Introduction to Energy System Modelling

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13 June 2017 – ICTP, Trieste, Italy

Energy system

- **Energy system – what is it?**
  - **Means different things to different folks**
  - **What is its purpose?**
  - **It is not an end in itself!**
  - **Contemporary issues call for fundamental (energy) system transformation**
    - **2030 Agenda for Sustainable Development**
    - **Paris Agreement**
- **So let's define it for the purpose of this Summer School (and hopefully well beyond it)**

Some elements of an energy system

Coal mine, hydro power plant, refinery, transmission line, building, train, etc.

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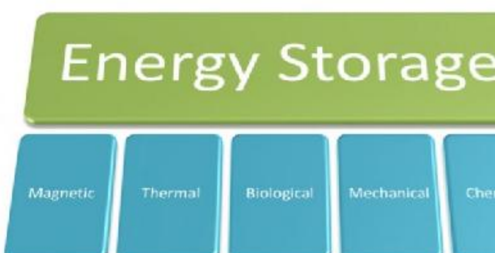


Architecture of the Energy System

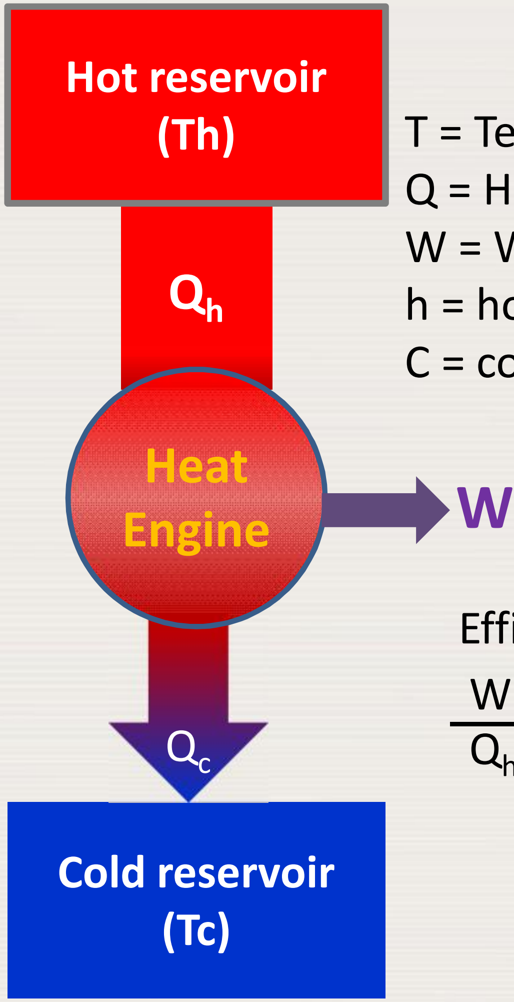
Sources	coal oil natural gas sunlight uranium wind biomass	What nature Provides
Extraction Treatment	coal mine, hydro dam, oil rig, cleaning, separation, benefication, liquef-action, gasifi-cation	
Conversion Technologies	hydro station, thermal power plant, oil refinery, nuclear generating station, photovoltaic cell, wind converter	Energy Sector
Currencies (fuels)	electricity gasoline methanol methane coal heat	
Distribution	electricity grid, gas grid, truck, dewar, railway, district heat grid	
Service Technologies	cities roads buildings factories shopping malls schools automobile, light bulb, telephone, furnace, microwave oven, aircraft, PC	*Infrastructure & Technology*
Services	transportation, communication, keeping warm/cold, food potable water, health care, security, consumer goods	What people want

Terminology

- Words shape actions
  - Popular terms can send the wrong message – you cannot:
    - 'Save energy' – but one can use it more rationally (do more with less)
      - improve efficiency of the conversion process
      - behavioral changes
      - structural economic change
    - Produce or consume energy – but convert it to more useful forms or generate an energy service
    - 'Save emissions' - but one can avoid/reduce emissions
      - efficiency improvements
      - behavioral change
      - add abatement technology
      - change the process or the technology

Terminology

- Energy conversion is subject to the 1st and 2nd Law of Thermodynamics
  - Any energy conversion generates at least two energy streams
    - One useful output (e.g., work or heat)
    - One rejected heat (waste heat)
  - The change in the energy of a system equals the heat flow in the system from/to the surroundings minus the work done by the system on the surroundings
  - The law states that the total energy of a system and its surroundings remain constant (energy conservation)

