Clean Techn Environ Policy
DOI 10.1007/s10098-015-0969-y

PERSPECTIVE

Is the success of clean energy guaranteed?

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Received: 1 January 2015 / Accepted: 22 April 2015

Abstract We are witnessing a huge growth of clean energy technologies during the last 15 years, spearheaded by government policies. Can this growth be sustained through challenges of economic crisis, the complications of achieving higher penetration of variable renewables, and high socioeconomic costs of slowly winding down fossil fuel sector? This paper will argue that the clean technologies are now technically and economically viable with much lower level of support and that new financial mechanisms built on grid parity and hourly markets will enable the continuation of the transition process. Policies should now be directed towards decreasing fossil fuel subsidies and other barriers to renewables. Also, the technologies needed to enable the increase of penetration of variable renewables, such as flexible combined and Rankine cycle power plants, and smart energy systems based on demand side management, including through the integration of power, heat, water, and transport systems, are now at various levels of readiness. The integration will slowly enable the transition from a power system in which supply is following demand to a power system in which demand is following variable supply. The main issue will be the growing opposition from fossil fuels sectors, which are starting to be hurt by the new technologies.

Keywords Energy transition · Renewable energy · Smart energy systems · Integration of energy systems · Transport system · Water supply system

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Published online: 09 May 2015

Introduction

It has been shown that clean energy systems based on renewable energy sources (RES) are technically feasible. Duić and Carvalho (2004) confirmed that they are technically feasible on an island, which is most difficult, due to low capacity factor of variable renewable energy sources (VRES) on a small area. Lund et al. (2011) displayed in the special issue dedicated to the 5th Conference on Sustainable Development of Energy, Water, and Environment Systems (SDEWES Dubrovnik 2009) how various technologies may help towards the 100 % renewable energy systems. Mathiesen et al. (2011) demonstrated that 100 % RES energy systems are also economically beneficial, if external costs are taken into account. Lund (2014) set forth a straightforward, comprehensive methodology for comparing different energy systems' capabilities to integrate VRES. IPCC (2011) corroborated how RES can mitigate the climate change. IEA (2012a) showed that transition to clean energy systems is fully economically viable. So, why it is happening so slowly? Obviously, there are vested interests, in upstream, midstream, and downstream of fossil fuels, in car industry and industry of plants equipment: burners, boilers, turbines, etc., and also in academia. There is also huge invested capital that has to be paid back, otherwise the social costs of insolvencies would possibly slow the economic growth. There are also jobs that would disappear and new jobs to be created. It is clear that clean energy creates more jobs than it destroys, but the new jobs require different skills and time is needed for labour force to adjust (UNEP 2011). Meanwhile, the main issue is huge subsidies (Ecofys 2014) given to the fossil fuels, direct and indirect, which make renewables less competitive than they would otherwise be. The International Energy Agency (IEA) has estimated that consumer subsidies to fossil fuels amounted to USD 548 billion in 2013 (IEA 2014). In the same year, subsidies to renewable energy were estimated at USD 121 billion. However, a comparison of numbers does not reveal the extent to which renewable energy is being disadvantaged in favour of continued reliance on fossil fuel generation. To understand the true impact, Bridle and Kitson (2014) explore the range of subsidy mechanisms. This paper will demonstrate how the transition towards clean energy will manage to replace conventional energy, even with such high barriers on its way. Therefore, authors (De Schepper et al. 2014; Maroušek et al. 2015) who try to prove that subsidies to renewables are wrong are widely off the track, since they do not take into account fossil fuel subsidies. Only when authors take into account many more issues, they come to opposite conclusion (Cucchiella et al. 2015).

