
- Mid-base capacity underestimated with TIMES model.
- Peak capacity dependent on peak equation calibration.

**Continental**

- **Base**
- **Mid-merit**
- **Peak**

**Madone (TIMES)**

- **Base**
- **Mid-merit**
- **Peak**
In the tests we made, a multi scenario approach helps reducing the gap for mid-merit capacity but leads to a larger over-estimation of peak capacity.

- Choice of a (limited =4) set of scenario: how to select the right ones?
- Calibration of peak equation could be a solution… but largely dependent on the system studied.
Madone is suitable to provide a “merit order” between technologies including the mix and geographic distribution of renewables

- Representing explicitly dynamic constraints in a long-term TIMES large planning model doesn’t seem realistic for the time being.

- Without modeling operation margin and reserve requirements & dynamic constraints, the generation dispatch is not accurate.

  - For instance, a peak equation imposes investment in back-up capacity, not its use.

- … but the objective is to have the « right » merit order between technologies investment decisions,

  - « right » = least cost + meeting capacity adequacy & flexibility adequacy system requirements.

- And then to assess, ex-post, if the generation mix calculated meets the electricity system constraints (Option 2)

  - Renewables mix per country: F (cost/potential) with sensitivity to interconnection.

  - Continental model with investment loop.

  - Flexibility and adequacy constraints.
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1: USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES
   
   EXAMPLE 2: USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS
   
   EXAMPLE 3: USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
CHAIN OF SIMULATION TOOLS FOR DETAILED FLEXIBILITY ASSESSMENT OF CONTINENTAL MODEL SCHEDULING SOLUTIONS

Madone/TIMES model

Detailed description of VG
- Location of VG
- Load factors (with resolution 1h or lower)
- VG forecast errors

Input data
- Demand time series
- Investment costs
- Generation dynamic constraints
- Fuels costs
- CO2 price
- Network transfer capacities

Investment / hourly dispatch

Investment loop

Continental Model

Flex Assessment

Economical analysis

Dynamic simulation model

Generation mix
- Interconnection load factors
- Generation load factors
- VG curtailment
- Market prices and generation costs
- Plant revenues
- Reserves and flexibility adequacy
- Frequency stability
European decarbonization targets from the energy system determine the volume of EU ETS permits allowed

-43% in 2030/2005 (EU31): this constraint applies for an aggregated level for several years («banking» allows to store from one year to the next)
- Market Stability Reserve after 2019

This interacts with the RES targets

- 27% RES of the energy consumption in 2030 (EU28), and NREAP à 2020
- implies 45% RES in power generation, 27% wind and solar
- assuming a reduction of RES costs
- and large RES potential
This simplified approach takes into account the inter-annual trajectory from 2013 to 2030.

**Input data**

- CAPEX, OPEX, life expectancy, efficiency and emission factors
- PV and wind potential (R&D MFEE)
- Fuel costs

**Year demand (TWh)**

**Load and RES generation curve (288 time steps, 1 average deterministic scenario)**

**Retirement of thermal units according to their technical life expectancy**

**CO2 emissions authorized**

**System costs minimization over the period 2013-2030+**

**Results**

**New installed capacities (GW)**

**Generation mix (TWh)**

**CO2 emissions trajectory (Mt)**

**CO2 price (€/t)**

**Fuel costs**

**PV and wind potential (R&D MFEE)**
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1 : USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES

   EXAMPLE 2 : USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS
   
   EXAMPLE 3 : USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
Simulation of the EU Energy Roadmap « HiRES 2030 » Scenario

60 % RES (generation)

40 % Wind & Solar

HiRES scenario
EU energy roadmap
Generation Mix 2030

6% Wind offshore
12% Solar
7% Nuclear
29% Thermal fossil fuel
14% Wind onshore
14% Biomass & Geothermal
18% Hydro power

High RES 2030 | GW | Load factor (h/yr)
--- | --- | ---
Solar (PV) | 220 | 1100
Onshore wind | 280 | 1900
Offshore wind | 205 | 3200
Hydro | 120 | 3800

