Revista Română de Inginerie Civilă, Volumul 9 (2018), Numărul 3

Energy system for tomorrow - role of exergy

Prof Dr. Peter NOVAK

Faculty for Technologies and Systems, Novo mesto, Slovenia

Abstract:
Exergy is a measure of energy quality. The amount of exergy in energy carriers is very different. Normally the price includes only the value of quantity and not the quality of energy. Exergy is the only part of energy available to do work. For different purposes we need energy with different amounts of exergy: for heating and cooling the energy mixture between small amount of the exergy and large part anergy is needed. Transition to sustainable energy system, without GHG emissions, based on RE, open the questions how to evaluate exergy from solar energy. Solar energy in all form (irradiation, water flows, wind, and biomass) consists of nearly 100% of exergy. Solar energy is free, conversion systems are not. To exploit at maximum the solar exergy we need a sustainable energy system using in great amount the present infrastructure and existing or new developed energy conversion technologies. There is common agreement that we need four main presently used energy carriers: electricity, gaseous, liquid and solid fuels. Our vision is the new Sustainable Energy System (SES) based on the use of solar and planetary energy for production of renewable electricity as a base for production of hydrogen. Hydrogen is a raw material for carbon recycling from biomass, making synthetic methane and methanol. The proposed SES is based on the existing infrastructure and known chemical processes. With regard to availability of renewable energy resources (RES) it is unrestricted and harmless in comparison to present fossil fuels use. The proposed SES consists of the three main exergy carriers: solar electricity, synthetic methane (CH4) and synthetic methanol (CH_3OH).

Key words: energy, exergy, evaluation, sustainable exergy system

1. Introduction

In the last years European Union (EU) in conformity with Paris Agreement has adopted many regulations and decisions with regard to energy management [1] including the EU Council decision on 40% greenhouse gas emission (GHG) reduction and the share of 27% of renewable energy (RE) in final energy (FE) until 2030. The common goal of these regulations is to change the present energy system to a sustainable one. In EU winter package documents is one of the most important statements: “To reach our goal, we have to move away from an economy driven by fossil fuels, an economy where energy is based on a centralized, supply-side approach and which relies on old technologies and outdated business models.”[2]

There are different ways and timing to achieve the proposed goals. One possibility is to integrate all those activities into Circular Economy [3]. What should be a “sustainable development” in the case of energy supply, distribution and use?

How can we measure the sustainability of energy system? Can we have a sustainable energy system with the circulation of organic carbon, going away from the expression ”a low carbon society” to a carbon recycling economy? We presented one of the possible solutions including tools for evaluation of their sustainability. Based on previous research results and proposals [4, 5, 6, 7, 8) we find, that one of the best criteria for measuring the sustainability of energy system is exergy approach.

Normally we are selling fuels, electricity, heat and cold. The amount of exergy in these energy carriers is very different. In their prices only the quantity and not the quality of energy is included.

This means the value or amount of exergy, as the measure of quality, in it is not always included in the price. But in real life we need energy with a different amount of exergy: for heating and cooling energy mixture between small amount of the exergy and large part anergy is needed. For work and lighting the 100% of exergy is needed.

The transition to sustainable energy system, without GHG emissions, based on RE, opens the questions how to evaluate exergy from solar energy. How important are the irreversibility's of our processes in solar energy conversion system? The answer is only possible if we know what type of processes will be used.

There is common agreement that we need in practice a sustainable energy system with four main energy carriers: electricity, gaseous, liquid and solid fuels to exploit at maximum the present infrastructure.

2. Exergy

The word “exergy” was introduced by Zoran Rant [9] and the present common definition is: “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”.

According Rant the energy W is a sum of exergy Ex1 and anergy A (~energy of environment):

$$W = Ex + A \quad (1)$$

Exergy is a measure of quality of energy. Energy is always conserved and can neither be produced nor consumed. Exergy can be very easily converted in anergy through irreversibilities in the conversion processes. Therefore the most used expression in daily life “consumption of energy” should be changed to “consumption of exergy” as the only thermodynamically correct expression.

