Exergy as measure of sustainability of energy system

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"Living well within the limits of the planet....“ (EU)

4 main problems on the World:

1. Population growth

For a first billion we needed 12,000 years. At present we need only **14 years** for a new billion. Can we survive such exponential growth?

2. GHG emissions

400 ppm of CO_2 was overridden in 2016. Temperature rise of 1,5°C is achieved!

3. Ecological footprint

We need 1,7 Earth

4. Uneven political, economic and social development

GDP/cap: ~ 1: 350

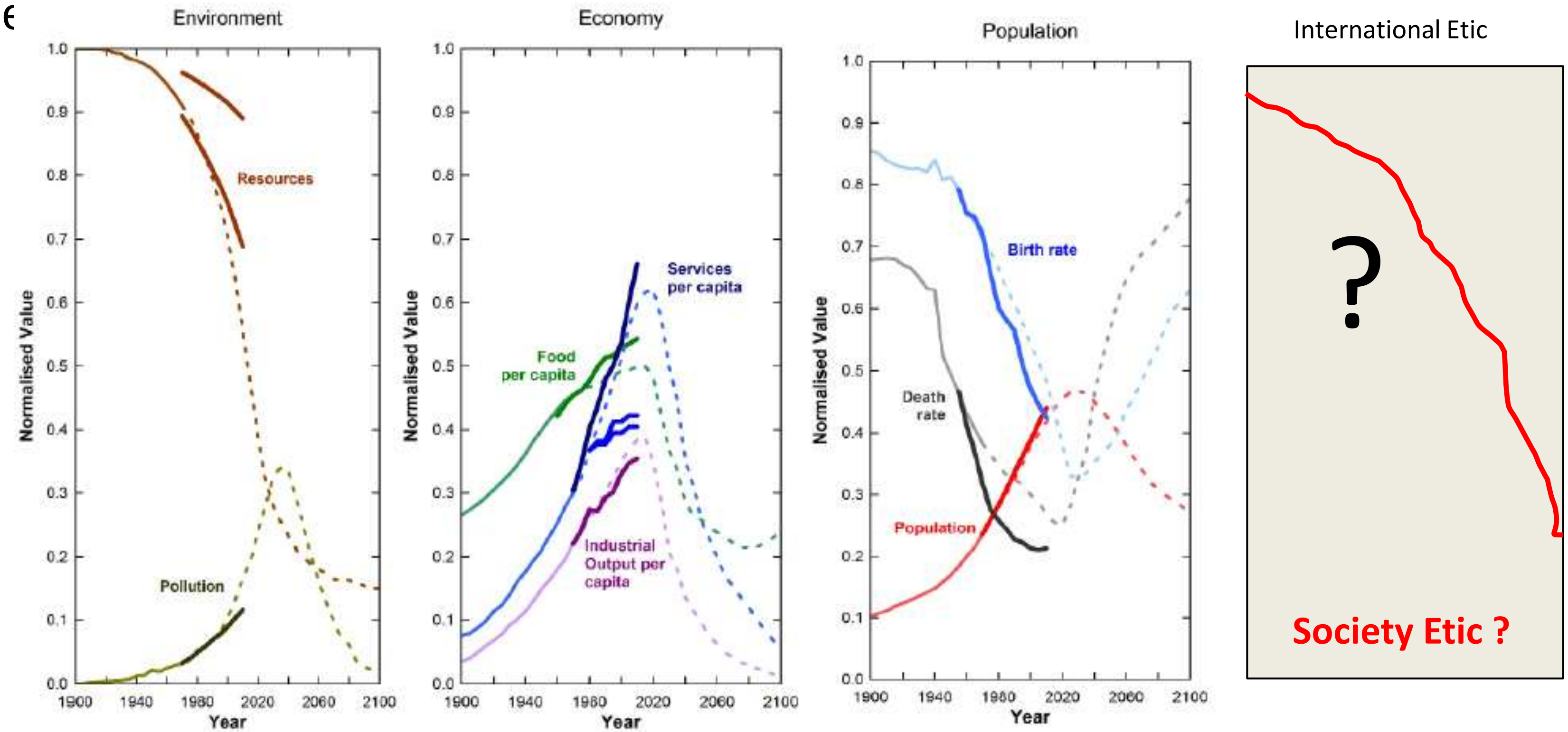
Energy/cap: ~1 : 115

Water, Fertile land and Energy are basic resources for development

The problem can be partly solved with sustainable exergy system

In 45 years we have been not able to change our development patterns!

In the Club of Rome book „Limit of the Growth“, 1972 we can find simulation model for world development „Business as usual“ . We put in the graph the real development on the world (UN Statistic) for last 40 years, and find large agreement with prediction they made. Humanity is approaching the collapse in next decades. To the three graphs we add fourth one, showing the falling



Why Exergy ?

