Pathways to energy autonomy – challenges and opportunities

Edward Bentley* (1), Richard Kotter (1), Yue Wang (1), Ridoy Das (1), Ghanim Putrus (1), Jorden van der Hoogt (2), Esther van Bergen (2), Jos Warmerdam (3), Renee Heller (3), Bronia Jablonska (3)

(1) Northumbria University, Ellison Place, Newcastle upon Tyne, NE1 8ST, UK.

(2) Stichting Cenex Nederland, Amsterdam, NL.

(3) Amsterdam University of Applied Sciences, Amsterdam, NL.

* Correspondence address: edward.bentley@northumbria.ac.uk

Abstract

The need to reduce carbon emissions calls for more use of renewable generation, particularly distributed resources. The intermittency of renewable generation, and concerns about energy security, require us to become more independent from central grid operation by use of local or regional (micro-grid) electricity systems. Distributed generation, allied to the commercial availability of battery storage products, permits this – the pathway to energy autonomy. This paper reviews the contribution of different renewable energy sources (RES), trends in energy storage technologies to enable energy autonomy, and the centralised and decentralised techniques that coordinate the associated energy management.

The paper covers energy autonomy at different scales, ranging from household levels to district levels. The improvements in grid independency are measured accordingly. There is discussion of this measurement and of the economic and ecological benefits from energy autonomy in the context of policy frameworks.

Keywords: Energy Policy, Storage, PV, Wind Energy

List of Abbreviations

ADSM Active Demand-Side Management
ANN artificial neural network
BESS battery energy storage system
BCR benefit cost ratio
CAES compressed air energy storage
CHP combined heat and power
COE cost of energy
DR demand response
DG distributed generation
DNO Distribution Network Operator
DSM demand side management
EA Energy Autonomy
ECS energy capacitor system
EDLC electric double layer capacitor
EMS Energy Management System
EPCI public institution for intercommunal cooperation
ESS energy storage system
ETC Ecological Transition Contract
EUCAD European Unit Commitment and Dispatch
EV Electric Vehicle
FCEV fuel cell electric vehicles
FiT Feed-in Tariff
FFR Firm Frequency Response
FPSP flexible-possibilistic stochastic programming
ICE internal combustion engine
ICT information and communications technology
LCOE levelized costs of electricity
LOLE loss of load expectation
MCHP micro combined heat and power
MDMP ratio of maximum power demand to maximum PV output
MDP Markov decision process algorithm
MG micro grid
NEEAP National Energy Efficiency Action Plans
NPV Economic net present value
POPF probabilistic optimal power flow
PAC pumped hydro accumulation storage
PHEV plug in hybrid electric vehicle
PV photovoltaic generation
RES renewable energy sources
SAEV shared autonomous electric vehicle
SG Smart Grid
SNPV simple net present value
TEMS transactive energy management system
ToU Time of use
TSO Transmission System Operators
V2H Vehicle to House
V2G Vehicle to Grid
ZEB Zero Energy Building

1. Introduction

In 1882 Edison built the first centralized DC generating station in New York to supply electrical power more cheaply and efficiently than could be provided by a stand-alone plant for each consumer. In 1870 the engineer and industrialist Lord Armstrong had installed an isolated DC hydroelectric plant at his rural house Cragside in the UK. Both supply approaches, central and stand–alone generation, have been available since then. With the development of AC technology by Tesla in the late 1880s it became possible to transmit power over long distances with relatively low losses, impossible with Edison’s DC system with its fixed low voltage output.

The AC system developed into national grids where a few large efficient central stations produced most of a nation’s power, distributed at high voltage to minimise resistive I^2R losses. Some isolated locations (e.g. islands) still needed to generate their own power because of the cost of grid connection. At the end of the 20th century, new technologies such as cost-efficient photovoltaic generation (PV) and wind power challenged the grid model. Money could be saved in some cases by local generation for local consumption (also called self-consumption), with local storage if necessary, avoiding the costs and losses of grid connection. The term Energy Autonomy (EA) in an electrical context means the degree to which local generation for local consumption can replace grid power. EA can range from 100% (total autonomy) to zero (full grid dependency).

