Mathematical modeling of long-term energy sources mix dynamics

Dott. Ing. Franco Almerico

General Manager - INTELLIGENT SYSTEMS S.r.l.
20035 LISSONE (MI) – ITALY
f.almerico@gmail.com

INTERNATIONAL FORUM ATOMEXPO 2010
Moscow, 7-9 June, 2010

atomexpo

Summary

- Why is very long term energy view needed?
- Modeling of energy supply chain
- Mathematical representation
- Case study
- Energy resources - reserves
- Present global energy trends
- Results
- Hypothesized global energy trends
- Role of nuclear energy
- Towards a sustainable energy era

Why is very long term energy view needed?

- To achieve a better consciousness of the criticality of a correct management of the energy problem for ensuring human species’ life development and survival
- It can help in evaluating the correct size and dynamics of energy crises, in spite of uncertainties
- To anticipate large and irreversible energy crises that could threaten survival of future generations

Why is very long term energy view needed?

- To forecast what will happen in the long term, in order to support decisions to make now: what seems good now, could be bad in the long term
- Return of infrastructures' investments requires a long term view of energy supply chain dynamics
- Long term view allows to better absorb short term economy and energy prices fluctuations
- Moral duty to leave a sustainable world to future generations

Modeling of energy supply chain

- The energy supply chain can be schematized in a series of three major systems: production, logistics and final uses.

Simplyfication of energy supply chain model

- For the purpose of the present work the energy supply chain can be simplyfied, including the production system in the logistic system, thus leaving in input only the primary energy sources:

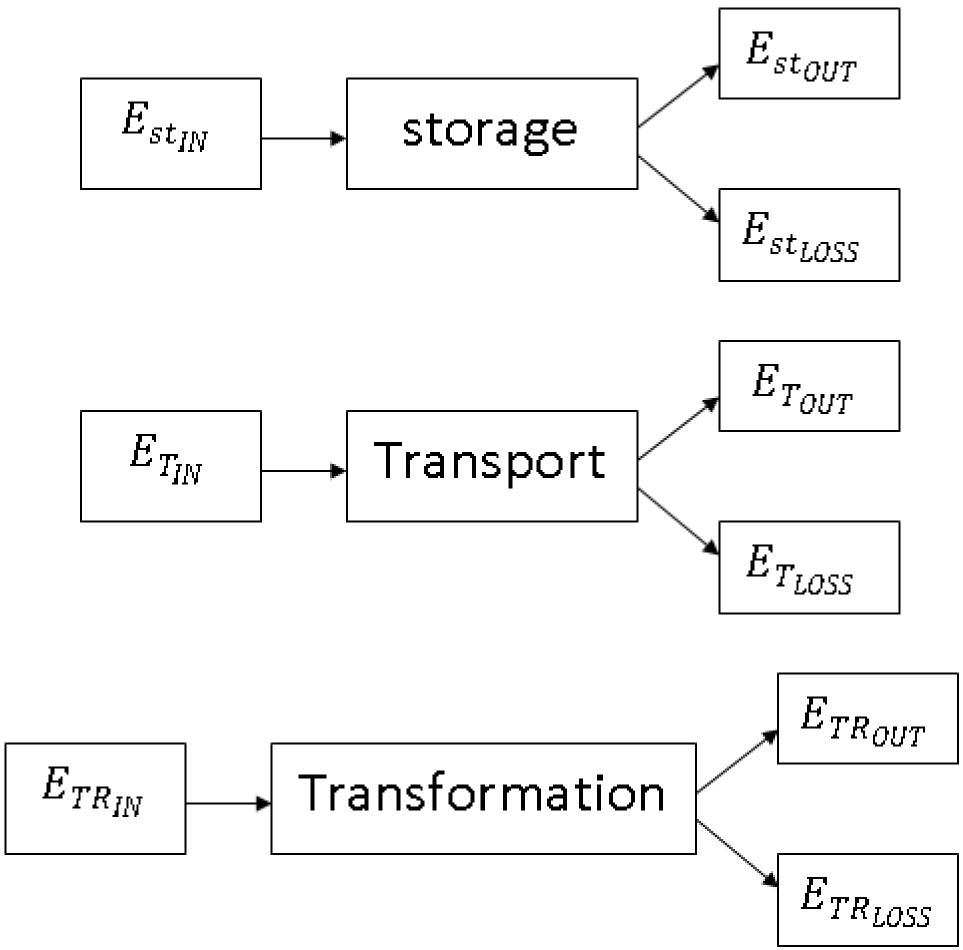
Scopes of the model

- Time dependent simulation and resources time duration estimation
- Individuation of logistic system critical behaviour: capacity overload; underload and utilization factor; need for expansion, reconfiguration, dismission
- Analysis of time dependent logistics versus production mix or final energy uses variations
- Input to economical analysis of risk or profitability of existing or needed investments

Limits of the model

- No material flows: all flows are converted into energy flows
- Short-time logistic delays not considered because of the long term view
- Logistic system energy losses (consumption) can be incorporated into the final energy uses or in an overall logistic efficiency

Building blocks



Mathematical representation

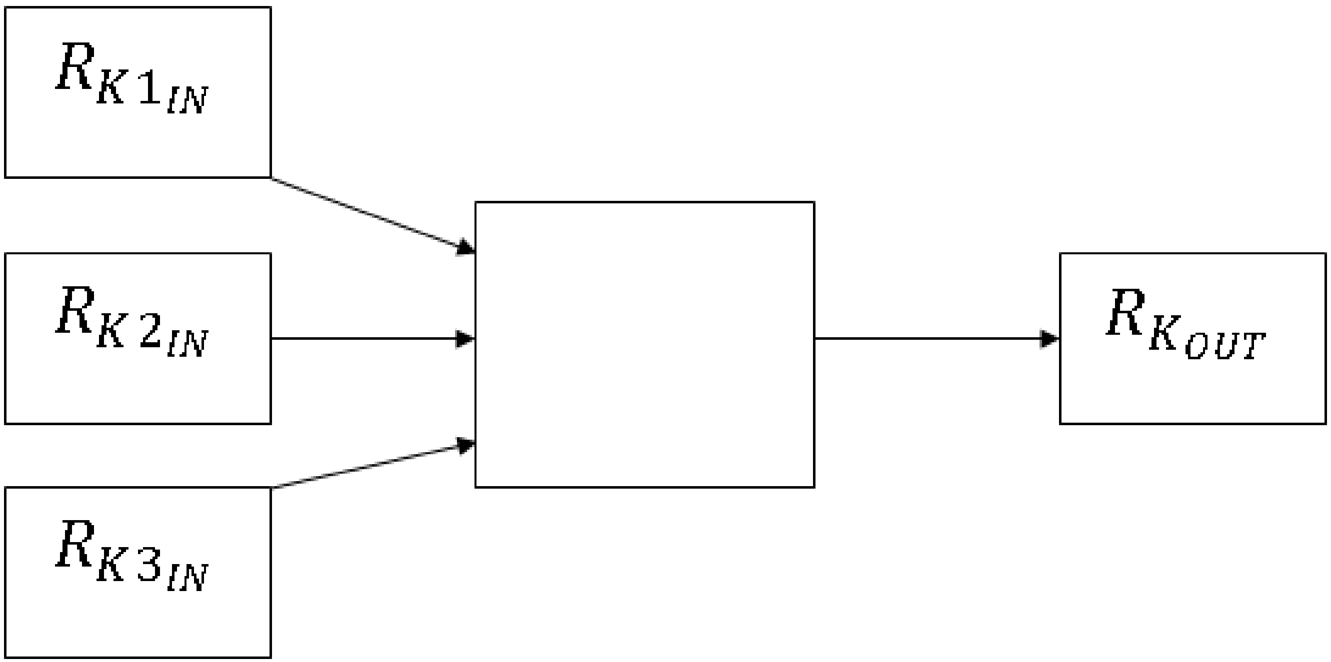
- Balance equations
- Reduction equations
- Matrix representation
- Matrix equations
- Constraints
- Primary resources equations

