Energy Analysis and Modelling: Power Sector Modelling with TIMES

Uwe Remme, Luis Munuera

Energy Training Week 2014
8-9 April, 2014
Module overview

- 8 April: Power Sector Modelling with TIMES (1)
  - Introduction to energy systems modelling and TIMES
  - Getting started in running a power sector model in TIMES (using ANSWER-TIMES and a simplified Excel interface)

- 9 April: Power Sector Modelling with TIMES (2)
  - Refining the power sector analysis:
    - Treatment of load curves
    - Modelling storage technologies
Introduction to Energy Systems Modelling and TIMES

Uwe Remme, Luis Munuera

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Interdependencies in the energy system

Global energy flows in 2009
Electricity generation mixes in 2011 in participants’ countries

Can you spot your country?
Current situation, future challenges and opportunities are quite diverse around the world.
Why energy planning?

- Integrated analysis is key for energy sustainable development (including linkages to land and water use)
  - Economic way of covering energy needs
  - Efficient use of domestic resources
  - Enhancing energy security
  - Access to energy
  - Reducing environmental impacts

- Essential for sound decision-making and policy design
  - Developing long-term strategies (avoiding stop-gap policies)
  - Exploring and testing policy options
  - Identifying the investment and financing requirements
Why energy modelling?

- **Technology/Energy carrier level**
  - Long-term nature of planning decisions (e.g. lifetime of power plants)
  - Future development of technologies
  - Comparative assessment of technologies

- **System level**
  - Infrastructure for energy (e.g. T&D for electricity)
  - Interdependencies of technologies and sectors (e.g. electric heat pump or EVs with power sector)
  - Integration of variable renewables

- **Stakeholder level**
  - Tool to develop strategies involving wide range of actors in energy sector (from households, industry to government)
  - Communication

- **Policy level**
  - How to reach policy goals
  - Effectiveness and impacts of individual policy measures

Energy system does not allow for real-world experiments

- Scenarios: Exploring the future
- Models: Developing consistent scenarios
Type of energy models

Energy models

Energy system models

- Focus on the energy system alone
- Description of large number of single energy technologies
- Capturing dynamics of the system, such as substitution of energy carriers, energy savings or technology deployment
- Typical results: energy consumption, energy technology mix and capacities, emissions

Economic models

- Relationship of the energy sector to the general economy central element
- Energy system described in a highly aggregated way
- Technologies embedded in production functions
- Typical results: energy consumption, emissions, GDP, employment, trade balance
Universe of energy models

Technology-rich least-cost models

- MARKAL/TIMES
- MESSAGE
- PRIMES
- OSeMOSYS

Bottom-up

Optimisation

Technology-rich simulation models

- LEAP
- MoMo

Simulation

Econometric models

- DEEP
- OECD ENV-Linkages
- POLES
- E3MG

CGE models

(Source: van Ruijven and van Vuuren, 2009)
Top down economic models

Econometric models

Input-Output-Table

Economic models

Computational General Equilibrium models

- Producers
  - Maximise profits
  - Production of goods
  - Factor inputs (labor, energy)
  - Demand for goods
  - Perfect markets in equilibrium (simulation)
  - Taxes, transfers

- Households
  - Maximise utility
  - Labor supply
  - Demand for goods

- Markets for goods
  - Factor markets
  - Taxes
  - Government interventions
Energy system models: Technology-rich representation

Cost and emissions balance

- Prices
- Energy flows
- Emissions

Technology

Commodities

Coal processing

Process

Coal

Flows

2.2 kWh

0.27 kg_{SKE}

Supercritical coal plant (SCP)

Flows

Electricity

0.736 kg

0.27 kg

1 kWh

Energy prices, Resource availability

- Domestic sources
- Imports

Primary energy

Final energy

Capacities

Demands

- Costs

Energy demand services

GDP

- Process energy
- Heating area
- Population
- Light
- Communication
- Power
- Passenger kilometers
- Freight kilometers

Final energy
**Technology representation**

**Process**

Coal

Flows

2.2 kWh

0.27 kg

Supercritical coal plant (SCP)

Electricity

Flows

1 kWh

0.736 kg

CO₂

**Commodities**

**Efficiency eqn**

\[ \eta_{SCP} \cdot FLO_{SCP,COAL} = FLO_{SCP,ELC} \]

**Emission eqn**

\[ \epsilon_{SCP,COAL,CO2} \cdot FLO_{SCP,COAL} = FLO_{SCP,CO2} \]

**Activity definition**

\[ ACT_{SCP} = FLO_{SCP,ELC} \]