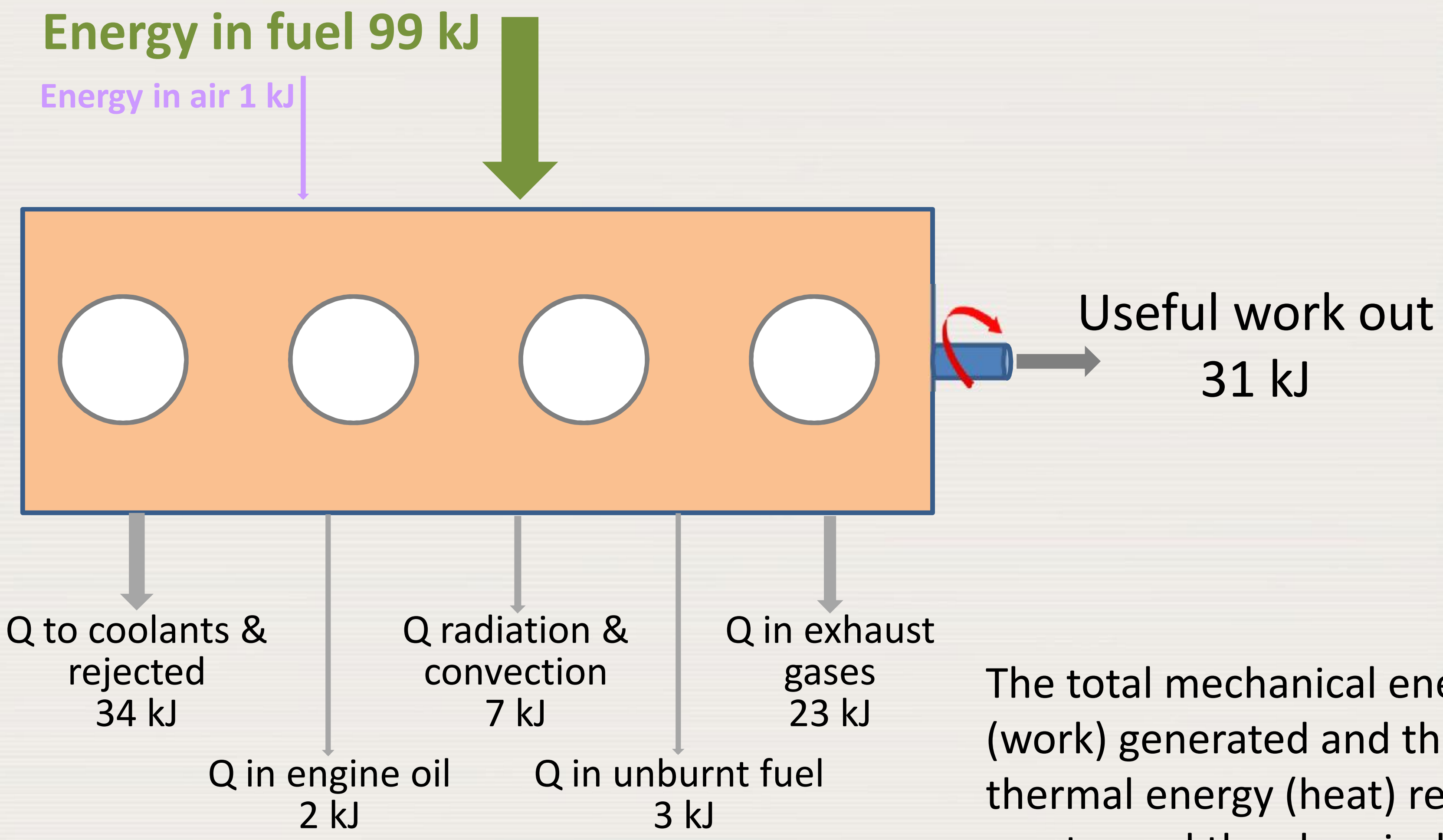


T = Temperature (K)
Q = Heat (j)
W = Work
h = hot
C = cold

Efficiency:

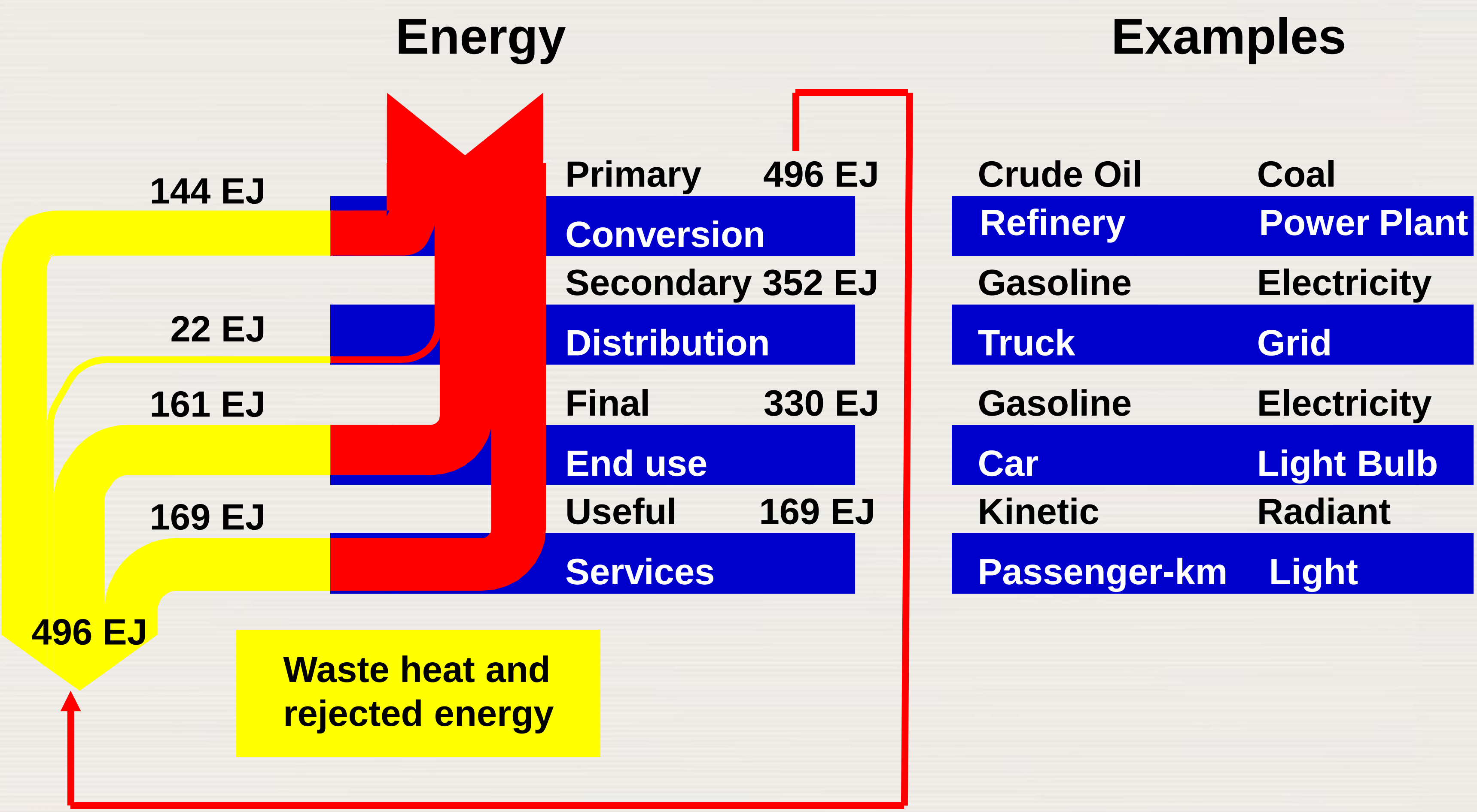
$$\frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h}$$

1st Law energy balance of a diesel engine



The total mechanical energy (work) generated and the thermal energy (heat) rejected must equal the chemical energy contained in the fuel and heat in the combustion air.

First Law of Thermodynamics: Energy conservation



Why energy planning?