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>86 €/t</td>
</tr>
<tr>
<td>Gas</td>
<td>10 €/MMBtu</td>
</tr>
<tr>
<td>Oil</td>
<td>107 €/baril</td>
</tr>
<tr>
<td>CO₂</td>
<td>35 €/t</td>
</tr>
</tbody>
</table>
A SIMPLIFIED APPROACH TO PLACE RES GENERATION ACROSS EUROPE

Wind and solar energy targets 2030

Describe the power system:
- Thermal and renewable remaining units
- Interconnections
- Technical and economical characteristics.

TIMES élec
Builds the RES mix and optimize the location

Precise RES hypothesis:
- New turbines V112 & V126 taken into account when calculating the load factor
- Max density for wind onshore development constraints
- Installable yearly capacity limits for every technology

RES geographical distribution

European RES potential (TWh) illustration

Potentiels EnR 2020 EU27+2 (TWh), av. renf. réseau et balancing, densité de 225 kW/km²

- France
- Pologne
- Allemagne
- UK
- Espagne
- Italie
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1: USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES
   
   EXAMPLE 2: USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS
   
   EXAMPLE 3: USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
The model coupling can include multi-annual investment trajectories simulated with Times complemented with annual snapshot simulations with Continental Model.
WHERE TO INTEGRATE LARGE SHARE OF RENEWABLES WITH NETWORK CONSTRAINTS?

RES geographical distribution

Network development scenario

PV (GW)
Offshore wind (GW)
Onshore wind (GW)

Interconnection reinforcement (GW) similar to TYNDP 2014

TYNDP 2014 +47 GW en 16 ans

Interconnection reinforcement TYNDP 2010 (GW)
**Variable RES are key to the decarbonisation of electricity generation but the system still needs backup capacity for security of supply.**

Average CO\(_2\) with 60% RES = 125 g CO\(_2\) /kWh
Average CO\(_2\) with additional coal/gas replacement = 73 g CO\(_2\) /kWh
(average CO\(_2\) today = 350 g CO\(_2\)/kWh)

Full decarbonization can only be achieved with a significant share of carbon free base load, in particular nuclear.
**Flexibility Sources and Wind Curtailment Help to Balance Generation and Demand**

Wind and PV generation lead to a more variable net demand.

Interconnections, storage and wind curtailment help to smooth the demand addressed to conventional generation.

Conventional generation flexibility is used to follow the remaining variability.

- Wind curtailment is inevitable when must run generation plus variable generation exceed demand.
- In some cases wind curtailment is also used for economic reasons (cheaper than start and stops of conventional plants).
OUTLINE

1. EUROPEAN SYSTEM MODELING AT EDF R&D

2. REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS
   
   EXAMPLE 1: USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES
   
   EXAMPLE 2: USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS
   
   EXAMPLE 3: USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS
HYDROGEN COUPLES POWER AND GAZ SYSTEMS WHEN TRANSFORMED IN CH₄ COMBINED WITH CO₂

1. Energy use transfer
2. “Power to gaz”
3. Gaz demand for power generation

Power system
- Power demand
- Power network
- Power generation
- Power storage

Gaz system
- Gaz demand
- Gaz network and storage

Power and gaz markets
THE VITESSE² PROJECT EXAMINE THE TECHNO-ECONOMIC RELEVANCE OF METHANOL PRODUCTION, FROM CO2 EMISSIONS AND HYDROGEN

- In the future, the importance of hydrogen as an energy carrier could grow as it is a chemical intermediary with multiple applications.

- The present study examines how adding the flexible demand of the electrolyzers in France would impact the European power system while keeping the cost of hydrogen production close to competitiveness.
  - Renewable energy development (mainly photovoltaic and wind energies) is one of the means to decarbonize the European energy system: flexible electrolyzers could help managing the power system and reducing curtailment.
  - It could be a way to mitigate CO2 emissions if combined with CO2 to produce methanol.