**Utilization eqn**

\[ ACT_{SCP,ELC} \leq \alpha_{SCP} \cdot CAP_{SCP,ELC} \]

**Table**

<table>
<thead>
<tr>
<th>Coal PC Supercrit.</th>
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<th>2005</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
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<td>600</td>
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<td>Years</td>
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<tr>
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<td>Years</td>
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<td>35</td>
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<td>Efficiency (LHV)</td>
<td>%</td>
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<td>47</td>
<td>48</td>
<td>50</td>
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<tr>
<td>Max. availability</td>
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<td>7500</td>
<td>7500</td>
<td>7500</td>
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<tr>
<td>Spec. Investment costs (overnight)</td>
<td>€/kW_el</td>
<td>1175</td>
<td>1175</td>
<td>1140</td>
<td>1140</td>
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<tr>
<td>Fixed O&amp;M</td>
<td>€/(kW a)</td>
<td>40.5</td>
<td>40.5</td>
<td>40.5</td>
<td>40.5</td>
</tr>
<tr>
<td>Var. O&amp;M</td>
<td>€/MWh_el</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>

**Input parameter**

- \( \eta_{SCP} \): Plant efficiency
- \( \epsilon_{SCP,COAL,CO2} \): CO₂ Emission factor
- \( \alpha_{SCP} \): Annual availability

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Horizontal dimension of the RES: technology chains

Coal imports
Domestic mining

Coal, washed
Coal transport

Coal, power
Supercritical coal plant

Electricity LV
Appliances
Lighting
Urban trains

Grid MV & Transf.

Grid HV & Transf.

Industry

Backward Loops

Coal, washed
Coal, power
Supercritical coal plant
Grid HV & Transf.
Grid MV & Transf.

Electricity LV
Appliances
Lighting
Urban trains
Industry

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Vertical dimension of the RES: competition

Competing options to produce electricity:
- between technologies
- between old and new plants

Influenced by:
- Technology costs
- Efficiencies
- Emission factors
- Fuel prices…
System aspects: Limited resources
System aspects: substitution

Conversion sector

Primary energy supply
- Wind
- Hard coal
- Lignite
- Oil
- Natural gas
- Biomass

End-use sectors
Residential
- Gas heating
- Oil heating
- Elc. heating
- Local heat grid
- Gas water boiler
- Elc. water boiler
- Elc. heat pump

Commercial
- Room heat boilers
- Process heat boilers
- Warm water boilers

Industry
- Industrial boilers

Transport
- Gasoil car
- Gasoline car
- LH2 car
- Busses
- Trucks

Conversion sector

Elec sector
- Coal cond. PP
- Lignite cond. PP
- Coal IGCC PP
- Gas CC PP
- Wind converter

CHP sector
- Coal CHP
- Coal CHP
- Gas CC CHP
- Biomass CC CHP

Other sectors
- Electrolysis
- Gasification
- Liquefaction

Substitution options

Energy crops
- Area PV
- Solar thermal
- Residual wood
- Area Wind

Gas import
- Oil import
- Coal import

Gas resources
- Coal resources

Oil resources
- Lignite resources

Coal processing
- Refinery
- Gas processing

Industry
- Elec sector
- CHP sector
- Residential
- Commercial
- Transport

End-use sectors
- Residential
- Commercial
- Industry
- Transport

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Partial equilibrium

Power plants

RoR = run of the river
HB = hydro basin
PC = pulverized coal
CC = combined cycle
LWR = existing nuclear
GT = gas turbine
SF = steam fossil
IGCC = int. coal GCC
CC = combined cycle
Wof = wind offshore
BIO = biomass steam
GEO = geo hot dry
PV = photovoltaic

(Source: GianCarlo Tosato)
Interdependencies

At optimal solution:
- Equilibrium between electricity supply and demand

Changes in the system (e.g. introduction CO₂ price) yield new equilibrium e.g.:
  1) Shift to low-carbon technologies
  2) Increase in electricity price
  3) Substitution and saving of electricity in the end-use sectors
Mathematical formulation

Objective function:
Minimizing discounted system costs
= Sum of
• Import/Extraction costs,
• variable and fixed O&M costs,
• Investment costs,
• ...

