HYBRID PV-WIND-RENEWABLE METHANE POWER PLANTS – A POTENTIAL CORNERSTONE OF GLOBAL ENERGY SUPPLY

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ABSTRACT

Solar and wind resources are nearly abundantly available on earth. This resource availability enables the use of photovoltaic (PV) and wind energy technology on a large scale in most regions in the world. Long-term social sustainability requires a 100% renewable power supply on a low cost basis. The cost projections of PV and wind power are discussed on basis of the levelized cost of electricity (LCOE) approach for the year 2020. First results for the degree of complementarity of PV and wind power supply are discussed, but due to the fluctuating character of both major renewable power technologies an appropriate storage technology need to be added. Thus the renewable power methane (RPM) storage option is presented. The various integration options of hybrid PV-Wind-RPM power plants are discussed. Based on cost assumptions for the year 2020 the economics for hybrid PV-Wind-RPM power plants are derived on a global scale and discussed in more detail for an exemplarily site in China. First estimates for the global energy supply potential of hybrid PV-Wind-RPM power plants show both fast increasing competitiveness of the approach and comparably short distances between the centres of demand and least cost energy supply all complemented by nearly abundant resource availability. Hybrid PV-Wind-RPM power plants are characterized by all relevant attributes for becoming a potential cornerstone of the global energy supply in the next decades.

Keywords

Hybrid Power Plant, Renewable Power Methane, Fuel-Parity, Economic Analysis, Energy Options, PV Markets

1 Introduction

Photovoltaic (PV) is the fastest growing electricity generation technology in the world.[1] Second fastest growing electricity option is wind power.[2] Global solar and wind resource assessment clearly documents sustainable and the by far highest resource potentials for PV and wind of all power technologies available to the market. However the fluctuating solar and wind resources make it necessary to use fossil fuel power plant or storage capacities for balancing reasons. An emerging storage option is the renewable power methane (RPM) storage technology.

The purpose of the presented work is a first analysis of the global economic impact potential of RPM storage by end of the 2010s which would enable hybrid PV-Wind-RPM power plants establishing fully dispatchable power supply based on fluctuating wind and solar resources.

This paper presents an overview on the renewable power methane storage technology (section 2), solar and wind resource availability (section 3) and economics of system components (section 4). The global economics of hybrid PV-Wind-RPM power plants are estimated for the year 2020 (section 5) and presented in a more detailed view for the exemplarily potential market in China (section 6). The global power supply potential of hybrid PV-Wind-RPM power plants is discussed (section 7) and the results are summarized by the conclusion (section 8).

This conference contribution presents technological and conceptual results of Solar Fuel and Fraunhofer IWES and economic results of Q-Cells research. Initially the research focus at Q-Cells was led on hybrid PV-Fossil power plants [3-5] which resulted in quite similar economics for PV and wind power plants by the end of the 2010s for many sites in the world [6]. The complementarity characteristic of PV and wind power availability [7] generated the insight of firstly taking into account both major new renewable power technologies and secondly integrating the seasonal RPM storage technology for a 100% renewable power solution. All this mentioned topics are part of a more comprehensive work on the economics of hybrid PV power plants.[6]

2 Renewable Power Methane Storage

The risk mix of climate change impact, diminishing fossil fuels and nuclear hazards induces enormous pressure for restructuring the global energy supply, which is to about 87% dependent on the risk creating sources [8]. The only sustainable energy pathway is based on the various renewable energies. A stable power supply need to be based on full daily and especially seasonal adaption of renewable power supply to the load demand in the grids. The balance of seasonal renewable power supply and load demand is challenging, since both hydro storage dams and biomass power supply are very limited due to geographic and resource competition constraints.

Additionally, the major renewable power supply options are represented by solar PV and wind power (section 3), which are both fluctuating, hence flexible power generation units are needed for balancing resource availability and load demand for a stable electricity supply. This would be the case for oil, natural gas and coal fired power plants. However, the respective greenhouse gas emissions and diminishing fossil fuel resources allow these conventional power technologies only a limited function in the transition phase towards a fully renewable power supply. Nevertheless, fossil natural gas fired power plants, technically better called methane power plants, can be also fired by RPM. RPM can be produced by renewable power, air and water as input sources. The required seasonal storage of methane is already applied today. As a consequence, the power grid and natural gas grid become connected and an energy flow is made possible in both directions (Figure 1).

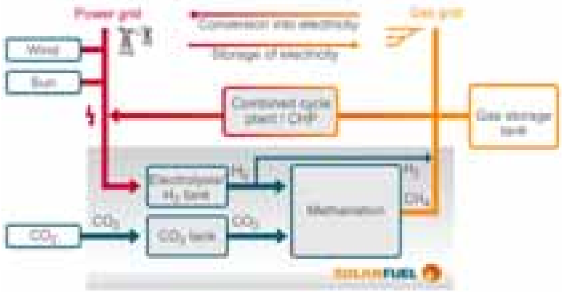


Figure 1: Hybrid PV-Wind-RPM power plant embedded in the power grid and the natural gas grid. Energy flows are possible in both directions, i.e. storage of electricity in the natural gas infrastructure and conversion of RPM into electricity. CO_2 can be used from several sources, like extraction from air, by-product of biogas plants, fossil fuel power plants or industrial processes.

Three elementary core processes are needed for RPM: electrolysis (conversion of electricity and water into hydrogen and oxygen), CO_2 supply (e.g. extraction from ambient air via dialysis process, by-product of biogas plants, fossil fuel power plants or industrial processes) and methanation (conversion of hydrogen, carbon dioxide and electricity into methane and water).[9] Good overview on the RPM concept, the relevant components and the energy system integration is given by Sterner [9], Specht et al. [10,11] and Sterner et al. [12].