The reduction in the costs of PV can make EA economic at a local level. Levelized Costs of Electricity (LCOE) of PV in Germany (about 12€ct/kWh) are less than German domestic electricity charges (about 30€ct/kWh) [1]. In the UK the average 2018 domestic electricity price was £0.151/kWh [2]. Assuming German levels of cost of PV generation, EA is now potentially profitable in the UK. Since March 2019 the UK Feed-in Tariff (FiT) has been discontinued for new entrants, but a 4kWp system installed in the UK with no FiT payments but with current export payments of 5.24 p/kWh would yield a rate of return of 4.85% [3], more than the cost of the installation from mortgage funding. Where possible it is now rational to use PV at home rather than to export it to the Grid, since in the UK one would save £0.151/kWh on power costs and sacrifice the export payment of £0.0524/kWh. Storage costs in 2018 are in excess of $0.124/kWh [4], suggesting that the economics of storage-based EA may be problematic.

A combination of central and stand-alone generation, distributed generation (DG), offers a framework within which money may be saved and energy from renewable energy sources (RES) used more fully since some renewably generated energy can often be consumed at the point of generation and a surplus can usually be exported via the grid. Security of supply can be increased.

Reasons for adoption of full or partial EA include:

- Energy security (EU/national/city), as much of the fossil fuel consumed in Europe is imported from politically unstable areas of the world, and supplies are at risk from war, terrorist activity and political decisions made abroad.
- In some cases grid connection is not feasible; notably in islands, remote areas, a lack of grid availability, or a lack of access to a grid for political reasons.
- Measures to promote EA often have the useful side effect of reducing the peak demand for power in the area concerned (peak shaving) which will tend to benefit the Distribution Network Operator (DNO).
- Direct use of RES, since with the reduction in the price of PV and wind generation, consumers and local communities may save money compared to the consumption of grid electricity; especially with the widespread availability of FiT and other incentives for RES.
- Transmission System Operators (TSO) are sometimes able to use RES to provide energy for balancing services.
- A sense of local community and empowerment follows from taking part in a joint RES scheme for mutual benefit.
- Area wide adoption of RES can be an appropriate use since the sources are usually low in energy density and may be more economic to operate at a community or regional level with partial or complete EA than at a household level. CO_2 emissions will be reduced as a by-product, an additional incentive to adopt EA.

The elements necessary to provide EA are the local generation system (diesel generators, biofuel or RES such as hydro, solar, wind, tidal, biomass and geothermal), the electricity demand and the electrical storage system; often also information and communications technology (ICT). The generation system aims to satisfy the internal demand, reducing grid absorption. This creates two arguments for a DG investment: electricity cost reduction and potential CO_2 emission savings. The investment payback is via electricity cost savings and any offered subsidies for RES including available FiT for export of energy to the grid.

A certain degree of EA may be already available through direct consumption, but further improvements may often be achieved by combining the generation system with an energy storage system (ESS) such as a stationary battery (BSS). Specifically for RES, which are intermittent and sometimes unpredictable, a BSS can store surplus energy in order to return it when there is a shortage of electricity. Electric Vehicle (EV) batteries can substitute for conventional BSS via Vehicle to Grid storage (V2G) or Vehicle to House (V2H) via bidirectional charging. Dubarry et al [5] find that battery charging/discharging for the autonomous system usually causes extra battery degradation. The costs of V2G must be compared with the cost savings from increased EA.

This paper reviews studies conducted on micro-grids and DG which aim to optimize EA. The emphasis is on a definition of EA as this determines the resulting outputs. The factors that influence the overall degree of EA (the self-consumption percentage of local generation that supplies the demand) or the self-sufficiency (the percentage of demand that is supplied by local generation) are the focus.

The concept of EA may be considered within a context where there is significant DG and ESS deployment, and concerns about energy security. EA has been equated to energy self-sufficiency [6] defined as the “ability of an energy system to function (or have the ability to function) fully, without the need of external support in the form of energy imports through its own local energy generation, storage and distribution systems”. Here discussion will be restricted to electrical EA. This refers to a restricted ‘local’ geographical area, and so the degree to which the electricity demand of an area is supplied by generation within that area. A distinction [7] may then be made between net EA, with aggregate power supply and demand balanced over the year, and complete EA, which requires that an area can satisfy its instantaneous power demands throughout the year without a grid connection.

Luthander et al provide [8] two definitions: self-consumption and self-sufficiency defined in Equations (1) and (2) and Table 1.

C represents the consumption directly supplied by RES generation in kWh.

B is the surplus RES generation energy after meeting the local demand in kWh.

A represents local consumption not directly supplied by RES in kWh.

$$Self\_consumption = \frac{C}{B+C} \qquad (1)$$

$$Self\_sufficiency = \frac{C}{A+C} \qquad (2)$$

Self-consumption / Self-sufficiency is therefore the ratio of the total load demand (A+C) to total generation (B+C) which determines the relative values of achievable self-consumption and self-sufficiency for a particular system. The factors that influence self-consumption and self-sufficiency include the relative sizes of RES generation and demand profiles. If the surplus RES generation increases but the consumption directly supplied by RES generation is unaltered, the self-consumption decreases; whereas the self-sufficiency either increases or remains unchanged [8]. When the self-consumption corresponds to the self-sufficiency, e.g. for a building in which generation equals the load, a Net Zero Energy Building (ZEB) results.