Balance Equations

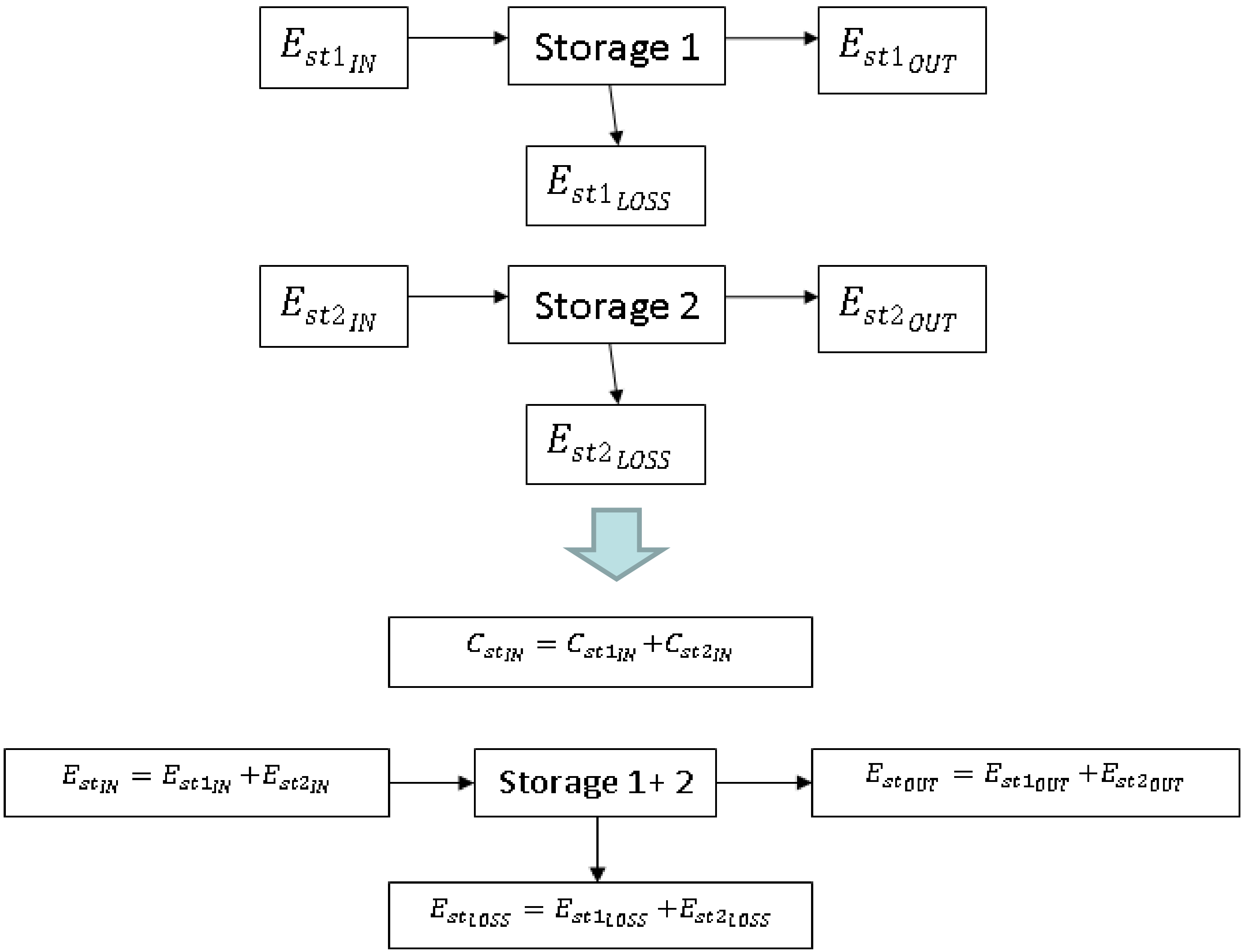
- Balance equations of these types can be written for the aggregation of primary energy resources or final energy uses production rates, at different levels. For example at the region level of aggregation:

$$R_{pi} = \sum_{k=1}^{N_R} R_{pik} \qquad R_{cj} = \sum_{k=1}^{N_R} R_{cjk}$$

Balance Equations



Reduction equations



Logistic matrix

- Element represents: energy repartition coefficient, energy flow rate, logistics efficiency, maximum capacity, time dependence
- Matrix can be divided into submatrices according to: primary energy source, final use, country, region, subregion, plant

Matrix Representation

$$\mathbb{R}_p(t) = \begin{bmatrix} R_{p1}(t) \\ \vdots \\ R_{pi}(t) \\ \vdots \\ R_{pN_s}(t) \end{bmatrix} \qquad \mathbb{R}_c(t) = \begin{bmatrix} R_{c1}(t) \\ \vdots \\ R_{cl}(t) \\ \vdots \\ R_{cN_{FE}}(t) \end{bmatrix}$$

$$\mathbb{M} = \begin{bmatrix} m_{11} & \cdots & m_{1N_{FE}} \\ \vdots & \ddots & \vdots \\ m_{N_s1} & \cdots & m_{N_sN_{FE}} \end{bmatrix}$$

Matrix Equations

$$R_p(t) = \mathbb{M} \cdot R_c(t)$$

$$R_{pi}(t) = \sum_{l=1}^{N_{FE}} m_{il} \cdot R_{cl}(t)$$

Constraints

- Capacity constraints are taken into account for each block or aggregate of the logistic system:

$$m_{il} \cdot R_{cl}(t') \leq C_{il}(t)$$

$$m_{il} = PARTITION\ COEFFICIENT$$

Primary resources equations

- Resource i discovery rate

$$R_{d_i}(t)$$

- Discovered amount of resource i

$$S_i(t) = \int_0^t R_{d_i}(t)dt$$

Primary resources equations

- Resource i production rate

$$R_{p_i}(t)$$

- Remaining amount of resource i

$$S_i(t) = \int_0^t R_{d_i}(t)dt - \int_0^t R_{p_i}(t)dt$$

Primary resources equations

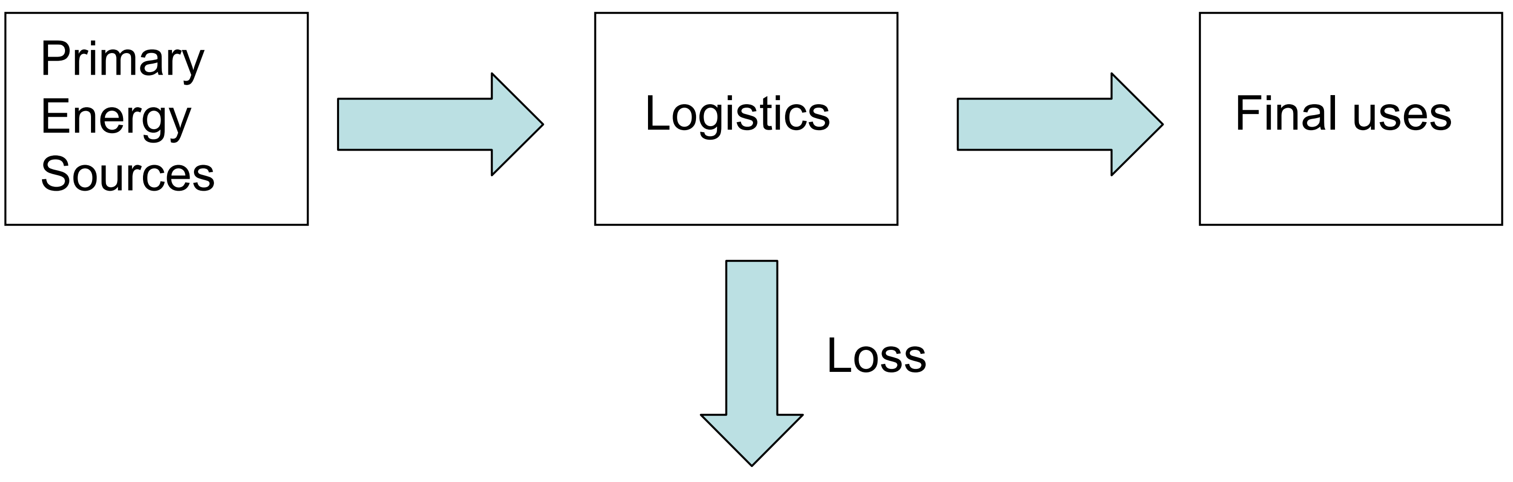
- Ultimate available amount of resource i

$$S_{i\infty}(t) = \int_0^\infty R_{d_i}(t)dt$$

Energy balance of supply chain

- The energy supply chain satisfies the following macro energy balance equation:

  Primary energy production = Logistics energy loss + Final energy uses



Case study

- Aggregation at world level
- Final energy trend imposed
- Primary energy rate (net/gross) as output
- Logistics system evolution, assuming no time change of the logistic system structure, but only proportional capacity increase
- Time evolution of specific elements of the logistic system

Oil & Gas Reserves and Resources

World Ultimately Recoverable Conventional Oil and NGL Resources, end 2007 (WEO 2008) (billion barrels)					
Remaining Reserves	Remaining Recoverable Resources	Current average daily production (mb/d)	Current year production (mb/y)	Remaining Reserves Time Duration (y)	Remaining Recoverable Resources Time Duration (y)
1241	2449	84.3	30769.5	40.33	79.59
World Ultimately Recoverable Conventional Natural Gas Resources, end 2007 (WEO 2008) (tcm)					
Remaining Reserves	Remaining Recoverable Resources	Current average daily production (bcm/d)	Current year production (bcm/y)	Remaining Reserves Time Duration (y)	Remaining Recoverable Resources Time Duration (y)
178.8	380	7.9	2916	61.32	130.32

Coal Reserves

World Ultimately Recoverable Conventional Coal Resources, end 2007 (BTCE)					
Ultimately Recoverable Resources	Remaining Reserves	Remaining Recoverable Resources	Current production (MTCE/y)	Remaining Reserves Time Duration (y)	Remaining Recoverable Resources Time Duration (y)
	736		4396	167.62	

Uranium Identified Resources

Changes in Identified Resources 2005-2007 (1000 t U)			
Resource category	2005	2007	Changes
Identified (Total)			
<USD 130/kgU	**4743**	5469	**726**
<USD 80/kgU	**3804**	**➢4456**	**652**
<USD 40/kgU	**> 2746**	**2970**	**224**
RAR			
<USD 130/kgU	**3297**	3338	**41**
<USD 80/kgU	**2643**	**2598**	**-45**
<USD 40/kgU	**> 1947**	**➢1766**	**-181**
Inferred Resources			
<USD 130/kgU	**1446**	2130	**684**
<USD 80/kgU	**1161**	**➢1858**	**697**
<USD 40/kgU	**> 799**	**1204**	**40**

Uranium Undiscovered Resources

Undiscovered Resources (1000 tU)			
Resource category	2005	2007	Changes
Total	10015	10539	**485**
Prognosticated Resources			
<USD 130/kgU		2769	
<USD 80/kgU		**1946**	
Speculative Resources			
Cost range unassigned		**2973**	
<USD 130/kgU		**4797**	
Total		7770	
Conventional Resources (Identified + Undiscovered) Total (1000 t U)		16008	

Uranium Unconventional Resources

Unconventional Resources (1000 t U)	
Resource category	2007
Uranium Phosphates Rocks	**22000**
Seawater	**4200000**

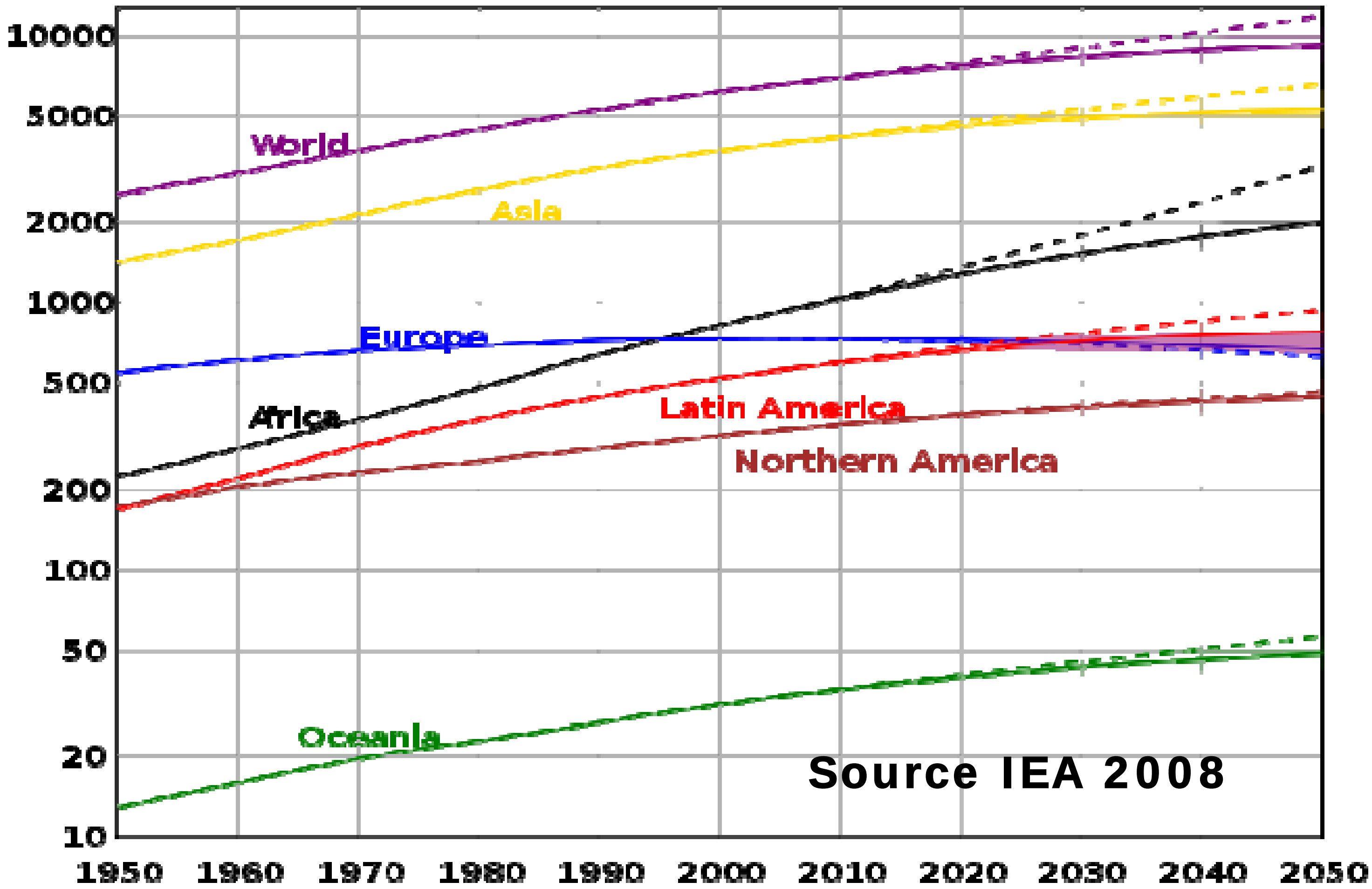
Uranium Production

Uranium Production (t U)						
Year	Total Pre-2004	2004	2005	2006	Total to 2006	2007
	2112349	40188	41943	39603	2234083	43328

Present Global Energy Trends

- Population
- Demand
- Production
- Growth rates
- Energy Era Indicators
- Remaining Resources Duration
- Climate