The first core process is the electrolysis converting renewable electricity and water into hydrogen and oxygen (Figure 1). Several electrolysis technologies are available enabling energy conversion efficiencies of up to 80%. The technology is used since decades and can be operated at various pressures, temperatures and is scalable for industrial applications in the range of some kW to MW.[9]

The hydrogen is used in the methanation (Sabatier process), the second core process, to convert hydrogen and carbon dioxide to methane and water (Figure 1). The energy conversion can reach efficiencies up to 85% in a catalytic exothermal process on a temperature level of 180 – 350 °C and a pressure of 1 – 100 bars.[9]

Several CO_2 sourcing routes are available, e.g. by-product of biogas plants, fossil fuel power plants or industrial processes, however the most elegant way is the extraction of CO_2 from ambient air. Several processes are known for extracting CO_2 from ambient air [9], whereas in the following the focus is laid on the energy efficient ZSW process based on absorption and electrodialysis.[13]

For producing 10 MJ_{th} RPM, it is needed 16 MJ_{el} for the electrolysis process including the methanation process plus further 4.8 MJ_{el} in case of extraction CO_2 from ambient air. This translates into a renewable electricity to RPM conversion efficiency of about 63% excluding energy for CO_2 souring. Specific energy consumption of the dialysis process extracting CO_2 from ambient air represents an energy conversion efficiency of about 77%. Thus RPM using CO_2 extraction from ambient air can be generated on an efficiency level of about 49%, whereas high temperature process heat of the exothermic methanation process might be used for other purposes. About 50% of the electric energy can be chemically stored in RPM and afterwards used for all purposes fossil natural gas is used for. In case of burning RPM in modern gas power plants, i.e. in combined cycle gas turbines (CCGT) of about 58% efficiency, the full cycle efficiency would be about 37% (CO_2 available on site) and 29% (CO_2 extraction from ambient air). This full cycle storage efficiency is rather low and induces high specific cost for such stored electricity, however an easy usable seasonal energy storage would be enabled and the entire natural gas infrastructure could be used.

There are only a few and very limited seasonal electricity storage options, in particular for large scale energy storage (Figure 2).

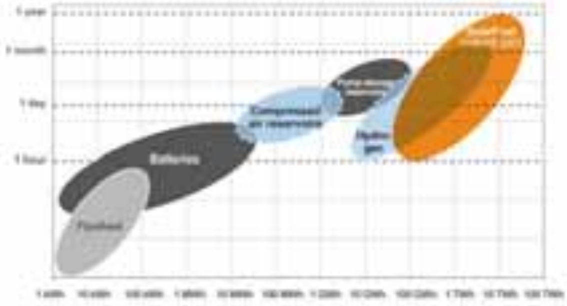


Figure 2: Overview on major electricity storage technologies in dependence on energetic storage capacity and charge cycling. RPM (denoted as Solar Fuel) is one of only few seasonal storage options for large scale energy storage.

Pumped hydro storage is the most preferred energy storage on the power plant and power grid level due to relative low cost, relative high energy storage reservoirs and a high flexibility in switching from charge to discharge operation mode. However, geographic prerequisites of substantial difference in altitude and available topographic sites limit this large scale energy storage. But a seasonal energy storage would also induce high storage cost due to a respective low cycle frequency. The remaining two seasonal storage solutions are hydrogen and methane. Seasonal storage on RPM basis might be preferred due to higher storage efficiency and already existing transport infrastructure in most regions in the world plus available energy converting units, like power plants, heating for houses, powering the transport sector and using RPM in the chemical industry.

Based on the new link power-to-gas, 100% renewable energy supply systems are designed (Figure 3). The key elements are direct renewable power generation (main "primary energy source"), renewable electromobility [14], heat pumps, RPM and overcoming traditional biomass. By integrating smart power networks, heat networks and natural gas networks, a full renewable energy supply is enabled. Several 100% renewable energy systems based on hybrid PV-Wind-RPM plants are presented, reducing global energy-related CO_2 emissions by 95%. One new key element is the mutual linking of power and gas networks.

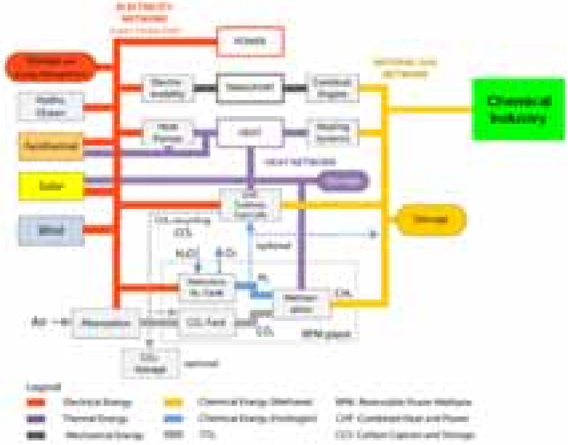


Figure 3: Hybrid PV-Wind-RPM plant (Figure 1) as the integral centrepiece of a future sustainable energy supply system.[9] The four main energy systems are integrated and positively influenced by renewable power methane, i.e. power network, natural gas network, heat network and transportation network.

Several integrated concepts with CO_2 from air, biomass, industrial processes and fossil fuels are designed. In this way, renewable power can be stored in the natural gas network and used temporarily and spatially flexible for balancing power and long-term power storage, for process heat and for (long-distance) transportation with a high-energy density CO_2-neutral energy carrier. The major benefit versus hydrogen is the use of the existing infrastructure. Hydrogen is "stored" in CO_2 and made thus available as natural gas substitute. RPM can be produced basically anywhere where water, air (CO_2) and renewable power (wind, solar, hydro) are available and thus decrease import dependence on fossil fuels and the need for new transmission lines by using existing gas grids. It can recycle CO_2 in the energy system by CO_2 capture from combustion or by the use of the generated O_2 for combustion of RPM in the oxyfuel process in combined cycle plants. This new approach can even act as carbon sink in combination with CO_2 storage and thus create "carbon sink energy systems".

3 Solar and Wind Resource Availability

The global energy supply potential of PV and wind power exceeds by far the energy demand of human mankind. Total primary energy demand has been about 151,200 TWh_{th} in the year 2008, i.e. about 17 TW of continuous energy flow.[8] However, substantial amount of this primary energy demand is wasted in inefficient energy use based on burning fuels, i.e. direct use of valuable electricity would reduce the aforementioned energy flow to about 11.5 TW provided for instance by solar PV or wind power.[15] The technical energy potential of solar PV and wind is assessed differently by various authors but always by factors or orders higher than total global energy demand. In 1978 Weingart estimated the solar PV potential energy flow usable for mankind being higher than 100 TW.[16] In 2003, the German Advisory Council on Global Change derived a harvestable energy flow potential for wind power of about 90 TW and a practically unlimited potential for PV.[17] However, these numbers have been adjusted in 2011 to a technical potential of about 54 TW for wind power and about 8,900 TW for solar energy hence also for PV.[18] In the 2008 'energy [r]evolution' study of Greenpeace the utilizable energy flow has been estimated to about 35 TW for wind power and 150 TW for PV.[19] Also in 2008, Sawin and Moomaw estimated the energy flow potential to about 145 TW for PV and about 55 TW for wind power.[20] In 2009, Lu et al. estimated the energy flow for wind power to about 80 – 150 TW.[21] Jacobson and Delucchi derived an energy flow of 40 – 85 TW for wind and 580 TW for PV.[15] In 2011 the IPCC derived a theoretically utilizable energy flow of about 190 TW for wind power and about 120,000 TW for PV.[22] Other authors clearly pointed out that wind and solar energy will become the backbone of the global energy supply and that this could happen already before 2030.[23] The insight of the necessity to establish a solar powered society lays many decades in the past and was emphasized for instance by Hubbert already in 1949.[24]