- Energy is strategic in the key dimensions of sustainable development: Economic, Social and Environment
- Energy is integrated: One part of the system affects other parts
- Energy is intra-grated: Energy policies affect and are affected by a myriad of other decisions/developments
- Energy systems are dynamic and moving targets
- Energy planning is about choices & dealing with current & future uncertainties
  - Technology
  - Fuels and prices
  - Policy
  - Demand
  - Behavior / preferences

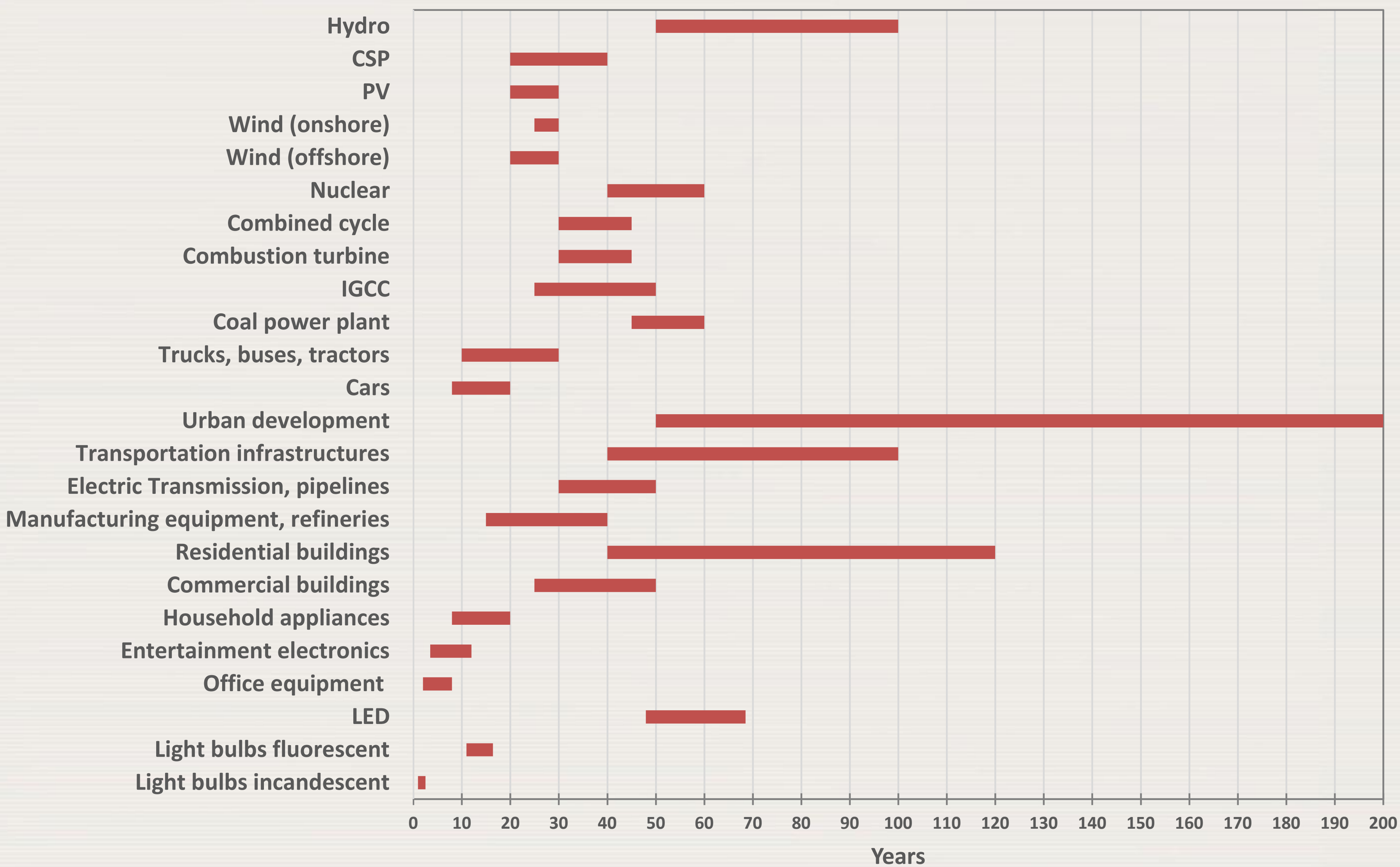
Why energy planning?

- Comprehensive energy planning essential for sustainable (energy) development
  - A prerequisite for informed decision making
    - Assessing future energy demand
    - Evaluating options & reviewing different ways to meet those needs
    - Identifying risks and benefits
    - Exploring "what if..." questions
  - Optimal domestic resource allocation
  - Inherently long lead and life times
  - Shift from sequential stop-gap measures to integrated energy system planning

Why energy planning?

- Testing of effectiveness of policy measures
- Compliance with environmental constraints and climate objectives
- Investment requirements and financial viability (finance)
- Social/public/political commitment & acceptance
- Economic development & environmental protection
- Regional approaches & infrastructure sharing
- Communication tool (public, investors, stakeholders, neighbors)

Energy infrastructure life times



The essence of energy planning

- Preparing for an uncertain future in a comprehensive, organized and transparent manner

- Dealing with trade-offs

Planning addresses the energy tri-lemma

- Energy security
  - Supply security
  - Reliability
- Economic competiveness
  - Affordability
  - Access
- Environmental considerations
  - Climate change
  - Local and regional pollution

