The Abdus Salam International Centre for Theoretical Physics

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19 - 23 April 2010

Representing Impacts of Extreme Weather Events in the Energy Supply Models MESSAGE

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Representing Impacts of Extreme Weather Events in the Energy Supply Models MESSAGE

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Overview

1. MESSAGE: basics
2. MESSAGE: key features
3. Hydropower
4. Renewables & decentralized supply
5. Summary and conclusions

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MESSAGE

Model for Energy Supply System Alternatives and their General Environmental impacts

Software designed for setting up optimization models of energy supply systems to assess capacity expansion and energy production policies

A Physical Flow Model

For a given vector of demands for energy goods or services, it assures sufficient supplies utilizing available technologies and resources

Based on specified criterion, it optimizes the system expansion and operation

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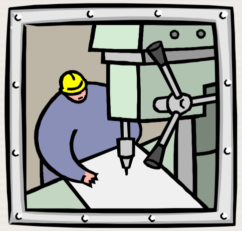
Criteria and Techniques

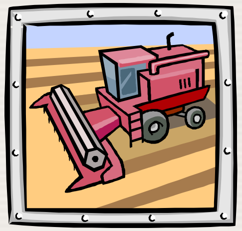
- **Criteria**
  - Cost minimization
  - Profit maximization
  - Multi-objective optimization
- **Mathematical Techniques**
  - Linear programming
  - Mixed-integer programming
  - Non-linear programming

Elements of Energy Supply System

- Oil extraction facility, Hydro Power plant, Transmission line, Car etc.



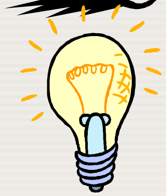










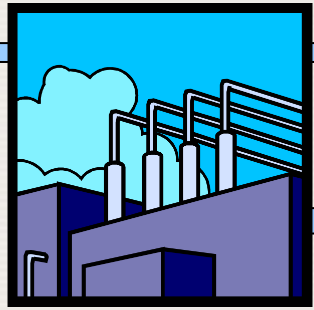


⑩Energy Chain

⑩Oil extraction

⑩Coal import

⑩Power Plant Refinery



⑩Conversion

⑩T&D Network

⑩Transmission & Distribution

⑩Consumer

⑩Conversion

⑩PRIMARY

⑩- oil
- gas -
coal -
water

⑩SECONDARY

-diesel
- kerosene
- gas
- electricity
- coal

⑩FINAL

- diesel
- kerosene
- gas
- electricity
- coal

⑩USEFUL

- heat
- light
- mechanical energy

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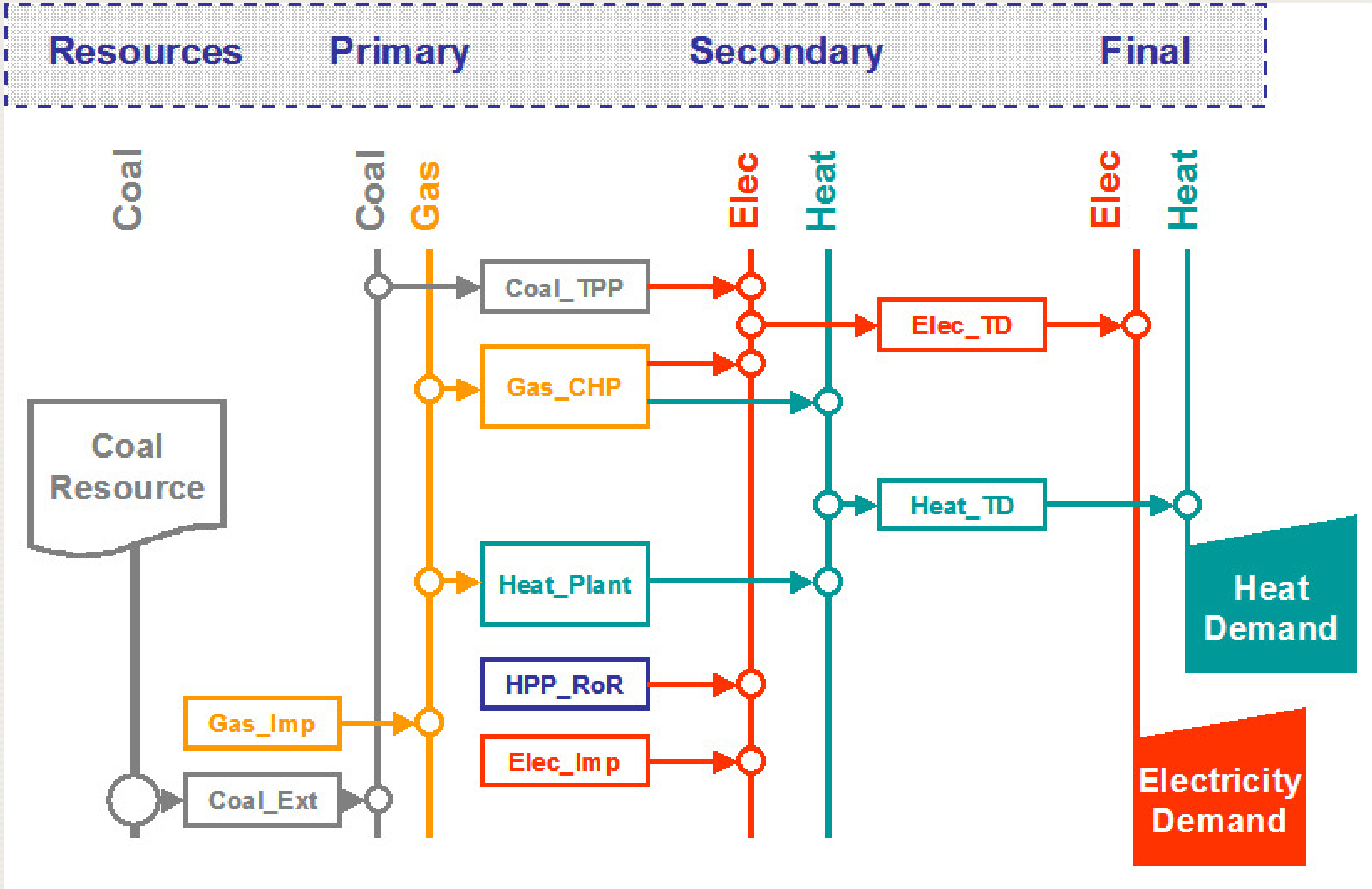
Energy Chain in MESSAGE



An Energy Supply System

- consists of
  - **Energy Resources** — (coal, oil, gas, wind,...)
  - **Energy Forms** — (energy extracted from resources, processed, converted, transmitted, and distributed)
  - **Technologies** — (that extract, process, convert energy from one form to another other or to energy service, transmit and distribute)

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Energy Levels & Energy Forms

Energy supply model is built by characterizing various energy forms/fuels with:

- various levels

  e.g., resources, primary, secondary, final

- various energy forms at each level

  e.g., gas, coal. electricity

Resources in MESSAGE

Resource level can be grouped into different grades based on

- Geographic locations
- Geological uncertainty

and can be characterized by different resource extraction cost

Technologies in MESSAGE

A Technology represents a process that

- Converts one energy form into another energy form or into energy service
  - e.g. conversion of crude oil to oil products, oil products to electricity, electricity to light
- Transfers/transmits/distributes an energy form
- Supplies/produces an energy form (e.g. hydro power, oil import)

❿ Technologies in MESSAGE

Characteristics of a conversion technology that can be built into the model may include:

- Multiple inputs and outputs
- Seasonal variation in capacity
- Efficiency varying with time
- Costs varying with time
- Limits on production
- Capacity build-up constraints
- Market penetration
- Emission control

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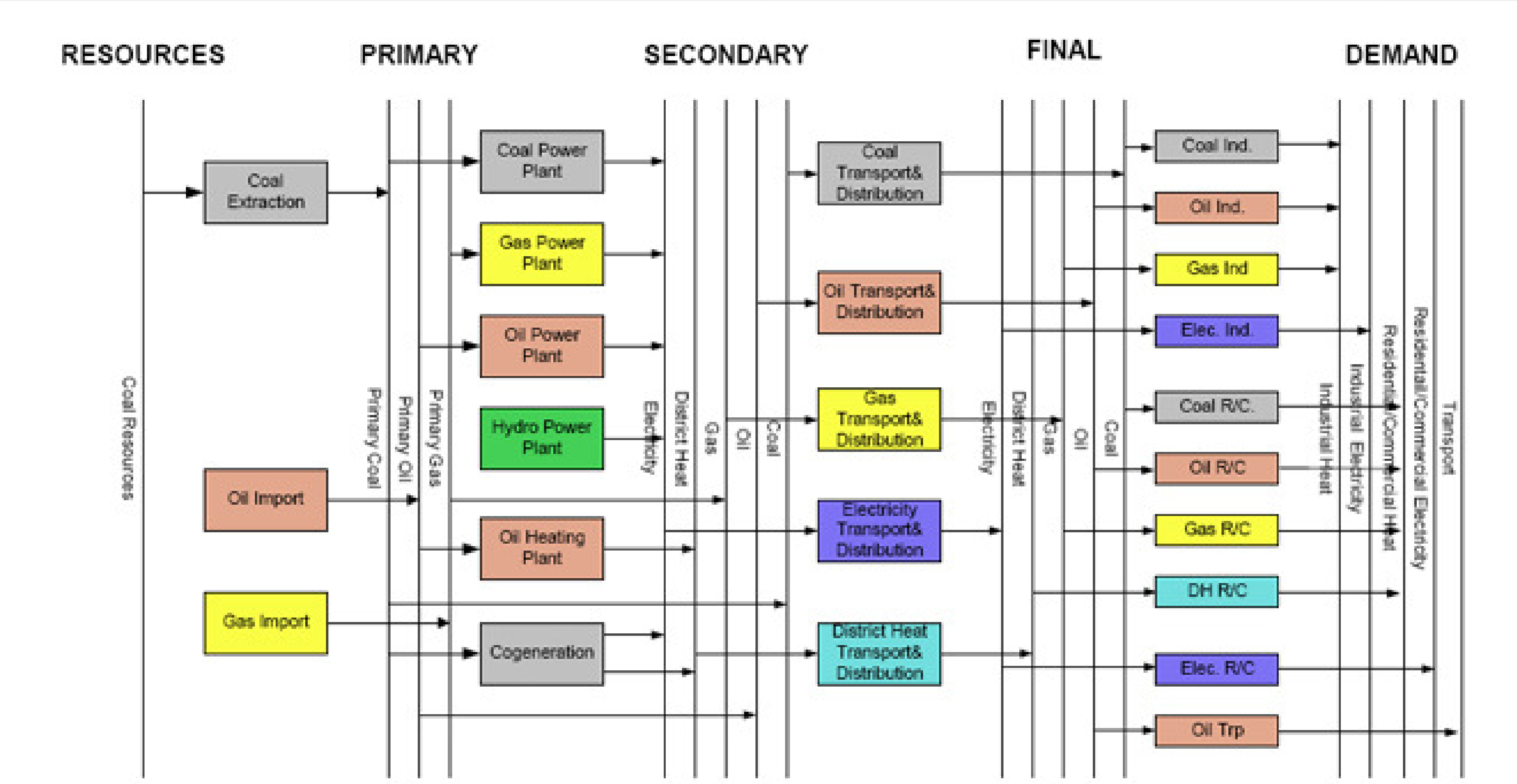
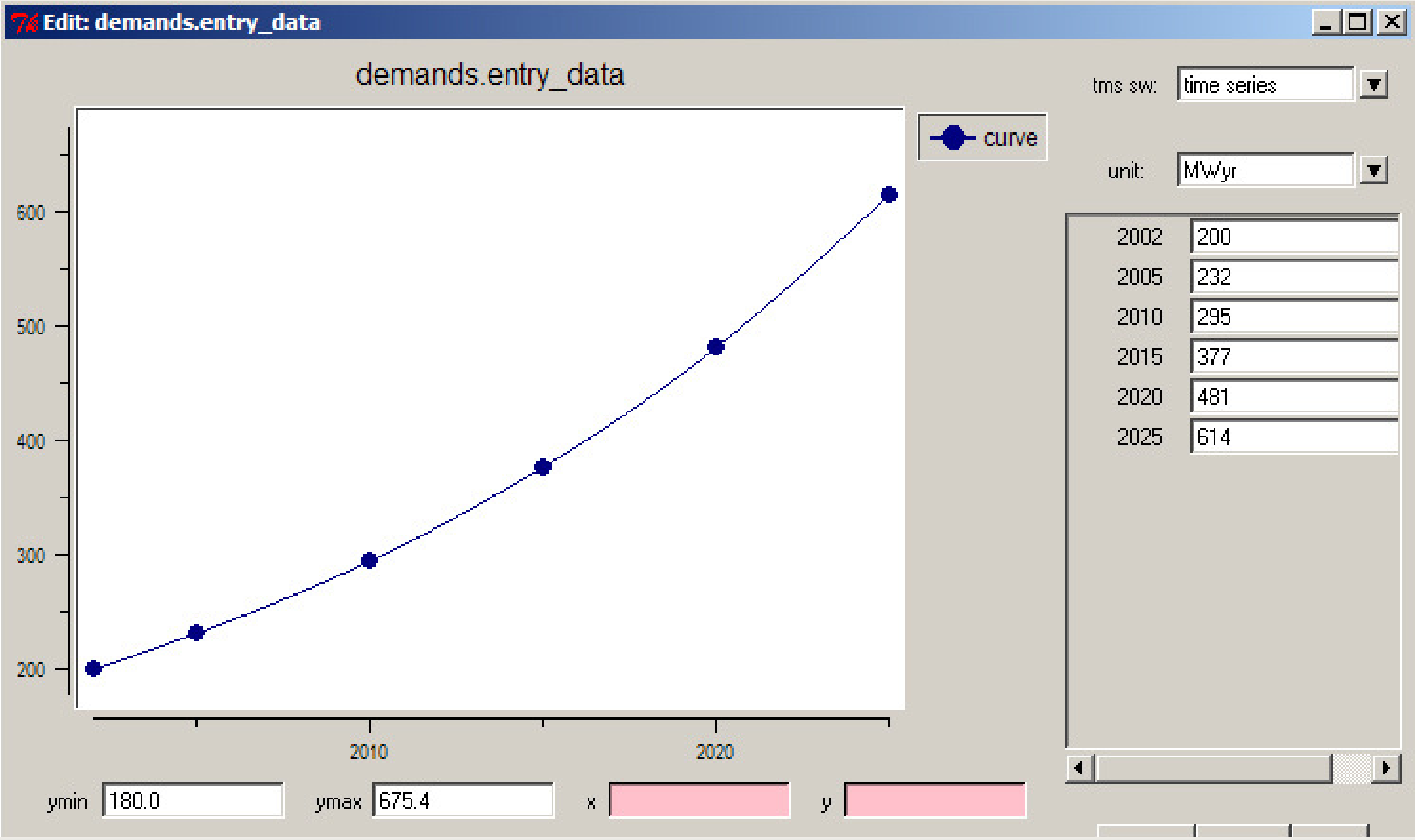
Energy Chain in MESSAGE