The three major power technologies in relation to minimised fully loaded social cost are solar PV, wind power and hydro power (section 4). But only solar PV and wind power have access to nearly abundant resources, whereas the solar resource is the most homogeneous distributed energy source in the world. It is a godsend that the two least cost energy options for the 21st century are fully complementary to each other.[7]

A first global analysis of the complementary characteristics of PV and wind power plants gives plenty of indications that this two major renewable power technologies complement each other to a very high extend (Figure 4) and show nearly no competition due to the fundamental underlaying solar and wind resources.[7] The degree of complementarity is measured by overlap full load hours (FLh), i.e. the amount of power provided by PV and wind power plants adjacent to each other in the same time interval. However, typically the overlap FLh indicate a good complementarity due to part load conditions of the respective power plants. For extracting the amount of power being problematic, the critical overlap FLh are defined, i.e. the amount of power being above the rated capacity of PV or wind power per geographic unit and time interval. In these cases the renewable power might be lost due to limited power line, balancing power plant or storage capacities. The first insights for the analysis of the complementarity of PV and wind power is depicted in Figure 4.

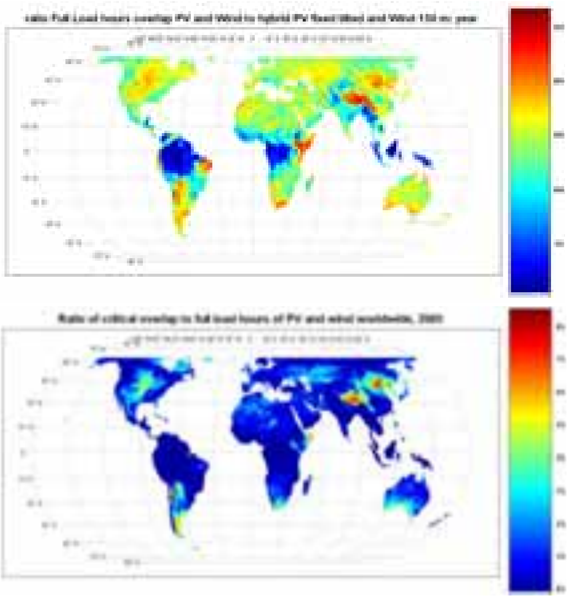


Figure 4: Ratio of annual total (top) and critical (bottom) overlap full load hours of PV and wind power to added up full load hours of both power technologies.[7] Assumed are PV fixed optimally tilted power plants and wind power plants at 150 m hub height. Calculations are performed on a mesh of 1°x1° latitude and longitude and a one hourly time interval for the year 2005. Power capacity of PV and wind power is set to an equal value.

Global average total overlap is about 15%, whereas maximum overlap is 25%. Critical overlap is significantly lower, i.e. available power per coordinate higher than rated power capacity of one power technology. Critical overlap FLh are worldwide below 9% and at most places even below 3% to 4%. Consequently, PV and wind power plants are finally no competition to each other.

Moreover, it can be expected that the complementarity of PV and wind power leads to significant reductions in further investments in the energy system and will enable the power sector to offer highly competitive solutions for the heat and transportation sector and maybe even for the chemical industry via renewable power generated methane.

For achieving power supply security balancing power plants are still needed. Natural gas (NG) power plant capacity of more than 1,100 GW is installed worldwide [8] and is perfectly suited for power balancing purposes. Hybrid PV-Wind-NG power plants are an excellent power plant option in the years to come [5,6], but this technological approach still depends on fossil fuels. Greenhouse gas emissions of NG fired CCGT are in the range of 400 - 500 gCO_2/kWh considering the full life cycle, being too much in a climate change constraint world. Moreover, peak in conventional oil production is a matter of fact and it is only a question of time when peak in NG production will occur. Nevertheless, global installed NG infrastructure might be of utmost relevance for fighting climate change and diminishing fossil fuel resources – as basis for the RPM diffusion.

4 Economics of System Components

This section is focused on the economics of the core system components of hybrid PV-Wind-RPM-CCGT power plants based on the technological conditions needed for RPM storage. Relevant system components for analyses are 1-axis horizontal north-south continuous tracking PV power plants (PV 1N), wind power plants at 150 metre hub height (Wind 150m), combined cycle natural gas power plants in the conventional and carbon capture and storage (CCS) version (CCGT and CCGT-CCS), hard coal power plants in the conventional and CCS version (coal and coal-CCS) and RPM storage composed by dialysis, electrolysis and methanation units. The preconditions for a successful hybridization are given for the hybrid power plants discussed in this paper but discussed elsewhere [5,6].

A cost model for all components of the hybrid PV-Wind-RPM-CCGT power plant enables the calculation of levelized cost of electricity (LCOE) [25] for all coordinates by applying local FLh for the PV and wind component in combination with FLh assumptions for the entire hybrid power plant. RPM storage is expected to be available on the large scale by the end of the 2010s, whereas first CCS power plants, as a potential CO_2 source, might be in the demonstration phase at that point in time. Based on the availability of these two major relevant components for a broad hybrid PV-Wind-RPM-CCGT power plant analysis the year 2020 is chosen for scenario evaluation. Besides typical capital expenditures (Capex) and operational expenditures (Opex), major cost positions are expenditures for fuel but not for related carbon emissions due to either CO_2 free power supply or application of CCS techniques. Such derived LCOE make it possible to compare them to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating hybrid PV-Wind-RPM LCOE is summarized in Equation 1:

$$LCOE = \sum_i LCOE_i \qquad \text{(Eq. 1a)}$$

$$LCOE_i = \frac{Capex_i \cdot crf + Opex_{i,fix}}{FLh_{i,el}} + Opex_{i,\mathrm{var}} + \frac{fuel_i}{PE_{th,i} \cdot \eta_{i,el}} + \frac{carbon \cdot GHG_i}{\eta_{i,el}} \qquad \text{(Eq. 1b)}$$