"Exergy of a system in a certain environment is the amount of mechanical work that can be maximally extracted from the system in this environment" (Rant, 1955 et all)

- **According Rant the energy W is a sum of exergy E_x and anergy A (~energy of environment*)**

  $W = E_x + A$
- **Exergy is a measure of quality of energy with regard to the environment.**
- **Energy is always conserved and can neither be produced nor consumed.**
- **Exergy can be very easily converted in anergy trough irreversibility's in the conversion processes.**

* Some authors have other definitions

Resources evaluation, exergy, sustainability and circular economy

- **Resources cannot be evaluated only according to mass and energy balance, because they not disappear.**
- **Using the exergy as measure of resources depletion we can evaluate quality of our processes taking into account the conservation of mass, energy and irreversibility's**
- **exergy efficiency E_xE = exergy-out/exergy-in**

Exergy destruction - ireversibilities

- **Sustainable development means les exergy destruction or depletion in all circumstances.**
- **Circular economy is a policy to minimize the use of resources, to minimize the thermodynamics irreversibility's, this mean to promote higher exergy efficiency over the life cycle** (LCE$_x$A and E$_x$ROE$_x$I).

Resource evaluation

Comment:

Even in scientific communities is normal to use expression: consumption of energy, water, steel, aluminium, etc.

This not in accordance with two basic law of physic: conservation of mas and energy.

LCE_xA calculation

LCE_xA (**L**ife **C**ycle **E**xergy **A**nalysis) we used as a method to **quantify depletion** of natural resources and to assess the efficiency of natural resources used.
The life cycle exergy analysis of a system usually consists of three separate stages with different exergy flows that are similar to the three steps in the life cycle of a product in an LCA:
- construction phase,
- operational phase and
- clean up phase.

During the construction phase, exergy is spent and none is created.
The exergy used for construction combined with the exergy used for maintenance and clean up make the **total input exergy**.

Priciples of LCE$_x$A (Wall, Gong,2000, Davidson, 2011)

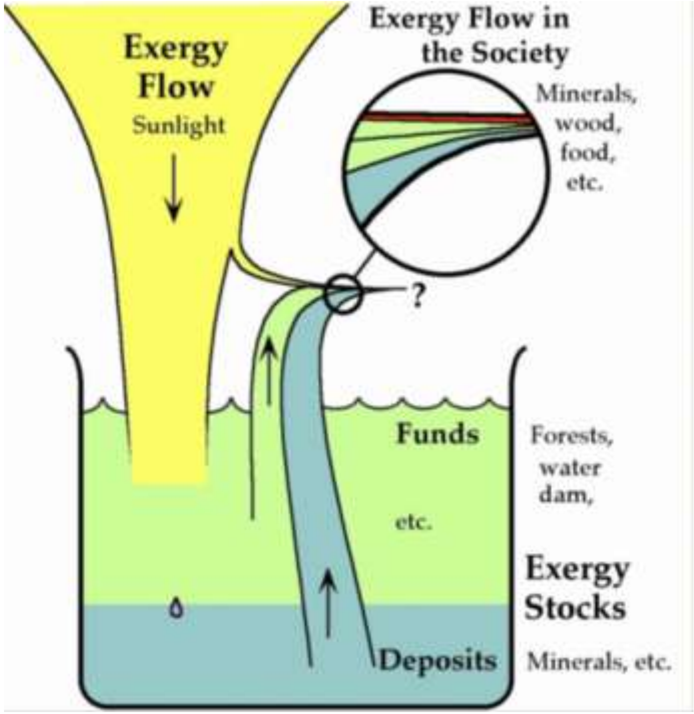
Natural energy resources are classified as

- natural flows and
- stocks.

Stocks are then divided into

- **deposits** (dead stocks) and
- **funds** (living stocks).