Trade-offs

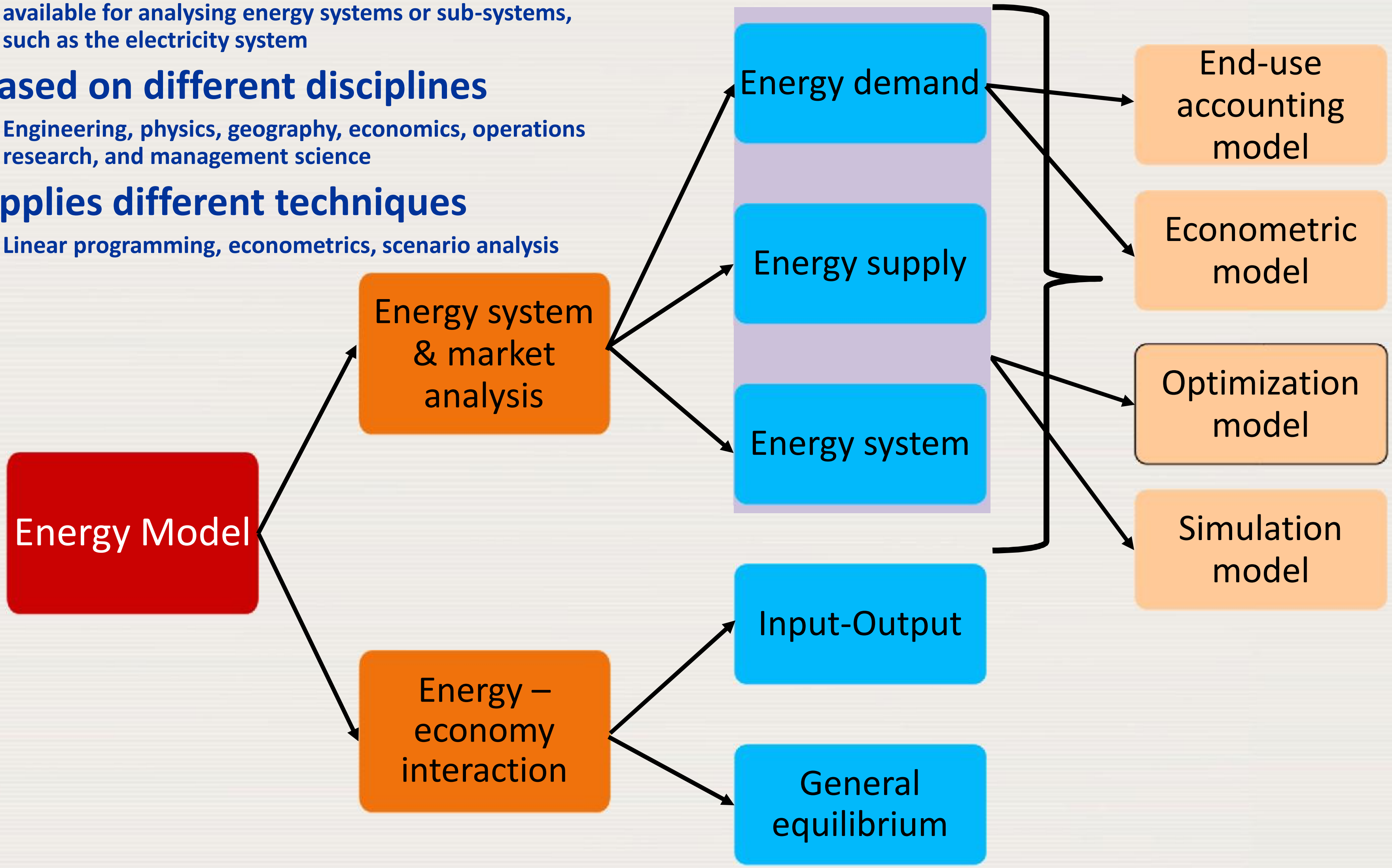
- Trade-offs between environmental, economic and social sustainability components are inevitable
- Trade-offs are often influenced by value judgments
- Emphasis on economic development harms the environment
- Emphasis on environmental protection adversely affects the economy
    - Poverty is the largest polluter
- Emphasis on economy penalizes renewables (current accounting systems)
- Emphasis on environment penalizes fossil chains
- Emphasis on social aspects penalizes nuclear

Energy modeling – a panacea for planning?

- **Energy modeling is an art…….**
- **Energy modeling provides insights NOT answers**
- **Energy modelling has multiple purposes**
  - **Better understanding of current and future markets – supply, demand, prices; facilitating a better design of energy supply systems in short, medium and long term; ensuring sustainable exploitation of scarce energy resources; understanding of the present and future interactions energy and the rest of the economy; understanding of the potential implications to environmental quality**
- **Different actors require different answers and thus different approaches (no one size fits all)**
- **Answers for and thus information to decision and policy makers and markets are not trivial – analysis and planning tools (with their deficiencies are inevitable prerequisites)**
- **Energy planning never ends…**

Simplified classification of energy models

- **Energy modelling has a long history**
  - Since the early 1970s, a wide variety of models became available for analysing energy systems or sub-systems, such as the electricity system
- **Based on different disciplines**
  - Engineering, physics, geography, economics, operations research, and management science
- **Applies different techniques**
  - Linear programming, econometrics, scenario analysis



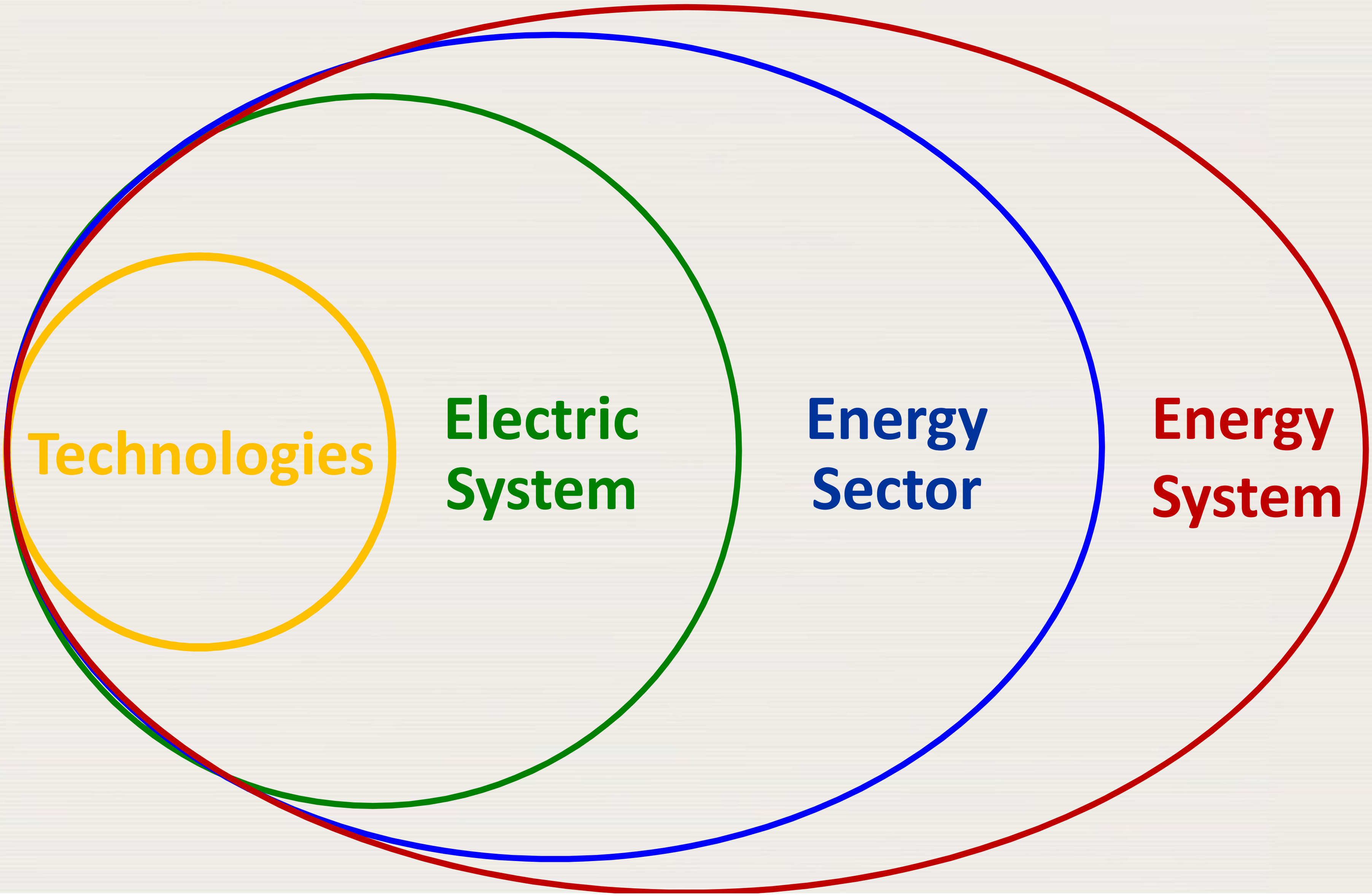
Energy Models - A small selection.....