Time resolution is important because a lower resolution leads to an overestimation of self-consumption: the fluctuations are averaged, so part of the mismatch between generation and load is ignored. If an annual basis is used then overproduction during summer is compensated by overconsumption during winter. RES market value will be measured wrongly if the temporal resolution is inadequate [9].

Table 1 Self-Consumption and Self-Sufficiency

Self-Consumption	consumption directly supplied by RES generation/ total generation
Self-Sufficiency	consumption directly supplied by RES generation/ total load demand

2. Methodologies for enhanced energy autonomy

Methods exist to increase self-consumption and self-sufficiency. Self-sufficiency is already improved with the installation of a PV system in a household. The aid of an ESS may assist further. As noted by Luthander et al [8] ESS can enable load shifting, thus increasing the level of self-consumption. Common technologies include batteries, flywheels, compressed air energy storage (CAES), fuel cells, pumped hydro storage, and super capacitors. An alternative is demand side management (DSM), influencing consumption to modify the shape of the load profile to better match generation.

Luthander et al [8] analysed methods of increasing self-consumption, with BSS of 0.5-1 kWh per kW of PV it increased between 13% and 24%. Increased battery capacity non-linearly increases self-consumption. DSM increases self-consumption by 2-15% according to the PV system size. The control strategy used affects the maximum level of self-consumption. If the battery is charged simply when there is a PV production surplus and discharged when the consumption is higher, the level of self-consumption increases. But, once the battery is fully charged the subsequent part of the peaks is not reduced. It may be better to charge the battery at a lower rate for a longer period when a larger storage battery may be required.

The influence of social-economic and technical behaviours on EA has been evaluated in social communities [6]. The main influences are degree and scale of EA, ability to match demand with supply, and the importance of political and socio-economic factors. The scale of the system determines the number and range of the stakeholders, the available resources and the available decision-making processes. The motivation of achieving EA has to be compared with the financial and technological barriers. Hence, with grid connection available there is an appropriate level of autonomy that can be achieved, which balances the possibility of additional cost against the benefits of increased EA.

Two options to improve the matching of PV demand and supply exist: BESS and DSM. If available the grid itself can be used to store surplus PV generation; when there is inadequate PV the demand is satisfied from the grid.

The grid can be adversely affected by reverse power flow. The battery makes it possible to have local storage/of energy for use without significant losses. DSM is identified as an economic and straightforward way to achieve a certain level of energy autonomy. Nevertheless, DSM implies a change in user behaviour for most applications. Human motivations (ecological, economic, political or other) need to be understood. If users are aware of the benefits that RES and EA can bring to their community [10] they are twice as willing to implement or pay for small-scale RES as when there are large-scale developments. The lack of government support for local community projects, the difficulties to enter the market and network connections are barriers to community projects but financial incentives, support systems and training/education systems can foster user engagement.

Energy systems will need to be re-engineered to include ‘smart’ features which can allow operation solely from RES to supply power for general loads including transport [11]. Increasing use of RES requires a re-design of both supply and consumption systems which must incorporate ‘smart’ power grids, district level heat transfer systems and gas distribution networks. With these additions, a system copes better with the non-predictable nature of RES, making best use of fuel and energy storage including EVs. Uptake of bioenergy enhances sustainability. Østergaard [12] for instance analysed enhanced incorporation of wind power into the Western Danish power grid via heat pumps. Maximum wind power acceptance depends on whether the network is an ‘island’ or can exchange power with the remainder of the national grid. Maximum benefits from wind power, such as reduction in CO_2 and non RES generation, are obtained when they occur outside the local area. DSM can offer a localised solution to increase wind power absorption.

BESS is effective to enhance EA, its size being positively but non-linearly correlated to the improvement. DSM is an economically feasible solution to improve EA, requiring user acceptance and behavioural change in the user. Table 2 shows a summary. To achieve energy autonomy needs a trade-off with the economic, technological, social and political barriers. Government support for local community projects is required to enter the market and network connections.