Energy, work, exergy, and thermodynamics of energy systems

Locked in energy systems in which 80 % (IEA 2012b) of electricity is produced by Rankine process with efficiencies of meagre 20–45 %, or even with respectable 55 % for combined cycle, electricity is exergetically very valuable energy carrier, since it can be easily converted to work—the most valuable among the energy types. Converting it to low-temperature heat, or even high-temperature heat is considered thermodynamically undesirable. Meanwhile, once the electricity is produced directly from hydro, wind, or photovoltaic energy conversion systems, the issue becomes more complicated. Since these and especially variable renewables as wind, photovoltaic, and once-through hydro are depending on weather and hydrology and thus produce electricity when the variable resource is available, the exergy value of electricity is constrained with the ability of the system to actually use it. Thus, when the electricity is not needed to do work, it is better to use it for other purposes, even low-temperature heat, than not to produce it by curtailing generators. This issue does not exist when energy is stored as chemical energy, but it pops out and confuses engineers once the direct conversion to electricity becomes common. The wholesale market is the easiest way to determine when using electricity for particular purposes may be acceptable. When electricity prices are lower than variable costs of electricity produced using Rankine or combined cycles, the electricity does not need to do work only, but may be used for any purpose, even low-temperature heating.

Meanwhile, converting fossil fuels to low-temperature heat is always a loss of exergy and should be avoided whenever possible. This means that using gas for heating houses is thermodynamically undesirable. The amount of waste heat available from thermal power plants and industrial processes in European Union is higher than the heating demand (Heat Roadmap Europe 2014). In case where waste heat is too far from demand, it may be better to use heat pumps, if the overall efficiency is better, than to directly convert fossil fuels to low-temperature heat. That is only true if the energy efficiency of the fuel mix used to produce electricity is at least higher than reverse of the coefficient of performance, taking into account efficiencies of gas boiler and transmission system. The similar analysis can be made when comparing cars based on internal combustion engine and electric cars. All these technologies are becoming more thermodynamically viable with increased share of renewables in the fuel mix of electricity generation. According to Pensini et al. (2014), entire heating need in the United States could be covered using excess from VRES.

Future energy technologies

We have to thank fossil fuels and their energy density for huge increase of productivity that helped pull human civilization from abject poverty during the course of the twentieth century. Meanwhile, fossil fuels have several significant disadvantages, being abundant in some places and scarce in others, being exhaustible, and causing the increase of greenhouse gases' concentrations, which causes climate change and results in huge costs of adaptation to the change. Thus, it makes sense to assess possibility of replacing them with some other abundant source of energy, which can continue to fuel the growth into the twenty-first century. The problem is that the benefits of using fossil fuels go to the user, while the damage is global, which is a typical tragedy of commons problem. Therefore, future harm due to the climate change will not be strong enough driver to facilitate the development of alternatives, although it may serve as the best available negotiation and equity gauging principle. Security of energy supply may be a much stronger incentive for a country to invest in alternative energy source and that is what happened with European Union after 2000 (European Commission 2000), or Brazil after the oil shock (Rosillo-Calle and Cortez 1998). It will not be enough to drive the whole process towards clean energy sources, but it may serve to finance the learning curve, which can make new technologies viable, enabling *virtuous cycle* of the energy transition.

Nuclear energy was deemed to be the most promising alternative energy, but the melt-down of series of reactors starting with Three Mile Island made that technology off-putting. Also, the very limited reserves of fuel needed for existing technology bring about a need to develop a completely new technology in an environment where the technology is politically unacceptable to majority or due to significantly increased safety regulation has become too expensive. The new nuclear power plant planned to be built in the United Kingdom has been awarded a guaranteed price of 110 EUR/MWh, more than most other alternative technologies, although it may also be due to hidden cross-subsidy of military nuclear sector.

Hydro was around before fossil fuels and before the Rankine process was designed. Most of the cheap hydro power plants have been already built in developed economies, while the environmental costs have meanwhile become a serious obstacle to major future development.

Biomass is even older than hydro, being the fuel of choice since the prehistoric people started to use fire. Biomass energy is actually a variant of solar energy, if we consider that biomass chemical energy is the result of photosynthesis. The energy efficiency of photosynthesis is mostly up to 2 % (though sugar cane manages up to 8 %), while the energy efficiency of using biomass in Rankine cycle to generate electricity or using biofuels to power internal combustion engine is around 20 %, making overall solar-to-electricity/mechanic energy efficiency of 0.4 %. Meanwhile, photovoltaic conversion solar-to-electricity efficiency is upwards from 15 %. The conclusion is that thermodynamically speaking it is more efficient to sow PV panels instead of energy crops in most of climates. Since more land will be needed to produce food in future with increased global population and its increased consumption of meat, less will be available for energy use. This implies that generally only waste biomass should be used as energy resource. But, such waste biomass is rather limited in quantities (Panepinto et al. 2014) and often already utilized, taking into account the priorities imposed by the agricultural sector. The exception is the case when using biomass energy improves the financial resilience of the food or wood industry sector, as is the case of Brazilian bioethanol sector.