WASP	Wien Automatic System Planning	IAEA
MESSAGE	Model for Energy Supply System Alternatives and their General Environmental Impacts	IIASA/IAEA
MARKAL	Market Allocation Model	IEA
LEAP	Long Range Energy Alternatives Planning System	SEI
TIMES	The Integrated MARKAL-EFOM Systen	IEA
POLES	Prospective Outlook on Long-term Energy Systems	EU
ENPEP-Balance	Energy and Power Evaluation Program	Argonne
EFOM	The Energy Flow Optimization Model	IEPE, Grenoble
OSeMOSYS	Open Source Energy Modeling System	KTH/IAEA
NEMS	National Energy Modeling System	US DOE
MESAP	Modular Energy System Analysis and Planning Environment	IER Stuttgart
PRIMES	Price-Induced Market Equilibrium System	NTU Athens/ EU
MAED	Model for Analysis of Energy Demand	IAEA

Challenge: Determining the system boundary

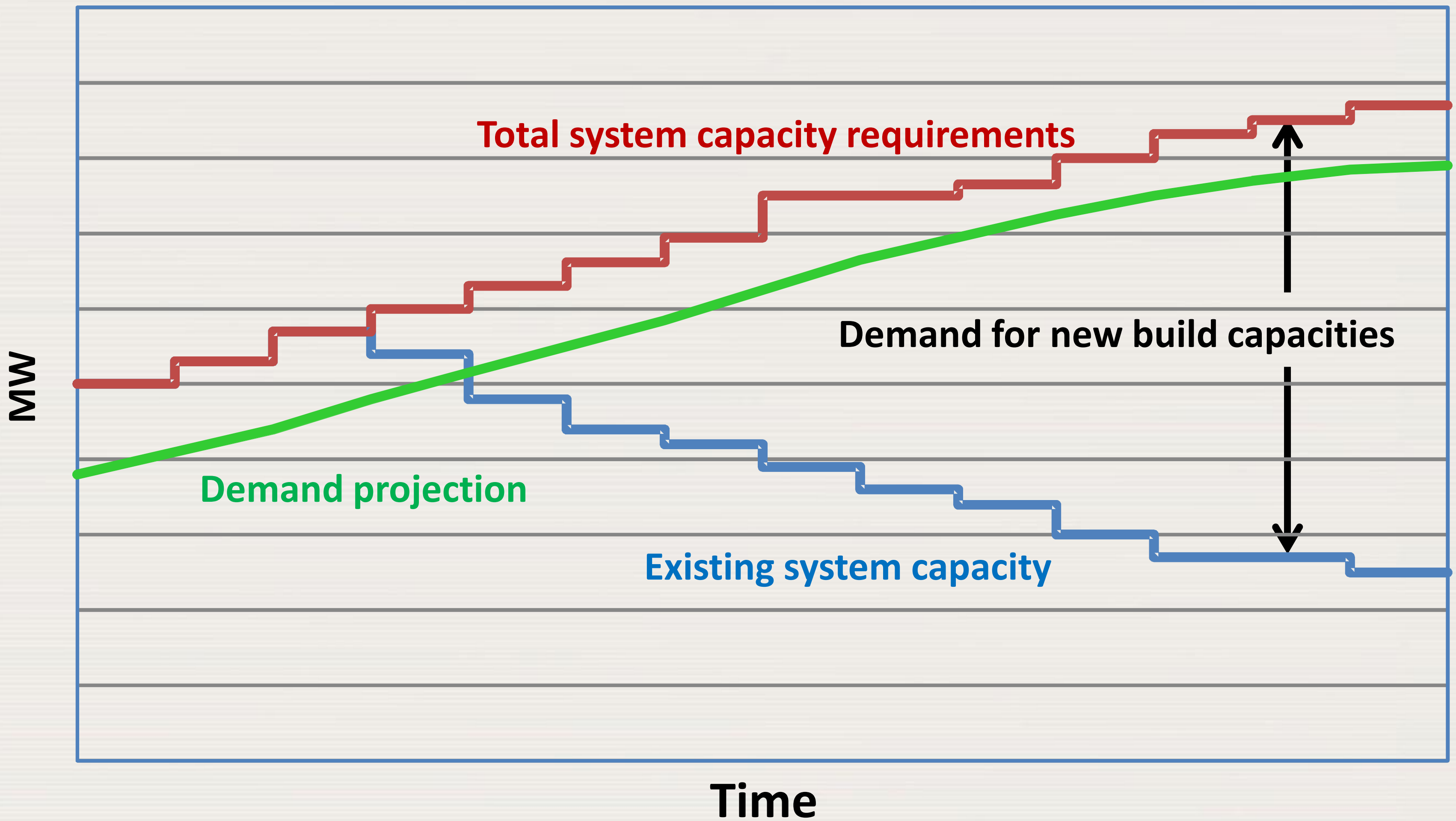
- **Function of the question at hand**
  - **Full energy system (energy services to trade & resource extraction) or subsystem?**
- **Data availability**
- **Technology representation: Detail and diversity?**
  - **Production & use of fuel in 15 min intervals or 10 year periods? Multiple fuels and products (CHP, refineries); individual technologies (large power plants) or groups of millions (e.g., light bulbs, air conditioners, vehicles, boilers), technology learning, etc.**
- **Level of interaction with other systems**
  - **Economy**
  - **Environment**
  - **Water, Land**
  - **Materials**
  - **Human resources**
  - **Etc.**