Population Growth Distribution

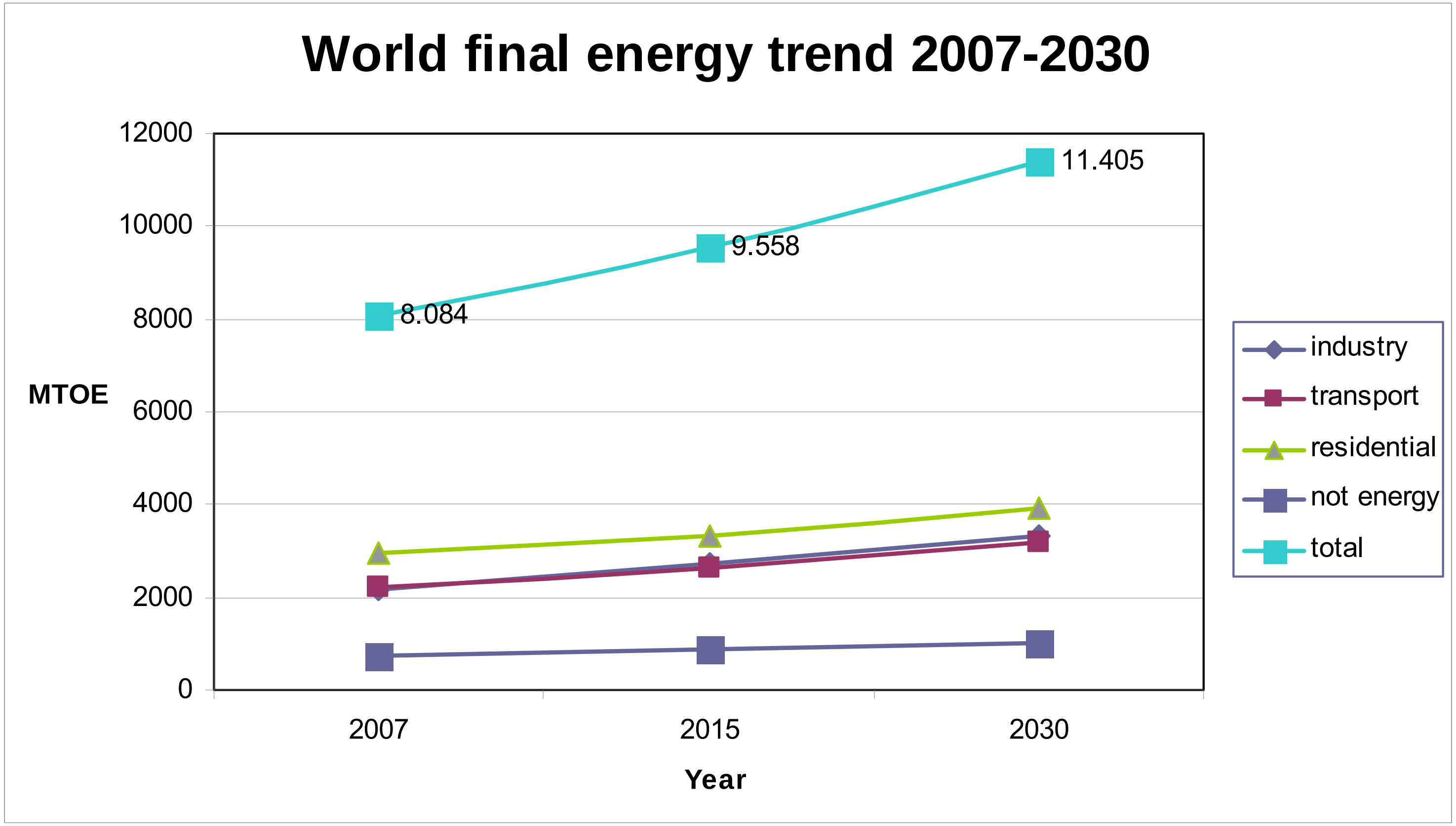


Results of case study

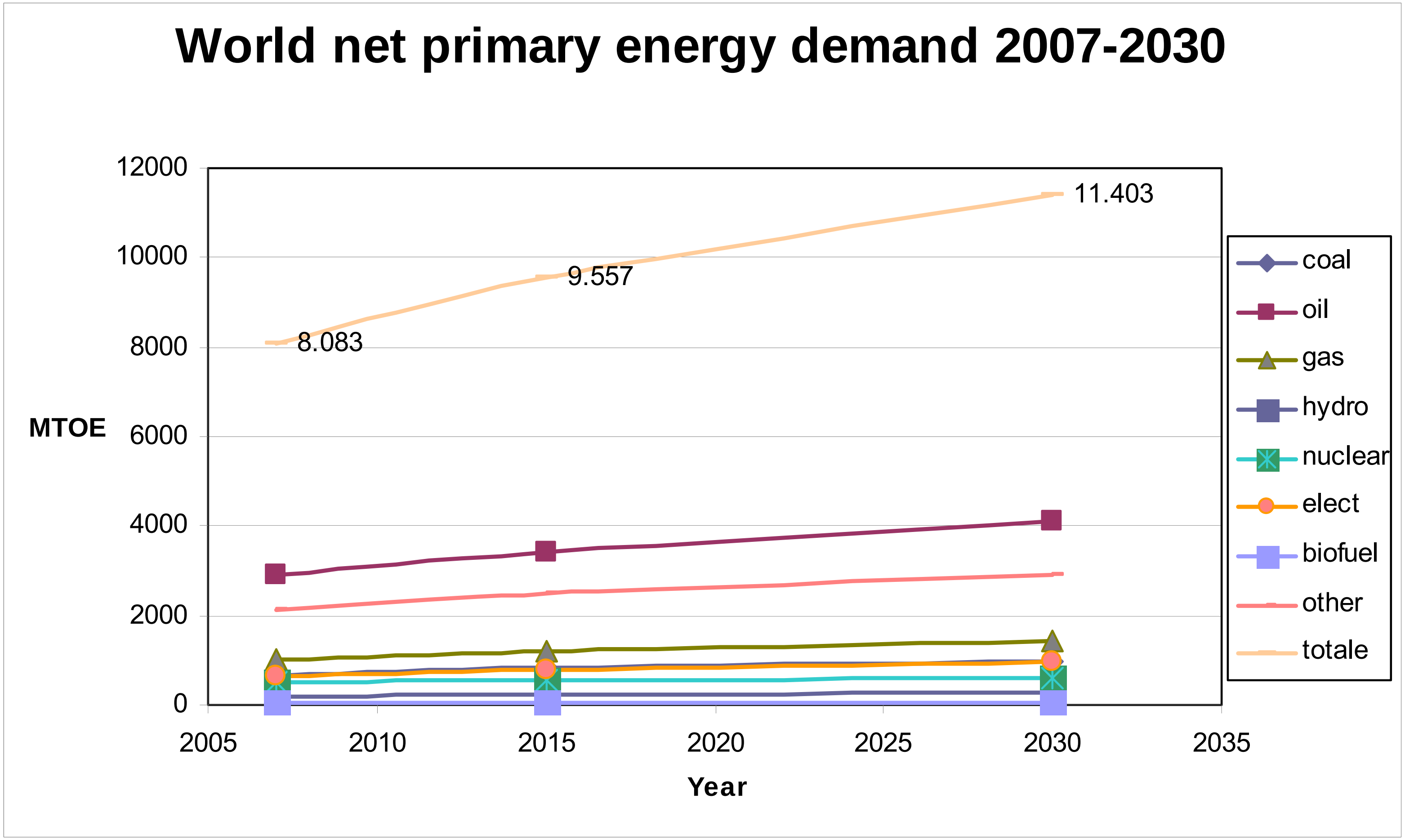
Starting from input final energy uses trend, the following results are obtained:

- output net primary energy
- output gross primary energy
- capacity changes required on specific elements of the logistic system
- energy era indicators

