Eurasian Super Grid for 100% Renewable Energy power supply: Generation and storage technologies in the cost optimal mix

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Abstract

Increasing ecological problems provoked by human activities, including the fossil fuel based energy sector, emerge the development of a renewable energy (RE) based system as the way to stop pollution and global warming but also to reduce total energy system cost. Small population density and availability of various types of RE resources in Eurasian regions including solar, wind, hydro, biomass and geothermal energy resources enables the very promising project of building a Super Grid connecting different Eurasian regions' energy resources to reach synergy effects and make a 100% RE supply possible. For every sub-region it is defined a cost-optimal distributed and centralized mix of energy technologies and storage options, optimal capacities and hourly generation. Charge and discharge profiles of storages are computed for regions interconnected by high-voltage direct current (HVDC) power lines. System cost and levelized cost of electricity (LCOE) for each sub-region are computed. The results show that a 100% RE-based system is lower in cost than nuclear and fossil carbon capture and storage (CCS) alternatives.

Keywords: *100% Renewable Energy, Eurasia, Russia, energy system optimization, storage, grid integration, Economic Analysis.*

1. Introduction

Installation of distributed small-scale and centralized PV plants is already profitable in numerous regions in the word and PV electricity generation cost tends to decrease further (Breyer and Gerlach, 2013; Vartiainen et al., 2015). However, the share of PV generation is bound by the need to install storage systems in order to reach a high PV share of more than about 30% in total energy supply. Interconnection of various regions with different demand and renewable energy (RE) resource profiles can decrease the need for storage solutions and increase the reliability of the RE-based system for reaching a 100% RE supply in the very end. A cost competitive 100% RE system can be reached in case of optimal design and wise utilization of all available RE resources in order to reach maximum synergy between various resources and different regions.

The idea of a global Super Grid for power supply was already discussed some years ago (Komoto et al., 2009) and again recently (State Grid Corporation of China, 2015), but attracted new attention by the Gobitec and North-East Asian Super Grid initiative, which considers the eastern parts of Eurasia as part of the North-East Asian Super Grid (Mano et al., 2014; Komoto et al., 2009; Taggart et al., 2012; Song, 2012; Song, 2014; Komoto et al., 2013; Breyer et al., 2015), influenced by the EU-MENA Desertec (Dii, 2012; Knies, 2009). Bridging technologies such as power-to-heat and heat storage (Böttger et al., 2014) will convert electricity generation losses and electricity curtailment to valuable heat for residential and industrial needs. Power-to-water in the form of seawater reverse osmosis (SWRO) desalination starts to play a major role for the clean water targets. Power-to-Gas (PtG) technology based on water electrolysis, CO_2 from air, and methanation reactors will provide 100% renewable synthetic natural gas supply for chemicals, fertilizers, other industries, transportation and other non-power sectors (Sterner, 2009; Agora Energiewende, 2014a). All these technologies and high renewable energy potentials of Eurasia makes the installation of a RE-based system in the region possible. However, a cost competitive 100% RE system can be reached in case of optimal design and wise utilization of all available RE resources in order to reach a maximum synergy between various resources, different regions and the integration of energy sectors. Design of optimal energy system is the main

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aim of this paper.

2. Methodology

In order to define a cost optimal 100% RE system we have created a model based on linear optimization of energy system parameters under given constrains. The energy system model includes various power generation and storage technologies, as well as water desalination and synthetic gas generation sectors, which operate as flexible demand.

2.1 Model overview

The energy system optimization model is based on a linear optimization of the system parameters under a set of applied constraints with the assumption of a perfect foresight of RE power generation and power demand. A multi-node approach enables the description of any desired configuration of sub-regions and power transmission interconnections, i.e. not all the sub-regions have to be interconnected, but a grid configuration can be defined in scenario assumptions or can be chosen close to an existing grid configuration. The main constraint for the optimization is the matching of the demand and generation of every sector for every hour of the applied year. The hourly resolution of the model significantly increases the computation time; however, it guarantees that for every hour of the year the total generation within a sub-region covers the local demand from all the sectors and enables a more precise system description including synergy effects of different system components for the power system balance.

The target of the system optimization is the minimization of the total annual cost of the system including the power sector and additional flexible electricity demand sectors (water desalination and gas synthesis sectors). System cost is calculated as the sum of the annual costs of installed capacities of the different technologies, costs of energy generation and generation ramping. The system also includes distributed generation and self-consumption of residential, commercial and industrial electricity consumers (prosumers) by installing respective capacities of rooftop PV systems and batteries. For these prosumers, the target function is minimal cost of consumed energy calculated as the sum of self-generation, annual cost and cost of electricity consumed from the grid, minus benefits from the sale of excess energy.

2.2 Input data

The model uses several types of input datasets and constraints:

- historical weather data for direct and diffuse solar irradiation, wind speed and precipitation amounts,
- historical daily water flow data in the major rivers and water reservoirs,
- synthetic geothermal energy potential data,
- synthetic load data for every sub-region,
- non-energy sector natural gas consumption for every sub-region,
- projected water desalination demand for every sub-region,
- technical characteristics of used energy generation, storage and transmission technologies, such as power yield, energy conversion efficiency, power losses in transmission lines and storage roundtrip efficiency,
- technical characteristics of used SWRO desalination,
- capital expenditures, operational expenditures and ramping costs for all technologies,
- electricity costs for residential, commercial and industrial consumers,
- limits for minimum and maximum installed capacity for all energy technologies,
- configuration of regions and interconnections.