Table 2 Effect on Self Consumption and Self Sufficiency of PV, Storage and DSM

Component of EA	Effect of additional PV	Effect of additional storage	Effect of DSM
Self-sufficiency	Enhanced	Enhanced	Enhanced
Self-consumption	Enhanced	Enhanced	Enhanced

3. Systems’ scale and boundaries

Some forms of EA generation such as Hydro may only be applied at a district scale (sections of very large cities or indeed urban aggregation or populated/infrastructures rural areas). Other forms of EA may be adopted at lower scale levels; neighbourhood, commercial and domestic. These include PV and BESS. Figure 1 below shows the scheme.

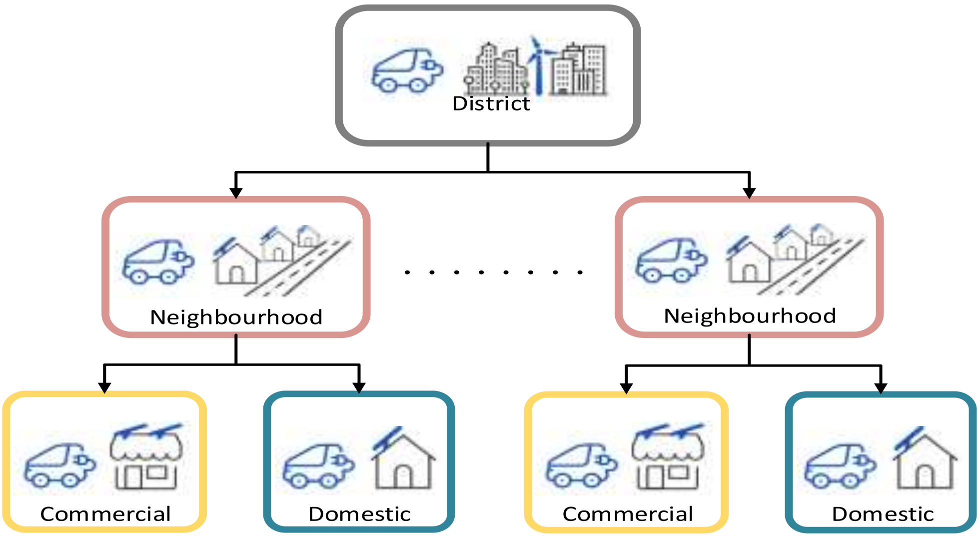

Figure 1. System scales

Energy autonomy realisation needs to take into account the different scales of the technical, economic and social barriers and enablers (Fig 1). This section concerns households/buildings, neighbourhoods and districts for the combination of PV and energy storage, as well as DSM.

3.1 Single House/Building

A six apartment micro-grid (MG) [13] was provided with 20 kWp PV, a solar thermal installation, ground source heat pump, heat storage and 11.6kWh of BSS. Self-consumption of 60% was achieved at the cost of significant battery degradation. Similarly, a 10 kWp solar panel with heat pump, solar thermal plant and thermal storage were three technology options for a ‘Net Zero Energy Building’ in Denmark [14]. In the selected conditions the best arrangement was the use of PV coupled with a heat pump. Any dwelling could then enjoy nearly 100% energy autonomy. The components were oversized to ensure continuity of supply even in winter.

A number of studies considered the effects of combining PV with BSS for a single building. The coupling of PV with BSS would give the best long-term economic solution, and be profitable. Akter et al [15] compared grid linked and stand-alone regimes in Victoria, Australia varying PV and BESS capacities. The cost/benefits were examined via energy cost, reduction in CO_2 and degree of grid independency. PV ranged from 3 to 10 kW, and BESS capacity from 4 kWh to 12 kWh; investment costs and savings increased with PV and BESS sizes. Payback was more rapid with smaller sized units. The NPV was positive only for the grid connected three smallest sizes of the PV unit. The LCOE was about 0.1 AU$/kWh for PV only and between 0.25 AU$/kWh and 0.3 AU$/kWh for PV with BESS, for both grid linked and stand-alone configurations. The higher the investment, the greater the CO_2 reduction. When the FiT declined a shorter payback time was obtained by sale of excess power to neighbours. Weniger et al [16] reached similar conclusions using German data.