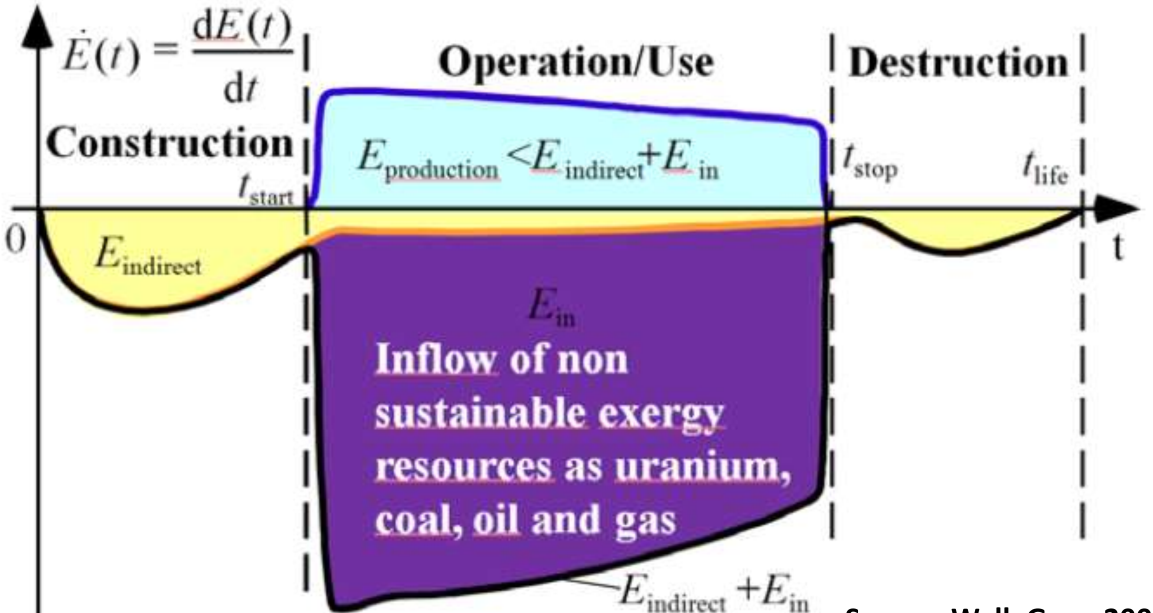
Natural flows and funds are renewable while deposits are non-renewable.



Source: Davidsson, LCEA of Wind Generator, 2011

The direct exergy input (e.g. solar, water, wind,...) of renewable sources can be disregarded since they represent a natural flows. If natural exergy flows are not used will be lost and transformed in anergy – heat of environment.

Example of exergy flow diagram for LCE_xA of a power plant using fossil fuels



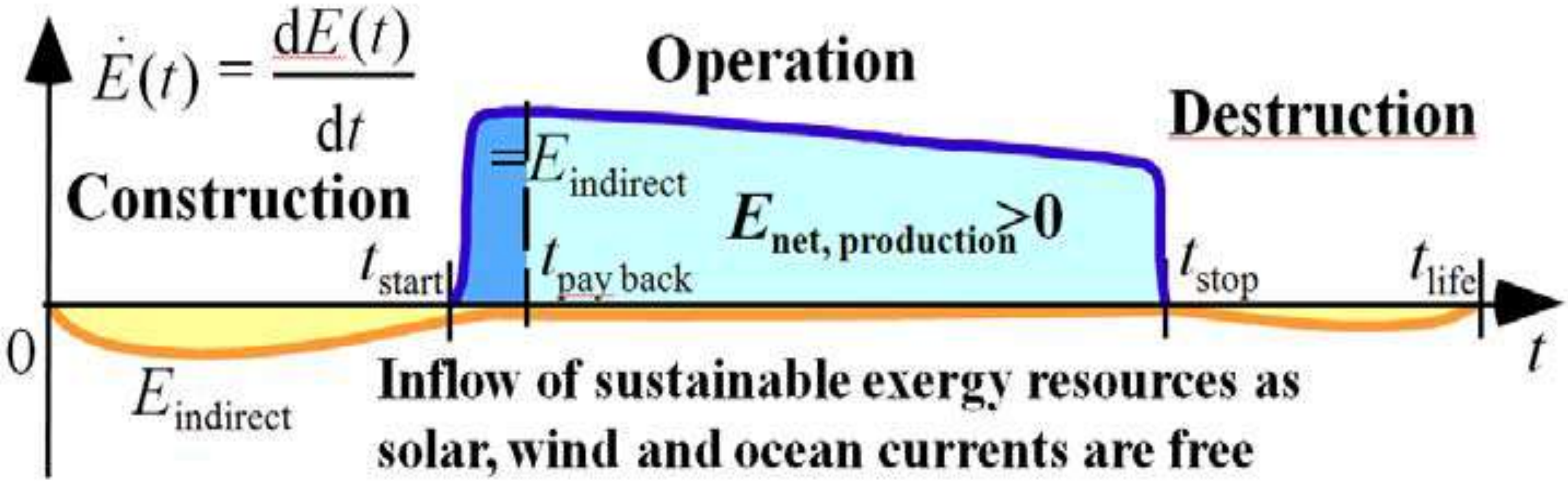
Source: Wall, Gong 2001,Davidsson, 2011

A fossil fuels power plant takes the exergy from the fuels used during the operational phase.

The exergy of the output electricity will always be **lower** than the exergy of the fuels used during the production.

Power plant using fossil fuels can therefore **never be sustainable** since it uses more exergy than it generates. E_xE is always less than 1.