The datasets for solar irradiation components, wind speed and precipitation are taken from NASA databases (Stackhouse and Whitlock, 2008; Stackhouse and Whitlock, 2009) and partly reprocessed by the German Aerospace Center (Gerlach et al., 2011; Stetter, 2012). The spatial resolution of the data is 0.45˚x0.45˚. The time resolution is hourly for wind speed and solar irradiation, and monthly for precipitation. The feed-in time series for fixed optimally tilted solar photovoltaic (PV) systems is computed in accordance to Gerlach et al. (2011), based on Huld et al. (2008) and for single-axis north-south oriented continuous horizontal tracking, on

Duffie and Beckmann (2013). The feed-in time series for wind power plants is computed in accordance to Gerlach et al. (2011) for standard 3 MW wind turbines (E-101) for hub height conditions of 150 meters (Enercon, 2014).

Geothermal data are evaluated based on existing information on the surface heat flow rate (IASPEI, 2015; AAPG, 2015) and surface ambient temperature for the year 2005 globally. For areas where surface heat flow data are not available, the extrapolation of existing heat flow data were performed. Based on that, temperature levels and available heat of the middle depth point of each 1 km thick layer, between depths of 1 km and 10 km (Chamorro et al., 2014a,b; Huenges, 2012) globally with 0.45˚x0.45˚ spatial resolution, are derived.

Water demand is calculated based on water consumption projections and future water stress (Luck et al., 2015). It is assumed that water stress greater than 50% shall be covered by seawater desalination. Transportation costs are also taken into account; calculations are described in Caldera et al. (2015). Industrial gas consumption is based on consumption and distribution data from central statistical database of the Federal State Statistics Service of Russia (2015), BP gas consumption data (BP, 2014) and IEA gas consumption projections to the year 2030 (IEA, 2014; IEA, 2013).The synthetic load data are based on public available hourly load data on a national level, e.g. for Japan but also European countries, and takes into account local data such as gross domestic product, population, temperature and power plant structure.

2.3 Applied technologies

The technologies applied in the Eurasian energy system optimization can be grouped into three main categories: conversion of RE resources into electricity, energy storage, and electricity transmission.

The technologies for converting RE resources into electricity applied in the model are ground-mounted (optimally tilted and single-axis north-south oriented horizontal continuous tracking) and rooftop solar PV systems, concentrating solar thermal power (CSP), wind onshore, hydro power (run-of-river and dams), biomass plants (solid biomass and biogas), waste-to-energy power plants and geothermal energy.

The energy storage technologies used in the model are battery storage, pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES) and power-to-gas (PtG) technology. PtG includes synthetic natural gas (SNG) synthesis technologies: water electrolysis, methanation, CO_2 scrubbing from air, gas storage, and both combined and open cycle gas turbines (CCGT, OCGT). SNG synthesis process technologies have to be operated in synchronization because of hydrogen and CO_2 storage absence. Additionally, there is a 48-hour biogas buffer storage and a part of the biogas can be upgraded to biomethane and injected to the gas storage.

The electricity transmission technologies are represented on two levels: power distribution and transmission within the sub-regions are assumed to be based on standard alternating current (AC) grids and inter-regional transmission grids are modelled on high voltage direct current (HVDC) technology. Power losses in the HVDC grids consist of two major components: length dependent electricity losses of the power lines and losses in the converter stations at the interconnection with the AC grid. The full model block diagram is presented in Figure 1.

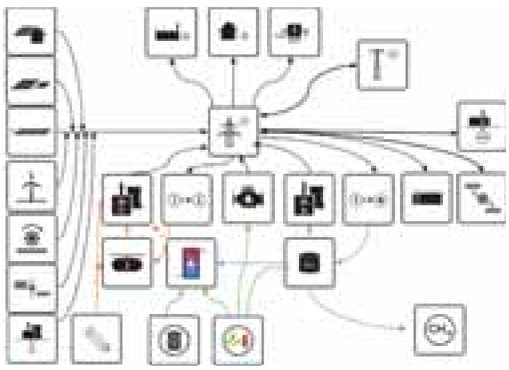

Fig. 1. Block diagram of the energy system model for Eurasia.

3. Scenario assumptions

3.1 Regions subdivision and grid structure

The Eurasian region is divided into 13 sub-regions. These are seven Federal Districts of Russia, Belarus, Kazakhstan, Uzbekistan, Turkmenistan, Caucasus regions including Armenia, Azerbaijan and Georgia, and Pamir including republics of Kirgizstan and Tajikistan. In this paper we discuss four scenarios of energy system development options:

- Region-wide energy systems, in which all the regions are independent (no HVDC grid interconnections) and the electricity demand has to be covered by the respective region's own generation;
- country-wide energy system, in which the regional energy systems are interconnected by HVDC grids within the borders of nations;
- area-wide energy system, in which the country-based energy systems are interconnected;
- integrated scenario: area-wide energy system with water desalination and industrial gas demand, in which the PtG technology is used not only as a storage option within the system, but also covering the industrial gas demand.

The Eurasian region's subdivision and grid configuration are presented in Figure 2. Structure of HVDC grid based on existing configuration of Integrated Power System (IPS) grid.

Fig.2. Eurasian sub-regions and HVDC transmission lines configuration.