Energy Demand

- Demand data are exogenously given for all the energy forms defined at the secondary, final, or useful level
- The demand may have seasonal variations
- MESSAGE computes seasonal demand using information on "load region" (seasonal division of the year specified by the analyst), and "load data" (distribution of the demand by load region)

Energy Demand in MESSAGE



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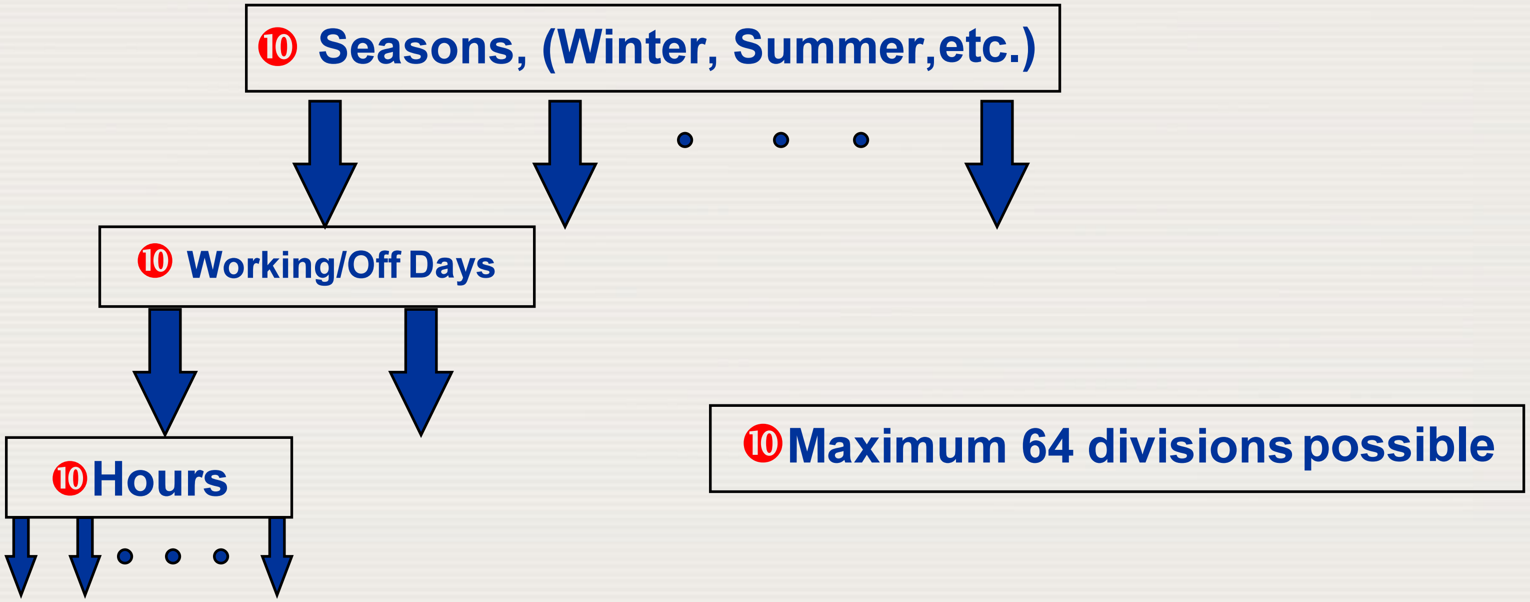
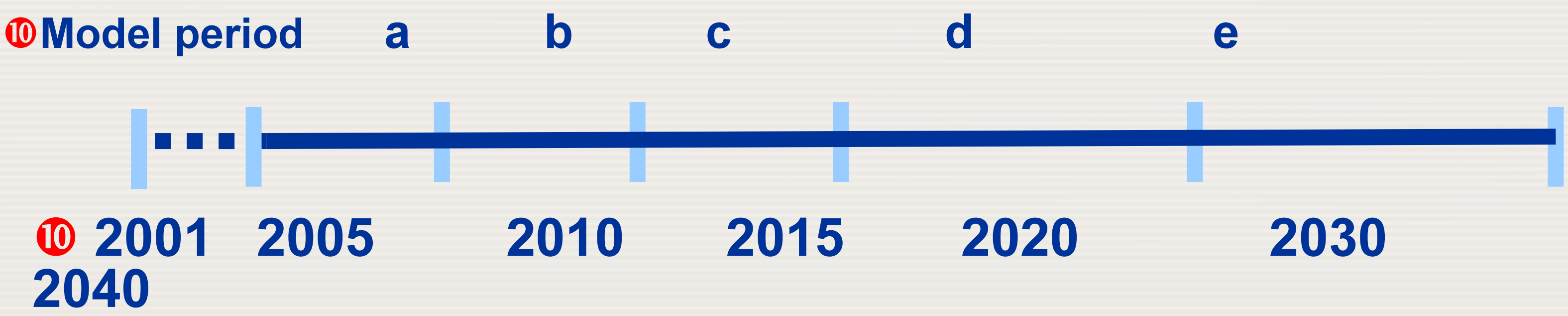
Load Regions

- **Sub-division of a year: e.g. by seasons**
  - Number of seasons,
  - Division of each season by type of day
  - Division of each type of day by parts



Time Frame – Model periods

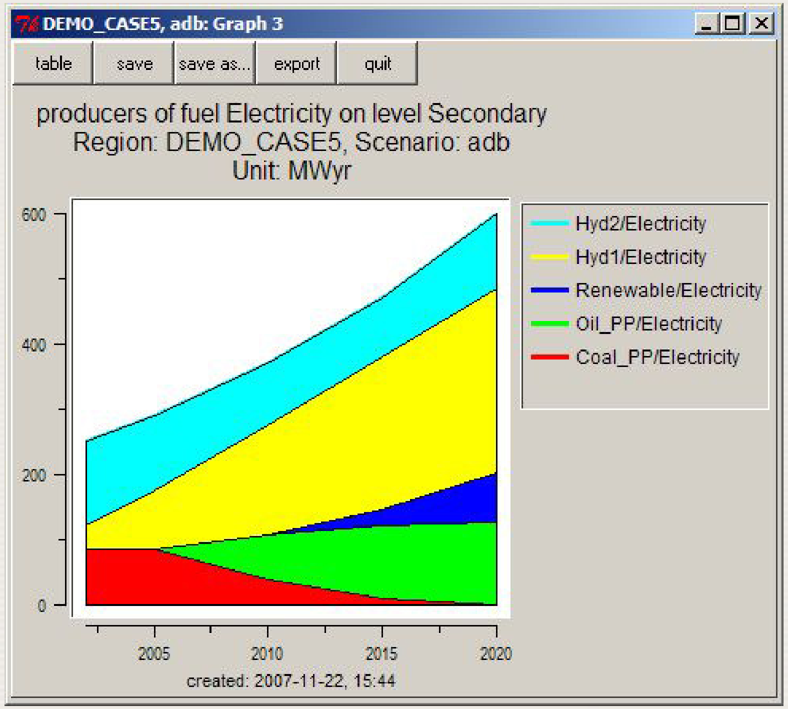
- A base year is needed to specify initial conditions
- The first model year and the last model year determine the study period
- Study period is divided into time steps
- Time Steps can be of varying lengths
- Max. number of time steps is 64



MESSAGE Output

- **Capacity expansion plan & production schedule**

  MESSAGE computes the new capacity requirement taking into account the existing capacities and their retirement time, and the necessary production to satisfy a growing demand



- **Implications of the plan, e.g., financial, environmental, energy security, etc.**

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Limits on Energy Resource/Technology

- limit on a technology in relation to some other technologies (e.g., a maximum share of wind energy in total electricity generation),
- a common limit to be met by a set of technologies (e.g., maximum limit on emission of SO_2 from all technologies emitting it; given in millions tons of SO_2),
- constraints between production and installed capacity
- … and others (MESSAGE is flexible)

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Interpretation of the Results

Policy implications can be obtained by analyzing alternative least-cost energy systems developed under alternative assumptions and constraints, in terms of, e.g.:

- Costs
- Emissions
- Energy security
- Reliabilities, etc.

Optimization

Optimization is used to calculates the least-cost energy supply system

- **Criteria**

  minimization of the total discounted energy system cost, subject to the constraints representing demands, resource scarcity, capacity bounds

- **Mathematical Techniques**

  Linear programming

  Mixed-integer programming

Type of Optimization Problem (1)

The linear programming (LP) technique:

The objective and all of the limits are **linear functions** of the decision variables.

An example of a linear function is:

$40\ x_1 + 38\ x_2 + 35\ x_3$

where x_1, x_2 and x_3 are decision variables.

Type of Optimization Problem (2)

The mixed-integer programming (MIP) technique:

- Some of the **decision variables** are required to have only **integer values** at the optimal solution.
- The objective and all of the constraints functions are **linear functions** of the decision variables

Total System Costs

The discounted sum of the following cost items:

- Investment cost
- Fixed and variable operation and maintenance costs
- Fuel costs
- any additional penalty costs defined for the limits, bounds and constraints on relations

Discounting

- Discounting makes the costs occurring in different points in time comparable by using weights given to the cost incurred at different periods in the total system cost
- Discounting takes into account opportunity costs which can be represented by the long-term real interest rate

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Setting Up a Case Study

1. Define the scope of the study by identifying the policy issues addressed
2. System configuration
   - Build existing energy chains into MESSAGE
   - Identify alternatives
3. Scenario representation
   - Introduce limits
   - Set up relations

Defining the Scope of the Study

Scope of the study depends on the policy question that you want to address

- What is the study period? What are the time steps?
- What is the level of detail represented in the analysis?

Building the Existing Energy Chains into MESSAGE

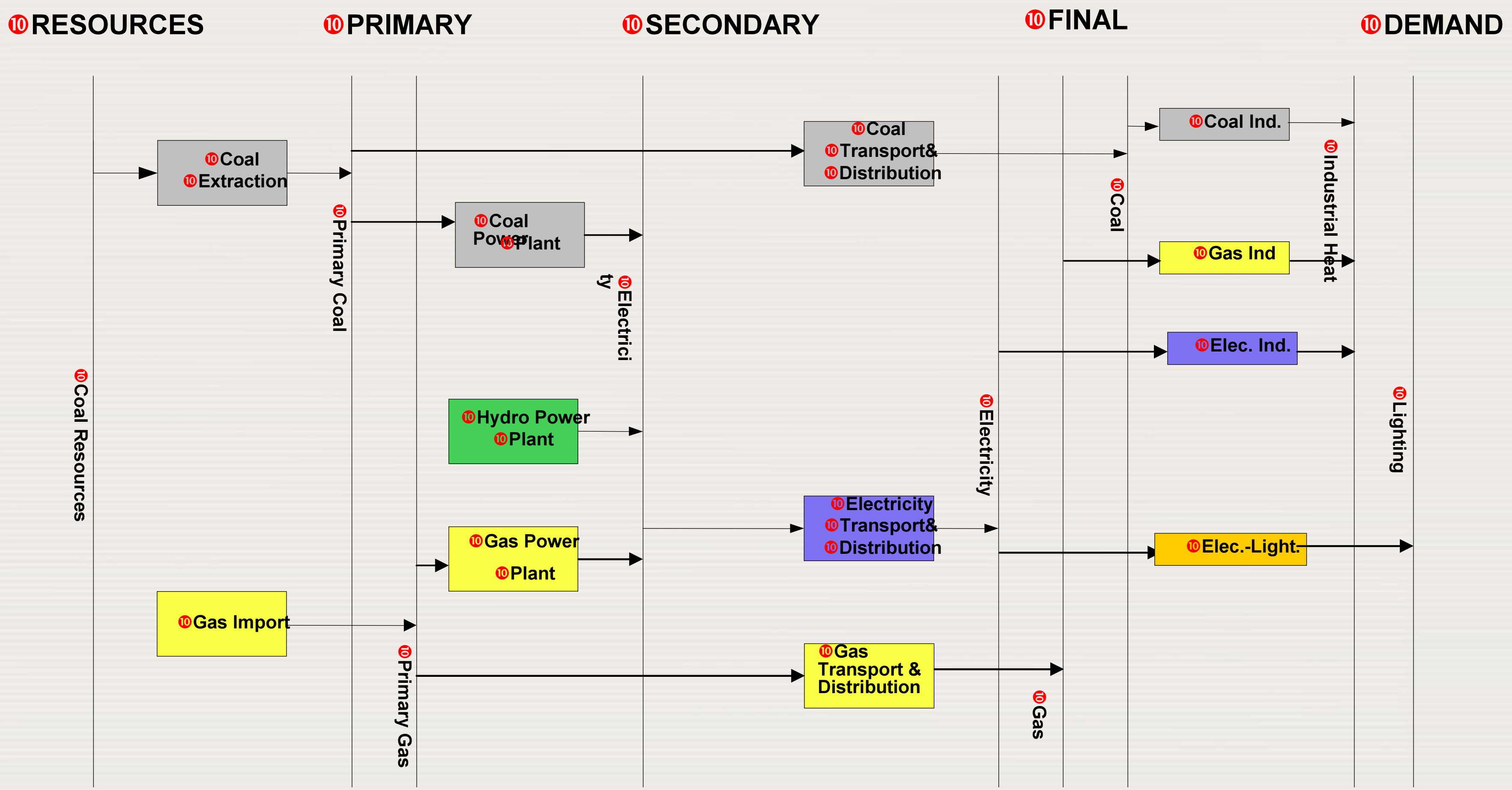
To model the initial conditions of the system

To Identify the existing competitions in the system

Note: Model is an abstracted form of the real world

- Aggregate some of the levels: e.g., transmission and distribution networks unless required for some policy issues or plans
- Aggregate some facilities with common features: e.g., one technology to represent a set of existing coal-power plants unless required for some policy issues or plans

A Simple Energy Supply Model in MESSAGE



Identify Alternatives

Identify any possible alternatives in the supply system that could be introduced to help meeting the policy objectives and targets