Model equations:
Transformation relationship
(→ e.g. efficiency relationship for power plant)
Energy and emission balances
Inter-temporal constraints on new capacity additions
(→ e.g. early investments needed for using technology on larger scale in later periods)
Capacity-activity constraint
(→ e.g. available capacity limits elec gen of power plant)
Cumulated constraints over time
(→ e.g. available fossil resources)
Peaking constraint
(→ Ensuring reserve capacity at peak load)
Load curve equations
Storage equations (e.g. pumped storage)
Scenario specific constraints
(→ e.g. bound on CO2 emissions, quota for renewables)

Input data
Cost data
Efficiencies
Full load hours
Emission factors
Demands ...

Decision/Output variables
Process activities
Energy/Emission flows
New capacities
Fundamental prices
Not only about modeling, but also data analysis

Energy system model

- Outputs from macro and demand models
- Assumptions
- Demand projections
- Other energy system models
- Experts
- Stakeholder workshop
- Literature review
- Technology database
- Scenarios
- Policy
- Reference

Constraints
- Energy security
- Behaviour
- Existing policy

Statistics
- Resources
- Expert knowledge
- Government statistics
- Calibration of energy & emissions
- International statistics

Source: William Usher, 2010
Consistent data set for more than 60 energy supply and demand technologies

Free access on www.iea-etsap.org
Getting a free evaluation license for ETSAP tools

To test ETSAP’s modelling tools, visit [http://iea-etsap.org/web/AcquiringETSAP_Tools.asp](http://iea-etsap.org/web/AcquiringETSAP_Tools.asp) and get a free 60-day evaluation license.
Example of an energy system model: TIMES

Advanced Features/Variants
- Multi-regional
- Inter-temporal
- Elastic demands
- Endogeneous learning
- Discrete capacity expansion
- Early retirement of capacity
- Macroeconomic linkage
- Climate extension
- Stochastic programming
- Alternative objective functions
- Multi-criteria optimization

Methodology
- Bottom-up Model
- Perfect competition
- Perfect foresight (or myopic)
- Optimization (LP/MIP/NLP)

Min/Max Objective function
s.t.
Equations, Constraints
Decision Variables <-> Solution
Input parameters

Development
- By ETSAP (Energy Technology Systems Analysis Program; www.iea-etsap.org)
- Implementation in GAMS
- Model generator

TIMES
(The Integrated MARKAL EFOM System)
Applications of MARKAL/TIMES around the world

Used by more than 150 institutions in 63 countries
ETP modelling framework

- ETP-TIMES model for supply side supplemented with spreadsheet-based end-use sector models
- Model horizon: 2009-2050 (2075) in 5 year periods
- 28-36 world regions/countries depending on sector
ETP model regions
Applications: Island of Réunion (TIMES)

(Source: Maïzi, N. et al., Flexibility and reliability in long-term planning exercises dedicated to the electricity sector, XXI World Energy Congress, Montreal, September 12-16, 2010)
Experience with energy models in your organisation?

Which energy models are used in your country or region?
Summary

- Energy models provide a consistent analysis framework
  - Energy models are simplified representation of the real-world system
  - Level of detail depends on questions to be addressed and available data

- Choice of model type depending on analysis question
  - Energy system models: focus on role of technologies and interactions within the energy sector
  - Economic models: focus on interdependencies of the energy sector with the remaining economy

- Energy modelling is a long-term and continuous process, involving experts from different disciplines

- Limitations of individual model approaches important when interpreting model results (no analysis is perfect)

- Energy planning not about predicting the future, but supporting decision making under inherent uncertainties
Getting Started with TIMES: Running a Power Sector Investment Model

Uwe Remme, Luis Munuera

Energy Training Week 2014
8-9 April, 2014
Key challenges

Decommissioning scenario for existing global capacity

- Aging power capacity has to be replaced
- Investment characterized by long lifetime and high upfront capital demand
- Decisions have to take into account long time horizon with uncertain or unknown conditions:
  - Long-term energy prices?
  - Economic development?
  - Market conditions?
  - Technology development?
  - Climate policies?
  - Operational aspects (variable renewables, electrification)?
Typical structure of a power sector model

- **Fuel supply**
  - Coal supply
  - Gas supply
  - Wind potential, onshore
  - Wind potential, offshore
  - Hydro potential, run-of-river

- **Generation**
  - Coal plant, subcritical
  - Coal plant, supercritical
  - NGCC
  - Gas turbine
  - Wind turbine, onshore
  - Wind turbine, offshore
  - Hydro, run-of-river
  - ...