Wind energy was used for ages sparingly in windy countries as energy source for powering mills and irrigation pumps, maritime transport, but also as small electricity generators. Only the oil crisis in seventies spearheaded the development of modern wind conversion energy systems. In order to finance the necessary innovation and to reach economies of scale, some countries developed financing model that guaranteed such power plants the electricity sale price which would be enough to recoup the investment. The most popular financial mechanism was feed-in-tariff (FIT), which was adopted by more than 60 countries, and has led to installation of 320 GW of wind power satisfying 2 % of global electricity demand in 2013. In its improved form, wind energy is now cheaper than new nuclear, oil, or gas power, being only slightly more expensive than coal power,[1] if compared on levelised cost of electricity (LCOE) based on technically realisable load factors and without taking into account external costs and subsidies (Ecofys 2014). Another important advantage of wind energy is that it is widely available. Meanwhile, due to the variability of wind, which typically produces 20–40 % of energy compared to its nominal size (capacity or load factor), and having in mind electricity demand patterns, wind energy will easily cover only 10–20 % of demand. For example, in Denmark wind covered 34 % of electricity demand in 2013 (and 39 % in 2014), in Portugal 24 %, Spain 21 %, Cape Verde 19 %, Ireland 17 %, Germany 10 %, Romania 9 %, Estonia, the UK, and EU overall 8 %, Greece and Sweden 7 %, Lithuania 6 %, Cyprus, Italy, and the Netherlands 5 %, Austria, Belgium, Bulgaria, India, Poland, and the US 4 %, Australia, Canada, Costa Rica, Croatia, France, and Morocco 3 %, and China, Hungary, Latvia, and Luxembourg 2 %. In cases of penetration higher than 15–20 %, wind will cover entire demand in some hours, while in others there will be no wind at all. Therefore, further increase of wind penetration will require a profound reform of the energy system, which may, but not necessarily will, mean significantly increased cost. How wind interacts and will continue to interact with current and future energy systems will be covered in the next section.

Solar energy was used in agriculture and housing since the beginning of times, but only the oil crises gave rise to the development of photovoltaic (PV) technology that now prevails as solar energy of choice, due to impressive learning curve (Fig. 1). With slow start until in 2008 the price of wafer cells started to dive, 140 GW has been installed delivering 0.5 % of the global electricity needs. PV load factor is even lower than wind, only 10–15 %, but PV is better following the demand curve than wind, especially in hot summer days when it almost perfectly matches cooling load in some climates. While in the beginning of the technology development it was necessary to support PV technology with financial mechanisms such as feed-in-