3.2 Financial and technical assumptions

The model optimization is carried out on an assumed cost basis and technological status for the year 2030 and the overnight building approach. The investment cost (capex) and operation and maintenance (opex) numbers refer in general to a kW of electrical power, in case of water electrolysis to a kW of hydrogen thermal combustion energy, and for CO_2 scrubbing, methanation and gas storage to a kW of methane thermal combustion energy. Efficiencies of water electrolysis, CO_2 scrubbing and methanation refer to the higher heating value of hydrogen and methane, respectively. The financial assumptions for the energy system components including HVDC transmission lines for the 2030 reference year are provided in the Supplementary Material (Table I). The financial assumptions for storage systems refer to a kWh of electricity, and gas storage refers to a thermal kWh of methane at the lower heating value. Financial numbers for HVDC transmission lines and converter stations are given for the net transmission capacity (NTC). Assumptions are mainly taken from Pleßmann et al. (2014) but also other sources (Komoto et al., 2009; Hoffmann, 2014, Fraunhofer ISE, 2014; Urban et al., 2009; European Commission, 2014a). The technical assumptions concerning power to energy ratios for storage technologies, efficiency numbers for generation and storage technologies and power losses in HVDC power lines and converters are provided in the Supplementary Material (Tables II, III and IV, respectively). Electricity prices for residential, commercial and industrial consumers in Russia for the year 2030 are taken from Gerlach et al. (2014) and applied for all other regions. Prices are provided in the Supplementary Material (in Table V). Excess generation, which cannot be self-consumed by the prosumers, is assumed to be fed into the grid for a transfer price of 2 €cents/kWh. Prosumers cannot sell to the grid more power than their own annual consumption.

3.3 Feed-in for solar and wind energy

The feed-in profiles for solar CSP, optimally tilted, single-axis tracking PV and wind energy are calculated based on NASA data on direct and diffuse solar irradiation, wind speed, temperature and surface roughness for the year 2005 reprocessed by the German Aerospace Center. The assumed wind power plants consist of 3 MW wind turbines at 150 meters hub height. The dataset is used in a 0.45˚x0.45˚ spatial and hourly temporal resolution for the real weather conditions of the year 2005. Feed-in full load hours for sub-regions are computed on the basis of the 0.45˚x0.45˚ spatially resolved single sub-area data using a weighted average formula. The sub-regions' numbers are calculated using the rule: 0%-10% best sub-areas of a region are weighted by 0.3, 10%-20% best sub-areas of a region are weighted by 0.3, 20%-30% best sub-areas of a region are weighted by 0.2, 30%-40% best sub-areas of a region are weighted by 0.1 and 40%-50% best sub-areas of a region are weighted by 0.1. The computed average full load hours for CSP, optimally tilted, single-axis tracking PV systems and wind power plants are provided in the Supplementary Material (Table VI).

The aggregated profiles of solar PV generation (optimally tilted, single-axis tracking), CSP solar field and wind energy power generation, normalized to maximum capacity averaged for Eurasia, are presented in Figures 3.

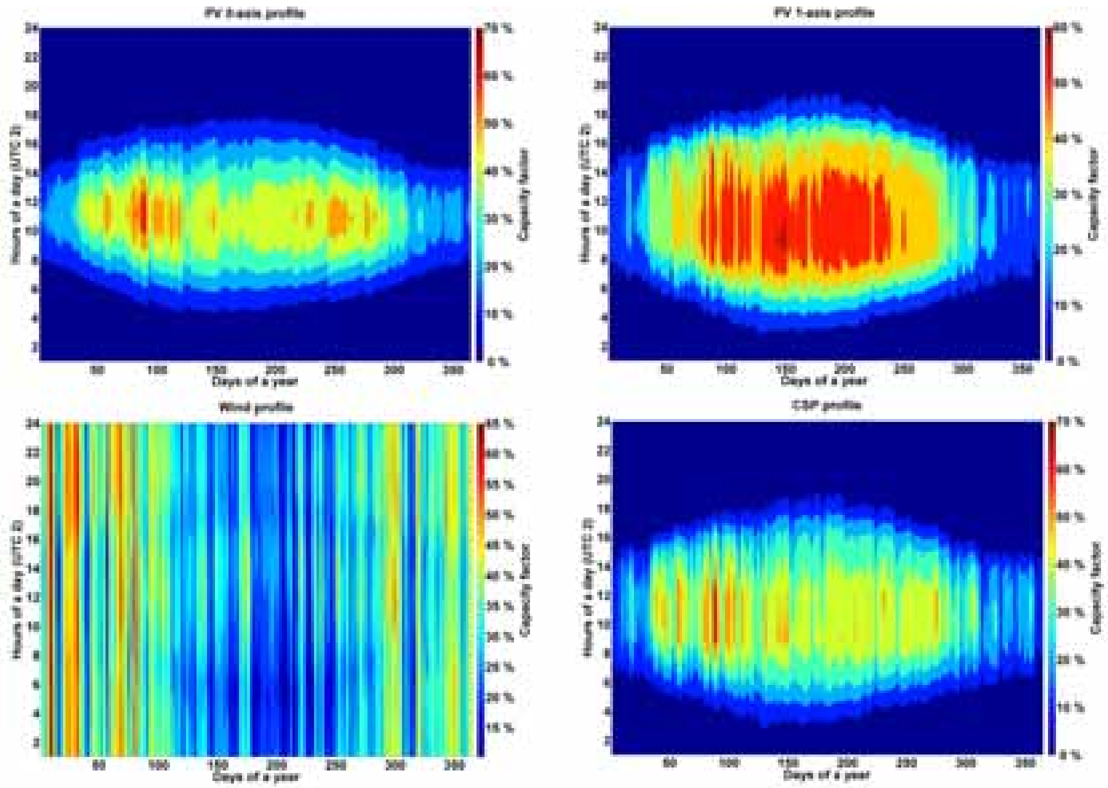

Fig.3. Aggregated feed-in profiles for optimally tilted PV (top left), single-axis tracking PV (top right), 3 MW 150 m hub height wind turbine (bottom left) and CSP solar field (bottom right).