$$crf_i = \frac{WACC \cdot (1+WACC)^{N_i}}{(1+WACC)^{N_i} - 1} \qquad \text{(Eq. 1c)}$$

$$WACC = \frac{E}{E+D} \cdot k_E + \frac{D}{E+D} \cdot k_D \qquad \text{(Eq. 1d)}$$

$$FLh_{PV,el} = Y_{ref} \cdot PerfR \qquad \text{(Eq. 1e)}$$

$$FLh_{RPM,el} = FLh_{total,el} - \left(FLh_{PV,el} + FLh_{W,el}\right) \qquad \text{(Eq. 1f)}$$

$$fuel_i = fuel_{crudeoil} \cdot cf_i \qquad \text{(Eq. 1g)}$$

Equation 1: Levelized cost of electricity (LCOE) for hybrid PV-Wind-RPM-CCGT power plants. Abbreviations stand for: capital expenditures (*Capex*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), annual fixed Opex (*Opex*$_{fix}$), variable Opex (*Opex*$_{var}$), annual full load hours of component *i* (*FLh*$_{i,el}$), fuel cost of component *i* (*fuel*$_i$), thermal energy conversion factor of component *i* (*PE*$_{th,i}$), primary to electric energy conversion efficiency of component *i* ($\eta_{i,el}$), weighted average cost of capital (*WACC*), lifetime of component *i* (N_i), equity (*E*), debt (*D*), return on equity (k_E), cost of debt (k_D), reference yield for a specific PV system at a specific site (Y_{ref}), PV performance ratio (*PerfR*), renewable power methane components (*RPM*), fuel cost of crude oil (*fuel*$_{crude\ oil}$), ratio of fossil fuel *i* to crude oil as coupling factor (cf_i) and primary to electric energy conversion efficiency of component *i* ($\eta_{i,el}$). Components *i* of the hybrid PV-Wind-RPM-CCGT power plant are: PV fixed optimally tilted, PV 1-axis horizontal north-south continuous tracking, Wind 150 metre hub height, RPM storage units (dialysis, electrolysis, methanation), combined cycle gas turbine (CCGT) and carbon capture and sequestration (CCS). These components are compared partly or fully to natural gas (NG) fired CCGT-CCS and coal fired coal-CCS power plants.

The scenario assumptions for calculating LCOE are summarized in Table 1 and are based on experience curve assumptions for PV and wind power plants [5,6]. Major LCOE component of PV and wind power plants are the capital cost, whereas conventional fossil power plants are more dependent on the fuel cost in contrary to fossil CCS power plants showing a higher dependence on capital cost. Fossil fuel cost are indirectly coupled to the crude oil price due to the specific thermal energy [5] and tend to fluctuations and long-term escalation.

Total FLh of the hybrid PV-Wind-RPM-CCGT power plant are composed by the renewable source, i.e. PV or wind or hybrid PV-Wind, and the balancing CCGT which receives the methane by the RPM component of the hybrid plant. The RPM is assumed to be generated by not needed excess electricity and CO_2 either by extraction CO_2 from the ambient air (dialysis) or provided by the carbon capture and storage (CCS) component of the CCGT plant. The dialysis and electrolysis components show lower FLh due to its adaption to the availability of fluctuating excess electricity. However, the methanation component can be run in baseload operation modus due to internal hydrogen storage. Some minimum FLh are assumed for practical reasons, i.e. minimum 500 FLh of CCGT component, minimum 500 FLh of NG-CCS component, minimum 500 FLh of critical PV and wind overlap being very conservative (section 3) and minimum total 5,000 FLh of the hybrid PV-Wind-RPM-CCGT power plant. The latter assumption is rather conservative, since the global power plant capacity is operated for about 4,300 FLh in average [6]. The hybrid power plant in this configuration can use the RPM as both a daily but also a seasonal storage.

PV and wind power plants are on an excellent cost trend and are expected to achieve LCOE of about 40 – 60 €/MWh in regions of good resource quality in the year 2020 (Figure 5). Major advantage of the hybrid PV-Wind power plant component are the higher FLh compared to only one renewable power source leading to beneficial total LCOE of the hybrid PV-Wind-RPM-CCGT power plant.

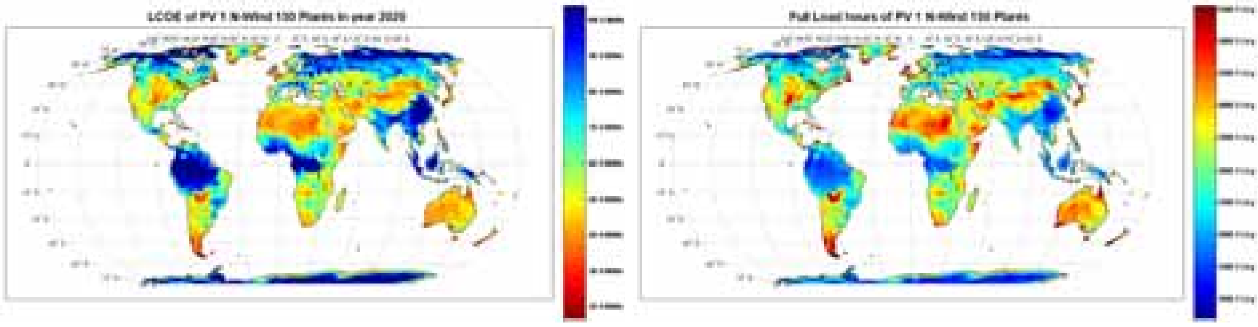


Figure 5: Hybrid PV-Wind power plants characterized by their global LCOE (left) and FLh (right) projected for the year 2020. Assumed hybrid PV-Wind sub plants are 1-axis horizontal north-south continuous tracking PV power plants and wind power plants at a hub height of 150 m for the conditions of Table 1. The underlaying resource data are provided by NASA SSE 6.0 [26] but reprocessed and discussed elsewhere [6,27].