Our attention will be given to the exergy of renewable sources of energy as the core of future energy system. In real energy conversion processes we always have a loss of exergy. This means that energy can be balanced but the exergy in a closed system cannot be. Exergy destruction or vanishing of exergy because of irreversibilities is a natural phenomenon which can be to some extent controlled by design of our energy conversion equipment.

---

1 Symbol Ex is used for exergy, to distingwish betwen symbol E many authors used for energy or exergy.

Exergy efficiency is therefore a quality measure of our processes. The quotient between output exergy Exout and input exergy Exin is the standard definition of exergy efficiency ExE:

$$\varepsilon = Exout / Exin \quad (2)$$

Using standard data for exergy content in different energy carriers and the embedded exergy in materials used in practice [10] we can calculate this efficiency. Besides the exergy efficiency it is important also to analyze the exergy destruction in processes during the time.

2.1 Exergy, sustainability and resource accounting

Resources cannot be evaluated only according to mass and energy balance, because they do not disappear. Using the exergy as the measure of resource depletion we can evaluate the quality of our processes taking into account the conservation of mass and energy.

Circular economy promoted in the last years is a policy to minimize the resource destruction, to minimize the thermodynamics irreversibilies with higher exergy efficiency. To push the circular economy on the top of society development we need a serious exergy analysis (ExA) of present technologies and economic patterns. The exergy destruction during a process is proportional to the entropy created due to irreversibilities associated with the process. Exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation or technology. It can also quantify the heat quality in rejected streams. The main aim of exergy analysis is to identify the causes of irreversibilities and to calculate the true magnitudes of exergy losses.

Exergy analysis [8] is a methodology that uses the conservation of energy principle (embodied in the first law of thermodynamics) together with non-conservation of entropy principle (embodied in the second law) for the analysis, design and improvement of energy and other systems.

LCExA (Life Cycle Exergy Analysis) can be used as a method to quantify depletion of natural resources and to assess the efficiency of natural resource used. It can be used for energy system with fossil and renewable sources of energy, for different materials and in broader sense for exergy of societies. In our case LCExA will be used to analyze sustainability of proposed exergy system, based on organic carbon circulation in future circular economy.

2.2 Life Cycle Exergy Analysis of Renewable Energy

The use of exergy in life cycle assessments (LCExA or sometimes ExLCA) has been suggested by many different researchers since the late 1990s. Based on work of Davidsson using LCExA for wind energy system analysis [7], where the renewable resources are separated from non-renewable, we accept the same methodology.

Natural resources are classified as natural flows and stocks.

Stocks are then divided into funds (living stocks) and deposits (dead stocks). Natural flows and funds are renewable while deposits are non-renewable. All in- and outflows during the life cycle of production, use and disposal or recycling, are then considered as exergy power over time.

The direct solar exergy input (e.g. solar irradiation, water, wind, waves) of renewable sources (including geothermal and planetary exergy) can be disregarded since they represent a natural flow and are therefore renewable. If not used natural exergy flows will be wasted and lost as anergy – heat of environment. Non-sustainable use of exergy funds, like clearing of forests in a non-sustainable fashion and the use of exergy deposits are regarded as non-renewable resources. The simple presentation of LCExA is given in [7, 32] and is shown on the Figures 1, 2 and 3.

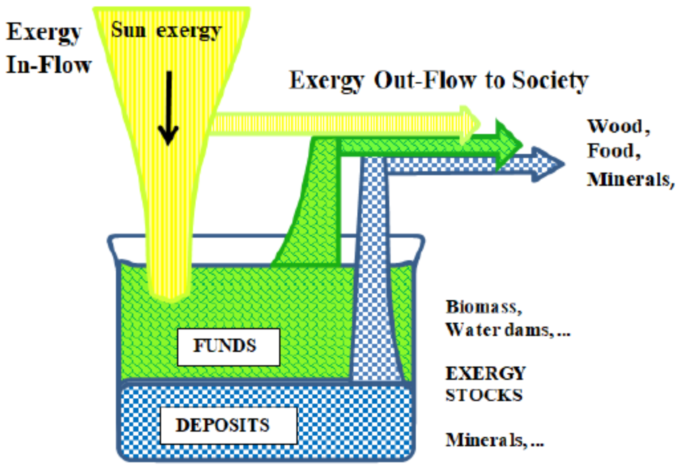

Figure 1: The exergy flow from the sun and the exergy stocks on the earth create the resource base for human societies on the earth. [7, 32]

The life cycle analysis of a system usually consists of three separate stages with different exergy flows that are analogous to the three steps in the life cycle of a product in:

1- Construction phase,

2 - Operational phase and

3 - Clean up phase.