3.3 Biomass and geothermal heat potentials

Biomass and waste resource potentials are mainly taken from DBFZ (2009). All bio-waste is divided in three components: solid waste, solid biomass and biogas sources. Solid waste is comprised of municipal and industrial used wood; solid biomass includes straw, wood and coconut residues; biogas sources are excrements, municipal bio-waste and bagasse. Costs for biomass are calculated using data from the International Energy Agency (IEA, 2012) and Intergovernmental panel on climate change (IPCC, 2011). For municipal solid waste a 50 €/ton gate fee is assumed for waste incineration. Calculated solid biomass, biogas, solid waste and geothermal heat potentials are provided in the Supplementary Material (Table VII). Prices for biomass fuels are provided in the Supplementary Material (Table VIII), and price differences between countries are explained by various waste and residue component shares.

Regional geothermal heat potentials are calculated based on spatial data for available heat, temperature and geothermal plants for depths from 1 km to 10 km. For each 0.45˚x0.45˚ area and depth, geothermal LCOE is calculated and optimal well depth is determined. It is assumed that only 25% of available heat will be utilised as an upper resource limit. The total available heat for the region is calculated using the same weighed average formula as for solar and wind feed-in, except for the fact that areas with geothermal LCOE exceeding 100 €/MWh are excluded.

3.4 Upper and lower limitations on installed capacities

Lower and upper limits are applied to renewable energy sources (PV, wind onshore, and hydro power) and pumped hydro storage. For CSP, biomass, biogas, waste-to-energy power plants, gas turbines, battery and gas storage, and units of the power-to-gas process, the lower limit is set to zero. For lower limitations of PV systems, wind power plants, hydropower plants and PHS storage systems, data of existing installed capacities in Eurasian sub-regions have been taken mainly from the GlobalData (2015) database and the Platts (2012) database . Lower limits on already installed capacities in Eurasian sub-regions are provided in the Supplementary Material (Table IX).

Upper limits for CSP, PV systems (optimally tilted, single-axis tracking) and wind power plants are based on land use limitations and the density of capacity. The maximum area covered by solar systems is set to 6% of the total sub-regions' territories and for wind power plants to 4%, respectively. The capacity densities are 225 MW_{th}/km^2 for the CSP solar field, 75 MW/km^2 for PV systems (optimally tilted, single-axis tracking) and 8.4 MW/km^2 for wind onshore power plants. For hydro power plants and PHS storage, upper limits are set to 150% and 200% of already installed capacities by the end of 2013. All upper limits of installable capacities in Eurasian sub-regions are summarized in the Supplementary Material (Table X). For all other technologies, upper limits are not specified. However, for biomass residues, biogas and waste-to-energy plants it is assumed, due to energy efficiency reasons, that the available and specified amount of the fuel is used during the year.

3.5 Load

The demand profiles for sub-regions are computed as a fraction of the total country demand based on synthetic load data weighted by the sub-regions' populations. Figure 4 represents the area-aggregated demand of all sub-regions in Eurasia. Electricity demand increase by year 2030 is estimated using IEA data (IEA, 2014), numbers for Kazakhstan and Belarus are based on GlobalData assumptions (GlobalData, 2010; GlobalData, 2013).

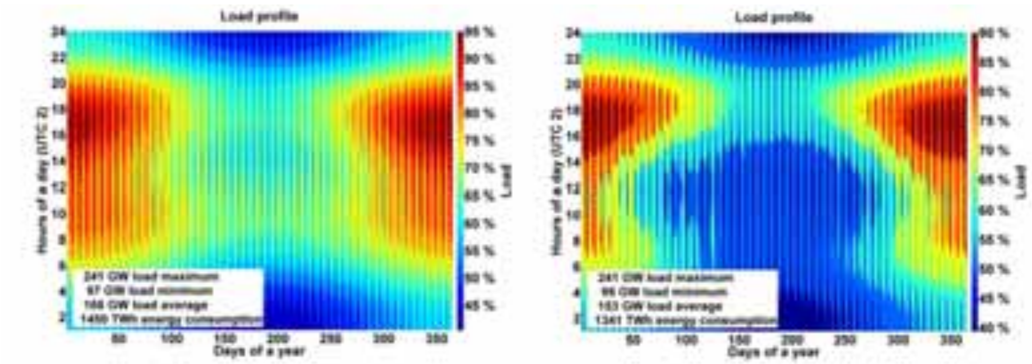

Fig. 4. Aggregated load curve (left) and system load curve with prosumers influence (right) for the year 2030.

Industrial gas demand values (gas demand excluding electricity generation and residential sectors) and desalinated water demand for Eurasia sub-regions are presented in the Supplementary Material (Table XI), gas demand values are based on the IEA data and the Federal State Statistics Service of Russia. Desalination demand numbers are based on water stress and water consumption projection.