Exergy flow diagram for LCE_xA of a power plant using renewable energy



Source: Wall, Gong 2001, Davidsson, 2011

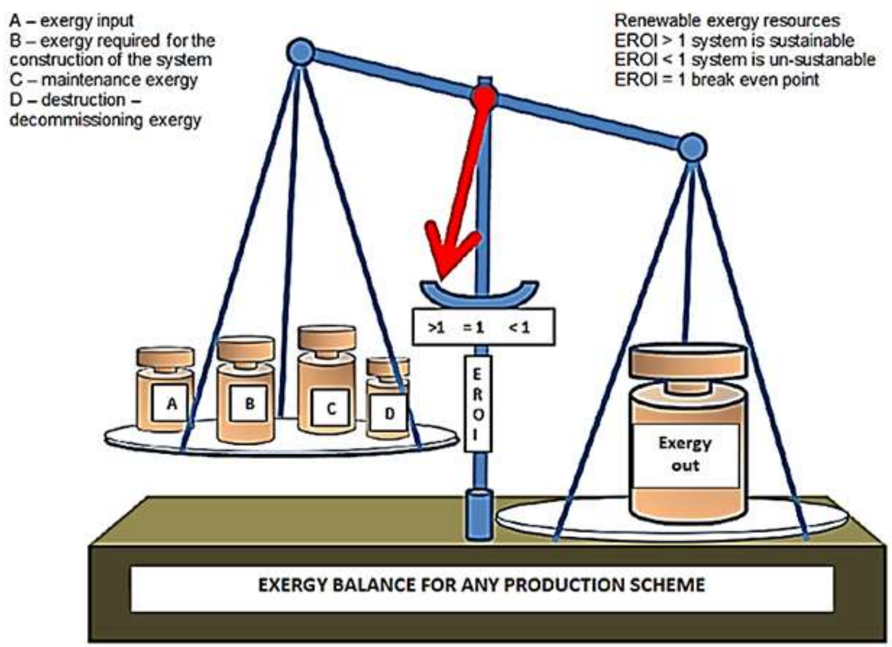
Power plant using the renewable energy sources for production of electricity convert exergy of a natural flow to a usable form of exergy - electricity.

During the operational phase it will produce **more exergy** than the indirect exergy needed during the life cycle for construction, operation and demolition.

Exergy balance for any production scheme

$E_x ROE_x I$ is exergy return of exergy invested. In case of exergy used only from RES the $E_x\ ROR_x I$ should be defined as:

$$E_x\ ROE_x I = \frac{life\ time\ exergy\ generated}{cumulative\ exergy\ required} = \frac{Life\ time}{E_x PBT}$$



Source: Davidson, 2011

Sustainable Exergy System - SES

as replacement of present

Energy System

Characteristics of sustainable exergy (renewable exergy) system - SES

To fulfil the daily exergy needs of different consumers, the new (energy) – exergy system has to response to the following six main requirements:

1. **Source of exergy must be inexhaustible, available everywhere on the planet;**
2. **Zero emission of GHG using the new exergy carriers;**
3. **Available any place and any time (in all needed forms of exergy: solid, liquid, gaseous fuels and electricity);**

Characteristics of sustainable exergy (renewable exergy) system - SES

4. **Must be compatible with existing infrastructures with minor adaptations;**
5. **In transition period the present energy system and SES has to work in parallel with no interference (coexistence of two systems);**
6. **Should be competitive with fossil fuels system if all external environmental costs will be included in their exergy carriers' price**

SES

Two basic energy cariers:

Solar electricity + biomass

Chemical storage of solar electricity

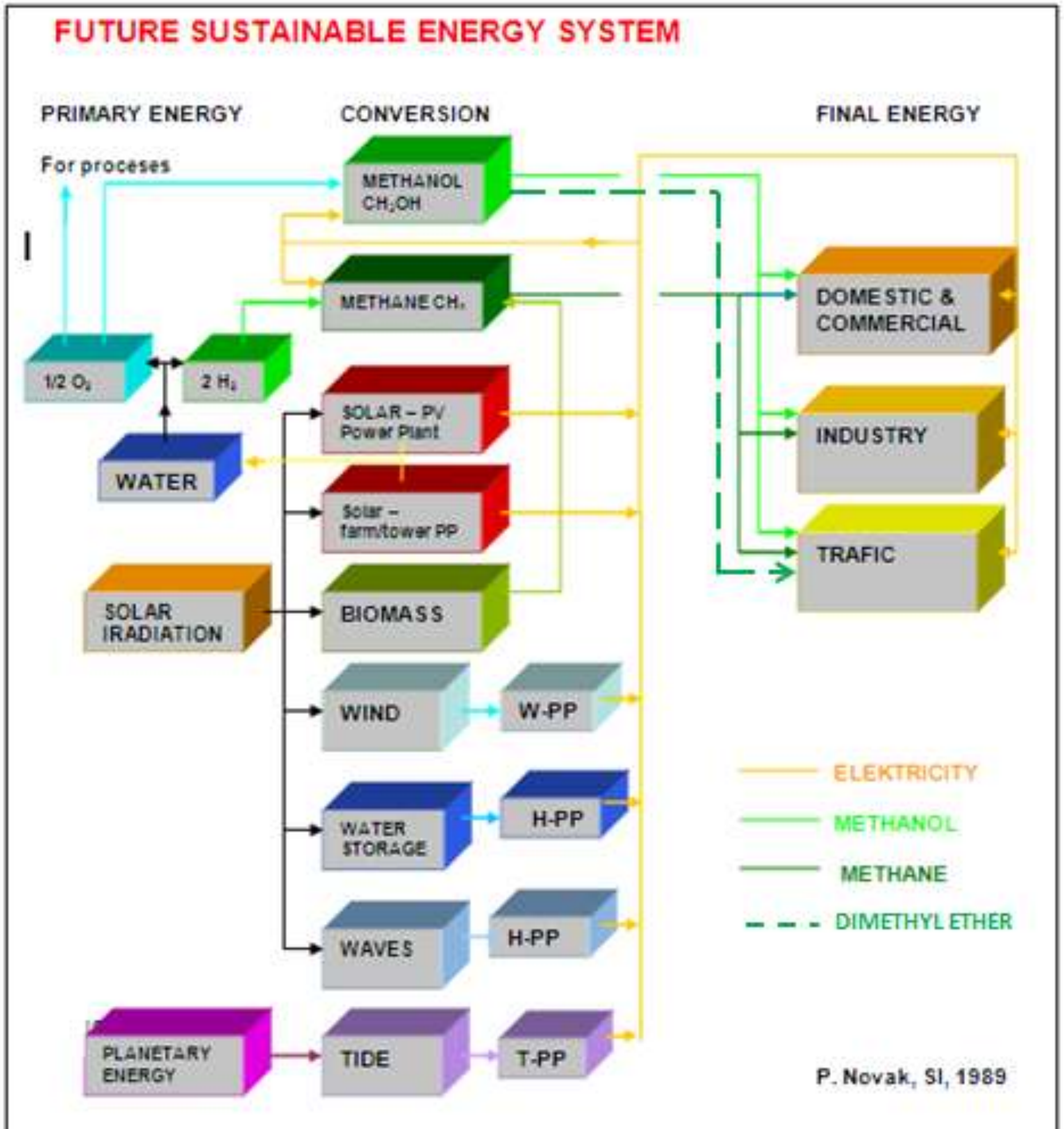
Hydrogen + Carbon from biomass

Metan

Methanol

Electricity

SUSTAINABLE ENERGY SYSTEM (PN,1989, 2001, 2003, 2015):



2 energy sources:

- solar irradiation and
- planetary energy

4 secondary energy carriers

5 conversion technologies

3 main final energy carriers:

1. **Electricity**
2. **Methane** CH_4 (gaseous fuel)
3. **Methanol** $CH_3(OH)$ (liquid fuel)
4. Ethanol (C_2H_5OH)
5. ***Dimethyl ether*** CH_3OCH_3 (liquid fuel)

Ethanol and Dimethyl ether can be a transition fuels (for gasoline and diesel engines).

System represent carbon recycling in nature and present solution acceptable for most of the countries on the world enabling surplus of renewable electricity to be converted in gas and liquid fuels (P2G, P2L) - as chemical storage of RE.

How the proposed SES comply with the 6 requirement?

1. Primary exergy sources - solar energy in all forms and biomass – are everywhere available;
2. No emission of GHG;
3. Proposed exergy carriers can be used any time on any place;