- Identification of some new technologies e.g. combined cycle power plant, CHP
- Identification of some new energy supply sources e.g. coal or gas import options
- Identification of some “future” technologies

Possible Trade Offs and Limits

Identify the trade offs for the new sources of supply and new technologies, e.g.:

- Assuming coal is the cheapest option but it has high air emissions; trade off between cost and conservation of environment
- Assuming imported gas option is comparable to the Coal option; Trade off is between cost and energy security
- Assuming Hydro is an economical option too but it has problem of seasonal variations; trade off between cost and reliability

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Introduction of Limits

- Identify physical/technical constraints in exploitation of each energy source and a technology
- Identify the limits for each source in terms of quantity of supply and time of supply

Setting Up Relations

Translate some policy “targets” into relations

For example:

- introducing nuclear power by 2020
- achieving certain share of electricity produced from renewable technologies
- limiting air pollution emissions
- limiting import dependency

2. MESSAGE: key features

The backbone of MESSAGE:

- Detailed description of the energy system being modeled, including definition of:
  - Energy forms at each level of energy chain
  - Technologies producing or consuming energy forms
  - Energy resources
  - Relationships between technologies or between technologies with demand, resources, environmental considerations

Energy Demand

- Demand for Energy/Fuels is an exogenous input
- Seasonal variation in demand for various Fuels
- Energy/Fuels Demand can be specified at any Level

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Load Regions

- Variation of energy demand during a year can be represented by Load Regions and Load Curves
- Each Year can be divided into several Load Regions; seasonal, chronological, ordered
- Number of Load Regions may vary for different years

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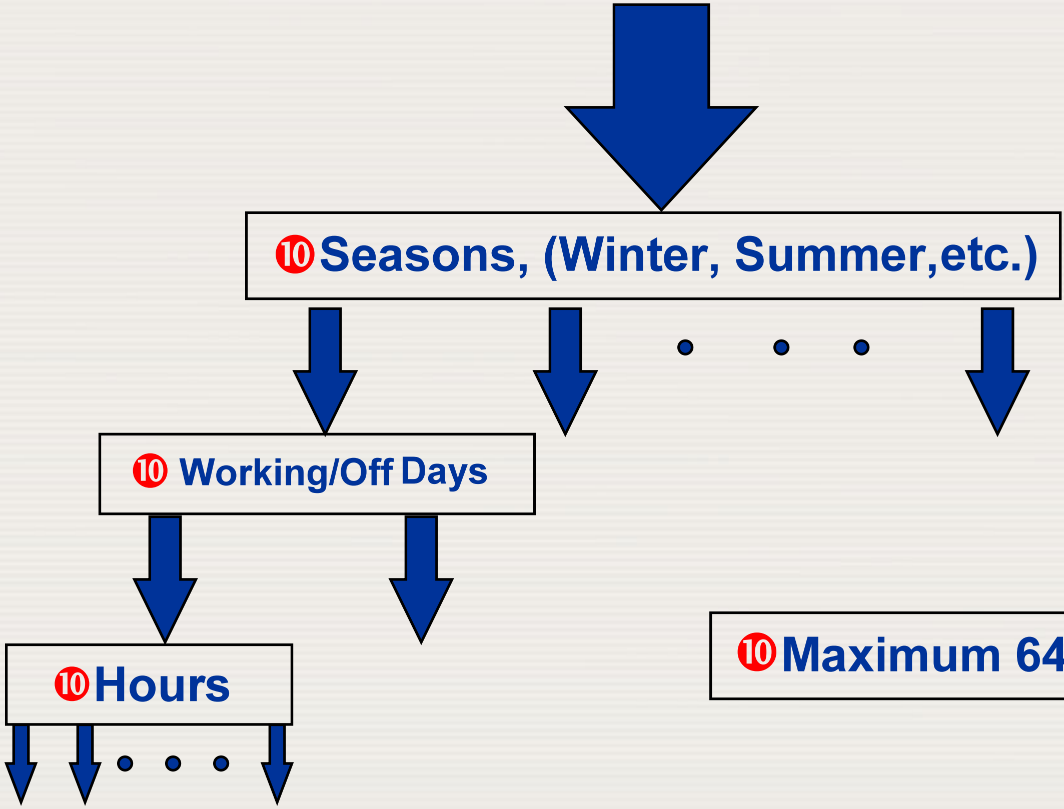
Load Regions
Seasonal Division of Year



Maximum 64 divisions possible

Load Curves

For each Load Region already specified,

Variation of demand for certain fuels within a year

e.g. Electricity, Heat, Gas

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Conversion Technologies

All energy technologies can be modelled

- Multiple inputs and outputs
- Seasonal variation in capability
- Efficiency varying with time
- Costs varying with time
- Limits on production
- Capacity build-up constraints
- Market penetration
- Environmental Regulation

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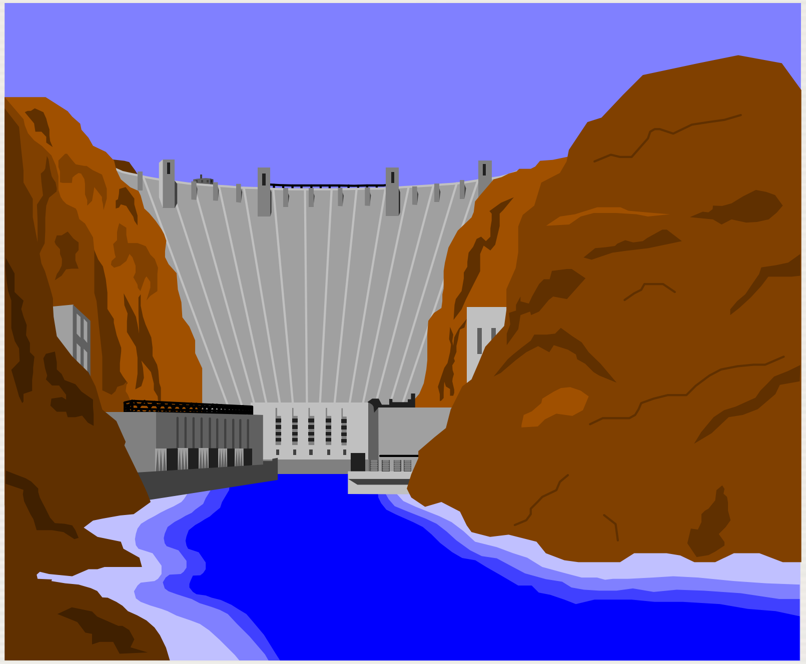
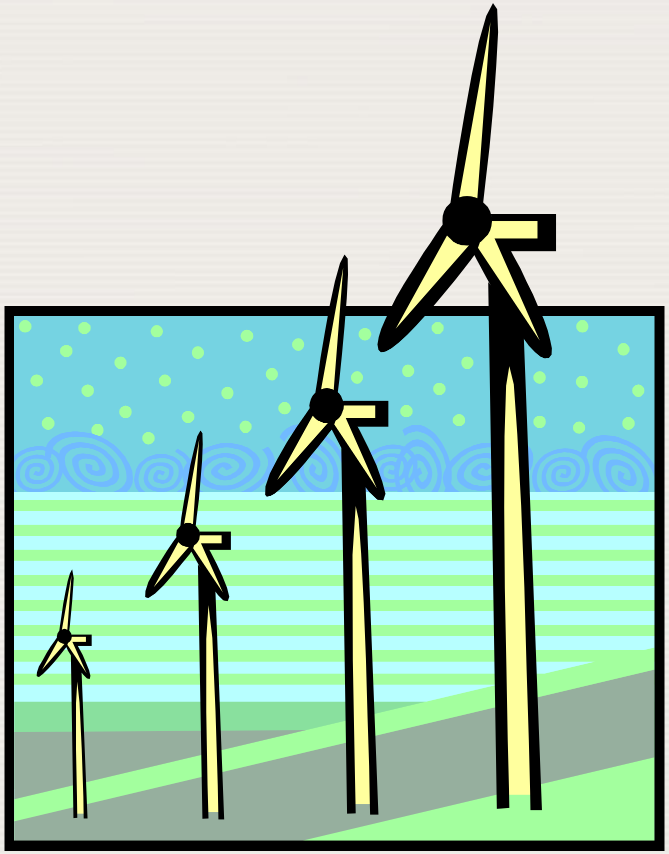
Hydropower Plants

- Seasonal Variation
- Water Inflows
- Mandatory Releases
- Storage Capacity
- Optimal Utilization



Renewable Technologies

- Renewable technologies can be represented with intermittent production
- Can be linked with storage or back-up systems



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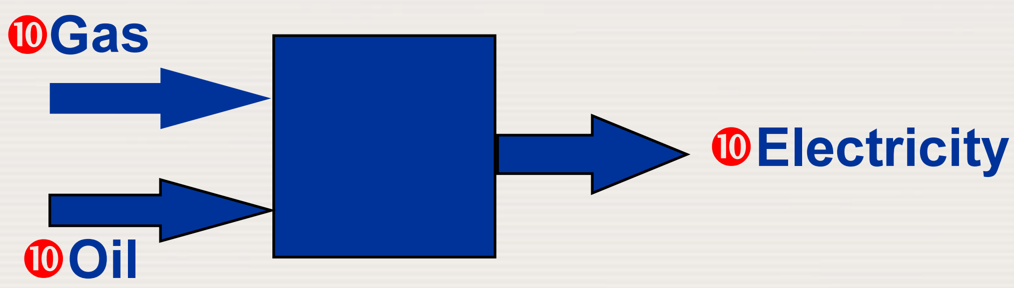
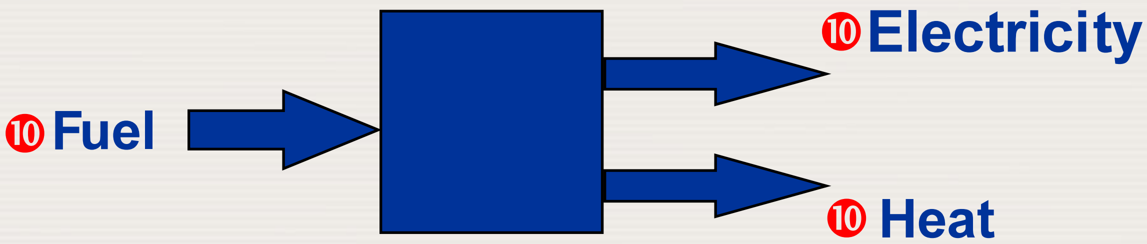
Dual Fuel Plants



- Fixed or Flexible Proportion Fuel Inputs
- Seasonal Limits on Fuel Use
- Efficiency may Vary with Fuel
- Emissions dependent on Fuel Use

Combined Heat and Power Plants



- CHP with fixed Heat and Power Output
- CHP with flexible Heat and Power Output
- Seasonal Limits on Heat and Power Output
- Overall Efficiency and Emissions dependent on Heat and Power Production

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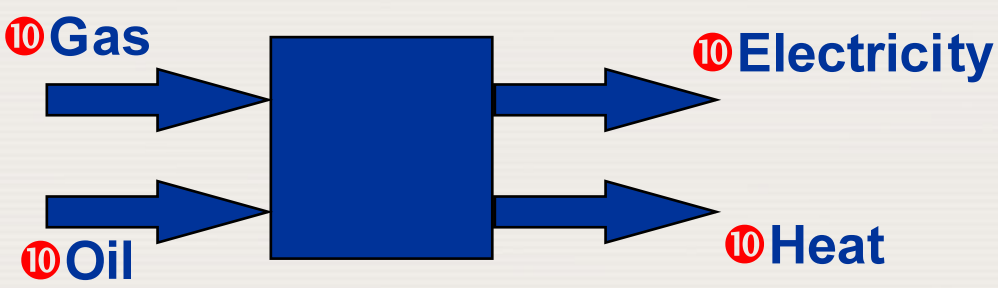
CHP Plants with Dual Fuels



- Fixed or Flexible Proportion Fuel Inputs
- Seasonal Limits on Fuel Use
- Fixed or Flexible Heat and Power Output
- Overall Efficiency and Emissions dependent on Fuel Use

Market Penetration of New Technologies

- Stock Vintage
- Market Inertia
- Economic Competitiveness
- Social Acceptability

Market penetration of new technologies can be controlled based on scenario assumptions, energy policy or regulations

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Energy Resources

- Various energy resource can be grouped into different Grades
- Grades based on extraction costs, geographic locations, or geological uncertainty
- Production costs may vary with time
- Resource extraction constraints; linked to total remaining amount or previous year's extraction level, or specific annual limits

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Energy Trade

- Imports-Exports of Fuels
- Fuel Prices varying within a year and over years
- Imports-Exports from/to different countries/region at different prices
- Market penetration