4. Results

To analyze the cost structure of the different scenarios, a set of fundamental parameters are computed according to methodology described in Breyer et al. (2015).

4.1 Main findings on the optimized energy system structure and costs

For all scenarios optimized electrical energy system configurations are derived and characterized by optimized installed capacities of RE electricity generation, storage and transmission for every modelled technology, leading to respective hourly electricity generation, storage charging and discharging, electricity export, import and curtailment. The average financial results of the different scenarios for the total system (including PV self-consumption and the centralized system) are expressed as levelized cost of electricity (LCOE), levelized cost of electricity for primary generation (LCOE primary), levelized cost of curtailment (LCOC), levelized cost of storage (LCOS), levelized cost of transmission (LCOT), total annualized cost, total capital expenditures, total renewables capacity and total primary generation, as presented in Table I. Weighted average cost of capital (WACC) is set to 7% for all scenarios, but for residential PV self-consumption WACC is set to 4%.

From Table I it can be easily seen that the installation of HVDC transmission lines has a positive impact on the electricity cost and annual expenditures of the system; electricity cost of the entire system in the case of area-wide open trade power transmission decreases 6.0% and 14.6% compared to the country-wide and region-wide scenarios, respectively. Grid utilization decreases the primary energy conversion capacities and generation by 10.0% and 21.0% in terms of installed capacities and by 4.0% and 8.9% in terms of generated electricity in reference to country-wide and region-wide scenarios, respectively. Grid utilization leads to a significant decrease of storage utilization, whereas cost of transmission is relatively small in comparison to the decrease in primary generation and storage costs. Curtailment costs do not decrease as much as storage cost in the case of broader grid utilization; however, the impact of excess energy on total cost is rather low. The rather small difference between area-wide and country-wide scenarios can be explained by the dominant share of Russia in the total electricity demand.

The integration of water desalination and industrial gas synthesis sectors results in a further decrease in LCOE of 18.9% compared to the area-wide open trade scenario. This cost reduction is mainly explained by a reduction of storage cost by 82% due to additional flexibility provided by the gas synthesis and desalination sectors decreasing the need of storage utilization. Primary electricity generation cost decreased by 5.3%, mainly because of increased flexibility of the system. Flexible demand simplifies utilization of low-cost wind and solar electricity, and that leads to a decrease of flexible geothermal and biomass power plants capacities, as can be seen in Table II. For the case of biogas a substantial fraction is re-allocated from the electricity sector to the industrial gas demand for efficiency reasons. The share of hydro dam power plants does not change since flexibility provided by this source is still needed and the upper limit is reached for most of the regions, even interregional electricity trade decreases, which leads to a 40% fall in electricity transmission cost.

Whereas the total installed capacity of RE decreases with an increase of grid utilization, the installed capacity of wind turbines increases the more the energy system is interconnected and integrated. For Eurasia wind is the least cost RE source, thus wind energy imports displace a part of higher cost inland solar PV generation. Optimally tilted PV share is close to zero in almost all regions. However, for the region-wide and country-wide scenarios in the Caucasus region the installed capacity of optimally tilted PV exceeds single-axis tracking PV capacity and is 77.5% of total power system PV capacities in the region due to the less favorable solar irradiation conditions, which decrease the benefits of the single-axis tracking PV technology. Obviously, transmission lines decrease the need for energy storage options; installed capacities of batteries, PHS, A-CAES, heat storage, Power-to-Gas and gas turbines decrease with the grid expansion. PHS capacity stays the same for all scenarios and equal to lower limit of installation.

Table I: Financial results for the four scenarios applied in Eurasian regions.

	Total LCOE	LCOE primary	LCOC	LCOS	LCOT	Total ann. cost	Total CAPEX	RE capacities	Generated electricity
	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[€/MWh]	[b€]	[b€]	[GW]	[TWh]
Region-wide	62.6	42.7	3.2	16.8	0.0	91	837	739	1771
Country-wide	56.9	41.8	2.2	10.5	2.4	82	758	648	1681
Area-wide	53.5	41.0	1.5	7.1	3.9	77	713	583	1613
Integration scenario	43.4	38.8	0.9	1.3	2.3	125	1166	981	2654

Table II: Overview on installed RE technologies and storage capacities for the four scenarios.

		Region-wide	Country-wide	Area-wide	Integration scenario
PV self-consumption	[GW]	91.5	91.5	91.5	91.5
PV optimally tilted	[GW]	6.0	6.0	6.5	0.2
PV single-axis tracking	[GW]	109.4	49.0	15.5	170.9
PV total	[GW]	206.9	146.5	113.4	262.6
CSP	[GW]	0	0	0	0
Wind energy	[GW]	327.2	317.9	300.0	559.8
Biogas power plants	[GW]	15.2	15.1	13.8	10.4
Biomass power plants	[GW]	17.3	16.7	16.4	14.5
MSW incinerator	[GW]	1.3	1.3	1.3	1.3
Geothermal energy	[GW]	2.7	2.7	2.7	2.4
Hydro Run-of-River	[GW]	0.2	0.2	0.1	6.4
Hydro dams	[GW]	88.4	87.8	90.9	91.2
Battery PV self-consumption	[GWh]	0	0	0	0
Battery total	[GWh]	15.2	15.2	8.7	0.5
PHS	[GWh]	9.0	9.0	9.0	9.0
A-CAES	[GWh]	1783.5	497.4	0.3	0.0
Heat storage	[GWh]	0	0	0	0
PtG electrolyzers	[GW_{el}]	32.5	21.7	15.8	105.2
CCGT	[GW]	48.4	33.5	27.2	0.6
OCGT	[GW]	40.3	37.1	28.6	33.3
Steam Turbine	[GW]	0.8	0.8	0	0