in year 2020		**PV 1-axis N-S horiz.**	**Wind 150m hub height**	**CCGT conv.**	**CCGT CCS**	**Coal conv.**	**Coal CCS**	**Renewable Power Methane Dial.**	**Renewable Power Methane Electrol.**	**Renewable Power Methane Methanation**
Capex	[€/kW]	1130	800	750	2100	1500	2800	500	300	400
Opex$_{fix}$	[€/kW/y]	17	15	15	40	20	70	10	6	8
Opex$_{var}$	[€/MWh$_{el}$]	-	-	1	2	1	3	1	1	1
plant lifetime	[y]	30	25	30	30	40	40	30	30	30
plant efficiency (PR)	[%]	80%	95%	58%	48%	44%	34%	78%	78%	82%
fuel price coupling	[fuel/oil]	-	-	80%	80%	30%	30%	-	-	-
in general			**remark**							
WACC	[%]	6.0%	despite of higher fossil risk profile identical for comparison reasons							

exchange rate	[USD/€]	1.40	
FLh Methanation	[h/y]	8000	baseload operation
FLh min CCGT	[h/y]	500	minimum FLh of CCGT component of respective hybrid RPM-CCGT plants
FLh min NG-CCS	[h/y]	500	minimum FLh of NG-CCS component of hybrid PV-Wind-NG-CCS plants
FLh min overlap	[h/y]	500	assumed time resolved FLh overlap of PV and Wind (conservative)

Table 1: Key economic assumptions of hybrid PV-Wind-RPM power plants and competing power plants projected for the year 2020. Abbreviations stand for: 1-axis horizontal north-south continuous tracking (1-axis N-S horiz), combined cycle gas turbine (CCGT), conventional (conv), carbon capture and storage (CCS), capital expenditure (Capex), operational expenditure (Opex), performance ratio (PR), weighted average cost of capital (WACC), full load hours (FLh), renewable power methane (RPM) and natural gas (NG). Data are taken from various sources and in case of the non RPM components given elsewhere [6].

Production cost of RPM by PV and wind power supply is visualized in Figure 6 for extracting CO_2 from ambient air and for CO_2 accessible by CCS. The calculations are based on scenario assumptions defined in Table 1 and visualized for respective hybrid PV-Wind plants in Figure 5.

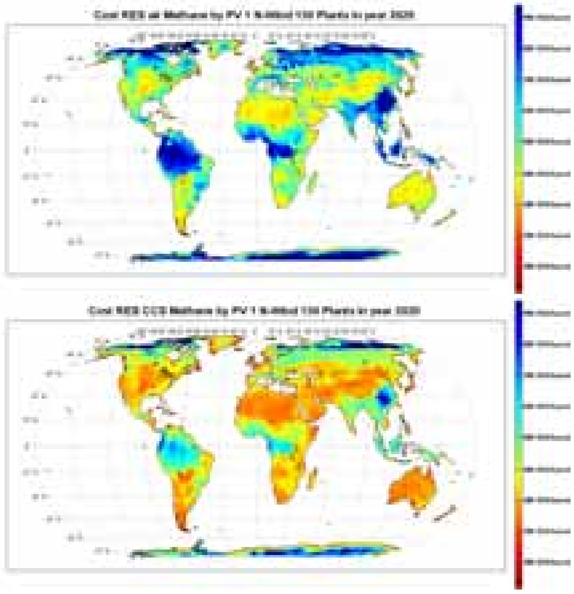


Figure 6: Cost of RPM production for CO_2 from the air (top) and supplied by CCS facilities (bottom) projected for the year 2020. Power supply by hybrid PV-Wind power plants (Figure 5) is assumed for the conditions of Table 1. Cost of RPM production might be at about 300 USD/barrel for CO_2 from air and about 200 USD/barrel for CO_2 from CCS route (excluding CCS cost) at sites of excellent solar and wind resources.

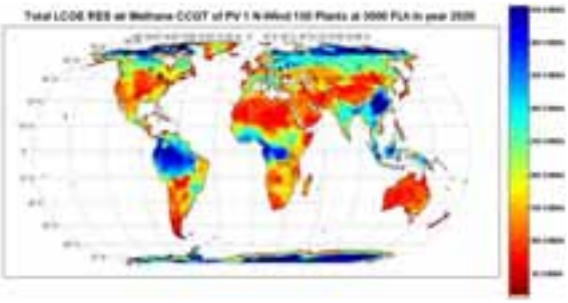
Results for RPM production cost based on PV and wind FLh and LCOE show challenging cost levels even in regions of excellent resource availability. In case of extracting CO_2 from ambient air, a cost level of about 300 – 400 USD/barrel can be reached (Figure 6). For CO_2 being available due to CCS the cost level is equivalent to about 200 – 300 USD/barrel (Figure 6). However the cost level might be not too high compared to typical fuel prices in industrial countries, since 200, 300 und 400 USD/barrel are equivalent to diesel prices of 0.90, 1.35 and 1.80 €/l, excluding any kind of taxation and subsidies.

The technological route of RPM production offers access to highly valuable fuels in many regions in the world (Figure 6), in contrary to today's fossil fuel resource availability. Based on a more homogeneous solar resource and wind resource distribution in the world, the perspective is given for an additional more homogeneously distributed renewable sourced hydrocarbon fuel availability.

5 Hybrid PV-Wind-RPM Power Plant Economics

RPM storage offers three key features: Firstly, direct renewable energy supply can be used as much as possible, e.g. PV and wind power. Secondly, storage can be charged by surplus energy for use in periods of lower load than renewable power in the grid, in particular for seasonal balancing. Thirdly, a stable power supply can be granted for the entire year. The remaining question will be whether it might be economically feasible to run hybrid PV-Wind-RPM-CCGT power plants as the centrepiece of such a potential fully stable and sustainable renewable electricity future.

Total LCOE of hybrid PV-Wind-RPM-CCGT power plants for 5,000 FLh are calculated on basis of Equation 1 and scenario assumptions in Table 1 for the renewable components 1-axis horizontal north-south continuous tracking PV, wind turbines on 150 meter hub height and the hybrid composition of these two sub-plants for the two CO_2 source routes, i.e. from ambient air and accessible by CCS (Figure 7).



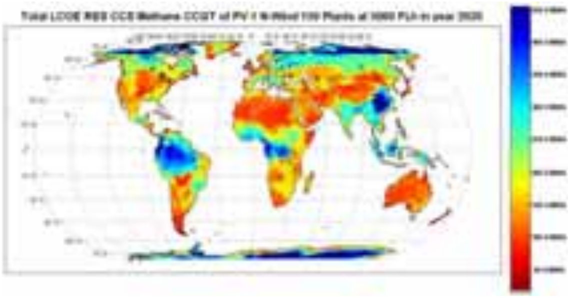


Figure 7: Global LCOE of hybrid PV-Wind-RPM power plants for CO_2 from air (top) and for CO_2 from CCS route (bottom) projected for the year 2020. Power supply by hybrid PV-Wind power plants (Figure 5) is assumed and 5,000 FLh in total for the hybrid power plant for the conditions of Table 1. LCOE of hybrid PV-Wind-RPM power plants might be about 80 €/MWh at sites of excellent solar and wind resources, whereas the CO_2 from air route could be slightly lower in LCOE mainly driven by challenging economics of CCS facilities.