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Reliability of Supply

Electricity Reserve Capacity - Hot and Cold Reserves

Gas and Oil Storage

New Storage Technologies

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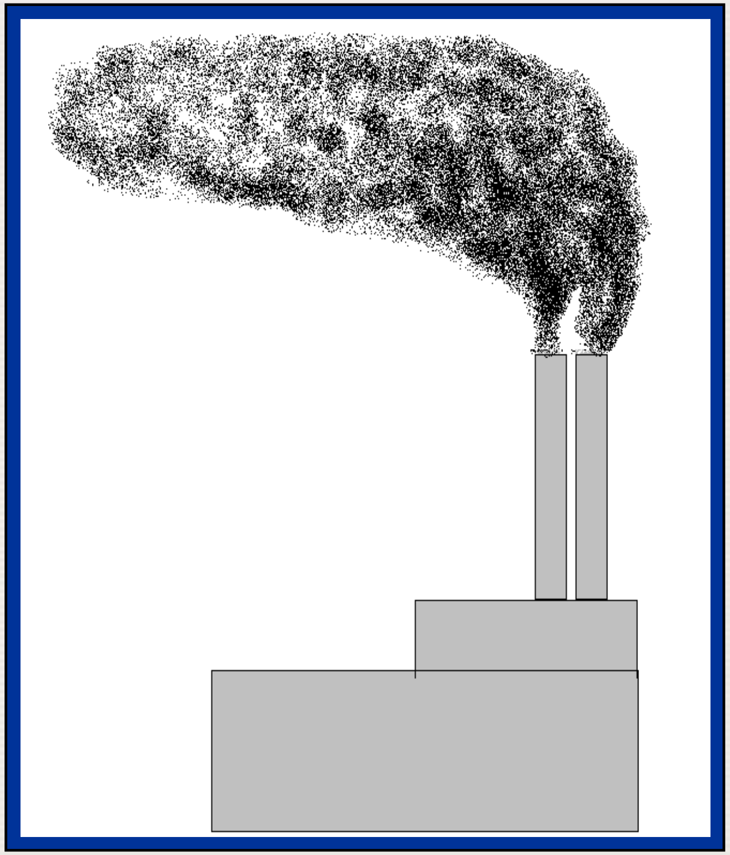
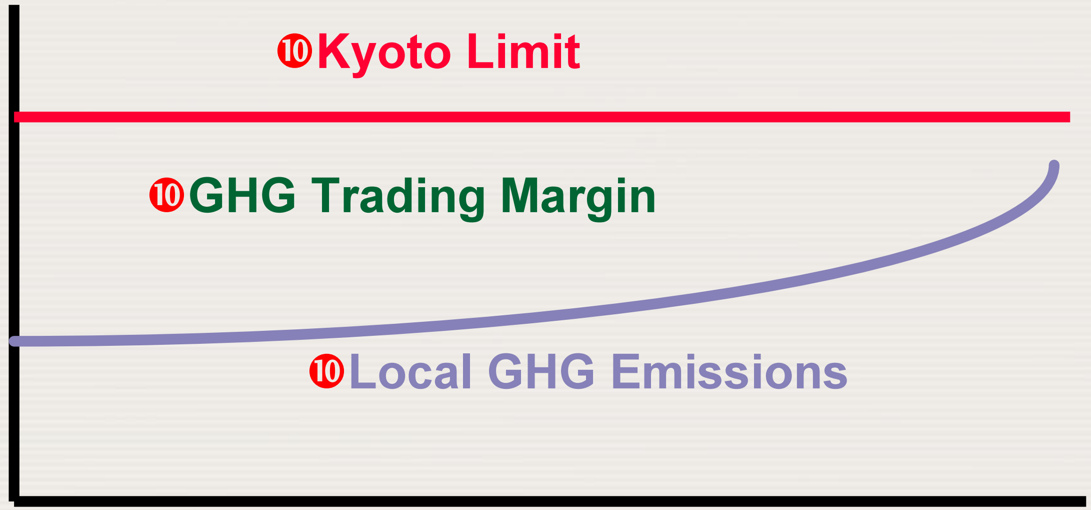
Modeling Environmental Regulations

- **Emission control limits can be imposed on Individual Plants or Group(s) of Plants**

- **Emission trading among plants/utilities possible, but more complicated**



Modeling Kyoto Mechanisms Emission Trading



- GHG Margin can be sold to one or more countries at different prices which may vary with time
- Limits on GHG sales to different countries
- Optimal Supply Strategy

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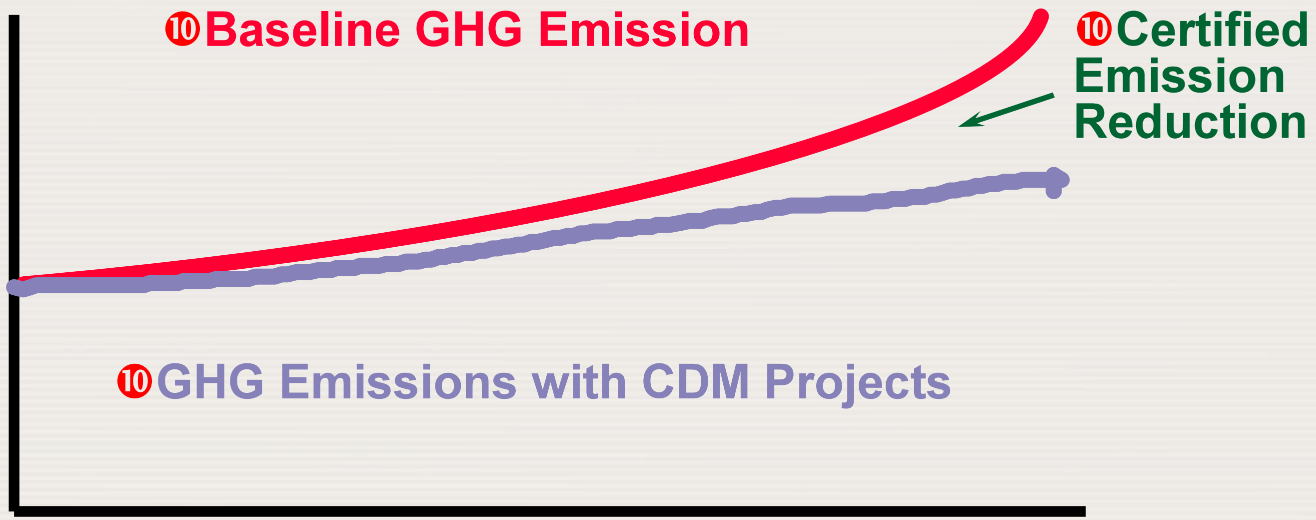
Modeling Kyoto Mechanisms: CDM



- Baseline GHG Emissions can be used as maximum allowable emission limits for CDM scenario
- CERs can be sold to Annex-1 countries
- Optimal supply & GHG mitigation strategy

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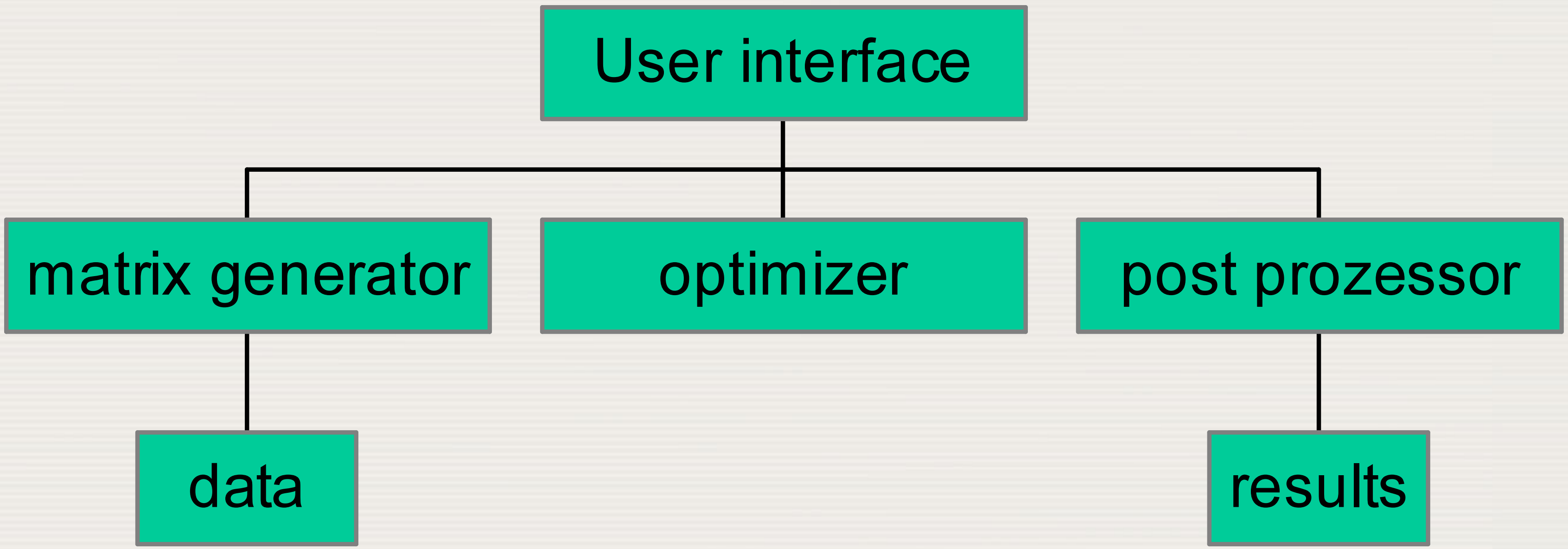
MESSAGE Modules



Mathematical Background

- Linear and mixed integer programming (LP and MIP)
- Linear variables for continuous processes
- Integer or binary variables for decisions and unit commitment
- Equations to model restrictions (technical, legal, environmental)
- Optimization target (objective): minimize cost, maximize profit

Modeling Hydropower Plants (HPPs) in MESSAGE

Special Features of HPPs

- Seasonal variation
- Water inflows
- Mandatory releases
- Storage capacity

Special Features of HPPs

- Water resources in the river usually have significant variation during the year.

- Installed capacity of hydro power plants is therefore often adjusted to the maximal water resources during the year.

Three types of Hydro Power Plants

- Run of Rver (RoR) HPP with or without water inflow
- HPP with storage
- HPP with pumped storage

Run of River Hydro Power Plants

- Use water as it is available from natural inflow
- Usually have some small storage
- Cause few alteration of the natural flow of river or stream
- Have large seasonal variation
- Generally have low head
- Have minimum environmental and social impacts

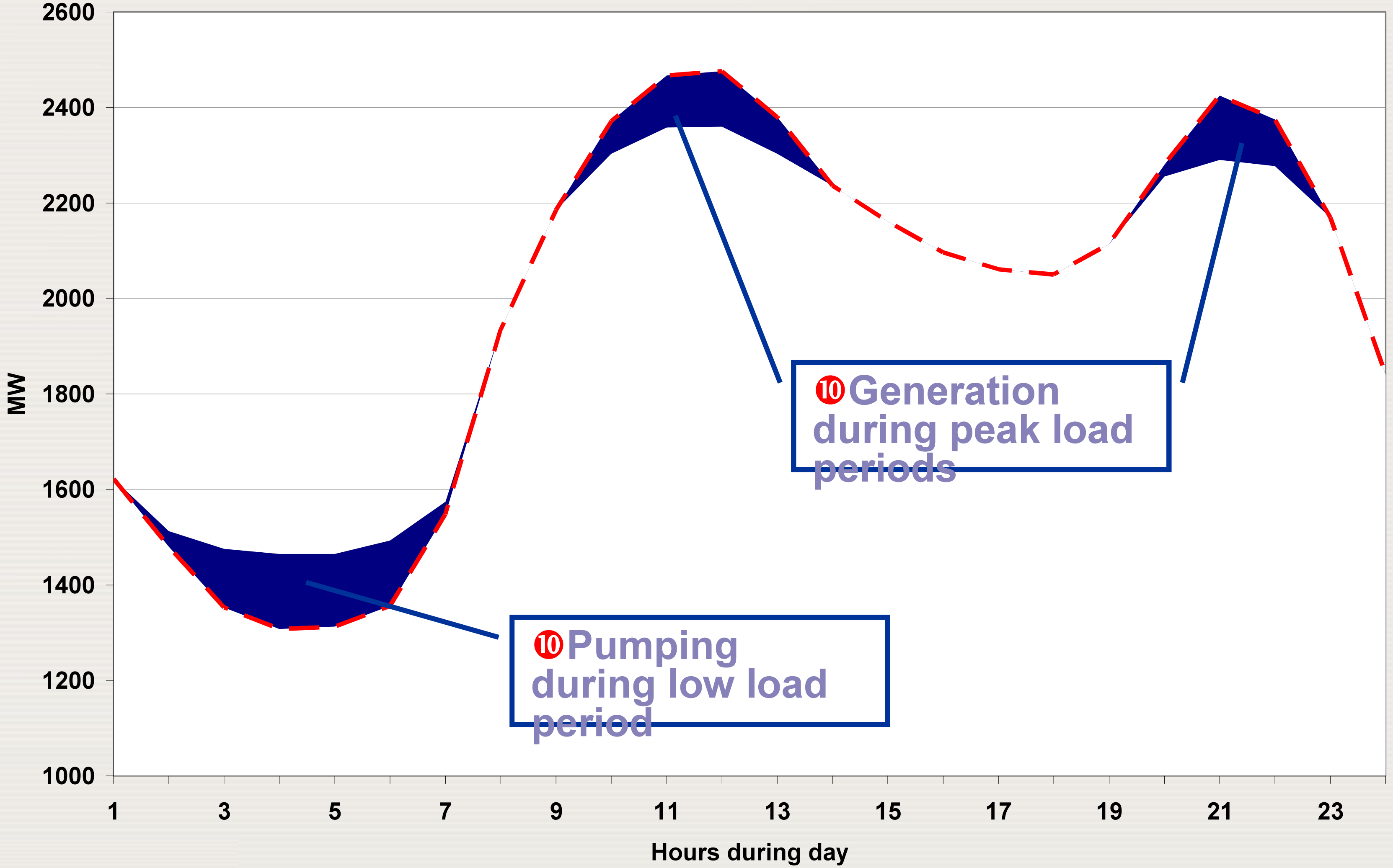
Storage Hydro Power Plants

- Large storage for handling variations in natural inflows
- Most of dams are multipurpose and are used for power, irrigation, municipal water supply, flood control, tourism, etc.
- Displacement of population
- Flooding of vast areas of land, loss of arable land
- Increased water logging and salination
- Interruption of aquatic life (fish)
- Greenhouse gas emissions due to inundation of biomass
- Loss of biodiversity