In the case of the region-wide open trade scenario, all sub-regions of Eurasia need to match their demand using only their own RE resources. In the case of the country-wide and area-wide open trade scenarios, a division of regions into net exporters and net importers can be observed. An annual import and export diagram for area-wide open trade is presented in Figure 5. Differences in generation and demand are mainly due to export and import, but in a minor quantity also due to storage losses, and for the area-wide integrated sector scenario (not shown in Fig. 5) due to energy consumption for SNG production. Figure 5 also gives a good overview on regions' RE resources; net exporters are sub-regions with the best renewable resources and net importers are sub-regions with moderate ones.

Fig. 5. Annual generation and demand diagrams for area-wide open trade scenario.

Figure 5 reveals the net exporter regions: North-West Russia and Pamir regions. Net importers are Central Russia and Belarus. Hourly resolved profiles for regional generation in Importer region (Central Russia), Balancing region (Kazakhstan) and Exporting region (North-West Russia) are presented in the Supplementary Material (Fig. 1, 2 and 3, respectively). For the integrated scenario a drastically increased electricity demand for the desalination and SNG producing sectors changes the picture dramatically; SNG producing regions tend to increase the intra-regional electricity generation to fulfill the increased demand.

PV self-consumption overview is given in the Supplementary Material (Table XII). Self-generation does not play a significant role due to low electricity price and covers only 37.3% of residential prosumers' demand, 30.7% and 31.8% of demand for commercial and industrial prosumers. An overview of installed capacities for the sub-regional energy system structures is presented for three different scenarios (region-wide, area-wide and integrated scenario) in Figure 6.

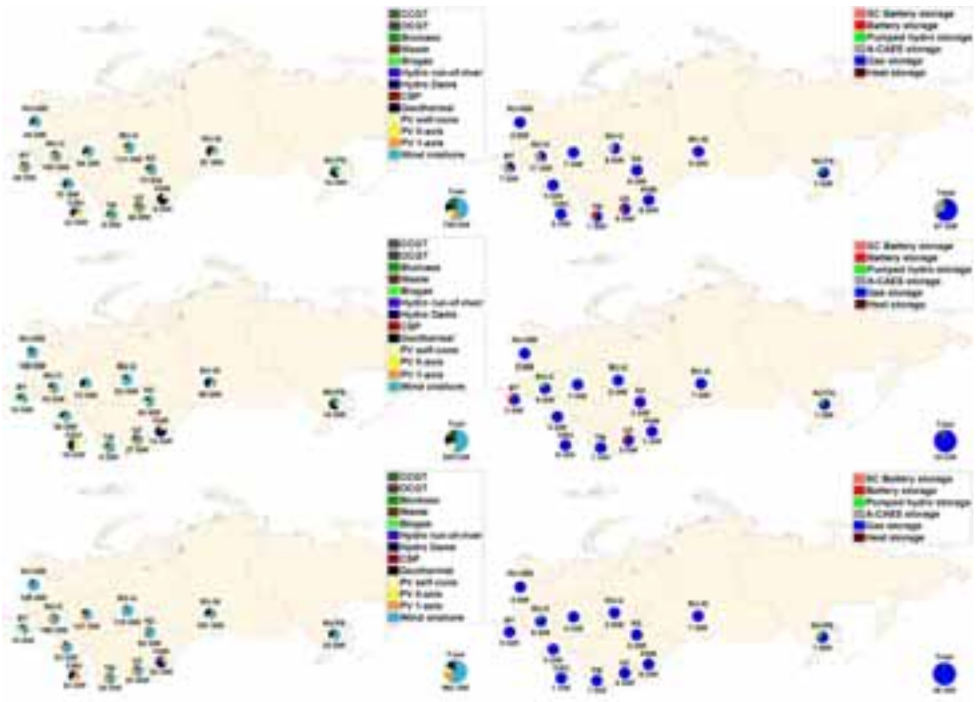

Fig. 6. Installed capacities of RE generation (left) and storages (right) for region-wide (top), area-wide (center) open trade and integrated (bottom) scenarios.

From Figure 6 we can see that in the case of region-wide open trade in the sub-regions of Belarus, Central

Russia and Caucasus, the solar PV capacities exceed 30% of all installed power capacities despite the fact that wind power FLH in these regions are better or comparable to PV FLH. Upper limit for wind is not reached as well, but optimal mix of capacities in these regions includes high share of PV. The interconnected HVDC transmission grid significantly decreases total installed capacities (Fig. 6 and Tab. II) and especially solar PV capacities, whereas installed capacities are increased in wind resource rich regions, such as North-West Russia.

For the integrated scenario the installed capacities of PV increase again because of a higher electricity demand and increased system flexibility. Additional demand in the case of a RE-based energy system can change the entire system structure because of shifting optimal cost structure parameters and areas being confronted with their upper resource limits.