Electricity and energy planning



One salient objective of electricity system planning

Type and schedule of new capacity additions for an uncertain future



Relative attributes of electricity generating technologies

	Nuclear	Coal steam	Gas CCGT	Wind onshore & solar PV
Investment cost	Very high	Moderate	Low	Moderate-high
Construction time	4-10 years	4-5 years	2-3 years	0.5-2 years
Operational & maintenance cost	Low-moderate	Moderate-high	Low	Very low
Fuel costs	Very low	Low-moderate	Low-very high	Nil
Operational characteristics	Baseload, limited flexibility	Baseload, moderate flexibility	Mid-load, high flexibility	Intermittency, low load factor
$CO_{2\text{-}eq}$ emissions	Negligible	High-very high	Moderate- high	Negligible
Key risks	Completion, regulatory (policy changes), public acceptance, market	Regulatory (CO_2 and pollution), public acceptance, market	Regulatory (CO_2 and pollution), market	Regulatory (policy changes)

Source: Adapted from IEA WEO, 2014

Relative attributes of electricity generating technologies

How to compare these alternatives?

How to combine these criteria?

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How to interpret the results?

Source: Adapted from IEA WEO, 2014

Setting up an energy system model

Be clear about the issue you are going to address

- Model = mathematical representation of the system
  - Geographical scope
    - Boundaries
    - Local detail (GIS)
    - Trade
  - Temporal scope
    - Time horizon
    - Temporal resolution
    - Load representation
  - System detail
    - Full energy system or subpart thereof
    - Sectoral disaggregation
    - Technology specificity
    - Energy resources

Setting up an energy system model

1. Calibration of the model to a base year
   - Develop base year energy flows / energy balance / trade flows
   - Existing infrastructures and technologies
     - Capacities and performance characteristics
       - Fix operating and maintenance costs
       - Life times
       - Load factors
       - Variable O&M costs
       - Conversion efficiencies / losses
       - Fuel inputs and fuel prices
       - Emissions & wastes
       - Fuel or service outputs
       - Utilization in base year
     - Vintage of historical capacities
   - Other constraints & restrictions
   - Run the model – iterations with parameter adjustments until it repeats the base year reasonably well

Note:
A Model is a simplified image of reality
The real world never operates "optimally" in a mathematical sense

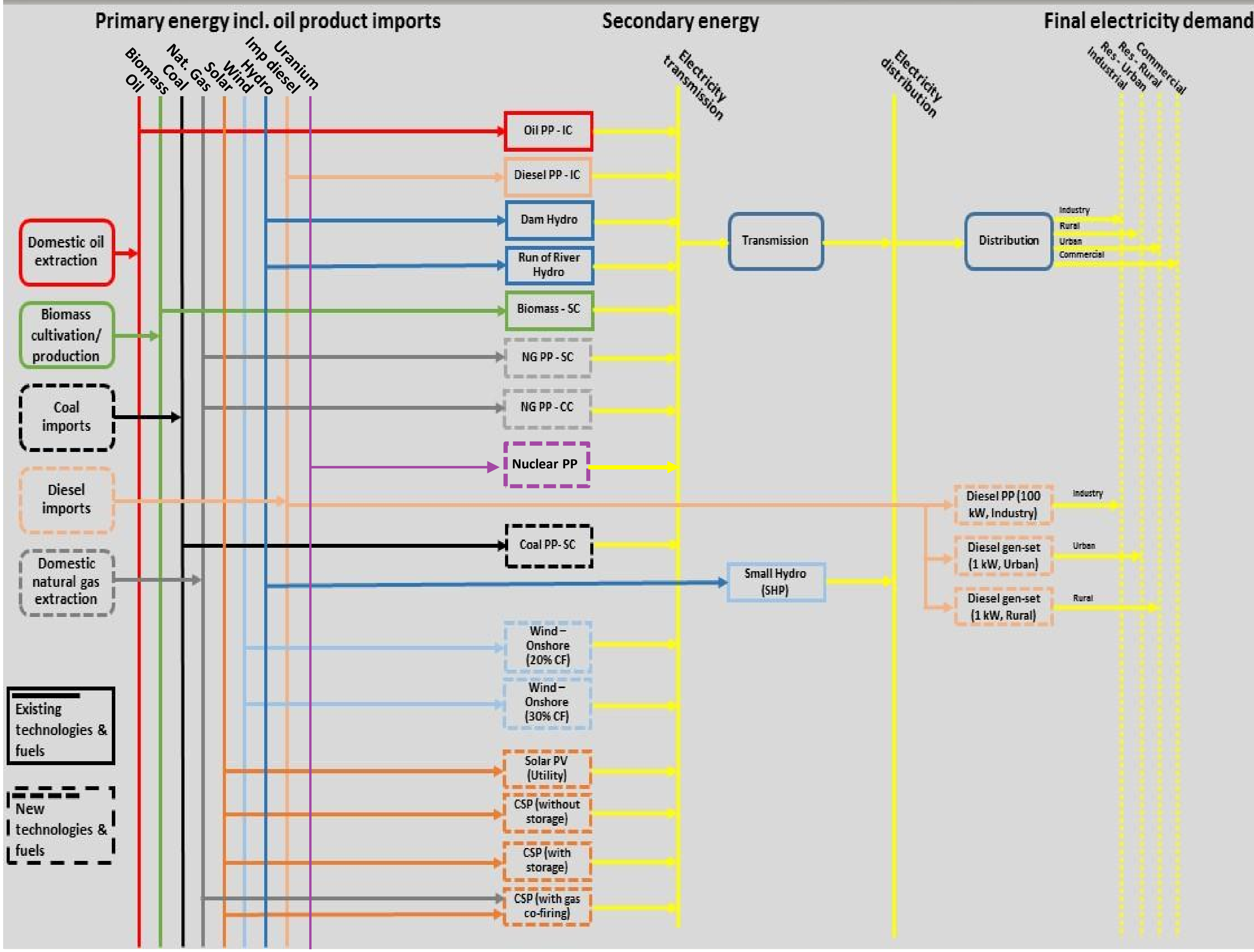
Setting up an energy system model

2. **New infrastructure, trade and technology portfolio options**
   (integral part of 'Scenario development' below)
   - Capacities and performance characteristics
     - Same as for existing technologies plus
     - Capital costs (static – dynamic – technology learning)
     - Future fuel and import price developments
     - Water, material and land requirements (direct and indirect)
     - Build up and market penetration constraints
     - Financial considerations
     - Policy considerations
   - Other constraints, restrictions & regulations