During the construction phase, exergy is spent and none is created besides eventual byproducts. Some exergy is used for maintenace and at end of life we need the exergy for clean up (recycling) of the equipment or plant. The exergy used for construction combined with the exergy used for maintenance and clean up make up the total indirect exergy.

A fossil fuels power plant takes the exergy from the fuels used for construction, during the operational phase and clean up. The exergy of output electricity will always be lower than the exergy of the fuels used. A power plant using fossil fuels can therefore never be sustainable since it uses more exergy than it generates. The exergy flow over the lifetime of a fossil fuel power plant is illustrated in Figure 2 [7, 32].

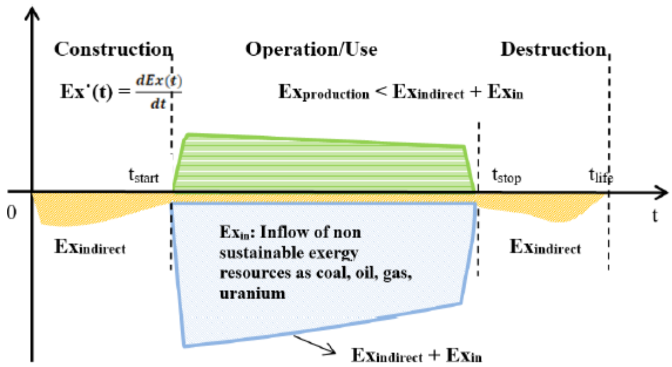

Figure 2. Exergy flow diagram for LCExA of a power plant using fossil fuels [7, 32]

The power plant using the renewable sources of energy for electricity production, on the other hand, converts the natural exergy flows to a useable form of exergy - electricity. As an example, a PV panel uses the solar exergy to convert it into electricity and same is done by the wind generators.

During the operational phase it will hopefully produce more exergy than the indirect exergy needed during the life cycle (for construction, maintenance and clean up). The exergy flow over the life cycle of such one power plant is illustrated in Figure 3 [7, 32].

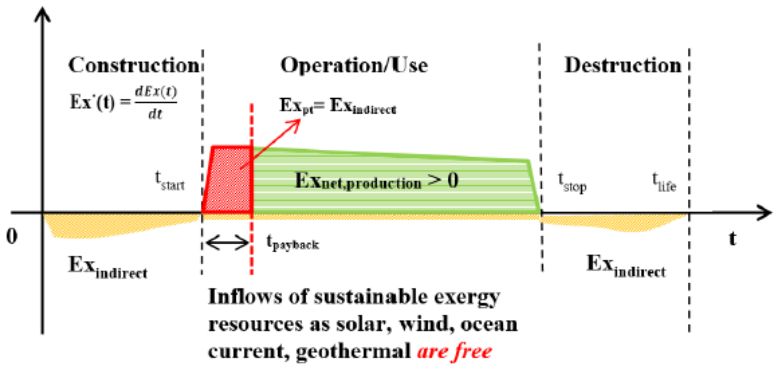

Figure 3: Exergy flow diagram for LCExA of a renewable energy power plant [7, 32].

LCExA method enables us also to analyze the influence of intermittency of RE taking into account the power factor CP and the capacity factor CF by producing heat and electricity. In this context we have to include storage systems which influence the exergy needed in the construction phase.