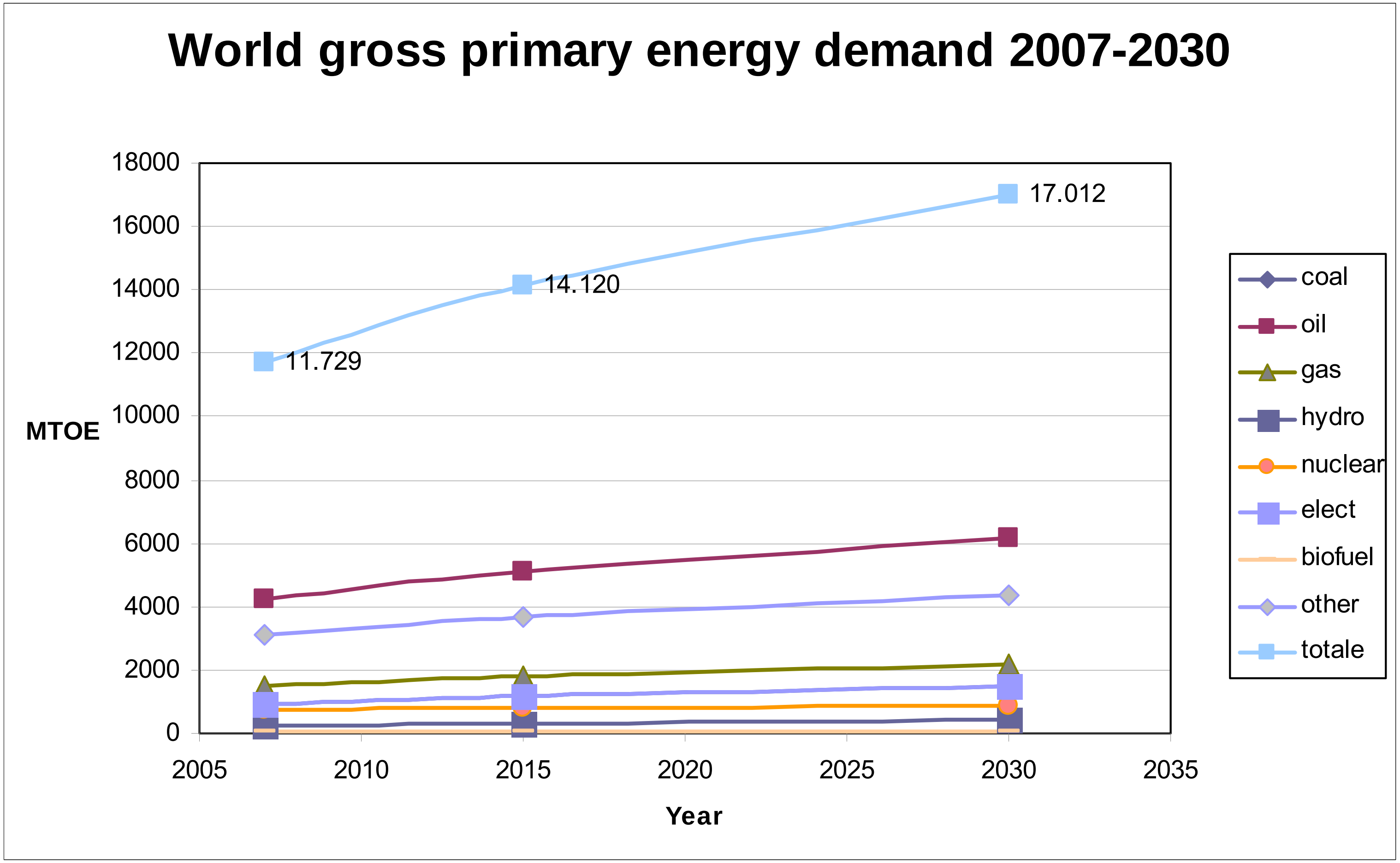
Input final energy uses trend



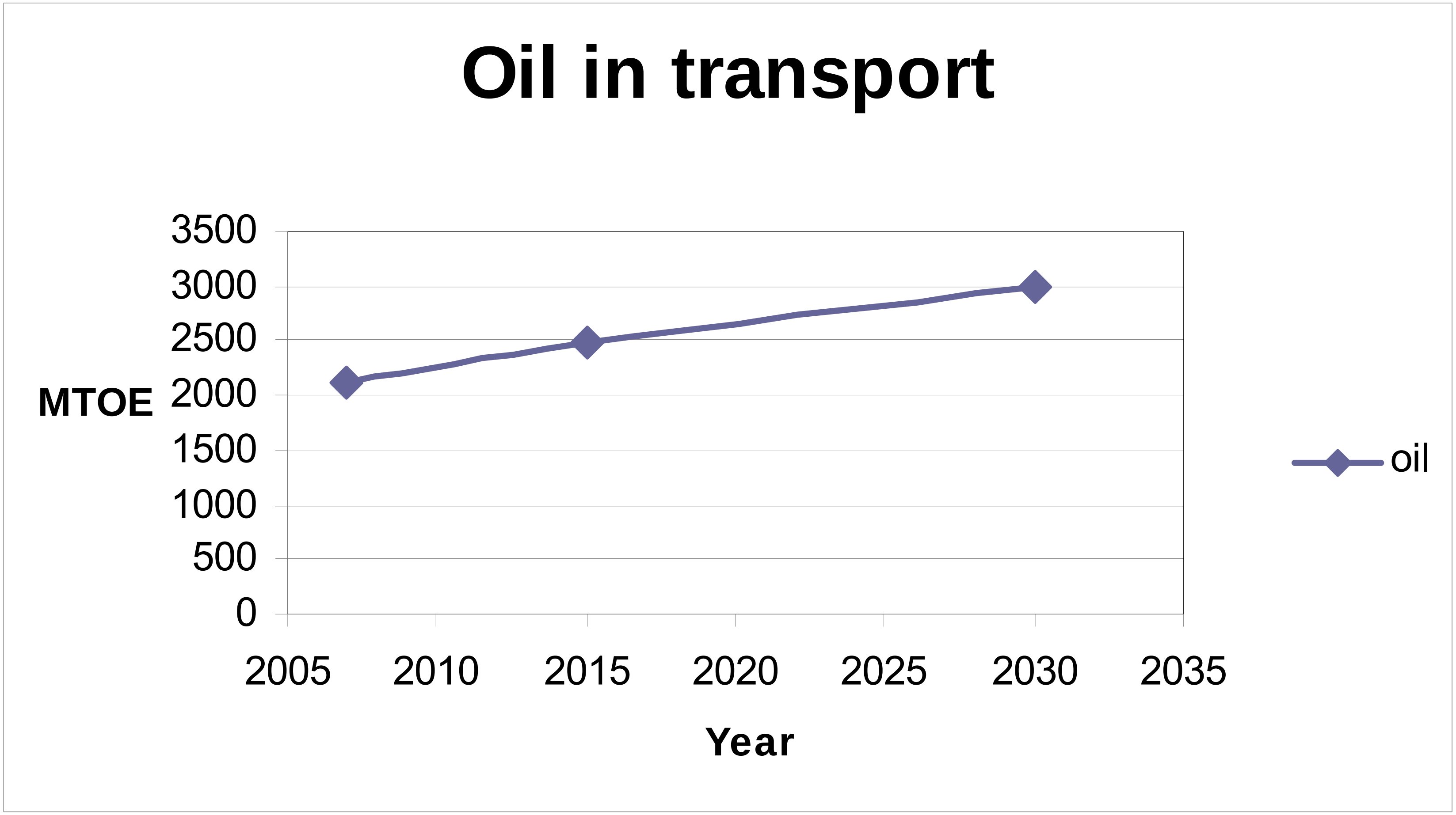
Output net primary energy



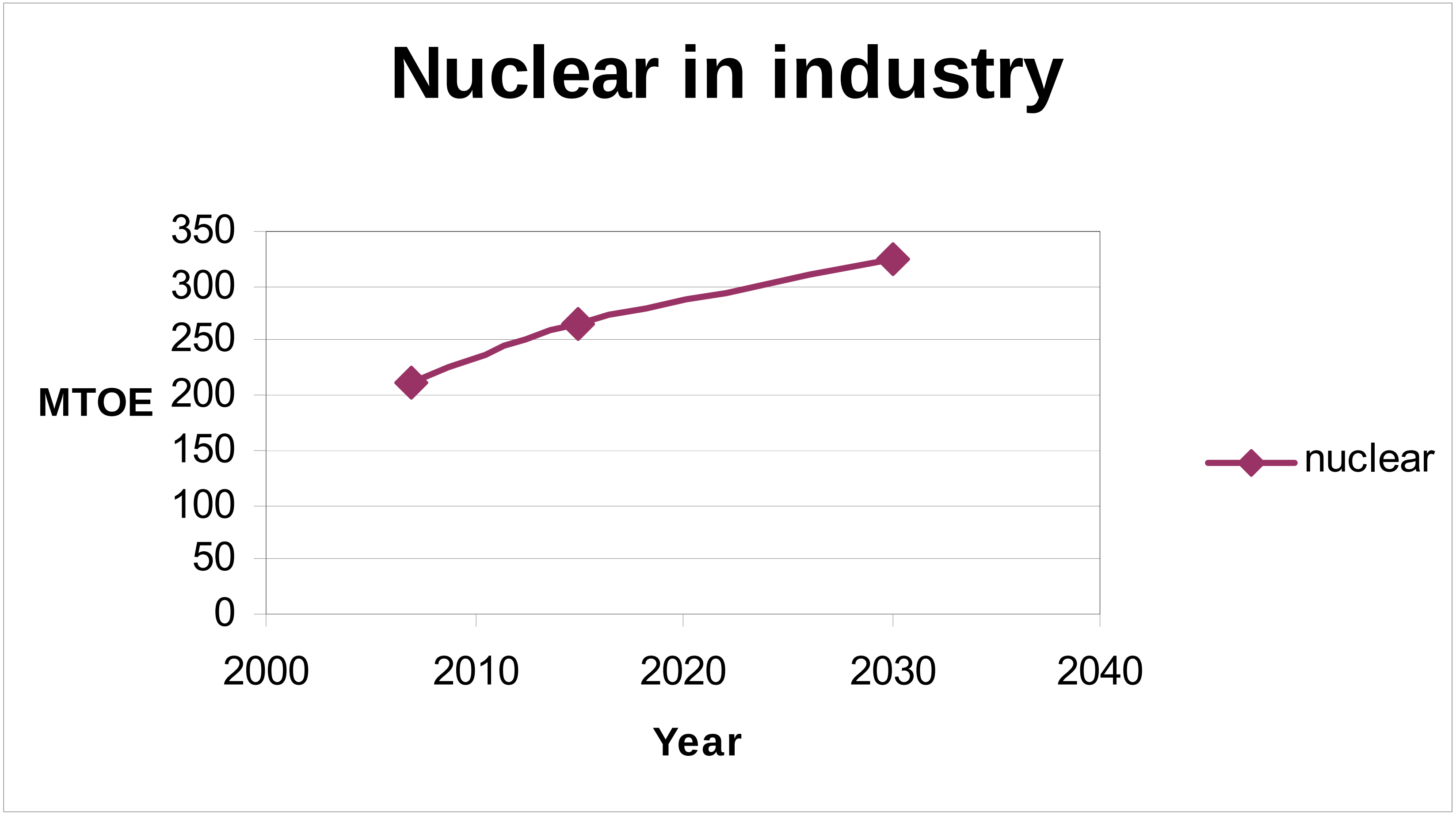
Output gross primary energy



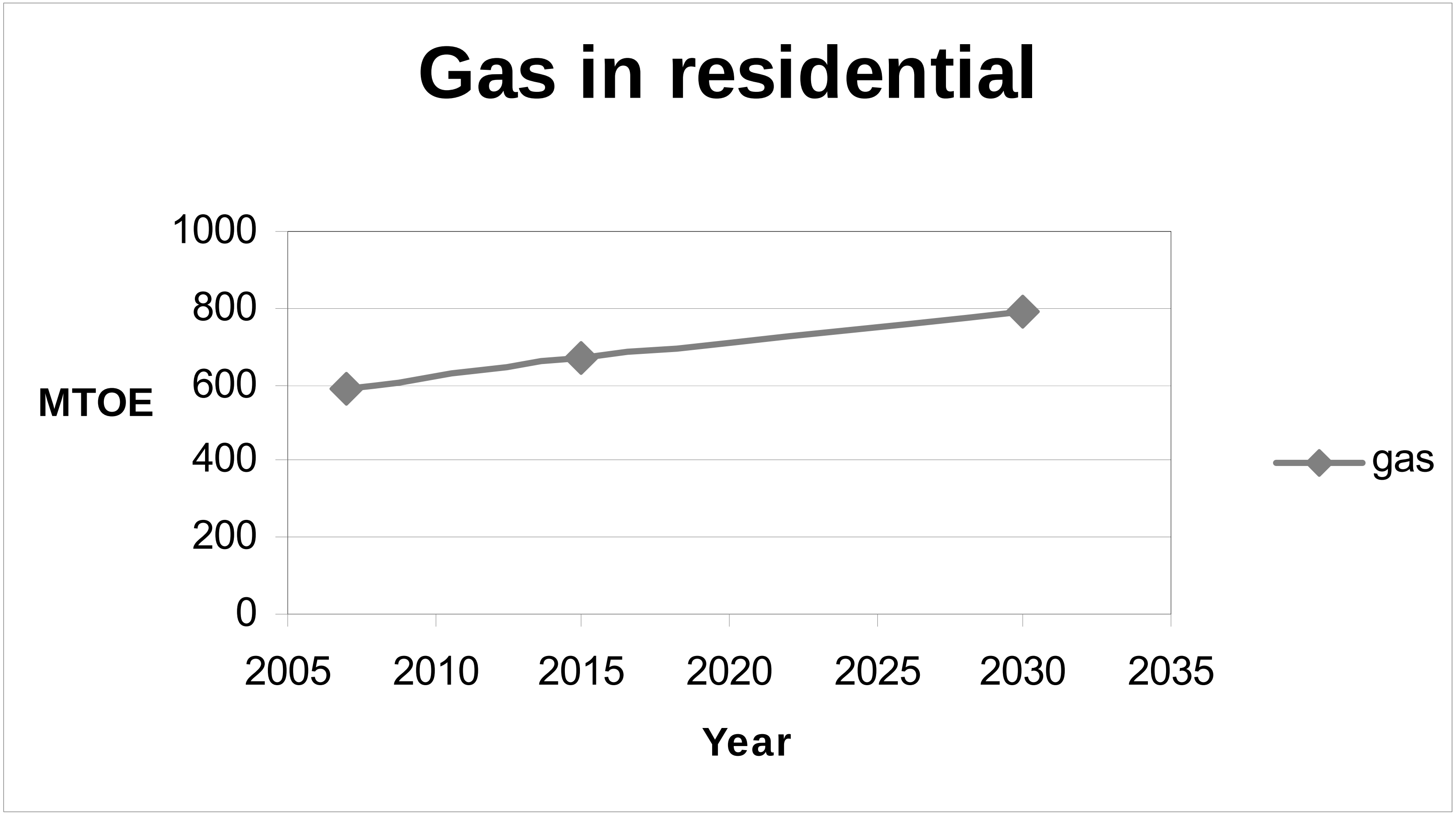
Specific logistic capacity change



Specific logistic capacity change



Specific logistic capacity change



Energy Era Indicators

- Population
- Population growth rate
- GDP per capita and GDP growth rate
- Primary Energy per capita
- Resources Consumption rate/Formation rate
- Spent/Remaining resources
- Time to resources final exhaust
- Resource substitution potential