The LCOE outcome of both CO_2 sourcing routes is nearly identical, whereas the CO_2 extraction from ambient air seems to be slightly lower in cost for the specific scenario assumptions (Figure 7). In both cases the hybrid PV-Wind sub-plant leads to lower than the PV-only or wind-only variation for the total hybrid PV-Wind-RPM-CCGT power plant, which is caused by the beneficial effect of extended FLh on a renewable low cost basis reducing costly RPM production on minimum level.[6] A hybrid PV-Wind sub-plant reduces the total LCOE on a level of 60 – 100 €/MWh in regions of good and excellent solar and wind resource availability, e.g. the US, Chile, Argentina, Bolivia, some locations in Europe, nearly the entire MENA region, parts of Central Asia and Australia.

Nearly identical LCOE results for hybrid PV-Wind-RPM-CCGT power plants for both CO_2 sourcing routes (Figure 7) is in contrast to the results of RPM production costs (Figure 6), where the CO_2 extraction from ambient air route is found to be about 40% higher in cost than the CO_2 accessible from CCS option. However, the CCS system approach is significantly higher in cost on the power plant level due to higher Capex of the CCGT-CCS versus the CCGT power plant component and lower respective primary energy conversion efficiency of CCGT-CCS versus CCGT (Table 1). As a consequence higher RPM production cost of the ambient air route is levelled out by beneficial power plant characteristics of the CCGT component.

This quite relevant result need to be analysed in a much deeper and broader scope than possible in this work. It might be possible that the enormous investments in CCS technology could end up as stranded cost on a macro economic level, in particular in case of lower total power generation system LCOE of hybrid PV-Wind-RPM-CCGT power plants using CO_2 extraction from ambient air versus fossil fuel powered CCS power plants. Enormous public financial means are needed for establishing the CCS technology and infrastructure, which might be superfluous not only in the end but right from the begin of CCS diffusion.

6 China – An Exemplarily Potential Market

Considerations in the last sections are focussed on least LCOE of respective hybrid PV-Wind-RPM-CCGT power plants in the global context. However, from the point of local view a more differentiated analysis is very helpful for understanding the local cost and technological dynamics. Key assumptions for this consideration are already defined in Table 1, which are applied for power plant configurations of 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel. The single components for establishing respective power plants are: fixed optimally tilted PV, 1-axis horizontal north-south continuous tracking PV, wind power at 150 metre hub height, conventional NG-CCGT, NG-CCGT-CCS, conventional coal without CCS, coal-CCS, RPM production using CO_2 extracted from ambient air and by a cyclical CCS route. Based on these nine components a variety of 24 hybrid PV-Wind-RPM-CCGT power plants and fossil fuel fired power plants is analysed. These analyses can be performed for all coordinates represented by a data point in the Figures 5 to 7, but exemplarily shown here for a coordinate in the North-West of Bejing in China.

Dynamics of the different power plant variations are depicted for a site in China in Figure 8. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by good solar and very good wind resource conditions.

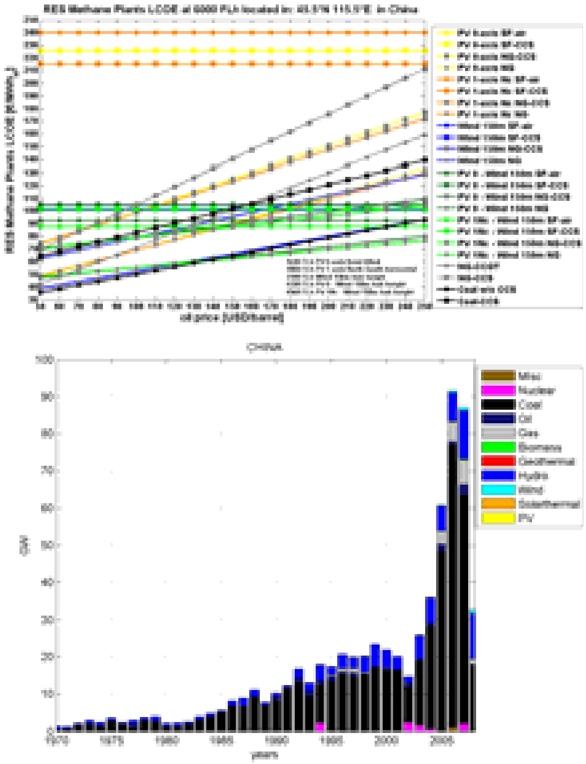


Figure 8: Hybrid PV-Wind-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in China (45.5°N/ 115.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant

capacity in China (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO_2 source options of extracting CO_2 from ambient air (air) and CO_2 accessible by CCS (CCS), whereas RPM is denoted as SF. FLh of renewable sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The hybrid PV-Wind components are characterized in Figure 5. Further assumptions for cost calculation are taken from Table 1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. Data are taken from UDI World Electric Power Plants database [28].

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 88 €/MWh supplied by a hybrid PV-Wind-RPM-CCGT power plant using CO_2 extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 90 USD/barrel at LCOE of about 65 €/MWh. A hybrid PV-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 215 €/MWh for the CCS CO_2 sourcing option.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of below 50 USD/barrel at LCOE of about 38 €/MWh. A hybrid Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 150 USD/barrel and would generate electricity at a LCOE level of about 100 €/MWh for the CO_2 extraction from ambient air option.

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 60 USD/barrel at LCOE of about 50 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 128 USD/barrel and would generate electricity at a LCOE level of about 88 €/MWh for the CO_2 extraction from ambient air option. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 75 USD/barrel at a LCOE level of about 88 €/MWh and for extracting CO_2 from ambient air.

The hybrid PV-Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 110 USD/barrel at about 88 €/MWh LCOE for the CO_2 extracting from ambient air option. The respective parity to coal without CCS is given at a fossil fuel price of about 230 USD/barrel at about 88 €/MWh LCOE and for extracting CO_2 from ambient air.

The total power plant capacity already available in China by end of 2008 (Figure 8) shows relative little investments in NG-CCGT capacities in the last years. Therefore the upgrading potential for hybrid PV-Wind-RPM sub-plants might be limited. However, the large coal and hydro power plant capacity should be taken also into account in respect to hybrid PV-Wind-Coal power plants [5] and hybrid PV-Wind-Hydro power plants [6].