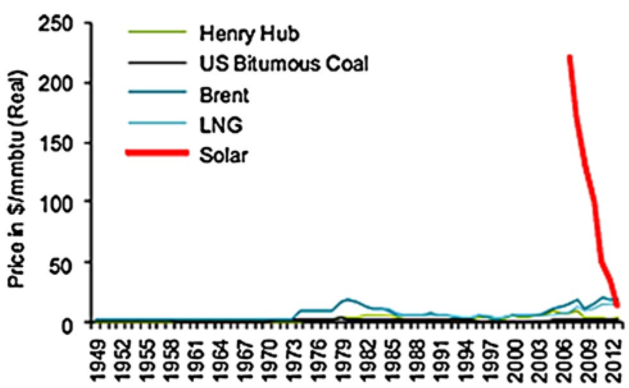
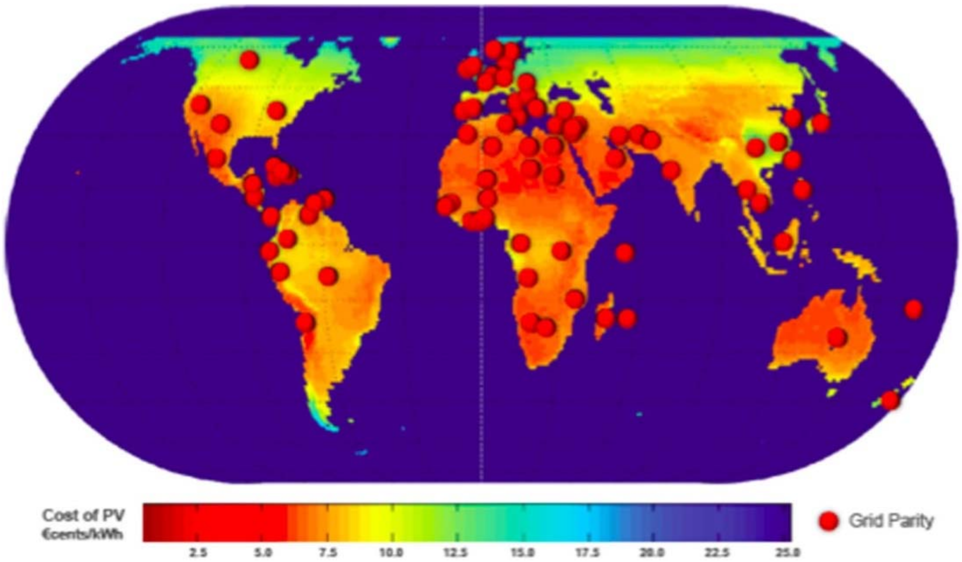


Fig. 1 Solar PV learning curve (Parker et al. 2014)

[1] With current gas prices in the US that does not hold, but very low prices are due to huge increase of shale gas production and constraints on gas exports. Once new LNG capacities are available, the effect on the gas prices in the US will be upward.

Fig. 2 Grid parity for roof solar PV installations reached in 102 countries (Parkinson 2013)



tariff, the learning curve has made technology already competitive with nuclear on large scale and competitive on roof installation scale with the grid electricity prices, bringing the so-called grid parity (Fig. 2). That has made PV actually competitive to cover significant part of the residential and small business demand, though there are is- sues of balancing costs, which will be discussed in the next section. Several more advantages of PV should be men- tioned, its modularity, availability of solar energy nearly everywhere, and its direct current nature, which will enable that residential installations are slowly converted from al- ternating to direct current, the type of electricity that is ac- tually mostly used in homes, reducing the conversion losses. Other technologies, as geothermal, wave, tide, and ocean thermal, will not be discussed since their potential is currently limited due to technology readiness and limited availability of resources. This does not mean that these technologies will not play an important role in the energy transition, but are not crucial for arguments laid out in this paper. Fusion is a perspective technology that may be vi- able one day, but by the day it arrives, the context will be different, because stationary power by then would already be decentralised. Fusion power is primarily thought as a centralised source, but its compatibility with the infras-
tructure is likely to become a barrier to its adoption.

Traditionally, technologies are compared on investment costs or levelised cost of electricity (Priya and Santanu 2013), which will generally prioritize old technologies, due to lock in effect and the fact that VRES are capital inten- sive with upfront cost. The choice of discount rate will be crucial, bringing into question which benefits are investi- gated, those to the private investors only, or social benefits also. Usually, investigators will make several errors in their analysis. They will try to show social long-term benefit using discount rate from the point of view of private in- vestor, not taking into account external costs that are huge for fossil fuels, and hidden subsidies for fossil fuels. Another error they will commit will be calculating costs based on technically realisable number of hours, instead of market feasible number of hours. Such analysis will yield wrong results favouring older technologies, those with lower capital and higher fuel cost, and those that transfer the external cost to other social systems.

Social acceptance of VRES is sometimes stated as a barrier, but, if correctly explained, the acceptance will be high (Fokaides et al. 2014). Often, communal opposition may be the result of the campaign paid and organised by vested interests. There are also environmental issues with VRES, but they are minimal compared to the conventional technologies, and when used as barrier, one can usually find behind such argument vested interest.

Future energy systems

Increasing the penetration of variable renewables (mainly wind and solar) has brought several consequences. The cost of feed-in-tariffs is usually borne by the consumers as part of the retail price and in some countries that surcharge has become high, for example more than 60 EUR/MWh in Germany. That is due mainly to the high cost of technology development, paid up front, and will not be needed in future in other countries due to learning curve. Instead of feed-in-tariff, roof scale PV has now reached grid parity and it is the best to be financed by some form of net metering.