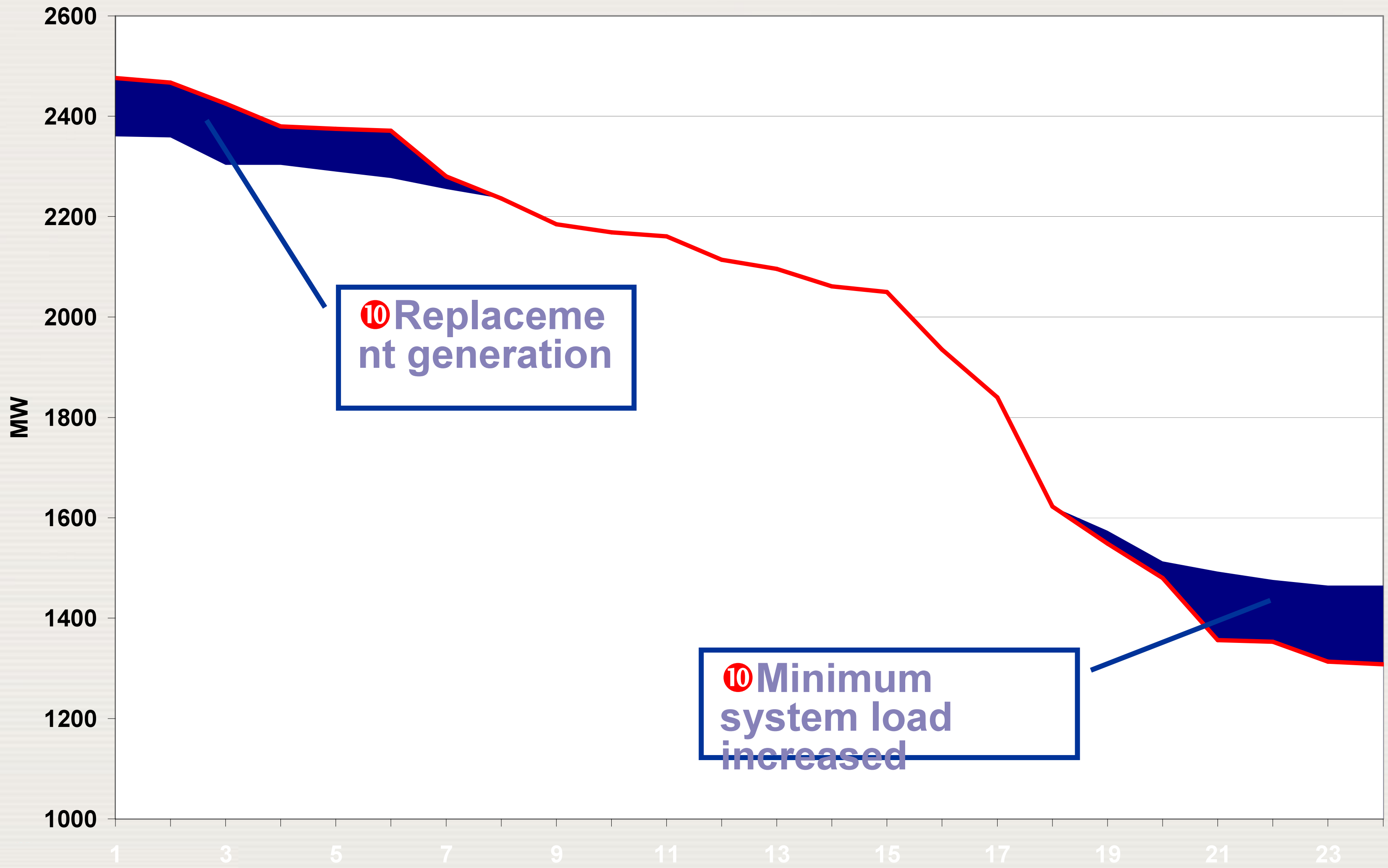
Pumped Storage HPPs

- Moves water between two reservoirs at different elevations: an upper reservoir and a lower reservoir
- When electricity demand is low (off-peak period), water is lifted from the lower reservoir to the upper reservoir consuming electricity. During the peak hours, when the electricity demand is high, water flows from upper reservoir to lower reservoir through turbines and produces electricity

Pumped Storage in Daily Load Diagram



Pumped Storage in LDC



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Modeling HPP in MESSAGE

In modelling a hydro power system in MESSAGE, the following must be specified:

- Rivers
- Storages on those rivers (with water inflows, water outflows, and water overflow)
- hydro power plant technologies

Simple Model

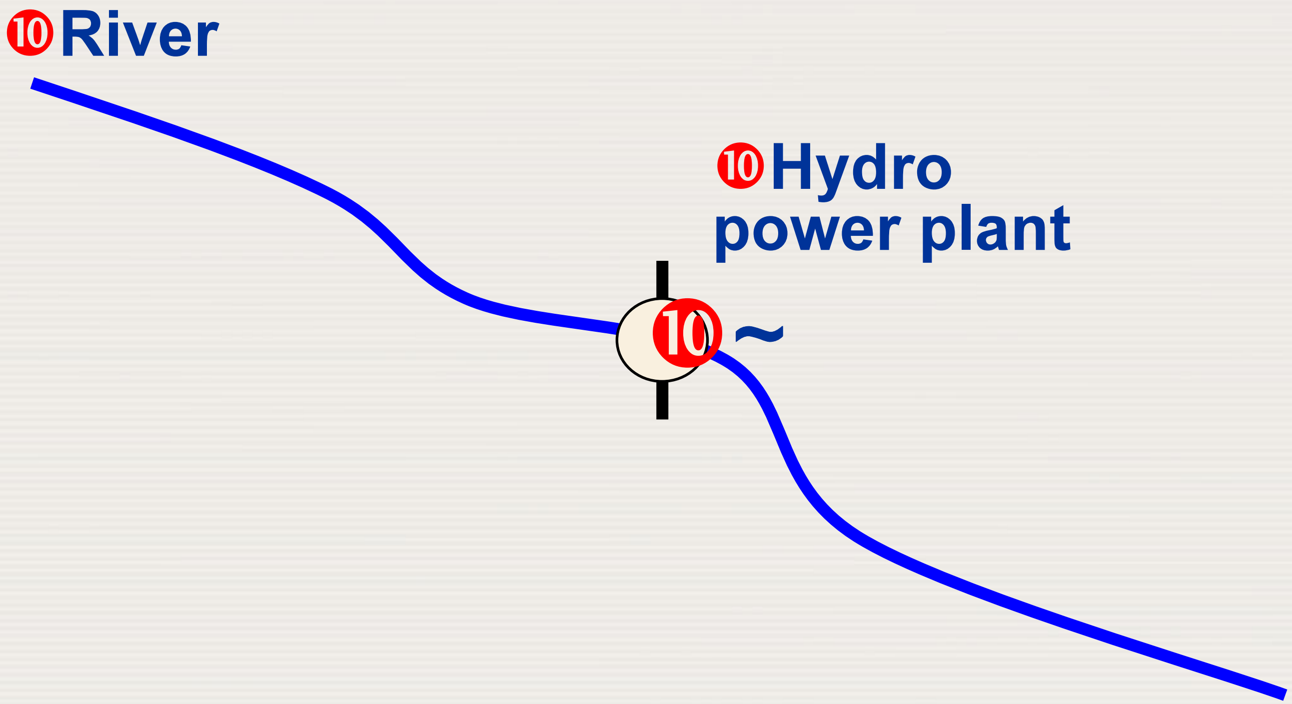
- Hydro plant producing base load
  → Large rivers where a change in water level is not permitted because of ships and/or recreation areas
- Hydro plant with given production pattern
  → Plants where throughput may not be changed for similar reasons as above

More General Model

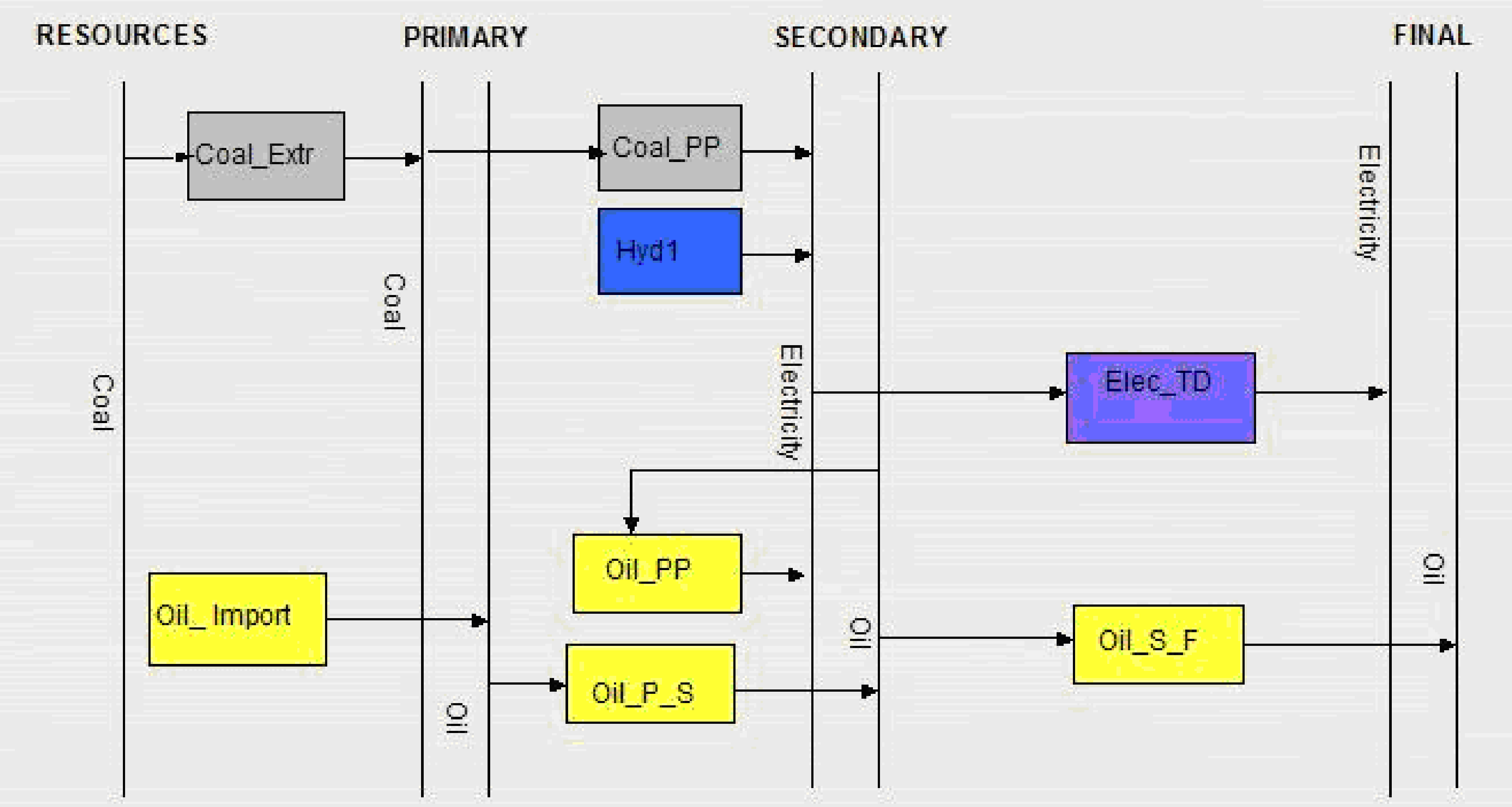
Hydro plant with optimized throughputs

- Modeled with storage and hydro power plant
- Max power > average throughput
- Difference depends on allowed variations
- Often also ramping rates are important

Run of River Hydro Power Plant



A Simple Energy Supply Model



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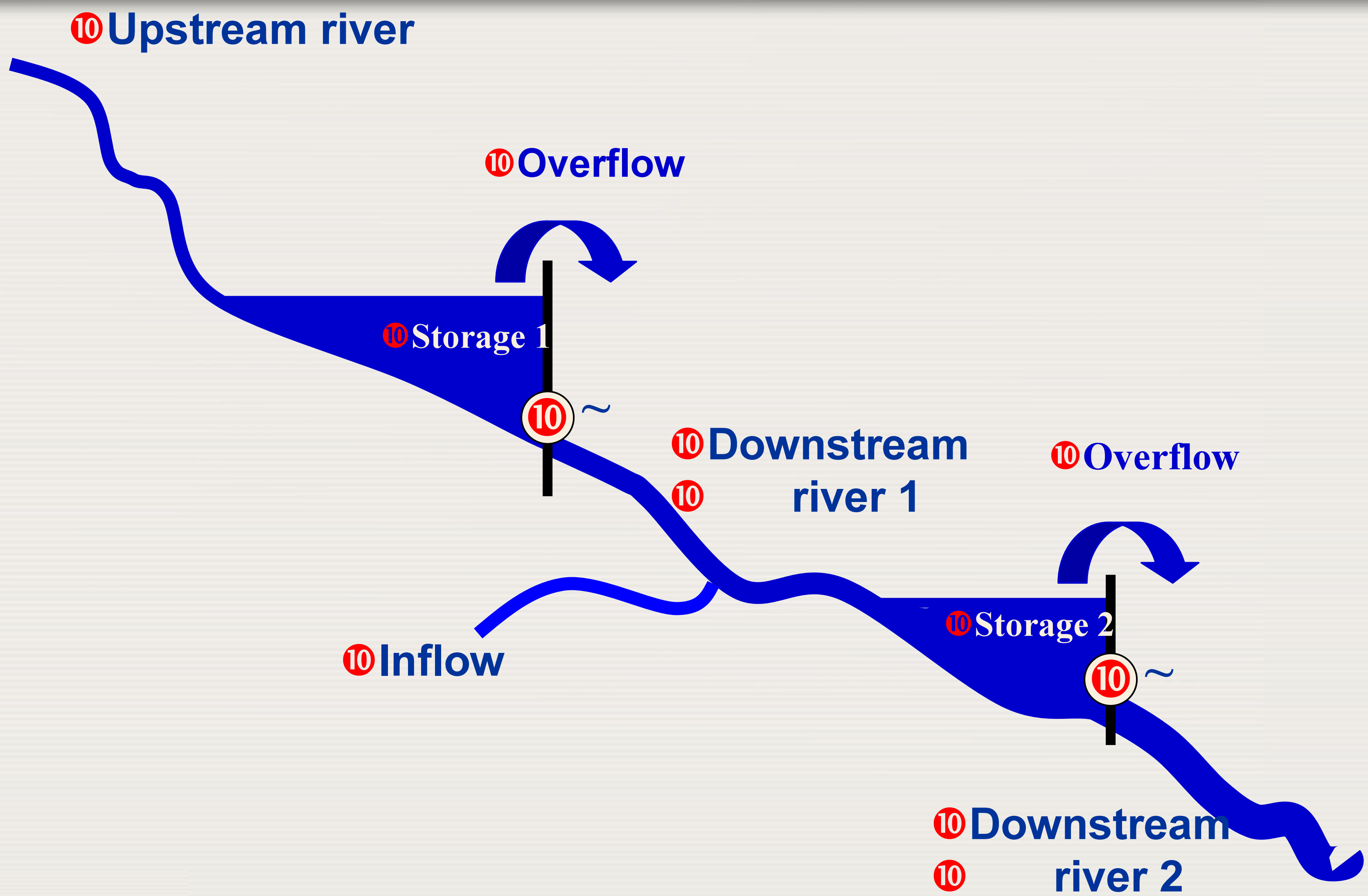
Storage HPP in MESSAGE

- Rivers with inflow and outflow are defined under “constraints/group2”
- River-storage connections are established and outflow is defined under “hydro type storages”
- Hydropower plants are characterized under “technology” (activity) as no-input technology and link with storage and rivers are established
- Constrains in annual generation by inflow energy is defined under “technology” (capacity)
- It is possible to model cascades of HPP