- **T&D**
  - Transmission and distribution

- **Demand**
  - Industry demand
  - Transport demand
  - Residential demand
  - Commercial demand

- **Approach:** Optimisation vs. simulation
- **Foresight:** Perfect foresight vs. myopic
- **Horizon:** Short-term (dispatch planning) vs. long-term (investment planning)
Least-cost optimisation

- **Objective function:**
  - Minimising total discounted costs of power system including investment, operating and fuel costs

- **Constraints**
  - Coverage of given electricity demand
  - Technical characteristics of power technologies
  - Capacity constraints
  - Resource constraints (domestic, imports)
  - Renewable potentials

- **Decision variables**
  - Dispatch of power plants
  - Operation of storage processes
  - Construction of new power plants
Basic model constraints based on fundamental principles

**Principle**

- Energy conservation
- Energy conversion
- Generation of a technology limited by available capacity

**TIMES equivalent**

- Commodity balance
- Transformation equation
- Capacity-utilisation constraint

**Decision variables**

- Flow variables
- Generation variables
- New capacity variables

**Objective function**

Minimise system costs

**Cost coefficients of decision variables**
Factors influencing power technology choice

- Reserve margin
- Capacity factor
- Firm capacity during peak load
- Load curves
- Total capacity
- Full load hours
- Electricity generation
- Efficiency
- Fuel input
  - Fuel prices
  - Fuel availability
- Existing capacity
- New capacity
- Inv. costs
- Tech. lifetime
- Econ. lifetime
- Bounds
- FOM costs
- Var. OM costs
- New capacity
- Existing capacity
- Full load hours
- Efficiency
- Fuel input
- Emission factors
- Emissions
- Tax
- Sectoral bounds
- Model variables
- Inputs parameters
- Load curves
- Capacity factor
- Firm capacity during peak load
- Reserve margin
Reference energy system (RES), i.e. network of commodities and technologies, used to describe real-world system

RES can be adapted to considered case study

RES contains existing and future technologies
Model interface: ANSWER-TIMES

Menu Bar: Tool Bar, showing all icons disabled apart from ‘Open Database’. Note also the ‘Region Management’, ‘Batch Management’ buttons.

Data Management:
- Scenarios display

Results Management:
- Cases display

Selected Scenarios display

Selected Cases display

Database: C:\AnswerTIMES\6\Answer_Databases\Utopia_LumpyInvestment.mdb

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ANSWER-TIMES: Technology representation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TIMES handle</th>
<th>Units</th>
<th>Value</th>
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<tbody>
<tr>
<td>Efficiency</td>
<td>ACT_EFF</td>
<td>-</td>
<td>0.44 (2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.50 (2050)</td>
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<tr>
<td>CO₂ emissions factor</td>
<td>FLO_EMIS</td>
<td>ktCO₂/PJ</td>
<td>95</td>
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<tr>
<td>Maximum availability</td>
<td>NCAP_AFA</td>
<td>-</td>
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<tr>
<td>Capital cost</td>
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<tr>
<td>Fixed O&amp;M costs</td>
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<td>Billion USD/GW (USD/kW)</td>
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<tr>
<td>Construction time</td>
<td>NCAP_ILED</td>
<td>Years</td>
<td>4</td>
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<tr>
<td>Technical lifetime</td>
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<td>Years</td>
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<tr>
<td>Existing capacity</td>
<td>PRC_RESID</td>
<td>GW</td>
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</table>
Question 1: Which gas price decline by 2050 is needed to see a switch from coal to gas in the new capacity additions in 2050?

Question 2: Introduce the CO₂ constraint, what is the impact on the electricity mix?

Question 3: What are the cost reductions needed to make wind more cost effective than nuclear under a CO₂ target?
Question 1 Gas price decline to see coal/gas switch
Question 1 Gas price decline to see coal/gas switch

- 9-10 USD / million BTU (~million USD/PJ)
Question 2 Impact of CO$_2$ constraint?
Question 2 Impact of CO$_2$ constraint?
Question 3 Cost reductions for wind
Question 3 Cost reductions for wind
Power Sector Modelling with TIMES: Load curves and storage

Uwe Remme, Luis Munuera

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Overview

- Power sector analysis:
  - Off-model approaches for assessing cost-competitiveness of power technologies: LCOE & Screening curves + load duration curves

- Hands-on exercise:
  - Load curves and storage in TIMES
**Levelised costs of electricity (LCOE)**

### LCOE Formula

\[
LCOE = \left( \frac{\text{inv} \cdot \text{crf} \cdot \text{idc} + \text{fom}}{\text{af} \cdot 8760} \right) \cdot 1000 + \frac{\text{fuelprice}}{\text{eff}} \cdot 3.6
\]