High growth of new capacity together with falling de- mand due to the higher energy efficiency and recession brought a glut of capacity in EU (Fig. 3), with an excess of

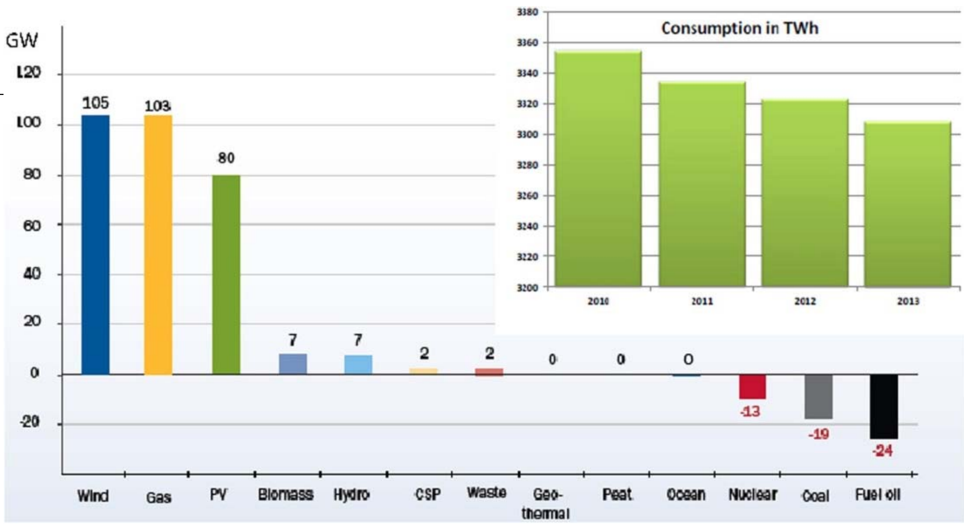


Fig. 3 EU electricity generation installed capacity net change, GW, 2000–2013, and electricity consumption in TWh, 2010–2013 (EWEA 2014)

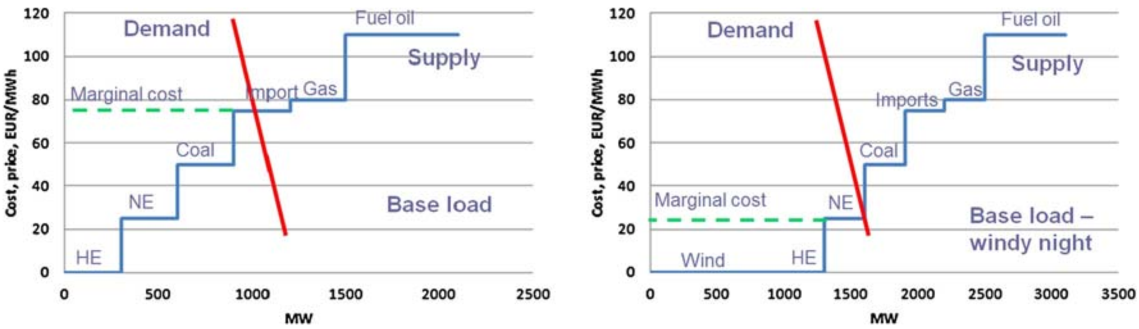


Fig. 4 Merit order without wind electricity and what happens to market base merit order due to wind power

Fig. 5 Price coupling of the regions. Price coupled areas up to March 2015

100 GW of thermal power plants. Similar situation has happened in the US. Even with the current level of capacity, it will take long time before the glut clears.

Higher penetration of VRES with very low variable cost of production (due to no fuel cost) has brought low prices to day-ahead markets (DAM) in EU, which made competing fuel-based technologies uncompetitive (see Fig. 4) during windy and/or sunny days. Market prices used to be high during days and low during nights, but still covering the variable cost of base load technologies (nu- clear and coal). The new prices usually do not cover or barely cover the variable cost of base load. Higher prices appear in morning and evenings, when demand is higher, sun weak or none and wind low. That should have opened market for more flexible technologies, like gas and hydro, but due to high price of gas currently in EU and low price of imported coal (overflowing from the US markets due to shale gas) that has not happened fully. As a consequence of falling oil prices and gas prices being still mostly bench- marked to oil, this might change in 2015.