Setting up an energy system model

3. Scenario development – dealing with an unknown future (in an internally consistent manner)
   - See 2) above plus
   - Demand projection
   - Discount rate
   - Energy security
   - Access
   - Environmental policy
   - Compliance with international treaties - 2030 Agenda (SDGs) or Paris Agreement
4. Happy modelling & analysis
   - Stakeholder involvement
   - Iterative modification of assumptions
   - Result interpretation
   - Result presentation

A reference electricity system



A Reference Energy System **(RES)** *Schematic representation of the energy flow from resource extraction to demand*

All boxes are technologies

All lines are energy (fuels) or /electricity flows

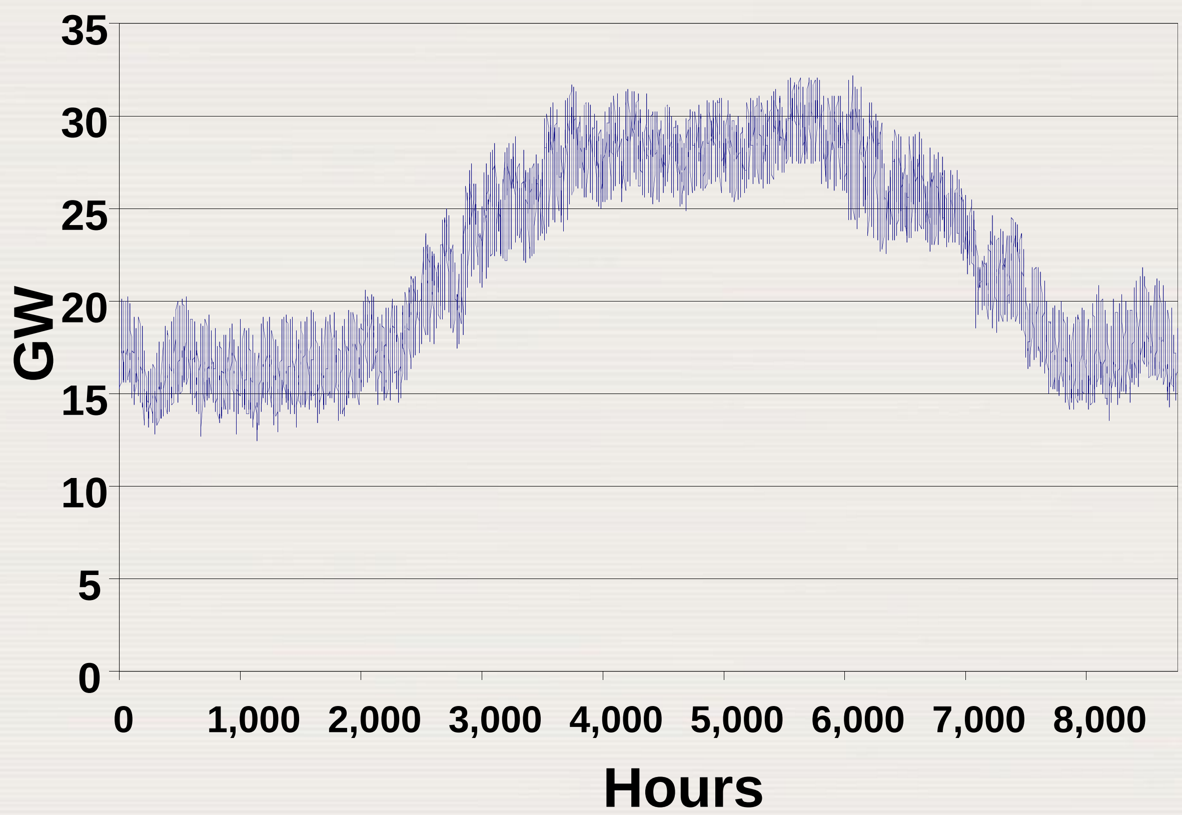
Most parameters relate to technologies (costs, efficiencies, load factors, emissions, etc.)

Non-technology parameters:

- Demand
- Emission
- Constraints
- Policy variables
- Reserve margin, etc.

Load curves

- **For each *load region* already specified:**
  - **Variation of demand for certain fuels within a year**
  - **e.g. Electricity, heat, natural gas**



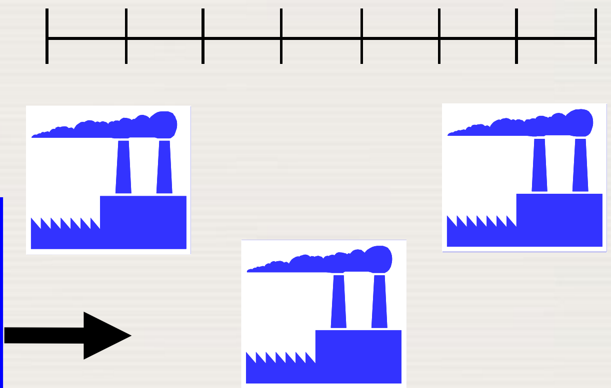
WASP

Wien Automatic System Planning Package

INPUT

- Load projection
- Existing system
- Candidates technologies
- Constraints:
  - Reliability
  - Implementation
  - Fuel supply
  - Generation
  - Emissions

OUTPUT



- Build schedule
- Generation mix
- Costs
- Fuel use
- Outages / unserved demand
- Emissions