The exergy conversion and use is usually presented either as exergy payback time (ExPBT) or exergy return on exergy invested (ExROExI) as indicators for sustainability [28]. The way the energy is compared can be a bit different between different assessments. In case of exergy produced from RE the ExPBT should be defined as:

$$\text{ExPBT}=\frac{\textit{cumulative exergy required}}{\textit{cumulative exergy generated}} \quad \text{[years]} \qquad (3)$$

And for

$$\text{ExROExI}=\frac{\textit{life time exergy generated}}{\textit{cumulative exergy required}}=\frac{\textit{lifetime}}{\textit{ExPBT}} \quad [-] \qquad (4)$$

Cumulative exergy generated includes exergy generated during the operation time. Cumulative exergy required includes exergy of construction materials, maintenance, exergy needed for operation and destruction, minus exergy available because of recycling of some materials.

The use of ExPBT and EROExI defined in (3, 4) are fairly good indicators that an exergy producing process actually produces more exergy than it uses during its life cycle, without regard to the source of exergy required.

3. Sustainable exergy (energy) system based on RE

3.1 Concept

Solar exergy is characterized by low density, high intermittency over day and year. The concentration of available solar exergy and storage system are needed for practical application. Different sustainable energy systems have been proposed using water, wind and direct solar irradiation including geothermal heat and biomass.

Most of them have no integral solution for exergy storage and transition technologies from present to a new, environmentally acceptable, energy system [11].

The sustainable exergy system (SES) as proposed in [16] consists of three main renewable exergy (energy) carriers, needed in industry, transport, services and homes: renewable electricity, gas (synthetic methane CH_4; s-methane), liquid (synthetic methanol CH_3OH; s-methanol) and as fourth solid fuels from biomass (important for developing countries). Renewable electricity is the main driver in the system used for transformation of two natural flows, water and biomass into two new exergy carriers used also as chemical storage of solar electricity (Figure 5). The methane and methanol are chosen, because there are only exergy carriers in nature with one carbon chemically connected with four hydrogens.

The necessary hydrogen and oxygen will be produced with electrolysis of water or other processes, equalizing the sun daily and yearly irradiation variations. Carbon will be taken from biomass where is stored trough photosynthesis from the air. For solid fuels (in transition period) we propose to use only the wood log.

S-methane and s-methanol represent the chemical storage of solar exergy (like do the nature in biomass) with exergy efficiency close to the storage of atmospheric carbon in biomass. In this way, the natural circle of carbon dioxide and water is closed. The proposed SES has no GHG emissions, because CO_2 and water are recycled in natural photosynthesis and vapor cycle process.

We muss stress out that these exergy carriers can be produced and used in well-developed energy conversion equipments and infrastructure in industry, buildings and transportation. To these three exergy carriers we can add in transition period also bio fuels as ethanol (C_2H_5OH), dimethyl-ether (CH_3OCH_3), and synthetic diesel made from the rests of biomass and organic waste. The last survey show, that methanol can be used on different ways in different internal combustion (IC) spark ignition (SI) engines with low emissions and high break thermal efficiency [35]. Methanol is a transportation fuel and has many significant advantages as compared to hydrogen, gasoline and can be in new turbocharged methanol engines good replacement for heavy duty diesel engines. Higher efficiency (nearly 43%) ower the wide range of motor speeds and loads in comparison to the standard diesel engines made methanol interesting fuel of the future.

3.2 Characteristics of sustainable (renewable) exergy system –SES

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

a. Source of exergy must be inexhaustible, available everywhere on the planet;

b. Using exergy carriers with zero emission of GHG;

c. Available at any place and any time (in all present forms of exergy needed: solid, liquid, gaseous fuels and electricity);

d. Must be compatible with existing infrastructure, with minor adaptations;

e. In transition period the present energy system and SES have to work in parallel with no interference (coexistence of two systems);

f. Should be competitive with fossil fuels system if all external— none acknowledged environmental costs will be included in their price.

3.3 How does the proposed SES comply with the six requirements?

1. Primary exergy sources

The first primary exergy source in the system is the solar energy (including direct irradiation and all secondary forms of solar exergy: biomass, water, wind, waves), the second is the planetary energy (geothermal heat and tide). Solar irradiation on the planet is about 174.103 TWy/y. In 2013 TPES (Total Primary Exergy Supply) on the planet was only 17.98 TWy/y.

2. No emission of GHG

The burning products of synthesized s-methane and s-methanol are water and CO2. Water normally circulates in the atmosphere.