Higher penetration of VRES has created the need to improve the transmission grid, so that electricity systems may be balanced more widely. The optimal balancing area with VRES is as large as possible, so that the physical flows are actually limited by transmission losses. A good insight into the limits of balancing by the grid has been made by Steinke et al. (2013). In order to make transmission more efficient, its capacity has to be auctioned transparently and in sync with the markets. Market coupling algorithm that was established in 2014 in Western Europe (Fig. 5) levels the electricity DAM spot prices as long as there is enough transmission capacity between any of two adjacent zones. It works according to the principle of communicating vessels. The joint process of market coupling and improving the transmission capacities will bring DAM prices close and in sync all over the Continent. The increased penetration of VRES will make new base load power plants hard to compete in wholesale mar- kets. Since wind and solar will make more and more encroachment on the base load, it will make sense to make base load more flexible, which is possible with coal (Cochran et al. 2013), but only up to a point with nuclear. That will make old coal still competitive, but with less than 4000 h per year it will not be competitive to build new capacity. Old capacity will in time be retired due to other policies, and when the current glut is removed from the market, only flexible power plants will be built to supply electricity when VRES are not available. The envisaged capacity markets will only prolong the agony, keeping more of the old base load plants online for longer time.

Liberalized spot markets with high penetration of VRES have brought rare negative prices, when there is lot of must-take VRES (when being on feed-in-tariff RES are sold on must-take ask) and inflexible base load (also on must-take ask). Since demand is currently barely elastic to price, the market-established merit order based on marginal cost may sometimes produce negative price. The reform of financial mechanisms now being put in place will replace inflexible feed-in-tariff with a more flexible mechanism, in which VRES are sold on spot markets, while there is a feed-in-premium only for technologies for which support continues to be needed and only when the spot market price is above 0. That will put the floor to the electricity price, but will not make base load significantly more profitable. For day-ahead markets to function well, forecasting of demand, wind, and solar becomes crucial and markets become weather driven. Even the best weather forecast will err on day-ahead hourly basis. Therefore, there is a need for corrective markets, which in Europe are called intraday markets, and work as hour-ahead or in Germany as 15-min ahead spot. Such intraday markets will iron most of the errors made in forecasting demand, wind, and solar on day-ahead market (which may amount up to 20 % for wind, but generally 75 % electricity is sold on DAM and 5 % on intraday), and although it was expected that its prices would be much higher than DAM, it did not happen. What has not been balanced on the hour-ahead basis (the error at forecasting wind may be 7 % hour ahead, Ela et al. 2011) will have to either be done by system-provided manual tertiary reserve, or better by a 15-min ahead intraday/balancing market. Most of the critical wind balancing is considered to be 15–60 min ahead, so a liquid market would be very useful. This will have to be done in the first phase by flexible power plants. Shorter term balancing is done by primary and secondary reserve, which are auto- matic and respond to the changes of frequency. It has been shown that there is no significant amount of additional primary and secondary reserve needed to balance high penetration of VRES (Ela et al. 2011), for which also the market mechanism is the best, but functions rather as available capacity market than spot energy market.

The issues discussed above have to be resolved before VRES reaches 20 % of yearly generation. What happens if the penetration continues to grow? There is more and more of electricity not produced from VRES (critical excess electricity production, CEEP) that is not exportable, and the spot market electricity prices are often very low, making all players less profitable. This CEEP is actually free electricity that could be produced at no additional cost, if there was market for it. Since there is no work in the search of such electricity, any use of it would be better than not producing it, even converting it to low-temperature heat. The crucial thing is that conversion systems must be market controlled, which does not make small heaters and heat pumps in residential sector an option without smart grid bringing the wholesale market information into the house. This is readily available in district heating, where large resistive heaters or even better heat pumps can store this excess electricity into heat. Heat storage is cheap compared to batteries. Such power to heat technologies can be made more economically viable through offering ca- pacity on primary and secondary reserve markets. That is important because they make the necessity of having conventional power plants always running with small ca- pacity just because of the system stability obsolete. District heating is popular only in Northern, Central, and Eastern Europe and China, while district heating and cooling may actually be viable in wider area. Sanitary hot water may also be an important demand that can be supplied by dis- trict heating, thus increasing the capacity factor.