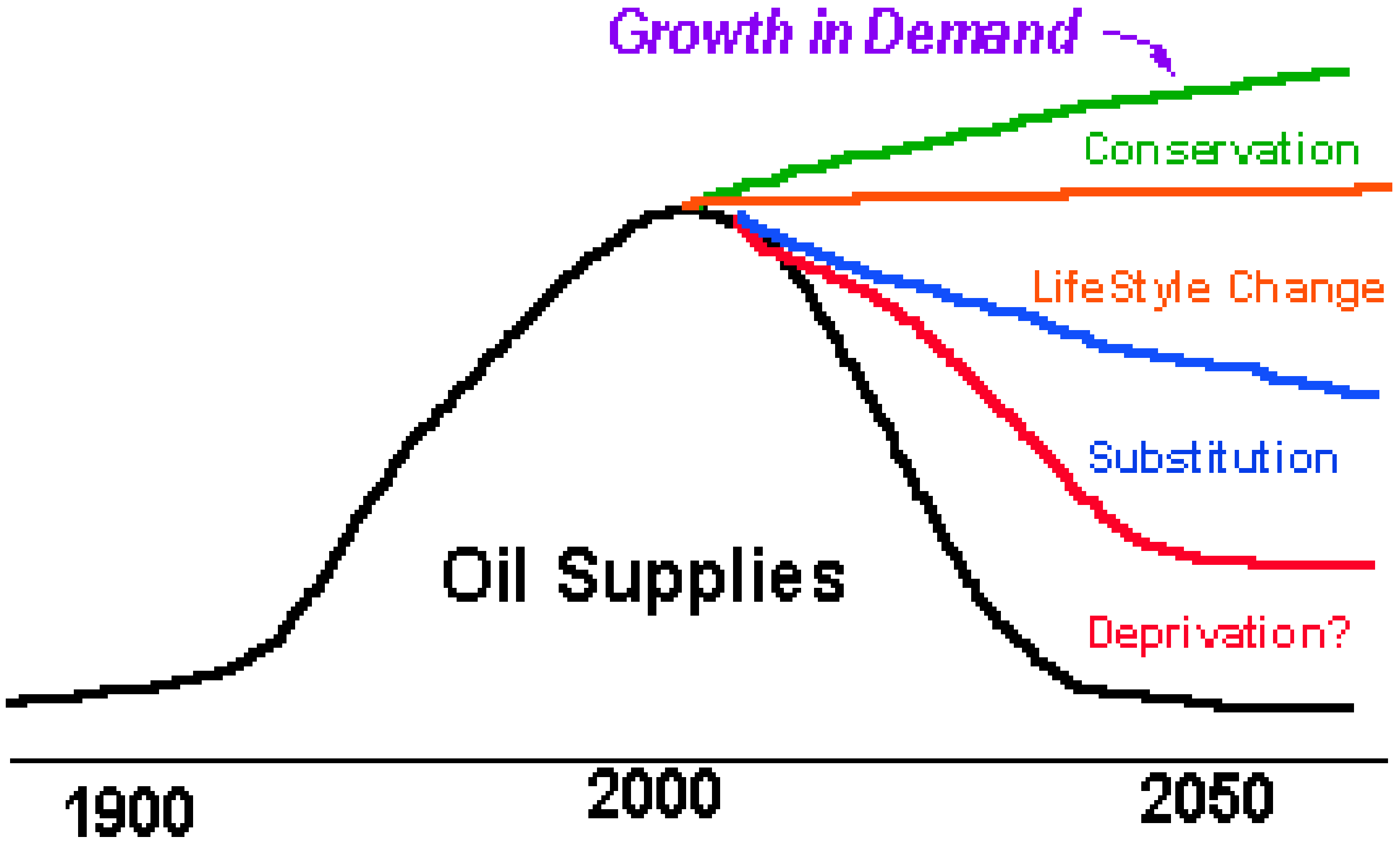
End of the Easy Energy Era Scenario A

Year	2008	2030	2050	2070
Population growth rate (%)	1,3000	1,0000	0,0000	0,0000
Population (billion)	6,7000	8,9019	10,8620	10,8620
GDP Growth Rate (%)	1,1000	1,1000	1,0000	1,0000
GDP per capita ($ 2007)	6716	6430	6559	8003
Primary Energy Demand Growth Rate (%)	1,6415	1,6000	1,6000	
Primary Energy Demand (MTOE)	11700	17014	23745	33140
Primary energy per capita (TOE)	1,74	1,91	2,18	3,05
Primary Energy Sources Formation Rate Growth (%)	-1,0000	-1,0000	-2,0000	
Remaining Resources (GTOE)	908,40	787,15	506,03	37,85
Time to final exhaust (y)	77,64	46,26	21,31	1,14
Resources substitution potential	1,0000	0,5959	0,2745	0,0147

End of the Easy Energy Era Scenario B

Year	2008	2030	2050	2070
Population growth rate (%)	1,3000	0,5000	0,0000	1,0000
Population (billion)	6,7000	8,9019	9,8357	9,8357
GDP Growth Rate (%)	1,1000	1,1000	1,0000	1,0000
GDP per capita ($ 2007)	6716,4179	6430,6569	7243,6459	8838,6246
Primary Energy Demand Growth Rate (%)	1,6415	1,0000	0,1000	
Primary Energy Demand (MTOE)	11700	17014	20968	21413
Primary energy per capita (TOE)	1,74	1,91	2,13	2,17
Primary Energy Sources Formation Rate Growth (%)	-2,0000	-4,0000	-4,0000	
Remaining Resources (GTOE)	908,40	808,31	539,76	115,37
Time to final exhaust (y)	77,64	47,50	25,74	5,38
Resources substitution potential	1,0000	0,6119	0,3315	0,0694

Swenson Curve



Hypothesized Future Global Energy Trends

- Population growth continues at decreasing rate
- Incresasing GDP and primary energy per capita
- Increasing energy consumption by non-OECD countries
- Rapid consumption of fossil energy resources and final exhaust
- Substitution of fossil fuels in a relatively short term
- Increasing importance of mix of renewables and nuclear energy

Role of nuclear energy

- Mitigating the fossil fuels depletion consequences
- Improving environmental conditions (contributing to climate change control)
- Coping with a variety of applications (heat, process, electricity, fuels and hydrogen production, water desalination)
- Giving a very long term response to the planet’s energy needs ?

World Uranium Demand

World Uranium Demand (t U)					
Year	2004	2005	2006	2007	2008
Number of reactors					
Operating				435	439
In construction				27	41
Shutdown				10	
Connected to the grid				7	
Net Electric Power (Gwe)				370,23	372,2
Global Electric Energy (TWh)	2524	2638	2630	2675	
Annual Uranium requirements (t U)			66500	69110	

World Uranium Supply

Primary Sources of Uranium Supply in 2006 (t U)	39603
Secondary Sources of Uranium Supply (t U) **Stock and inventories on natural and enriched Uranium** **Reprocessing of spent fuel and surplus of military Pu** **Re-enrichment of depleted Uranium tails**	26897
Total (t U)	66500

Uranium Resources Duration at present consumption rates

Resource category	2007	Resources duration (y) with Global Reactor Consumption in 2006 (t U)		2030	2030
		total	primary	low case	high case
Global Reactor Consumption (t U)		66500	39603	93775	121995
		Resources Duration (y)			
Identified (Total) <USD 130/kgU	5469	82	138	58	44
Undiscovered Resources (1000 tU)					
Total	10539	158	266	112	86
Conventional Resources (Identified + Undiscovered) Total (1000 t U)	16008	240	404	170	131
Unconventional Resources (1000 tU)					
Uranium Phosphates Rocks	22000	330	555	234	180
Seawater	4200000	63157	106052	44788	34427

Uranium Resources Duration with Fossil Fuels Substitution

Year	2008	2030	2050	2070
Population growth rate (%)	1,3000	0,5000	0,0000	1,0000
Population (billion)	6,7000	8,9019	9,8357	9,8357
Primary Energy Demand Growth Rate (%)	1,64	1,00	0,10	0,00
Primary Energy Demand (MTOE)	11700	17014	20968	21413
Primary Energy Demand (1000 GWh)	52466	76298	94029	96024
Number of operating reactors (LWR 1GW)	6558	9537	11754	12003
Nuclear Fuel (U) consumption rate (tU)	1003419	1459207	1798315	1836459
Remaining Uranium considering Conventional Resources (1000 tU)	16008	-11985	-18072	-22155
Time to final Uranium Exhaust (y)	15,95	-8,21	-10,04	-12,06
Remaining Uranium considering Conventional+ Phosphates Resources (1000 tU)	38008	10014	3927	-1557
Time to final Uranium Exhaust (y)	37,87	6,86	2,18	-0,08
Remaining Uranium considering unconventional resources (1000 tU)	4238008	4210014	4203927	4199844
Time to final Uranium Exhaust (y)	4223	2885	2337	2286