Carbon dioxide is released back into the atmosphere and is used for plants growth (~200 Gt/y, [12]).

3. These four energy carriers can be used at any time at any place

Renewable electricity, s-methane, s-methanol and wood can be used anytime and anywhere.

4. For the proposed system we do not need a new infrastructure

Solar electricity can be transported through existing grid on low and high voltage AC and DC lines. For storage of surplus of electricity, the hydrogen production will take place on location where water and biomass will be available. Liquified s-methane can be used as replacement for LNG for transportation in the transition period. The distribution of liquid methanol is well developed and normal gas stations can be (with minor adaptation) used for cars and trucks with adopted or new methanol engines [35].

Heating systems based on s-gas do not need any adaptations or new infrastructure. The boiler using heating oil can be used further, modifying only the burner to use the s-methanol.

5. Coexistence with present energy system

All four energy carriers can coexist with the present energy system.The transition from the present system to a sustainable one is simple and can be implemented very smoothly. In towns and buildings it does not require a new local infrastructure.

6. Should be competitive

All technologies for the conversion are almost well developed (solar cells, wind generator, hydro PP, electrolysis, methanol syntheses, etc.). Methane and methanol synthesis are old, known processes. New processes for direct conversion of CO_2 and hydrogen to methanol are under development. The costs of renewable energy conversion are falling. It is well known that world pretax subsidies for fossil fuels are distorting the energy/exergy market and expand considerably. In year 2011 fossil fuels subsidies go up to $523 billion/y (up 30%), compared to all subsidies for renewable energy which amounted only $88 billion/y.

According to IMF report (January 2013), the world fossil fuel pretax subsidies in 2013 have been $480 billion/y and 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 these subsidies in the final price of fossil fuels, competitiveness of RE will be out of question.