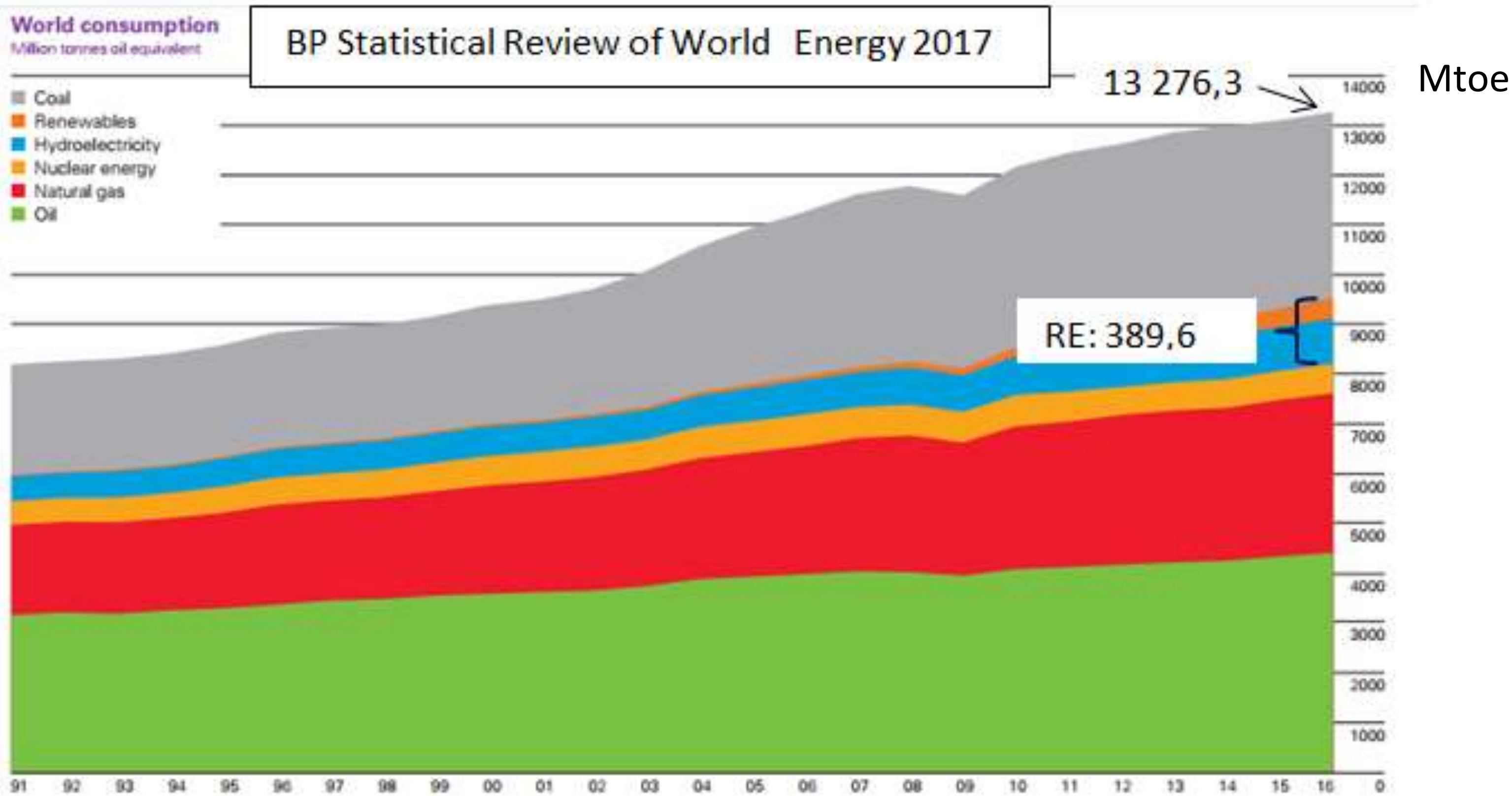
How the proposed SES comply with the 6 requirement?

4. For proposed system we don’t need a new infrastructures (power lines, gas pipelines, liquid storage also exist)
5. All exergy carriers can coexist with the present energy system
6. Should be competitive: According to IMF report the world fossil fuel pre-tax subsidies in 2013 have been $480 billion/y post-tax subsidies $1.9 trillion/y. Including the $1.4 trillion/y environmental damages, total direct and indirect costs, not included in the price of fossil fuels used are

$ 2.78 trillion/y.

Including this subsidies in the final price of fossil fuels, competitiveness of RE will be out of question.

Is fossil fuel replacement in next 33 years viable and possible?