The hybrid PV-Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 140 USD/barrel at a beginning LCOE level of about 60 €/MWh. Below 140 USD the hybrid Wind-NG-CCGT power plant is only 2 – 3 €/MWh higher in LCOE than coal without CCS. The hybrid PV-Wind-RPM-CCGT power plant LCOE is about 88 €/MWh, but cannot reach the least LCOE level below 250 USD/barrel. CCS technology is not needed for a competitive least LCOE system design.

7 Global Power Supply Potential

Upgrading NG-CCGT power plants by hybrid PV-Wind power plants typically leads to lower LCOE for fossil fuel prices of about 50 – 90 USD/barrel. In case of good solar and wind resource availability the hybrid PV-Wind-NG-CCGT power plant is very competitive beginning between fossil fuel prices of 70 – 90 USD/barrel onwards. The remaining natural gas fired in the NG-CCGT sub-plant still leads to CO_2 emissions but the natural gas can be replaced by RPM, however it will be higher in cost than the natural gas option in nearly all regions in the world and for fossil fuel prices up to 250 USD/barrel assuming no carbon emission cost.

The hybrid PV-Wind-RPM-CCGT power plant extracting CO_2 from ambient air is an excellent centrepiece of a 100% renewable power supply, which might be established on a LCOE level of about 80 – 90 €/MWh in regions of very good solar and wind resource availability. In regions of good solar and wind resources the LCOE ranges from about 100 – 120 €/MWh and for at least one good and one moderate resource the LCOE could be about 140 – 170 €/MWh. These LCOE levels are fully fossil fuel decoupled and represent the full social cost, i.e. no further external cost create an additional financial burden. Moreover, no CCS route is needed. CO_2 extraction from air leads in most cases to lower total LCOE and in cases of lower CCS CO_2 sourcing this is only slightly lower in cost. It is not clear whether CCS technology will be really available by 2020 or even in 2030, hence waiting for this route might waste a lot of valuable time. Concluding this, hybrid PV-Wind-RPM-CCGT power plants extracting CO_2 from ambient air enable a 100% renewable power supply in many regions in the world and show favourable economic performance.

The enormous solar and wind resource potential (section 3) lays the basis for analyses of the global energy supply potential of solar PV and wind power. The last sections clearly emphasise that 100% renewable energy supply is technically feasible on basis of PV and wind power using RPM for storage purposes, in particular for seasonal storage. Economic considerations result in total power generation cost of below 100 €/MWh in many large regions spread over the world (section 5).

In reality more renewable energy sources can be used for power supply. An excellent example how such a fully renewable powered energy system could work is analysed for the DESERTEC project.[29-32] Historic roots of the DESERTEC project have been laid in the 1920s focussing hydro power [33,34] and in the 1930s already based on first PV concepts linked to power lines [35,36] but have been changed in the 1980s to solar hydrogen [37,38] and in the 2000s to solar thermal power generation (STEG), again linked to power lines [29-32]. DESERTEC is based on all major renewable energy sources and the interconnection of centres of energy supply and centres of energy demand by high voltage direct current (HVDC) power lines. Solar PV, solar thermal and wind power are assumed to be major sources of power, whereas biomass and hydro power might act as a renewable balancing power. The EU-MENA DESERTEC project gained pace by the Desertec Industrial Initiative lead by industry giants [39] and might become a blueprint for similar interregional cooperation in other parts of the world reaching a global power grid.

The global energy supply potential for STEGs has already been analysed.[40] This analysis of global energy supply potential of solar electricity generated only in regions of excellent solar resources, i.e. at least 2,000 kWh/m²/y direct normal irradiation, clearly shows the true potential of solar power: 90% of world population could be supplied by solar power (solar PV and solar thermal) via HVDC power lines not longer than 3,000 km.

The indication is high, that based on STEGs a nearly 100% renewable power supply could be established. However, the STEG economics are not as favourable as the comparable ones for PV and wind power. Therefore it might be of very high relevance to perform a global energy supply potential for hybrid PV-Wind-RPM power plants on basis of economic competitiveness.

The last sections point out that a 100% renewable power supply is economically feasible at latest in the end of the 2010s in the regions of the world where at least good and very good solar and wind resources are available. Key question in this section is the global energy supply potential of hybrid RPM systems. The three major steps for answering this are: Firstly, it needs to be identified where hybrid PV-Wind-RPM-CCGT power plants are lower in cost than natural gas and coal fired CCS power plants, which would be the major competing power plant technologies in a CO_2 constraint world. Secondly, it need to be estimated how much energy can be provided by those regions. Thirdly, it need to be evaluated how many people live in that favourable regions and more relevant depending on the distant to that regions how many further people could be supply.

The regions of least LCOE for 100% renewable power plants on basis of PV, wind, RPM and CCGT components are shown in Figure 9 being derived on basis of cost competition against NG-CCGT-CCS and coal-CCS power plants and shown for a fossil fuel price of 150 USD/barrel.

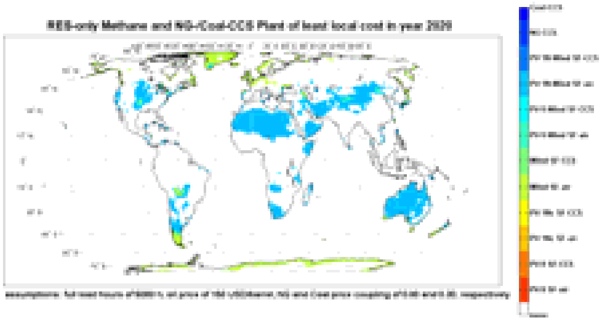


Figure 9: Hybrid PV-Wind-RPM-CCGT power plants of least local LCOE in competition to NG-CCGT-CCS and coal-CCS power plants for a fossil fuel price of 150 USD/barrel operated 5,000 FLh in the year 2020. The renewable sub-plant options are identical to Figure 8 for the two CO_2 source options of extracting CO_2 from ambient air (air) and CO_2 accessible by CCS (CCS), whereas RPM is denoted as SF. The hybrid PV-Wind components are characterized in Figure 5. Further assumptions for cost calculation are taken from Table 1.

The regions of most competitive hybrid PV-Wind-RPM-CCGT power plants are distributed all around the world and comprise the regions of very good solar and wind resource availability. The global energy supply potential of hybrid PV-Wind-RPM-CCGT power plants can be roughly estimated. The details for the calculation are discussed elsewhere [6].