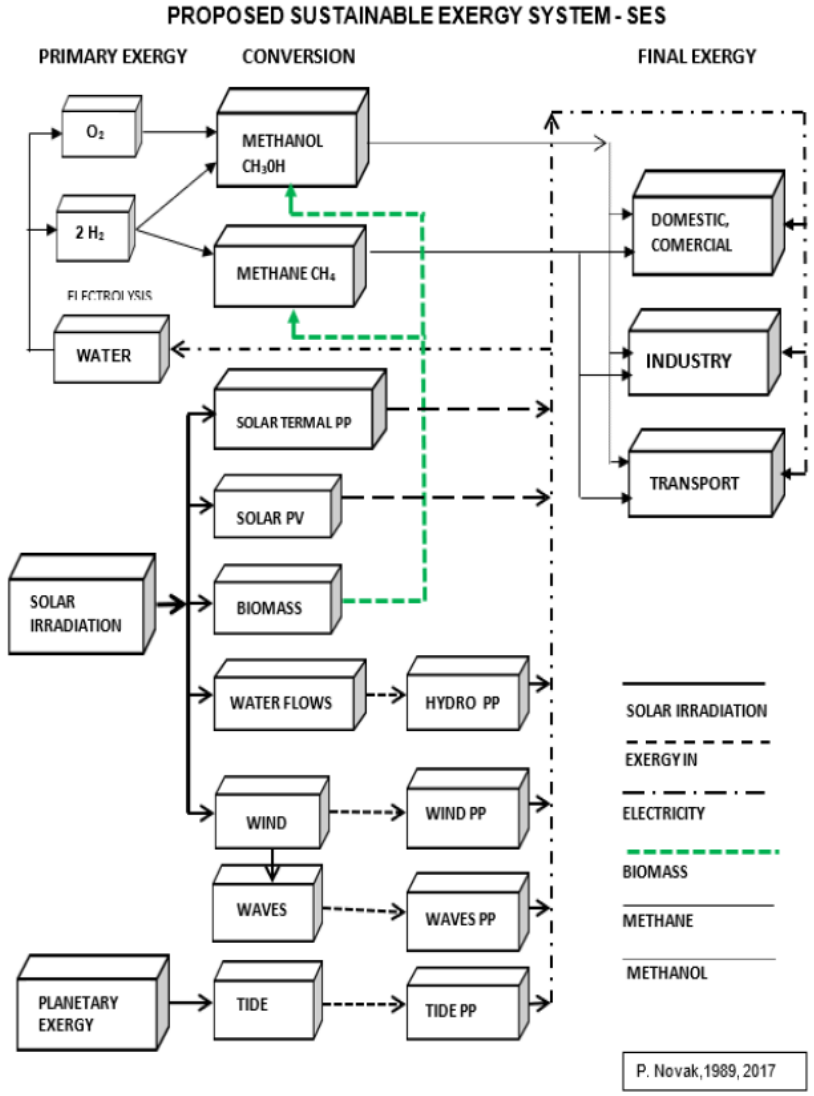

Figure 5: Sustainable energy – exergy - system without emission of GHG [16]

4. Exergy as measure of sustainability of SES

4.1. Exergy efficiency

Some energy and exergy efficiency data of present electrical devices, calculated according to the second law of thermodynamic, are given in Table 1 [8, 10].

Table 1

Energy and exergy efficiency for selected electrical devices [8, 10]

Device	Energy efficiency %	Exergy efficiency %
Generation		
Coal fired power plant	40 ÷ 64	38 ÷ 62
Nuclear power plant	30	28
Hydro power plant	90	90
Wind turbine	0.475 ÷ 0.576	0.475 ÷ 0.576
PV system	6 ÷ 25	6 ÷ 25

Device	Energy efficiency %	Exergy efficiency %
Solar thermal	10 ÷ 30	8 ÷ 25
Co – trigeneration system		
Cogeneration	74	31
Trigeneration	94	28
Resistance space heater	~ 100	6
Hot water heater	90	10
Heat pump –COP 3,8	380	19

Sustainability indicator of the conversion device ExROExI, based on LCExA methodology are for RE defined as quotient of life time of conversion device and expected ExPBT (Eq.4). It can be defined also as quotient of life time exergy produced and cumulative exergy required for construction, maintenance and destruction in the life time, based on meteorological data Exergy for operation, if not from renewable exergy, can be calculated on the same principles. Exergy for equipment destruction or decommissioning is expected to be from renewable sources at a life time over 30 years. In transition period the exergy for construction will be a mixture of non-sustainable exergy from fossil fuels and sustainable exergy from renewable energy.

Exergy efficiency of biomass can be calculated as fund, or as exergy of used biomass. In the first case (fund) we have to include the efficiency of solar exergy conversion by plant. If we use the biomass as exergy flow, we have to include exergy for harvesting.

Using biomass for the final product e.g. electricity or sin-fuels we have to include all conversion efficiencies.

4.2. Sustainability indicator ExROExI for proposed SES

Table 2

ExPBT and ExROExI 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 ExROExI more than 1.

For information: Present conversion efficiency from **solar irradiation** over sugarcane to **bio-ethanol** is under 0,032% compared to PV system efficiency of ~16% on the same irradiated area (verified on real data from Brazil bio-ethanol production).

5. Concluzii

In articles we show, that resources cannot be evaluated only according to mass and energy balance, because they do not disappear. Energy cannot be consumed; it can be only transformed in different forms. Using the exergy as the measure of resource depletion we can evaluate the quality of our processes taking into account the conservation of mass and energy. Exergy is also closely connected with sustainability. Sustainable development means less exergy destruction or depletion.

Circular economy promoted in the last years is a policy to minimize the resources destruction, which means minimizing the thermodynamics irreversibiliesties with higher exergy efficiency. To push the circular economy on the top of society development we need a serious exergy analysis during the life cycle (LCExA) of present technologies and economic patterns. The exergy destruction during a process is proportional to the entropy created due to irreversibilities associated with the process therefore exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation or technology.

Exergy approach to evaluate the sustainability of present energy system using the ExROExI as sustainability indicator gives us the possibility to make a distinction between fossil fuels conversion technologies and technologies for conversion of renewable sources of energy. To fulfill the requirement of sustainability indicator ExROExI should be 1 or more.