This power system approach enables to perform a cost-benefit analysis of using electricity for some new use.

\[
\begin{align*}
\text{Electrolysis: } & \quad \text{CH4} + \text{H2O} \rightleftharpoons \text{CO} + 3 \text{H2} \\
\text{Reforming: } & \quad \text{CO} + \text{H2O} \rightleftharpoons \text{CO2} + \text{H2}
\end{align*}
\]

H₂ Cost

CO₂ emissions
METHODOLOGY:
USING AN HOURLY LONG TERM ECONOMIC DISPATCH MODEL

- Power plant production planning
- Electrolysis demand positioning through system cost minimization
- Electricity marginal cost

Non-marginal approach: influence of electrolysis system penetration on marginal costs

Assumption: marginal cost ~ electricity spot price
MARGINAL COST FORMATION

- Power plants start-up: merit order according to the variable costs
- Market price ~ marginal cost of the electricity area (i.e. France)
ELECTROLYZER OPERATION: SELECTION OF A THRESHOLD PRICE

- Hydrogen production: additional electricity demand which is satisfied while not exceeding a threshold price

Situation #1
The flexible demand is completely met

Situation #2
The flexible demand is partly met

Situation #3
The flexible demand is not met at all
TWO PROSPECTIVE SCENARIOS: MEDIAN AND RUPTURE

- Time horizon: 2030

- Scenarios for France; simulation of the whole European system

  - **Median scenario:** business-as-usual; in line with the French TSO assumptions
    - Nuclear power: 56 GW (-7.1 compared to current situation)
    - Renewables: +99 TWh compared to current situation

  - **Rupture scenario:** very voluntaristic; based on the EU "HighRES" scenario
    - Renewables: +47% compared to the median scenario
    - Nuclear power: 65 GW (slightly higher than current situation)
    - Also: high level of interconnections
Not exactly a hydrogen carbon content

Rather a carbon impact of flexible hydrogen production implementation

Marginal approach:

Comparison of the CO_2 emission level of the European power system between
- the reference case: no additional demand
  and
- the hydrogen implementation case: including the electrolysis unit demand
EVALUATING THE ECONOMIC COMPETITIVENESS OF FLEXIBLE HYDROGEN PRODUCTION IMPLEMENTATION

- Assessment of the levelized hydrogen production cost, including:
  - The investment annuity
  - The electricity consumption cost
  - Other O&M expenses

- The electricity consumption and annual hydrogen production depend on:
  - the threshold price
  - the selected scenario

- The electricity consumption cost is built with the electricity marginal cost
RESULTS:
NO OPPORTUNITY IN THE MEDIAN SCENARIO

- High carbon impact
RESULTS: IMPLEMENTING UP TO 50 ELECTROLYSIS UNITS IN THE RUPTURE SCENARIO

- Annual production: 500,000 tons
- Carbon impact: < 4 kg$\text{CO}_2$/kg$\text{H}_2$
- Production cost: as low as €2-3 / kg$\text{H}_2$, depending on the capex level

![Graph showing production cost and installed capacity of electrolyzers](image)
CONCLUSION

- Flexible production: an opportunity to reduce hydrogen production costs
  - Take advantage from low-cost low-carbon electricity

- Due to high investment costs it has to be used frequently to build a credible business case
  - Opportunity only in the framework of very proactive scenarios with high penetration rates of low-carbon energy → beyond 2030
  - In such scenarios: competition with any kind of flexible electric demand (storage, etc.)
TO FIND MORE…


- Pauline Caumon, Miguel Lopez-Botet Zulueta, Jérémy Louyrette, Sandrine Albou, Cyril Bourasseau, Christine Mansilla, Flexible hydrogen production implementation in the French power system: Expected impacts at the French and European levels, Energy, Volume 81, 1 March 2015, Pages 556-562, ISSN 0360-5442