Notably, good PV sites of about 2,000 FLh generate an annual electricity amount of about 107 GWh/km², whereas the good wind power sites of about 3,000 FLh generate an annual electricity of about 56 GWh/km², hence the practical specific energy generation density of PV is by a factor of two higher than that of wind power. However, the entire site need to be reserved more or less fully for a PV power plant, but the site beneath the wind turbines can be used similar to the purpose before, e.g. crop land, forests, etc.

For a crude oil price of about 150 USD/barrel, about 37 million km² fulfil the criteria of lower hybrid PV-Wind-RPM-CCGT LCOE than comparable fossil fuel fired CCS power plants. Only 1.3% and 6.9% of that area would be needed to cover the current power and additional thermal energy demand fully by the hybrid PV-Wind-RPM-CCGT approach. The number for the thermal energy is a worst case assumption due to enormous efficiency potentials. The required thermal energy might be by a factor of four too high, according to fundamental efficiency reasons. For the worst case it is assumes that there is a conversion of valuable electricity to methane and then subsequent conversions for the various thermal energy services, like transportation, heating, cooking, etc. However, it would be much more efficient to use the electricity in a direct way like electric transportation, electric heating and electric cooking which would be more efficient by roughly a factor of four, or even more.

The numbers for some decades in the future, based on a crude oil price of 200 USD/barrel, would be 12 billion humans, about 57 million km² of least local hybrid PV-

Wind-RPM-CCGT LCOE, 3.9% and 16.2% of that area needed for covering the electric and thermal energy demand and similar efficiency considerations for the hybrid PV-Wind-RPM-CCGT but also for the thermal energy demand. The area requirement might be not as high as it appears, since in the future 200 USD/barrel case only 11% of the earth's surface is classified for excellent hybrid PV-Wind-RPM economics, enormous efficiency potentials of about a factor of four in the thermal energy demand are to be realised, the energetic wealth level of the EU today might be too high for 12 billion people and all technologies for the hybrid PV-Wind-RPM-CCGT approach are still significantly improvable. In total, enormous amounts of energy under least local LCOE conditions are available for powering the energy needs of the humans without relevant sustainability criteria restrictions, in particular due to the fact that several other renewable power technologies are able to complement PV and wind power, the two core power technologies in the years and decades to come.

Besides the enormous energy supply potential of the most competitive regions on LCOE basis in the world, it is of highest interest how many people live in these regions and within what distance lives the other part of mankind. Many people live in the regions of least cost 100% renewable power supply based on PV and wind power plants even for low fossil fuel prices. For fossil fuel prices of up to 100 USD/barrel about 500 million (50 USD/barrel) and about 800 million (100 USD/barrel) people live within 100 km next to the regions of least cost power supply. These numbers sharply rise for higher fuel prices to about 1,200 million (150 USD/barrel), 1,800 million (200 USD/barrel) and 2,200 million (250 USD/barrel). The aggregated population in dependence on the distance to the least cost regions is depicted in Figure 10 for various fossil fuel price levels.

Power lines can transmit electricity over several thousand kilometres very efficiently. Distances more than about 800 – 1,000 km are economically best interconnected by high voltage direct current (HVDC) power lines, being applied since decades for distances of 2,000 km and more. HVDC power lines show a power transmission efficiency of about 97% per 1,000 km. Below 800 – 1,000 km conventional high voltage alternating current (HVAC) power lines represent the most cost efficient power transport solution.[31]

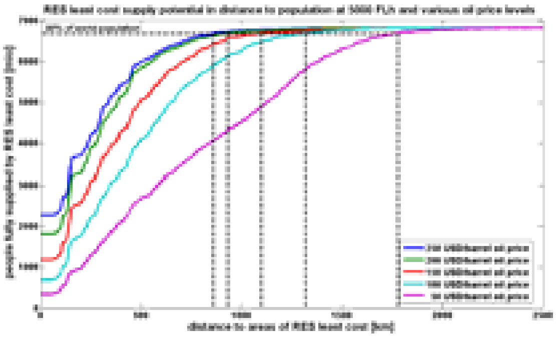


Figure 10: Aggregated people living in regions of least cost 100% renewable power supply and respective distance to these regions in dependence of fossil fuel prices in the range of 50 – 250 USD/barrel in the year 2020. The evaluation is based on least cost hybrid PV-Wind-RPM-CCGT power plants (Figure 9) and the distribution of global population density. Data for population density are provided by Center for International Earth Science Information Network (CIESIN) [41].

Within about 800 km next to the regions of least cost 100% renewable power supply most people in the world could be supplied depending on the fossil fuel prices, i.e. about 85% of world population based on the least cost situation for 100 USD/barrel, about 90% for 150 USD/barrel, about 95% for 200 USD/barrel and about 98% for 250 USD/barrel.

Comparing the results for the global energy supply potential of STEG versus hybrid PV-Wind-RPM power plants shows the beneficial consequences of good solar and wind resource potential accessible in many regions in the world. The supply potential for more than 90% of world population is lowered from 3,000 km to about 500 – 1,000 km. This reduction in distance is very important for lowering the political obstacles for the issues of transmitting large power amounts through various countries and the time consuming construction process of HVDC power lines. Moreover, the hybrid PV-Wind-RPM power plants enable the 100% renewable power supply and guarantee the least LCOE option.

8 Conclusions

Renewable power methane storage enables a bidirectional link of power and gas networks and represents a competitive seasonal storage option. Due to a comparably low efficiency of the full RPM process the cost of producing RPM is rather high. Therefore the input power LCOE need to be as low as possible.

PV and wind power reach quite competitive LCOE by the end of the 2010s, are nearly abundantly available and complement each other. However, both technologies are still fluctuating. Thus combining low cost PV and wind power with the balancing RPM storage to hybrid PV-Wind-RPM-CCGT power plants represents a new power option for a 100% renewable energy supply.

By the end of the 2010s, economics of hybrid PV-Wind-RPM power plants are very promising in all regions of good solar and wind resource quality. The hybrid PV-Wind-RPM-CCGT power plants might represent the fundamental centrepiece of sustainable and low cost power supply in the years to come. By the year 2020 about 90% of human mankind might be in reach to be supplied by 100% renewable power fully competitive to fossil fuel prices of about 150 USD/barrel and for practically not limited amounts of sustainably provided energy. The RPM approach enables long-term cost stability due to a fully decoupled cost structure from fossil fuels, no net CO_2 emissions and enormous power supply potential offering long-term sustainable economic growth. This hybrid plant topology might emerge into the role of the key energy supply cornerstone in the world, in particular if mankind intends to economically survive peak-oil and physically and economically survive climate change.

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