- **Specific investments costs (USD/kW)**
- **Availability factor as fraction**
- **Efficiency as fraction**
- **Fuel price (USD/GJ)**
- **Interest during construction factor**
- **Fixed operating and maintenance costs (USD/kW)**
- **Capital recovery factor**

### Graph Components

- **USC**
- **Gas turbine**
- **NGCC**
- **Onshore wind**
- **PV, utility**
- **PV, rooftop**
- **CSP**
- **LWR**

- **Fuel costs**
- **Capital costs**
<table>
<thead>
<tr>
<th>Technology</th>
<th>Overnight investment costs (USD/kW)</th>
<th>Fixed O&amp;M costs (USD/kW)</th>
<th>Technical lifetime (a)</th>
<th>Construction time (a)</th>
<th>Load factor (%)</th>
<th>Efficiency (%)</th>
<th>Fuel costs (USD/GJ)</th>
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<td>USC coal</td>
<td>2300</td>
<td>46</td>
<td>35</td>
<td>4</td>
<td>85</td>
<td>41</td>
<td>2.1</td>
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<td>Gas turbine</td>
<td>500</td>
<td>10</td>
<td>30</td>
<td>1</td>
<td>10</td>
<td>38</td>
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<td>NGCC</td>
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<td>30</td>
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<td>LWR</td>
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<td>115</td>
<td>50</td>
<td>5</td>
<td>90</td>
<td>36</td>
<td>0.7</td>
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</table>
What are the advantages and disadvantages of the LCOE approach?
Screening curves - Concept

Total annual power plant costs (USD/MW)

<table>
<thead>
<tr>
<th></th>
<th>Total annual power plant costs (USD/MW)</th>
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</thead>
<tbody>
<tr>
<td>Hours of operation during the year</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Fi</td>
<td></td>
</tr>
<tr>
<td>Variable costs Vi</td>
<td></td>
</tr>
</tbody>
</table>

Total annual plant cost = \( (\text{inv} \cdot \text{crf} \cdot \text{idc} + \text{fom}) + \frac{\text{fuelprice}}{\text{eff}} \cdot 3.6 \cdot t \)

Annual fixed costs \( F_i \)  Variabe costs \( V_i \)

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Screening curves - Example

Operating ranges

Gas turbine | NGCC | USC coal

Load factor

USD/ MW

Operating ranges

Gas turbine | NGCC | USC coal
Variability of the electricity system

- Demand load curves influence technology choice
  - Need for flexible generation
  - Storage to balance between peak and base load demand
  - Demand side response

- Fluctuations also on supply side: some renewables (wind, PV) and CHP plants (if heat-driven)
Load duration curve

Chronological load curve over a year

Reordering by load

Load duration curve
Combining screening and load duration curves

Graph showing load factor and cost (USD/(MW/yr)) for different technologies: USC, Gas turbine, and NGCC.
What are the advantages and disadvantages of the screening curve and load curve approach?
Hands-on exercise: Load curves and storage

TIMES_DEMO_V2.xlsm
Hands-on exercise model:
Load curves for typical days
Hands-on exercise model: Background on wind assumptions

Wind speed distribution

Assumed normalised operational curve for wind turbine

Distribution of wind generation for 1 MW
Hands-on exercises (TIMES_DEMO_V2.xlsm)

Question 1: Run the model without a CO\textsubscript{2} constraint, i.e. 5,000,000 kt upper bound. Save the run as BASE scenario. How sensitive is the model to a 40% increase/decrease to the gas price in 2050 (cells N46, N73)?

Question 2: Reset the gas price to 10 USD/GJ. Add a CO\textsubscript{2} constraint to the model (copy cells F10:N10 into F9:N9). How does the solution change?

Question 3: How does the solution change when allowing storage to be added (delete new capacity bound of zero in row 174)?
Key features of power sector analysis in energy system models

- **Strengths**
  - Detailed technology representation of power sector
  - Integrated optimisation of investment planning and system operation
  - Deriving least-cost strategies to cover given electricity demand taking into account possible additional policy goals (how-to)
  - Analysing impact of individual power technologies on costs, energy use and emissions (what-if)
  - Analysing interdependencies between different policy goals/instruments, e.g. CO₂ pricing and renewable support

- **Weaknesses**
  - Operational aspects represented in an approximated fashion:
    - No detailed representation of electricity grid infrastructure
    - Ramp-up, ramp-down constraints, start-up costs, minimum operation time, part-load efficiency generally not considered
  - Uncertainty can only be included to some extent (computational limitations)
  - Perfect competition on electricity markets, i.e. no market power of individual players