The structure of HVDC power lines and utilized RE resources strongly influences the total storage capacity needed, but also interferes with the composition of different storage technologies for the energy system in the same area. Data of storage systems discharge capacities, annual energy throughput and full load cycles per year are summarized in the Supplementary Material (Table XIII). The generation capacities of storage technologies decrease with integrations of the HVDC grid. However, for the integrated scenario capacities of storage technologies increase in absolute numbers. State-of-charge profiles for the area-wide scenario for battery, PHS, A-CAES and Gas storages are provided in the Supplementary Material (Fig. 4)

The findings for the aggregated area integrated scenario can be summarized in an energy flow diagram comprised of the primary RE resource converters, the energy storage technologies and the HVDC transmission grid. The difference of primary power generation and final electricity demand is subdivided into potentially usable heat and ultimate system losses. Both are comprised of curtailed electricity, heat produced by biomass, biogas and waste-to-energy power plants, heat of transforming power-to-hydrogen in the electrolyzers, hydrogen-to-methane in methanation and methane-to-power in the gas turbines, and the efficiency loss in A-CAES, PHS, battery storage, as well as by the HVDC transmission grid. This energy flow for the integrated system is presented in Figure 7; diagrams for the region-wide and area-wide scenarios are presented in the Supplementary Material (Fig. 5).

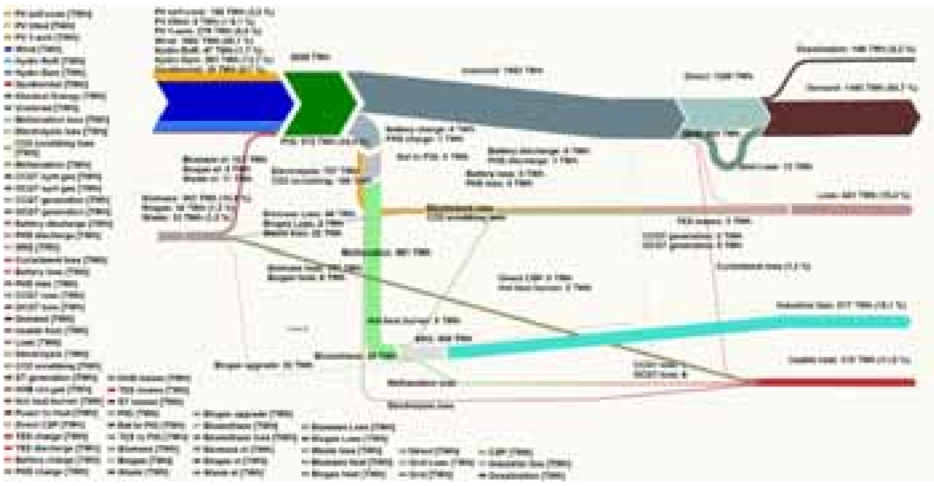

Fig. 7. Energy flow of the system for the integrated scenario.

The numeric values for LCOE components and the import/export share in all regions and scenarios are summarized in the Supplementary Material (Table XIV). The share of export is defined as the ratio of net exported electricity to the generated primary electricity of a sub-region and the share of import is defined as the ratio of imported electricity to the electricity demand. The area average is composed of sub-regions' values weighted by the electricity demand.

5. Discussion

The installation of a HVDC transmission grid enables a significant decrease in the cost of electricity in the RE-based system. The total levelized cost of electricity in the region decreased from 62.6 €/MWh for the region-wide open trade scenario to 56.8 €/MWh for the country-wide open trade scenario and 53.5 €/MWh for the area-wide open trade scenario. The total annualized cost of the system decreased from 91 b€ to 77 b€. In parallel the capex requirements are reduced from 837 b€ for the region-wide open trade to 758 b€ and 713 b€ for the country-wide and area-wide open trade scenarios, respectively. Additional costs of HVDC transmission lines (annual cost 5.6 b€, capex 61 b€ for area-wide scenario) are compensated by a substantial decrease in generation and storage capacities enabled by lower losses and costs of energy transmission compared to energy storage, and access to low cost electricity generation in other regions. In addition, the HVDC transmission grid enables additional benefits due to the large spatial east-west dimension of the Eurasian region.

PV self-consumption influences the power sector in an interesting way. The region-wide, country-wide and area-wide open trade scenarios are also calculated without PV self-consumption and the total demand is assumed to be covered by a more centralized system. The annualized costs for the more centralized 100% RE system is 1.7% lower for the region-wide scenario (89.5 b€ against 91 b€ base scenario), and 2.2% lower for the country-wide scenario, and 2.4% lower for the area-wide open trade scenario. PV self-consumption provokes additional costs because of a different target function of prosumers. Prosumers tend to reach their minimum annual cost of electricity consumption. The LCOE of PV self-consumption then must be lower than the grid electricity selling price, but can be higher than the total system LCOE. In addition to higher generation cost, prosumers' electricity generation provokes some positive and negative distortion in the system demand profile, i.e. the system reacts by installing more flexibility granting capacities, such as low cost RE or further storage capacities, which increases the system costs as well. The peak load in the system is not reduced due to the fact that peaks occurs in the winter time, when solar PV generation is negligible in the major parts of Eurasia, however the load gradients in the system are reduced from spring to autumn during daylight hours. For the region-wide scenario a comparable low cost increase due to the decentralized generation can be explained by the fact that additional disturbance cost in the system (provoked by prosumers) is compensated by access to low cost residential electricity (for residential consumers WACC is assumed to be 4%). Finally, PV self-consumption is in particular valuable in area constraint regions, since zero impact areas on rooftops can be utilized for local electricity generation, which in turn reduces the requirement of imports. This may be in some regions a policy option for reaching higher local value creation and less foreign policy risk, induced by higher electricity imports.