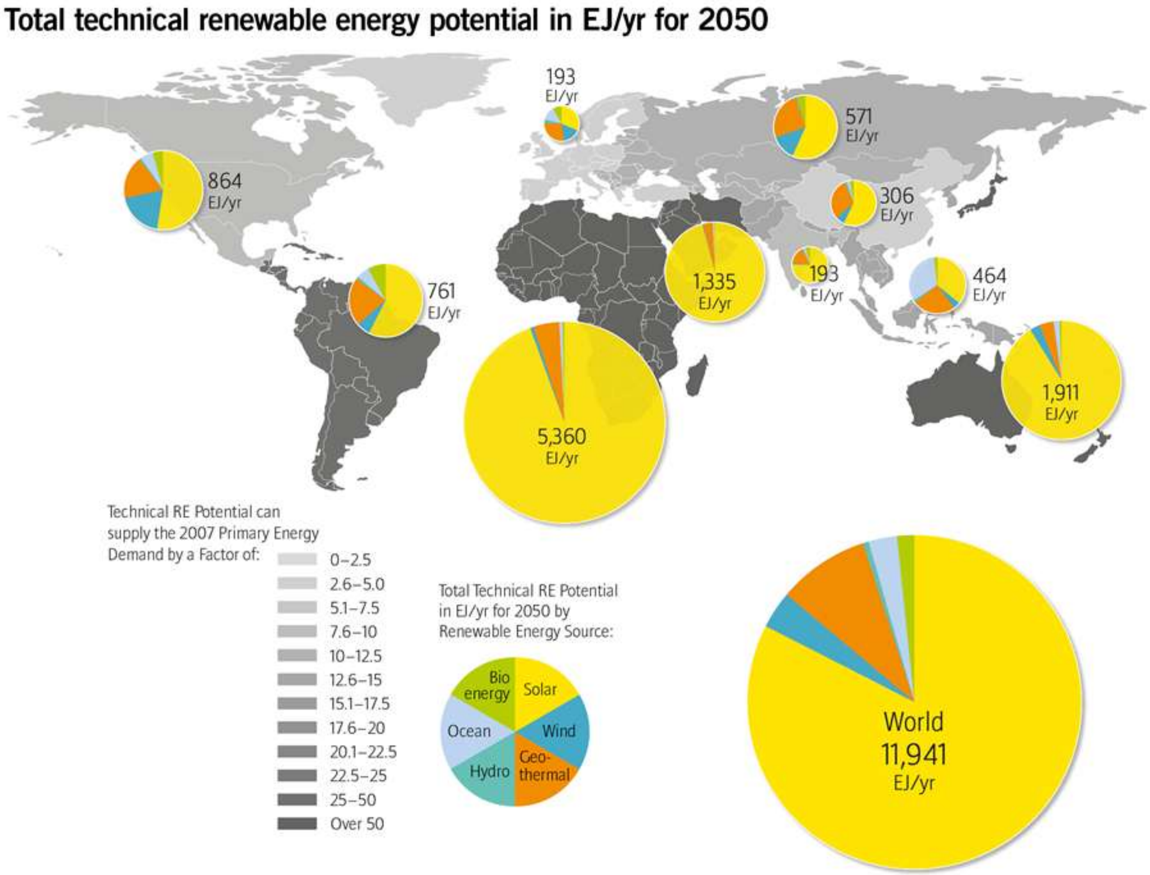
World primary energy consumption grew by 1.0% in 2016, well below the 10-year average of 1.8% and the third consecutive year at or below 1%. As was the case in 2015, growth was below average in all regions except Europe & Eurasia. All fuels except oil and nuclear power grew at below-average rates. Oil provided the largest increment to energy consumption at 77 million tonnes of oil equivalent (mtoe), followed by natural gas (57 mtoe) and renewable power (53 mtoe).

For next 33 years RE growth has to be ~ 290 Mtoe/y to achieve 80% lower GHG emissions on the world. RE growth 2015/2016 was only 80 Mtoe/y.

Do we have enough resources?

- **Solar energy?**
- **Organic carbon?**
- **Cooper?**
- **Lithium?**

Do we have enough resources?



Renewables Global Futures Report Great debates towards 100 % renewable energy

Available technical potential: 11.941 EJ/y

Needed exergy 2016

13 276.3 Mtoe (~575 EJ/y)

~800 EJ/y in 2050 or 6,7% of technical potencial.

REN21 Renewable Energy Policy Network for the 21st Century

Based on present known RE resources and technologies is fossil fuel replacement only the question of political will.

Carbon from biomass

Carbon stocks on the world are 500 billion tons of carbon (IPPC, tier 1, Global biomass carbon map, 2000).

Yearly amount of carbon in growing biomass is:

$C = 104.9.10^9$ t C/y (carbon, dry mater)* divided 50% onshore and 50% offshore.

Yearly needed carbon for replacing present fossil exergy use (11,354.3 Mtoe/y, 2016) as oil, gas and coal is

$C = \sim 7.8.10^6$ t/y

* https//:en.wikipedia.org/wiki/Biomass, 11.11.2013

Natural resources

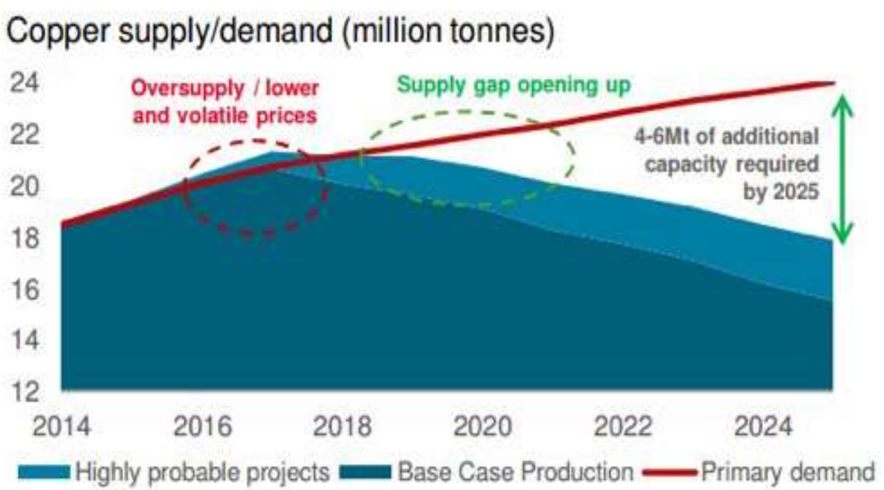
Hydrogen needed is: ~**$1,3.10^6$ t H_2 /y**

This can be covert be splitting of $11.7.10^6$ t/y of water

Conclusion: Natural resources for proposed SES are in abundance and can fulfil our expectations.