The most important fact is that ExROExI of RE is time independent, even more, with better technologies it will raise with time. On the other hand ExROExI of fossil fuels are descending with time, because of internalization of external costs and growing costs of fossil fuels mining from the Earth. In our case LCExA and ExROExI has been used to analyze sustainable energy system, based on organic carbon circulation in future circular economy. Natural resources are classified as natural flows and stocks.

Stocks are then divided into deposits and funds. Deposits are non-renewable while funds are renewable. Renewable exergy input in our analysis has been disregarded since it represents a natural flow. If not used, natural exergy flows will be wasted and lost as anergy – heat of environment.

Based on this background we proposed a sustainable exergy system without any GHG emissions. The sustainable exergy system (SES) as proposed in [16] consists of three main renewable exergy carriers, needed in industry, transport, commercial and homes: renewable electricity, gas (synthetic methane CH_4; s-methane), liquid (synthetic methanol CH_3OH; s-methanol) and as fourth exergy carrier solid fuels from biomass, important for developing countries in transition period. Renewable electricity is the main driver in the system. It is proposed using the surplus of electricity ower the demand for transformation of two natural flows into two new exergy carriers: water and biomass. Those are used also as chemical storage of solar electricity, solving the problem of intermittency of RE.

To fulfill the daily exergy needs of different consumers, the new exergy system has to fulfill the following six main requirements:

1) source of exergy must be inexhaustible, available everywhere on the planet;

2) new exergy carriers with zero emission of GHG;
3) must be available at any place and any time;
4) must be compatible with existing infrastructure;
5) in transition period enables coexistence of two systems;
6) should be competitive.

We show that proposed SES fulfills at large all six requirements.

All proposed energy carriers in the new SES have the ExROExI more than 1.

This means that the proposed sustainable energy system is longterm sustainable and from the social point of view acceptable for all countries on the planet Earth. Those not having enough biomass for carbon recycling have more direct solar exergy and can cover their needs for organic carbon by international trade of solar electricity to biomass.

We have to stress, that the proposed SES can exist with the present one in transition time to 100% of RE supply and is able to use most of the present infrastructure for distribution and conversion of proposed exergy carriers.

References:

[1] ECO Design Directive, 2009/125/EC; Renewable Energy Directive 2009/28/EC; Energy Efficiency Directive 2012/27/EU; EPDB 2010/31/EU; Energy Union /*COM/2015/080final*/, Closing the loop –An EU action plan for the circular economy, /COM (2015) 614 final/.

[2] http://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF.

[3] http://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF.

[4] Kabelac, S.'Exergy of solar radiation', Int. J. Energy Technology and Policy, 2005, Vol .3, Nos. ½, pp. 115-122.

[5] Zamfirescu C., Dincer I.: How much exergy one can obtain from incident solar radiation J. of Applied Physics; 2009, 105, 02291.

[6] Neri M. e. all: Computing the exergy of solar radiation from real radiation data on the Italian area, 12th Joint European Thermodynamics Conference, Brescia July 1-5, 2013, pp. 452 - 457.

[7] Davidsson S.: Life Cycle Exergy Analysis of Wind Energy system, http://uu.diva-portal.org/smash/get/diva2:435510/FULLTEXT01.

[8] Rosen A.M., Bulucea A.C.: Using Exergy to Understand and Improve the Efficiency of Electrical Power System, J. Entropy 2009,11, 820-835; doi:10.3390/e11040820.

[9] Rant. Z. Strojniški vestnik, Ljubljana, 1955, No. 1, pp. 1-3.

[10] The exergy calculator: http://www.exergoecology.com/

[11] M.Z. Jacobson, M.A. Delucchi: Providing all global energy with wind, water, and solar power, Part I, Part II: Technologies, energy resources, quantities and areas of infrastructure, and materials, Energy Policy 39(2011) 1159

[12] https://en.wikipedia.org/wiki/Biomass, 04.08. 2016;

[13] https://en.wikipedia.org/wiki/Geothermal_energy, 04.08.2016

[14] US DOE: U.S. Energy Information Administration / AEO2017 Levelized Costs /

[15] https://en.wikipedia.org/wiki/Wind_wave, 29.05.2016;

[16] P. Novak: The way to the energy sustainable world, Energy and Buildings, 14 (1990) 249–256; Sustainable Energy System with Zero Emissions of GHG for Cities and Countries, Energy and Buildings (2015), http://dx.doi.org/10.1016/j.enbuild.2014.10.085.