Towards a Sustainable Energy Era

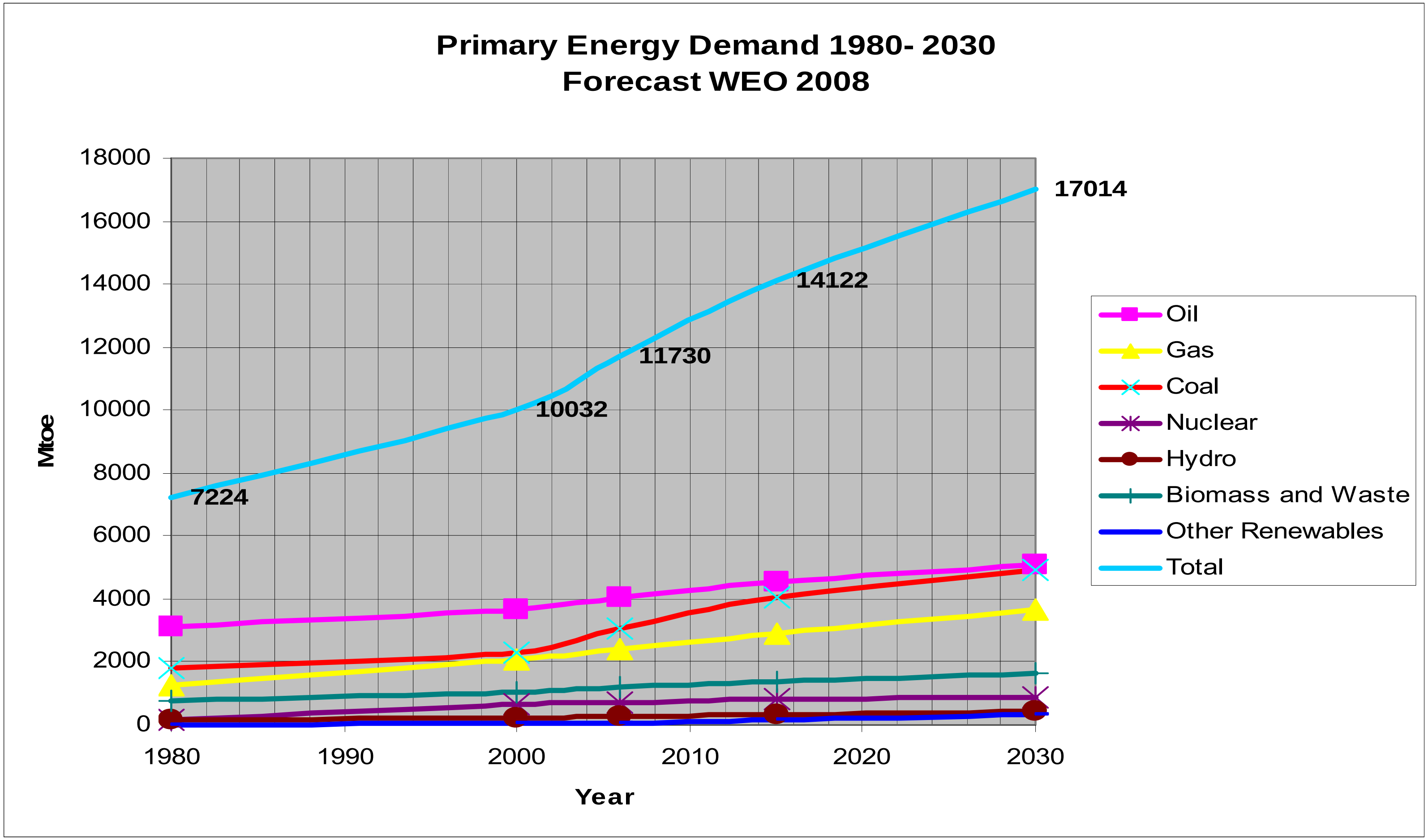
- In order to cope with the depletion and final exhaust of fossil primary energy sources, a variety of choices should be expolited: energy efficiency improvement, use of nuclear energy and CFC Fast Breeder Reactors, combined with all renewables seems to be the most promising mix.
- Based upon the simulations presented there is evidence of huge energy needs that could not be satisfied with any of the energy sources we are using or we know at present, unless a drastic reduction of final energy consumption is achieved in all sectors.
- A Global Nuclear Fuel Cycle infrastructure should be developed to match the needs of the energy production system within a planetary energy governance agreement in order to cope with the very difficult decisions to tackle.

The end

Thank You very much for your patient attention and for your questions !

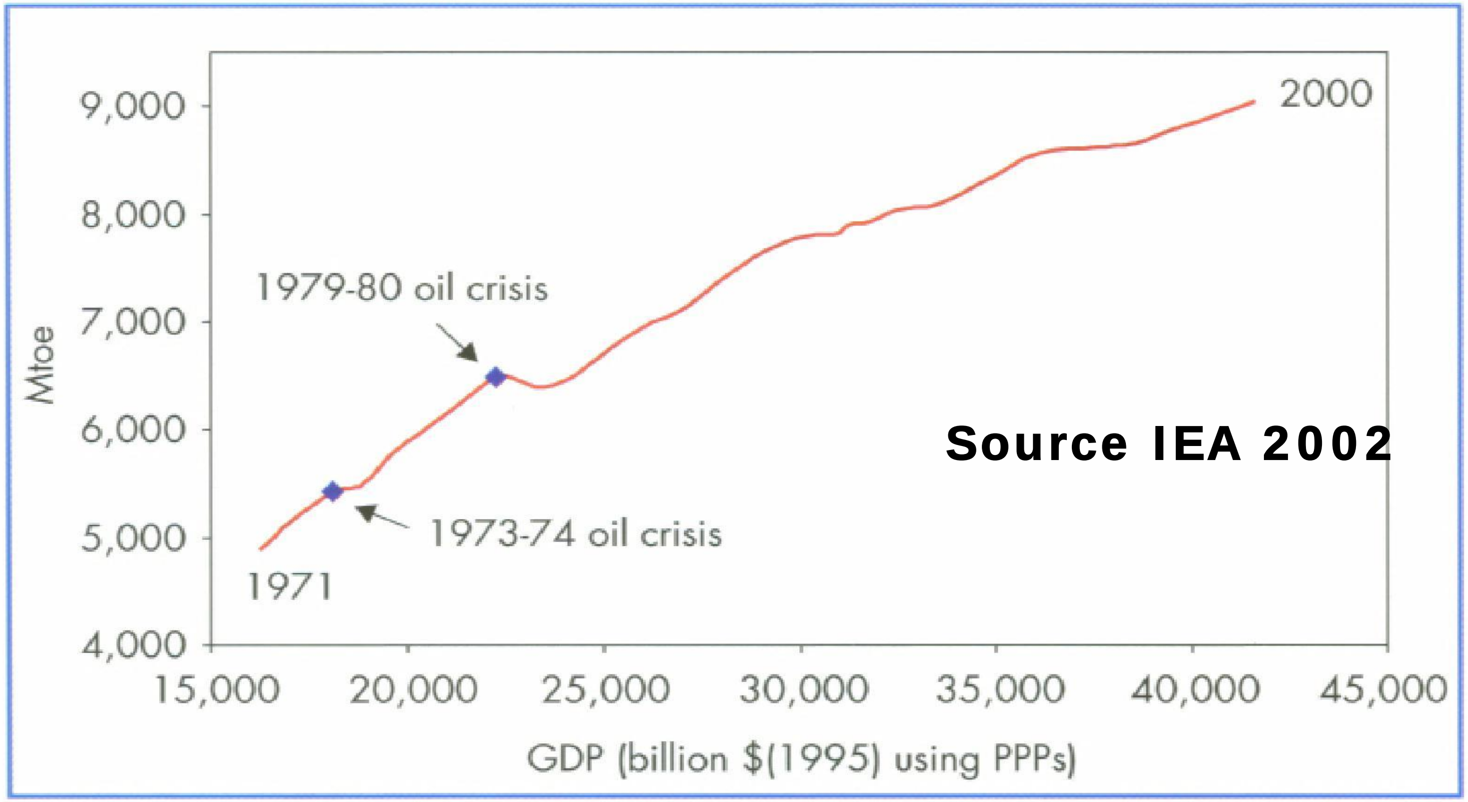
Спасибо за внимание

Primary Energy Demand



Primary Energy Demand and GDP

Figure 1.1: **World Primary Energy Demand and GDP, 1971-2000**



Source IEA 2002