APPENDIX
## Electricity System Functions and Flexibility

<table>
<thead>
<tr>
<th>Time scale</th>
<th>Domain</th>
<th>Elements affected</th>
<th>Flexibility sources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Close to real time horizon</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seconds</td>
<td>Frequency regulation: Frequency containment reserves (FCR)</td>
<td>Dynamic frequency stability</td>
<td>FCR reserve providers</td>
</tr>
<tr>
<td>Minutes</td>
<td>Frequency regulation: Frequency restoration reserves (FRR)</td>
<td>Frequency</td>
<td>FRR reserve providers</td>
</tr>
<tr>
<td><strong>Scheduling and dispatch horizon</strong></td>
<td>Minutes to hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replacement reserves (RR) and balancing Economic dispatch</td>
<td>Follow net load variation and FCR and FRR</td>
<td>Observability and Forecasting</td>
<td></td>
</tr>
<tr>
<td>Generation scheduling Day-ahead and intra-day markets</td>
<td>Generation dispatch Transmission and distribution operation Wind utilisation</td>
<td>Efficiency and Forecasting Ramping capability quick start plant</td>
<td></td>
</tr>
<tr>
<td><strong>Planning horizon</strong></td>
<td>Years</td>
<td>Generation adequacy Flexibility adequacy</td>
<td>Optimise generation mix Coordination between generation and network investment</td>
</tr>
<tr>
<td>Expansion planning</td>
<td></td>
<td>Transmission and distribution reinforcement</td>
<td></td>
</tr>
</tbody>
</table>
MADONE: a bottom-up TIMES model

PRIMARY ENERGY
- Uranium supply
- Oil & solid fuel supply
- Gas supply (Eurasian area)
  - Native gas production
  - Pipeline transportation
  - Gas storage
  - LNG
- Biomass-waste supply
  - Primary resources (17 types)
  - Conversion technologies (13)
  - Final bio-energy products (7)
- Wind, solar, hydro supply
  - Availability factors
    - Country + on/off shore + wind speed (9) + hours differentiation
  - Resources limits
    - Areas X capacity density hyp.
    - Ex: wind off-shore: km2 available per country according to wind speed (9), distance to coast (2) and depth (3)
    - Ex: solar PV: m2 of roofs available, land available...
- CO2 storage potentials
  - Saline aquifers, DGOF on & off-shore

FINAL ENERGY
- Industry:
  - 18 main sectors
  - 47 sub-sectors
  - 53 energy using technos.
- Residential sectors:
  - 8 types of dwelling
  - 11 energy needs (heating, HW, cook., light...)
  - 11 heating+hot water technologies
  - 3 cooking technos
  - 16 other electric appliances
- Service sectors:
  - 7 main sectors
  - 2 types of dwelling for each sector
  - 7 energy needs (heating, HW, light, computers...)
  - 6 heating+HW technos
- Transport sectors:
  - Passengers and freight
  - 9 transports modes
  - 23 transport means
- Agriculture:
  - 6 energy uses
- Non energy uses:
  - 6 energy uses
- Energy sector consumption:
  - Grid losses, ancillary conso etc.
  = linked to production

TRANSFORMATION PROCESSES
- Electricity & steam production:
  - >50 power generation technos
  - Cogeneration: 21 technos
  - District heating: 7 technos
  - Industrial boilers
  - Interconnections among countries
- Refineries
- Industrial transformations
VITESSE PROJECT - FLEXIBLE HYDROGEN PRODUCTION: ALKALINE ELECTROLYSIS

- **Technical characteristics**
  - Unit size: 125 MW
  - Power consumption: 47.9 kWh/kg$_{H_2}$ (constant)
  - No dynamic constraint

- **Economic data**
  - Capex:
    - Reference: €1200/kW (150 M€ per electrolysis unit)
    - "Optimistic": €636/kW
  - Plant life: 30 years
  - Electrolyzer replacement after 15 years
  - Maintenance: 2%/year of the capex
  - Discount rate: 8%