RoR HPP with Water Storages



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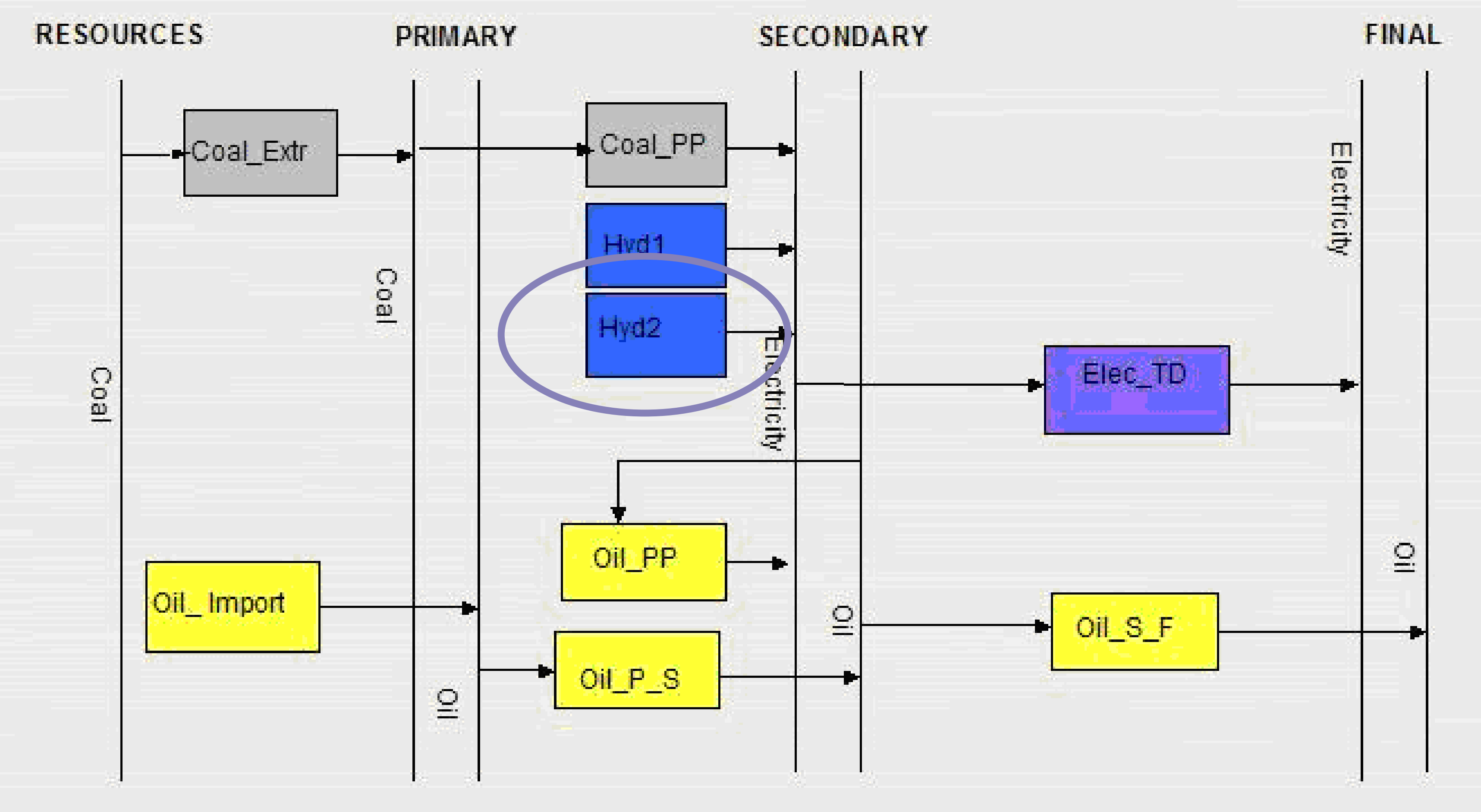
A Simple Energy Supply Model



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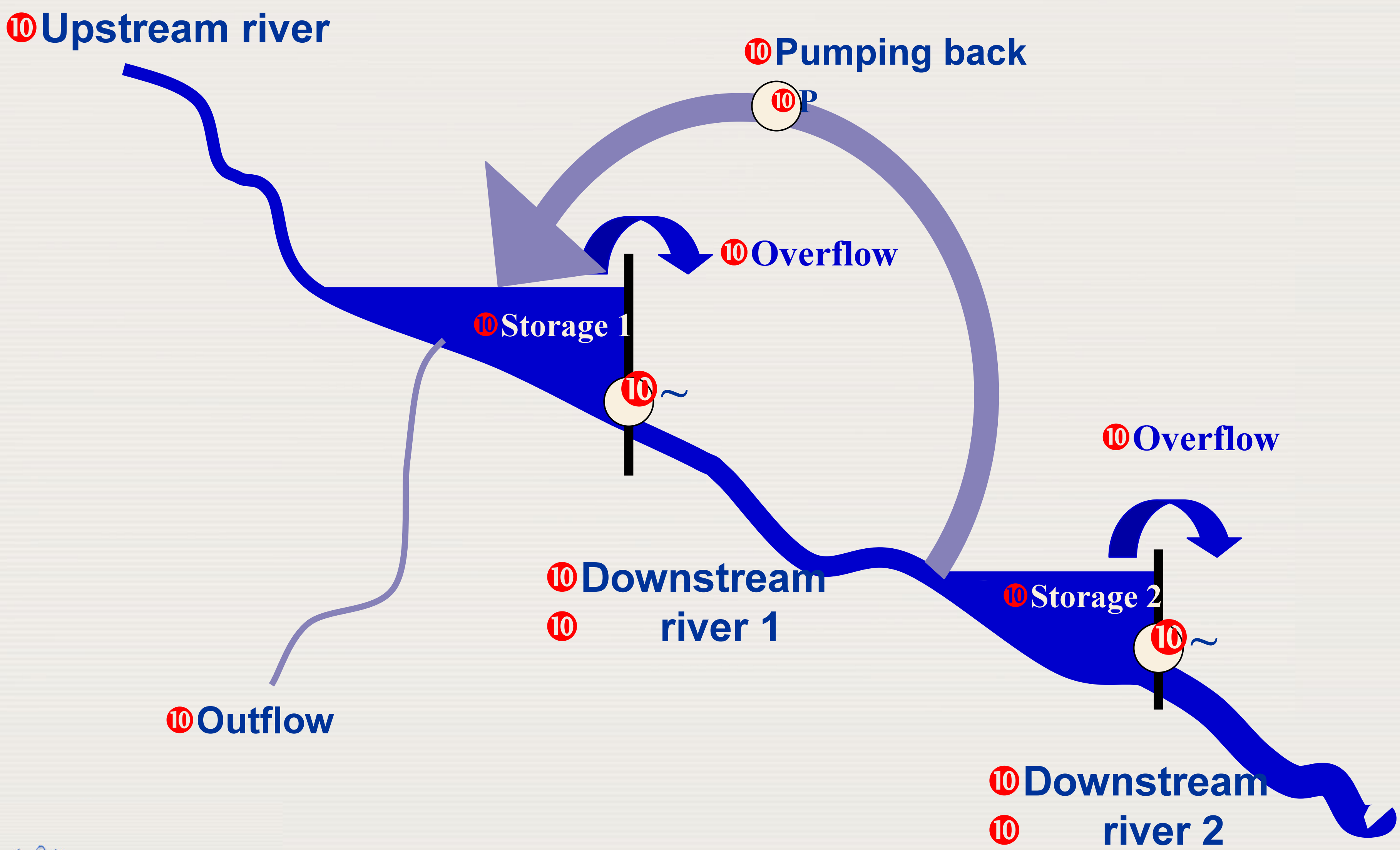
Pumped Storage HPP in MESSAGE

- Modelled using two technologies:
  - Turbine
  - Pump
- Upper/Lower reservoir modelled as a storage
- Connections between river-tech-storage

River System with Pumped Storage



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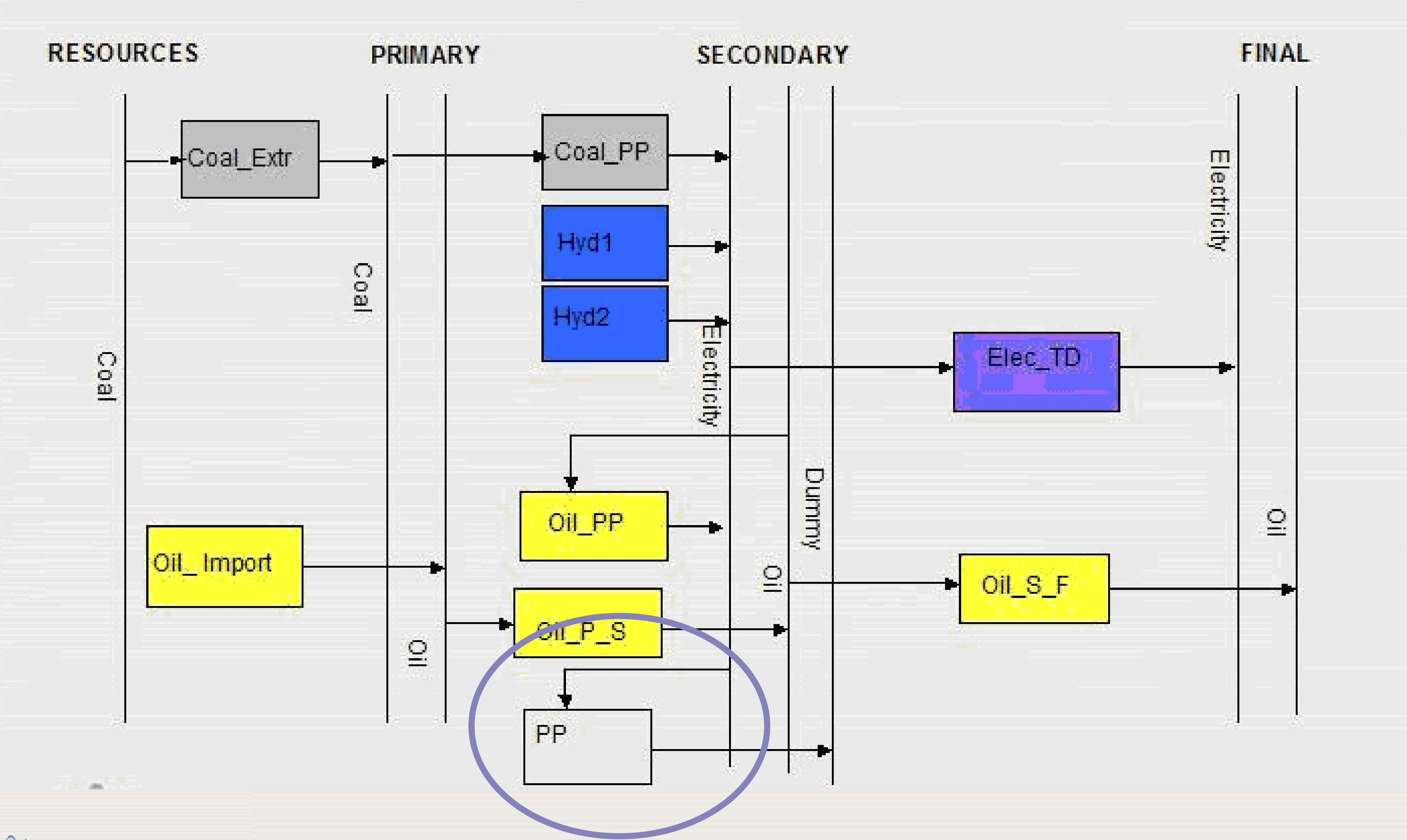
A Simple Energy Supply Model



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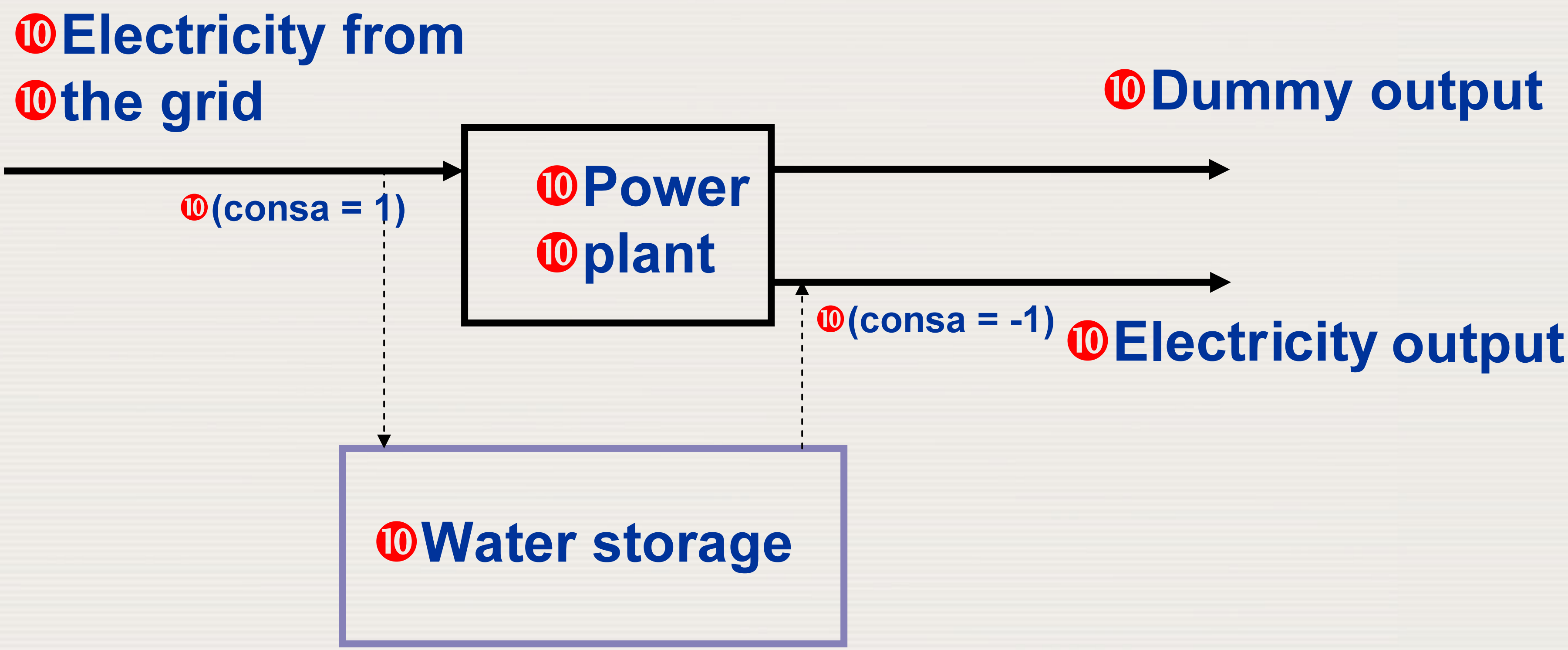
Hydro Pump Storage Power Plants