Cooling will generally follow solar irradiation, so it can be fully supplied by PV, and even if not market controlled, it will be well matched to the demand.

In countries in which heating is not an issue, water may be. In hot and dry climates, large quantities of water have to be desalinated, stored, pumped, etc., a type of load that easily can be moved in time with lot of CEEP. Storing water for irrigation and use has to be paid anyway, so with modest additional cost of higher installed power of pumps (in order to deliver same output in shorter time), only or mostly CEEP can be used. Power to water integration can easily be led by wholesale market prices, so it is crucial to wean water companies off the electricity tariffs and into buying electricity on the spot markets.

District heating and cooling, covering heating, hot water and cooling demand, and/or water supply system, if fully integrated with power system through markets, can enable the penetration of VRES to effortlessly reach 40 % (Lund et al. 2014).

Electrical personal cars are up to 5 times more efficient technology than internal combustion engine (ICE) cars. If the electricity used is from RES, then there is no thermodynamic issue with it. The problem may arise from charging. If all people would buy electric cars and all would want to have fast chargers (70 kVAR) at home then, if they all arrived home and plugged in at 17 h, the re- sulting load would be 20 times higher than the peak load in a country. Thus, a smart charger technology will have to arise, connecting chargers through smart grid to the markets. Since personal vehicles are used only 1 h per day, the rest of the day they could be used as storage where mostly CEEP would be stored. The price of that storage is collateral, since it is due to the transport demand. Only the cost of smart grid would be borne by the power system. Such a smart charging system would have total installed power much larger than any possible CEEP production.

The issue left would be where to get electricity from when there is no wind and no Sun? Vehicle batteries may be used up to a level, providing necessary power when no other sources are available, so-called vehicle-to-grid (V2G) mode. Its cost would be the decreased life of batteries in V2G mode. Partially, this missing electricity could be supplied by controllable RES technologies, like waste and biomass, but these may be needed in other sectors. It could be supplied by hydro, pumped hydro storage or reversible hydro. Electric vehicles may one day economically cover personal transport, short-distance commercial and public transport, and short-distance shipping and railways. Long-distance road cargo transport could find new charging technologies, like possibly constant inductive highway charging, etc., but will be hard to supply airplanes and long-distance ships.

All these technologies should be sufficient to cover electricity, low-temperature heat, cooling, water supply, and most of the transport. The rest of the transport may be supplied by waste biomass, but that also may not be enough. In that case, a solution may still have to be che- mical fuel made from excess electricity, more probably synthetic hydrocarbons than hydrogen, since no new in- frastructure would be needed. Or this level of consumption of fossil fuels may be tolerable for long time, until better technologies were found.

Regarding industry heat demand, its low-temperature part may also be covered with district heating, heat pumps, or renewables, while its high-temperature heat needs may force such a process to be converted to electricity (like smelting already partially is). The remaining energy needs may be supplied by waste biomass or synthetic fuels, or just continue to use fossil fuels.

Conclusions

Not only that clean energy systems based on renewables are technically and economically feasible, but also the transition towards them has finally reached threshold of no return. Increasing the penetration of renewable energy sources into the power system even slowly, conventional technologies are becoming less competitive. That will create excess of electricity that will then more and more be used in power to heat and power to water technologies since heat and water are cheap to store and make them renewable too. Electrification of transport based on high efficiency of electric power train and batteries and excess of renewable electricity will enable covering most of the energy needs by variable renewable energy sources, while the rest will be covered by biomass and waste and by power to synthetic fuels, or will simply be covered by small amounts of fossil fuels. The transition process will be slowed down by fossil fuel subsidies and vested interests, but, since different countries have different local resources, these will produce different vested interests. It will be enough that only some countries develop technologies that will then spread globally. Although it might be too late to save the climate, by 2050 clean energies may be completely in place or very nearly so.

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