[17] Goe, M. & Gaustad, G.; "Strengthening the case for recycling photovoltaic: An energy payback analysis"; Applied Energy 120(2014):41–48.
[18] Yue, D., You, F. & Darling, S. B. (2014). "Domestic and overseas manufacturing scenarios of silicon-based photovoltaic: Life cycle energy and environmental comparative analysis". Solar Energy 105: 669–678.
[19] Krebs, F. C. (2009). "Fabrication and processing of polymer solar cells: a review of printing and coating techniques". Solar Energy Materials and Solar Cells 93 (4);
[20] Bhandari, K. P., Collier, J. M., Ellingson, R. J. & Apul, D. S. (2015). "Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: "A systematic review and metaanalysis". Renewable and Sustainable Energy Reviews 47:133–141.
[21] Varun1, I. K. Bhat, Ravi Prakash: Life Cycle Analysis of Run-of River Small Hydro Power Plants in India; The Open Renewable Energy Journal, 2008, 1, 11-16
[22] Self S.J, Reddy B.V.; Rosen M.A: Energy and exergy analyses of geothermal plants with and without re-injection. Research J. Of Environmental Science 9 (2): 74-87, 2015;
[23] Khagendra P. Bhandarib, Jennifer M. Colliera, Randy J. Ellingsonb, Defne S. Apul:Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis, Renewable and Sustainable Energy ReviewsVolume 47, July 2015, Pages 133–141.
[24] http://tc4.iec.ch/FactSheetPayback.pdf Comparing Energy Options, 6.8.2016.
[25] Novak P.:Full cycle from solar irradiation to the ethanol, sugar cane to ethanol, Brasilia, EEA Seminaron Biomass, Copenhagen 2010; EEA Seminar: Transport, Mobility and Environment, Ljubljana, 02.10.2012.
[26] Kewen Li: Comparison of geothermal with solar and wind power generation systems, PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2013.
[27] Pandeyr S, Saini H: A techno-energetic review on hydrogen production using wind energy, International Journal of Innovation and Scientific Research, Vol. 11 No. 2 Nov. 2014, pp. 312- 321.
[28] Kimball J.: Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production, 17 OCTOBER 2011; http://8020vision.com/2011/10/17/energy-return-on-investment-eroi-foru-s-oil-and-gas-discovery-and-production/, 07.08.2016.
[29] Gupta A.K, Hall C. A.S.: A Review of the Past and Current State of EROI Data, Sustainability 2011, 3, 1796-1809.
[30] https://de.wikipedia.org/wiki/Power-to-Gas, 07.08.2016.
[31] http://www.biofuelstp.eu/factsheets/methanol-fact-sheet.html, 07.08.2016.
[32] G. Wall, M. Gong: On exergy and sustainable development—Part 1: Conditions and concepts/ Exergy Int. J. 1(3) (2001) 128–145; Part 2: Indicators and methods/Exergy Int. J. 1(4) (2001) 217–233.
[33] E. Sciuba., G.Wall: A brief Commented History of Exergy From the Beginnings to 2004/Int. J. of Thermodynamics, Vol. 10 (No. 1), pp. 1-26, March 2007 ISSN 1301-9724.
[34] http://www.greenpeace.org/international/Global/international/publications/climate/2015/Energy-Revolution-2015-Full.pdf, 07.08.2017, pg.44.
[35] Xudong Zhen, Yang Wang: An overview of methanol as an internal combustion engine fuel, Renewable and Sustainable Energy Reviews, December 2015, DOI: 10.1016/jrser.2015.07.083.
[36] Charles J. Barnhart,*a Michael Dale,a Adam R. Brandtb and Sally M.Bensonab: The energetic implications of curtailing versus storing solarand wind-generated electricity; Energy Environ. Sci. , 2013, 6, 2804.
[37] F. Ferroni, R.J. Hopkirk: Energy Return on Energy Invested (ERoEI) for photovoltaic solar system in regions of moderate insolation, J. Energy Policy 94 (2016), 336-344.