4. Renewables & Decentralized Supply

Modeling
Renewable Technologies and Decentralized Energy Supply Options
in MESSAGE

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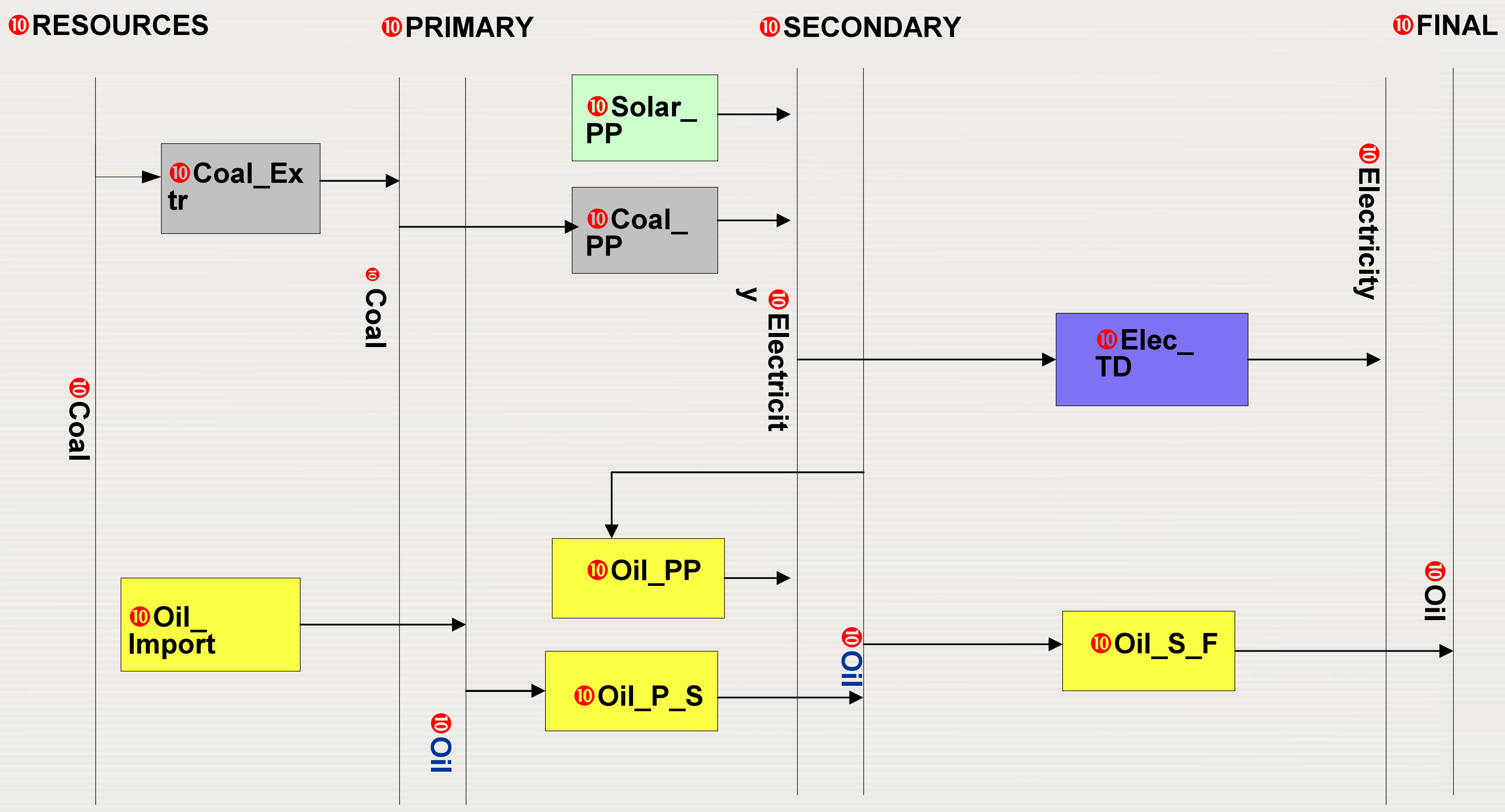
Modelling of Renewable Energy Sources in MESSAGE

Key Issues for System Operation

Intermittency

- Large penetrations of intermittent generation increases the uncertainty of predicting the balance between supply and demand
- This may imposes additional cost on operating the system to ensure controllability and performance of the host electricity grid

⑩A Simple energy supply model in MESSAGE - Physical Flow



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Modeling Renewable Technologies

In general, renewable technologies are modeled in MESSAGE using constraints

- Capacity limits: to reflect limits on available sources
- Output limits (load curves): to reflect seasonal, and day night variation in supply

Decentralized Generation

Decentralized generation is production of electricity and/or heat near the place of use or close to the load being served. It may or may not be grid connected

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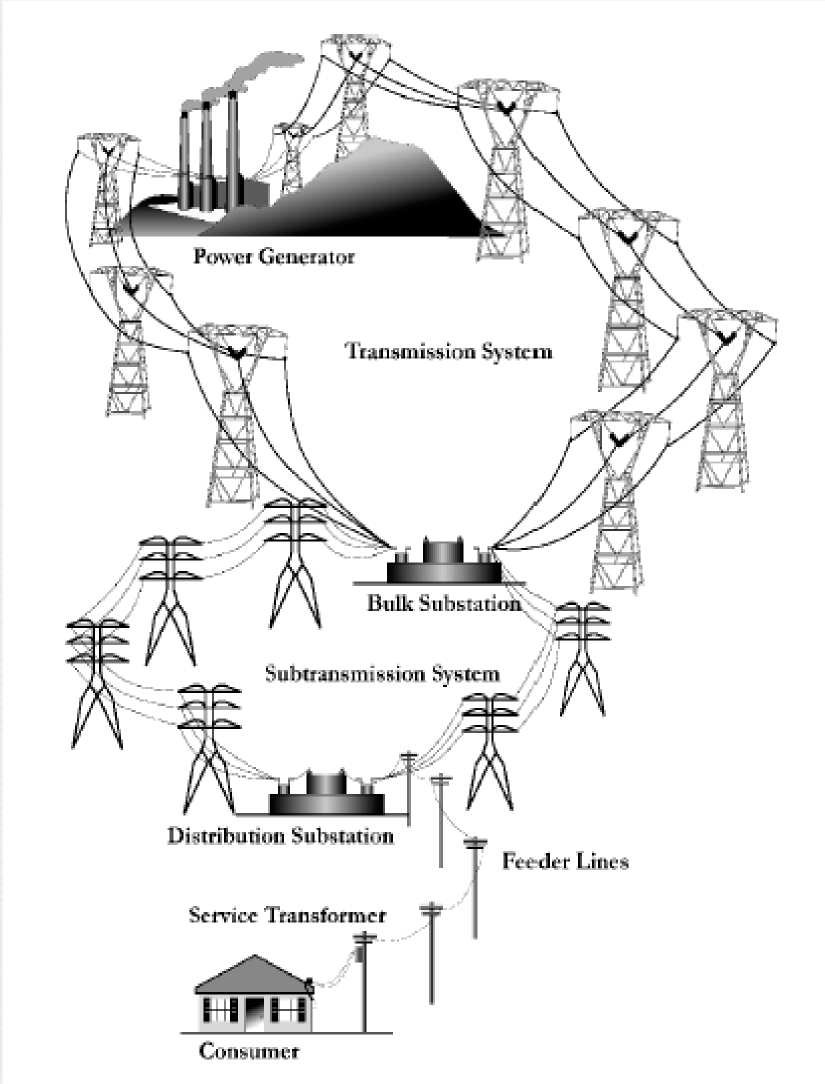
Centralized Systems

Consist of:

- Central generation units (usually big)
- Transmission and distribution networks
- Transmission and distribution substations
- Consumption is spread in wide area (not necessary in the neighboring locations)



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Decentralized Generation

- Stand alone – one or several small units providing energy to (usually) one costumer (household or producer):
  - Often "Home/farm/telecoms" systems
  - If renewable, requires storage (often)
  - Move to integrated solutions (PV and LPG)
  - Often (but not always) highly subsidized

- Mini-grid – Generator (s) provide electricity to more than one customer:
  - Frequently semi-formal arrangements are used
  - Much initial electrification

Remote shop in Mozambique using PV for powering a fridge

Decentralized Generation Technologies

Decentralized generation could include:

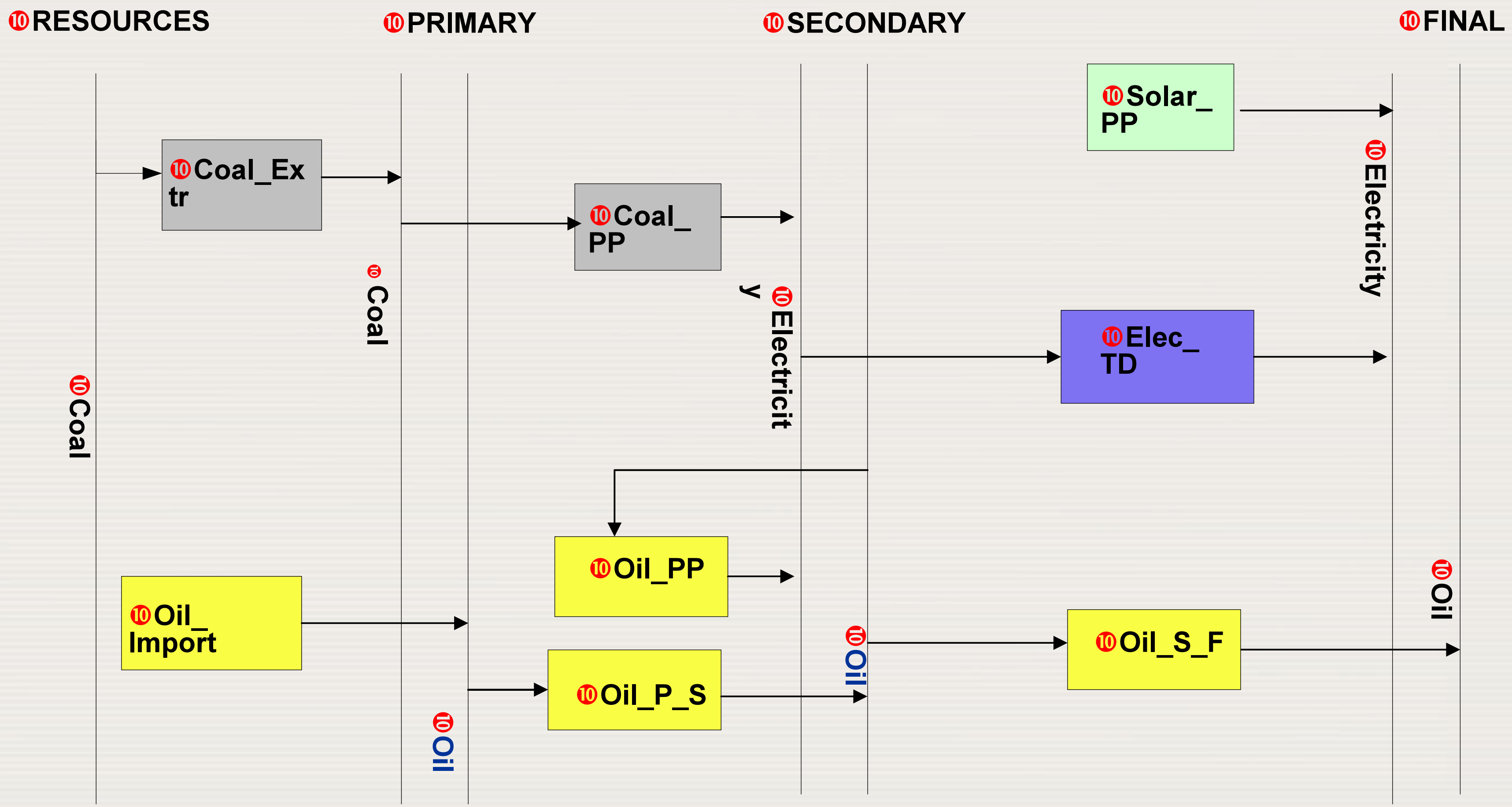
fossil fuel based technologies

- Internal Combustion Engines
- Micro-turbines
- Combined heat and power, CHP (on gas or other fossil fuels)

renewable energy technologies:

- Micro or mini hydro
- (Small) Wind
- PV
- CHP (on biomass, bio-gas, etc)
- Waist combustion, etc