Cooper?

- World reserves of cooper: 2 100 Mt discovered reserves and 3 100 undiscovered resources (USGS 2017)
- Present production 2016: 23. 9 Mt/y
- Energy needed for production Cu: 24÷31 MWh/t
- To replace 1 bn light vehicles presently in use with electric or hybrid cars we need 40÷80 Mt of Cu
- Same amount will be used for distribution and charging stations, WG, HE
- This mean ~ 8% of discovered reserves



Source: Wood Mackenzie, Rio Tinto

Problem is in capacity building!

Lithium

World reserves: 46.9 Mt (USGS, 2017)

Proven reserves: **14 Mt** (USGS, 2017

Present production 2016: **0.035 Mt/y**

*Lithium use present: 60% industry, 40 % batteries

*Lithium use 2025: 30% industry, 70% batteries

*Predicted production growth: 2017-2025: 4 times

* Deutsche Bank Market Research, Lithium 101, pg. 23

Where we stand with technologies?

How long is the E_xPT?

How big is the E_xROE_xI ?

E_xPBT and E_xROR$_x$I data for some RE technologies

Tecnology	E_xPBT (years)	E_xROE$_x$I LOW	E_xRE$_x$I HIGH	COMMENTS
PV	0.2÷0.4	3	6 (28)*	*E_xPBT 0,2
WIND	0.2÷0.5	18 (offshore)	34÷ 18 (onshore)	Cf ~ 0,35 ÷0,19
HYDRO RESERVOIR	1 ÷ 1.5	205	280	Long life time
HYDRO RUN OF	0.5÷1 small 1÷1.5 large	170	267	Long life time
BIOMASS WASTE	0.3÷0.5	10	27	

All this technologies are sustainable, having **E_xROE$_x$I more than 1**

For information: Present conversion efficiency from **solar irradiation** over sugarcane to **bio-ethanol** is **under 0,032%*** in comparison to PV system efficiency of ~16% on the same irradiated area.

*verified on real data from Brazil bio-ethanol production

Conclusions

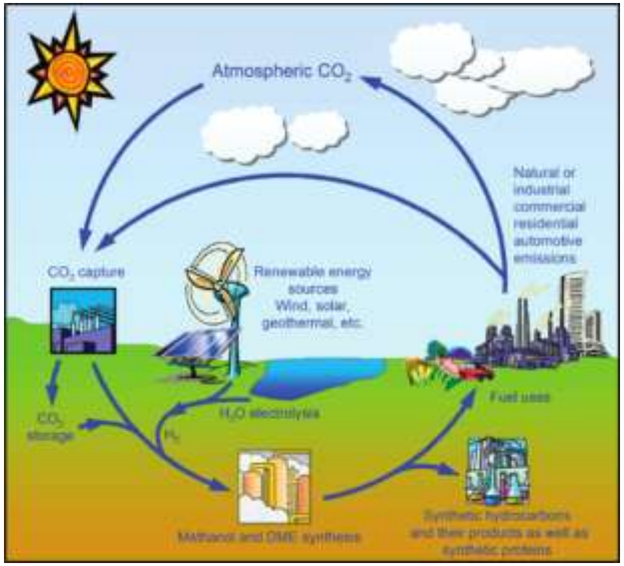
- Exergy efficiency E_xE and E_xROE_xI are good indicators of exergy conversion processes
- Proposed SES can replace the present system with further development of chemistry for biomass conversion in methane and methanol.
- SES with s-methane and s-methanol represent the chemical storage of solar energy - can be used everywhere.

Conclusions

- **Biomass conversion in liquid fuels need further optimization, improving significantly the exergy efficiency of the processes from land use to fuel.**
- **Synthetic gaseous and liquid fuels enables us further use of the ICE in light and heavy vehicles or hybrid cars.***
- **Time for transition is 33 years and is long enough to achieve our final goals.**

* (Zhen, Wang: An overview of methanol as an ICE engine fuel, J.R&SER, 2015

We have to return back to the sun.



Circular economy with Carbon recycling exergy system

with sunflower before Fukushima

and not with Sunflower after Fukushima

Thanks for attention, questions welcoming !