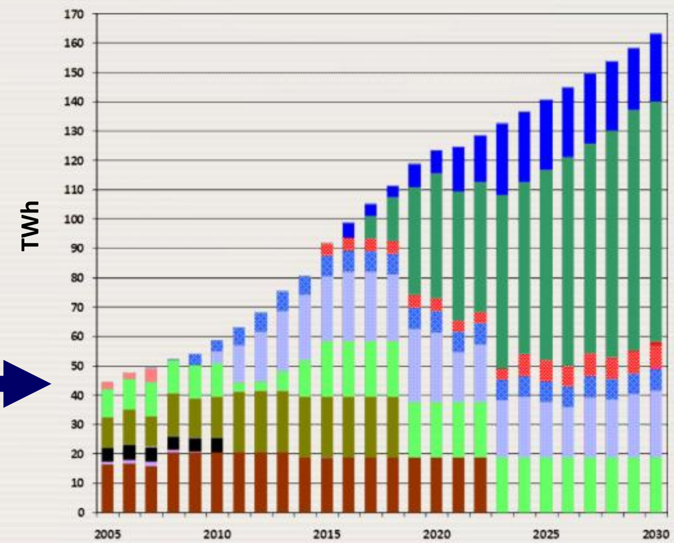
MESSAGE

Model for Energy Supply System Alternatives and their General Environmental Impacts

INPUT

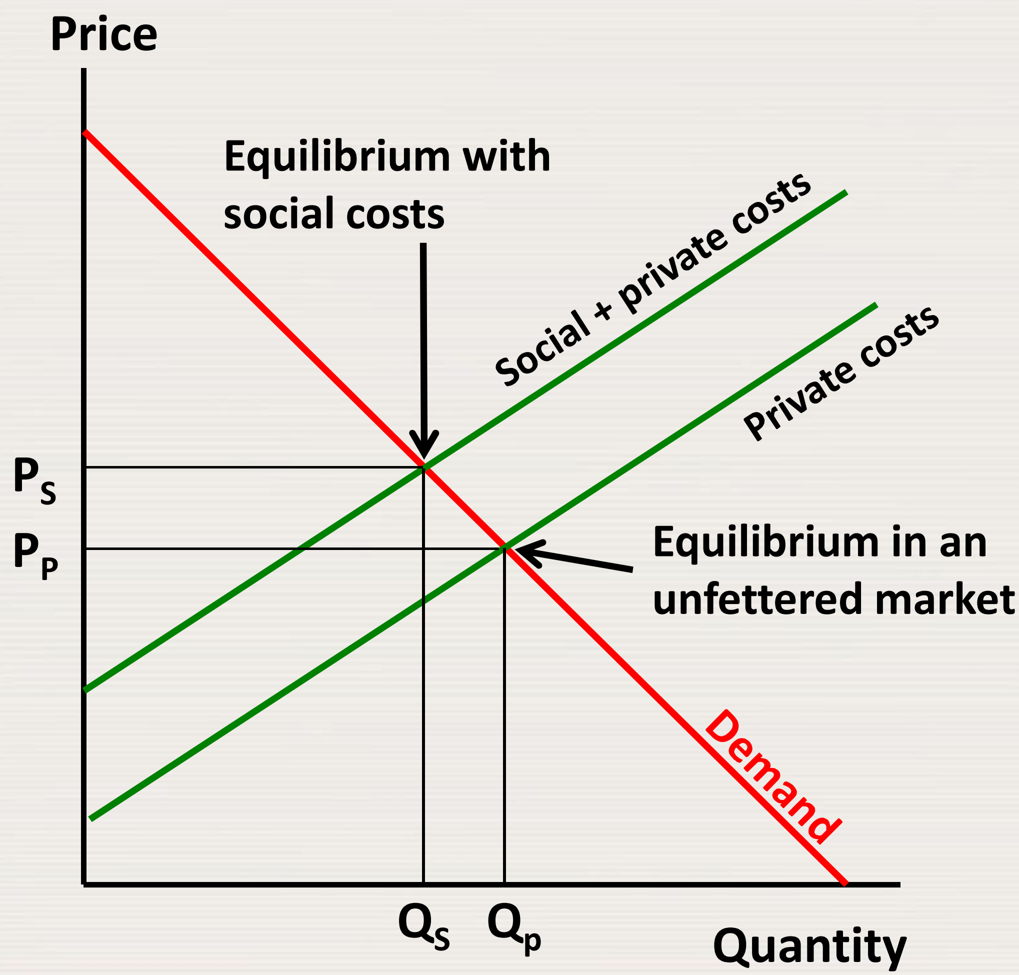
- Energy system structure (including vintage of plant and equipment)
- Base year energy flows and prices
- Energy demand projections (e.g. MAED)
- Technology and resource options & their techno-economic performance profiles
- International fuel market prices
- Technical and policy constraints
- Subsidies, taxes and feed-in tariffs
- ..and much more

OUTPUT



- Primary and final energy mix by fuel
- Electricity generating mix by technology and fuel
- Capacity expansion/retirement
- Emissions & waste streams
- Resource use (energy, water, land, etc.)
- Trade & import dependence
- Investment requirements
- Prices
- …. and much more

Modelling externalities



What is an externality?
A cost that is 'external' to the transaction...

Any examples?

OK, so we damage the environment... how much are you willing to pay to:

- **avoid the damage?**
- **fix the damage?**
- **live with the damage?**

Summary: Critical steps and features of energy modelling

- Determine geographical scope
- Determine temporal scope
- Define system boundaries
- Determine system detail
- Data collection, data generation and energy balances
- Model calibration & testing
- Introduce constraints gradually (interpretation)
- Select future scenario parameters, technology portfolio and infrastructure characteristics
- Transparency & communication
- Repeatability

Closing remarks

- Energy Planning is not about predicting the future
- It is about the analysis and evaluation of a set of different possible futures
- Communication tool (informed policy & decision making)
- No analysis is perfect
- Many more “what if” questions need to be explored
- New information
- Previously plausible assumption no longer stand the test of time
- Energy planning never ends…..

Against the backdrop of contemporary challenges - SDGs and PA

- **Fundamental energy system transformation is the only viable option**
- **Time and resource intensive process**
- **Longevity of energy infrastructure - No quick fixes**
- **No time to lose**
- **One size does not fit all – countries and regions are different**
- **Judge measures as to their climate effectiveness and consistency with sustainable development**
- **There is no 'silver bullet'**
- **Local conditions but also cultural factors determine the optimal supply and technology mix**

> If we all did the things we are capable of doing, we would literally astound ourselves" Thomas A. Edison (1847-1931)

A long and bumpy road ahead .....