The fourth scenario, integration, represents the possibility to cover projected natural gas demand (except the gas demand for power generation and residential purposes), and clean water demand by SNG generation and SWRO desalination, respectively. In parallel with supplying demand, such an integration gives the system additional flexibility, especially for seasonal fluctuation compensation. The availability of RE in Eurasia is sufficient to cover additional electricity demand for producing 517 TWh_{th} (49 bcm) of SNG and 18.3 billion m^3 of clean water. Adding 1100 TWh_{el} for gas synthesis and SWRO desalination induces an additional installation of RE generation capacities of 150 GW of PV and about 260 GW of wind energy. As well, former long-term gas storage is partly substituted by short-term battery storage. Next, there is a significant increase in electrolyzer units of about 90 GW and substantially reduced gas turbines and biomass powered plants capacities.

The system generates excess heat as a byproduct of biogas and biomass CHP plants, waste-to-energy incinerators, gas turbines, electrolyzers and methanation units. In addition, there is excess electricity, which can be curtailed or converted to heat, stored in heat storage and used finally in the heat sector. The usable heat amount varies from 223 TWh_{th} per year for the area-wide scenario up to 301 TWh_{th} for the region-wide scenario. The waste heat from biomass and gas power plants is evenly distributed over the year. At the same time, excess electricity is generated mainly during the period from October to April, when heat is most valuable. Cooling demand is included in electricity demand numbers and therefore does not generate an additional demand. For the integrated scenario the amount of usable heat is even higher, at 315 TWh_{th}, due to higher curtailment, whereas the heat profile distribution is mainly the same. In total the integration benefit for the electricity, water and industrial gas sectors is estimated to be about 37.7 b€ of the annual system cost. There are also decreases in the electricity demand by 355 TWh and the curtailed electricity by 46.6 TWh. These benefits account to 23%, 12% and 41%, respectively, compared to the non-integrated, separate systems. Further, the cost of clean water seems to be quite affordable at 1.49 €/m^3 and the cost of electricity decreases by 18.9% to 43 €/MWh for the integrated scenario compared to the area-wide open trade scenario without sector integration. However, the cost of synthetic gas, at 112.5 €/MWh, appears to be significantly higher than the current price.

The findings for the Eurasian 100% renewable resource-based energy system can be compared to recent insights in Europe about non-renewable options, such as nuclear energy, natural gas and coal carbon capture and storage (CCS) alternatives (Agora Energiewende, 2014). These alternatives could also lead to a low carbon energy system, which is of highest relevance for a climate change mitigation strategy. The LCOE of the alternatives are as follows (Agora Energiewende, 2014): 112 €/MWh for new nuclear (assumed for 2023 in the UK and Czech Republic), 112 €/MWh for gas CCS (assumed for 2019 in the UK) and 126 €/MWh for coal CCS (assumed for 2019 in the UK). However, a report published by the European Commission (European Commission, 2014b) concludes that CCS technology is not likely to be commercially available before the year 2030. The findings for Europe are assumed to be also valid for Eurasia in the mid-term. The 100% renewable resource-based energy system options for Eurasia presented in this work are considerably lower in cost (about 44 - 61%) than the higher risk options, which have still further disadvantages. These include nuclear melt-down risk, nuclear terrorism risk, unsolved nuclear waste disposal, remaining CO_2 emissions of power plants with CCS technology, a diminishing conventional energy resource base and high health cost due to heavy metal emissions of coal fired power plants. Dittmar (2012) also emphasizes the mentioned limitations on nuclear fission, but also points out that the financial and human research and development resources spent for nuclear fusion are no help either for the energy problems in the world and even worse these resources are not available for research of pathways towards a low cost energy future.

6. Conclusion

Existing RE technologies can generate enough energy to cover all electricity demand for the year 2030 on a significantly lower price level of 43 - 61 €/MWh_{el}, compared to non-renewable options, depending on geographical and sectoral integration. It is also possible to cover the gas demand of the industrial and transportation sectors with PtG technology, however for a gas price which is substantially higher than today. Heat generated as a byproduct of electricity, synthetic natural gas generation and curtailed electricity conversion can cover up to 300 TWh_{th} of heat demand. For the region-wide scenario PV plays the role of the main energy supply in some regions, however, with integration of the HVDC grid, the role of PV decreases in a first step, but it is increased again for a broader sectoral integration in a second step. The HVDC transmission grid plays a key role since the established Super Grid enables a significant cost decrease within the renewable resource-based energy system. The utilization of a HVDC transmission grid leads to a cut-off of storage utilization and significantly reduces primary generation capacities. At the same time, PV self-consumption induces a moderate increase of total electricity costs of 1.5 - 2.5%. This is due to the fact that consumers tend to utilize solar energy at a higher cost level and the excess electricity from prosumer generation provokes additional disturbances in the system. In turn, this increases the system need for flexibility.

For the integrated scenario it was found that industrial SNG generation displaces SNG storage as seasonal storage for the electricity sector. Instead of gas turbine utilization in case of an energy deficit, the system curtails the SNG generation in that system set-up as a major source of flexibility to the system.

More research is needed for a better understanding of a fully integrated renewable energy system in Eurasia. However, this research work clearly indicates that a 100% renewable resources-based energy system is a real low cost and low risk policy option.

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Supplementary Material

Supplementary data associated with this article can be found, in the online version, at www.researchgate.net on the profiles of the authors.

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