⑩A Simple energy supply model in MESSAGE - Physical Flow



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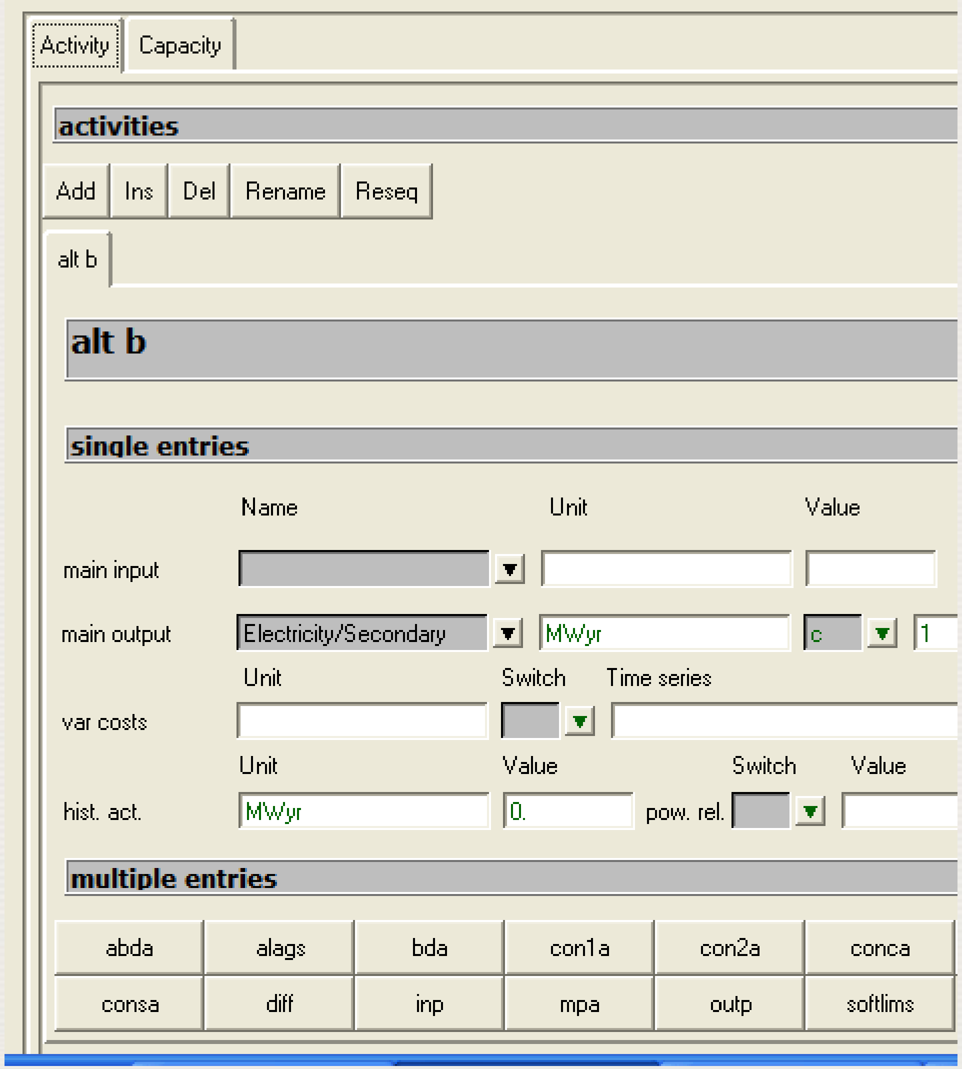
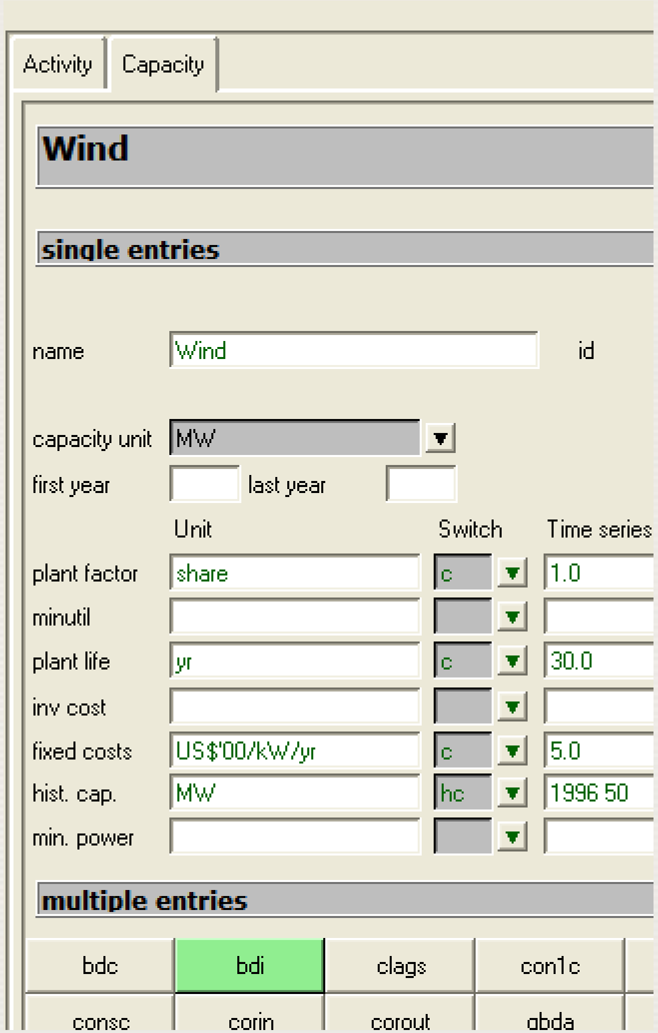
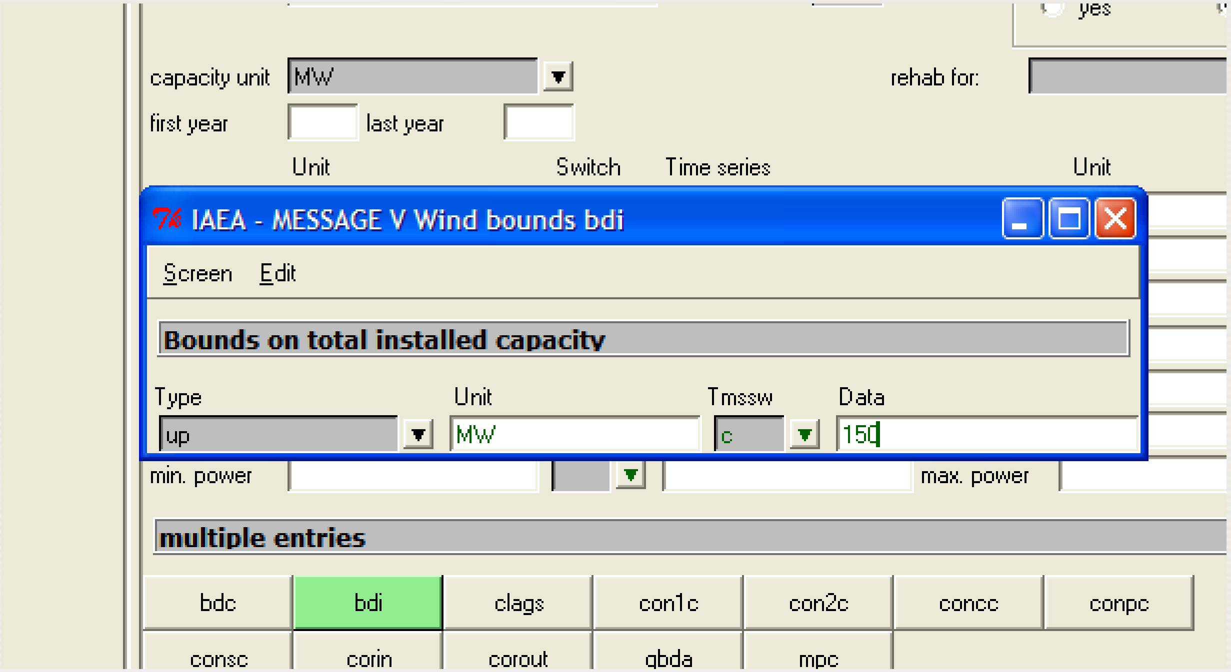
The Model: Wind – Basic Data

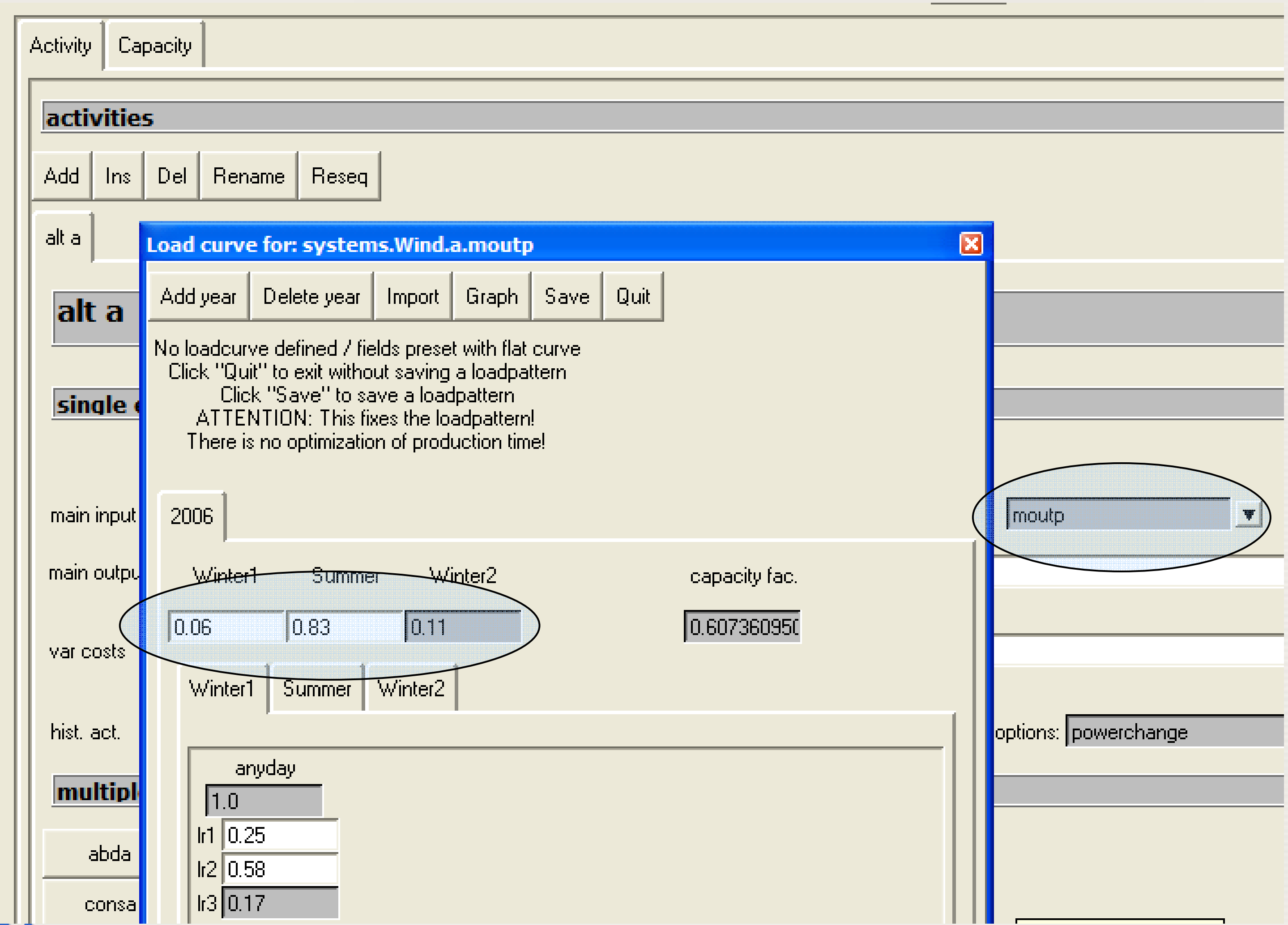




The Model: Wind – Capacity Limit



The Model: Wind – Output Limits



5. Summary and Conclusions

MESSAGE: powerful, flexible

Renewables: already included

Intermittency: simplified representation

Storage: included

Development need:

Better representation of extreme weather impacts

Options for managing weather impacts:

adaptation: technological, operational adjustments

vulnerability reduction: existing: structural changes

new build: design and construction innovation

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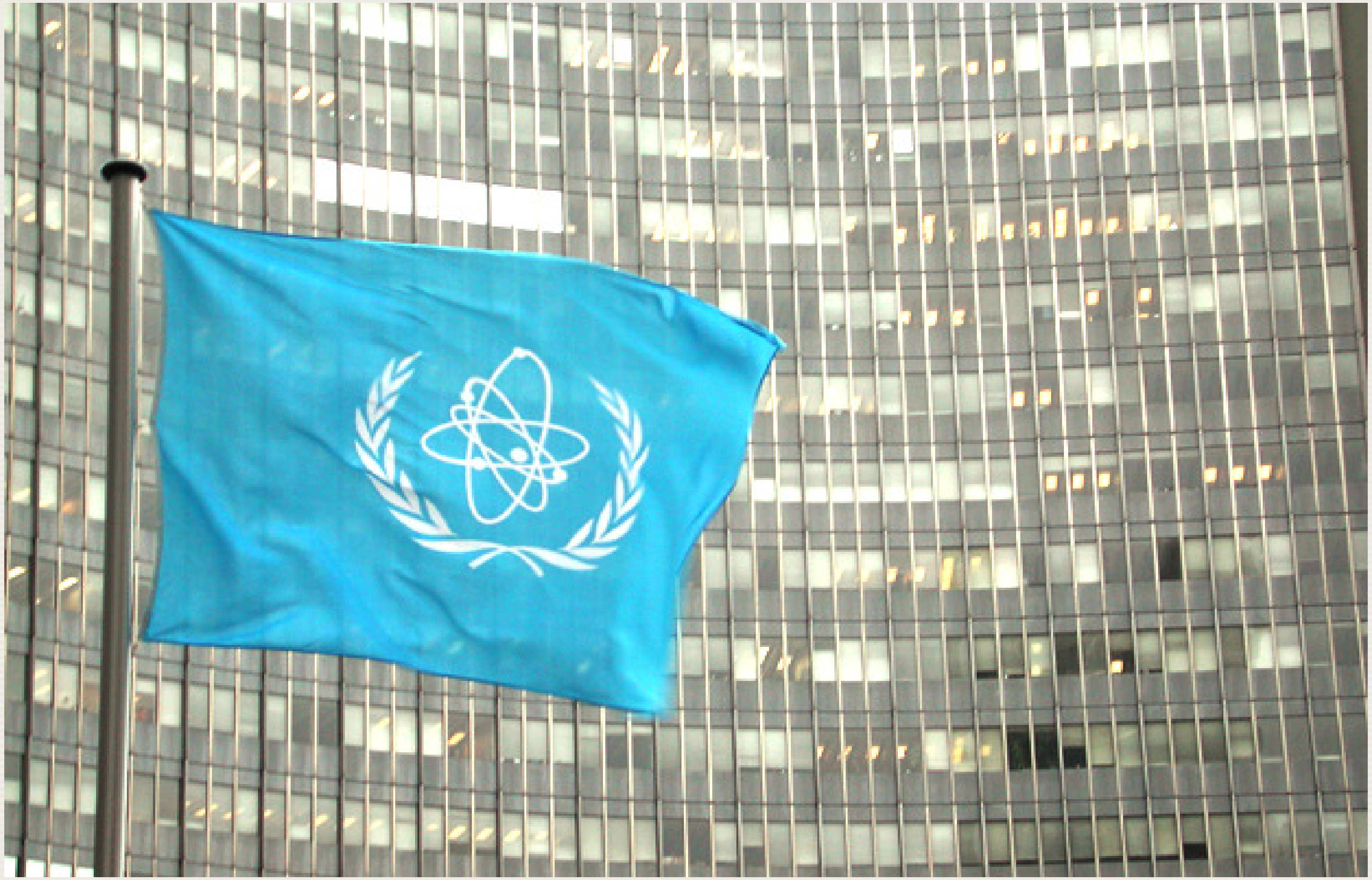

…atoms for peace.