Quoilin et al [17] evaluated self-consumption for typical households in Belgium, Spain, Germany, Hungary, Italy, Romania, France and the UK, taking it as a function of electrical demand, PV generation and BESS capacity. A self-sufficiency level over 80% was uneconomic owing to the costs of the necessary oversized system. A formula was given to calculate self-consumption from BESS and PV capacities. Lower battery costs are needed before the system provide savings. Mulder et al [18] considered optimal storage size for seven grid connected houses in Flanders with PV and small capacity BESS. A strong relationship existed between storage size and the volume of energy sent to the grid. If PV capacity matched demand then positive relationships existed between storage sizing as a function of PV power and synchronisation between production and consumption. Santos et al [19] simulated Portuguese BSS with real data. Three different storage regimes were modelled. Storage reduced the cost to 35% of the cost of PV alone; there was a 20% reduction in residential power flows with the grid. Hassan et al [20] modelled the combination under UK FiT to establish the interrelationship of battery capacity, battery cost and PV sizing. With PV without BSS, excess generation was sold to the grid. With UK electricity tariffs the battery charged from the grid at low or even negative electricity prices, and discharged at high tariff times. The BESS charged when PV generation was at a peak, charging from the grid when PV generation was reduced and the wholesale price was low. BESS could be economically sized up to 3 kWh becoming viable once BSS price dropped to £138/kWh. Mariaud et al [21] examined a London UK distribution centre, covering real time price models of electricity, and allowed for revenue from the provision of Firm Frequency Response (FFR) services. A financial model reduced investment uncertainty. Despite seasonal variations PV could supply 30% of energy consumed on the site with a 26% CO_2 reduction. The PV and BESS had an 8 year payback, with 5 year NPV savings of £300k.

Some work combines PV with BSS and DSM. Widén et al [22] matched distributed PV in Stockholm to the load profile via DSM variation in PV and storage capacity. BESS was found to be the most attractive option at large renewable penetration levels, whereas DSM was as effective or even better at lower levels of penetration. Mesarić and Krajcar considered EV batteries as BSS when grid connected and parked [23]. EVs together with DSM can contribute to micro-grid stability reducing dependence on the grid. These authors modelled a solar powered building, verified with a self-sustainable house in Zagreb, using DSM to reschedule appliance use and EV charging. The aim was to cause the daily load curve to track the RES production curve, thus maximising local absorption of RES. Castillo-Cagigal et al [24] examined Active Demand-Side Management (ADSM) and BESS to determine their effect on self-consumption through a grid-connected, self-sufficient house in Spain. Studies over differing time scales distinguished between deferrable and non-deferrable energy demand. A non-linear connection between the electrical power flows and storage capacity was shown. Lorenzi and Santos Silva [25] modelled augmentation of self-consumption in Portugal, with Time of Use (ToU) optimization applicable for use with both BESS and demand response (DR). DSM was preferable to BESS based on market prices of hardware. Vieira et al [26] modelled a control system to optimize self-consumption, minimizing household/grid power flows and energy costs for a typical household in Portugal. The energy exported to and absorbed from the grid was reduced by 76% and 78%, respectively, and the energy bill was reduced by 87.2%. The system will become cost effective with a lower BSS price.

The economics of EA can be addressed using the work of Uddin et al [27] who studied a medium sized house in Loughborough equipped with a 4kWp PV installation and a 1.6kWh storage battery. During 2016, PV generation totalled 3691kWh. Domestic demand was 4142kWh, of which 1347kWh were supplied from PV. The remainder (2344kWh) was exported to the grid, giving a self-consumption rate of 36.5%. In Spring 2019 UK domestic electricity prices averaged £0.151/kWh with an export tariff of £0.0524/kWh. Thus savings on the Utility bill would be 1347*£0.151 = £203.40. At current prices the export tariff would provide 2344*£0.0524 = £122.80 total savings from the presence of the PV installation at 2019 prices = £326.20. UK Government figures suggest an average 2018 installed price for a 4kWp PV installation is £1840/Kw [28] or £7360 for 4kWp. The capital recovery factor (CRF) gives the present value of a series of equal annual cash flows. A formula can establish the annual payments needed to repay a loan:

$$CRF(i,N) = i(1+i)^N/((1+i)^N - 1)$$

If the rate of interest i =3.5% [29] and the PV installation lasts for 10 years (N=10) then CRF = 0.12 giving an annual cost of £7360*0.12 = £883.20 over the lifetime giving an annual loss of £557 at current prices. The LCOE here is £883.2/3691=£0.24/kWh. Even if self-consumption = 100% there would still be a loss of £883.2 – 3691*£0.151 = £326.

In the more favourable case where i=2% [30] and assuming a PV lifetime of 20 years, the CRF = 0.0617 provides annual repayment of £454. This still yields an annual loss of £127.80 on existing consumption patterns, but the LCOE reduces to £0.123/kWh, less than the cost of grid power, in line with the Lazard estimates for domestic rooftop PV (LCOE $0.160-0.267/kWh) [31]. Break-even occurs when self-consumption = 71.6%. If self-consumption = 100% a profit of £103.34 arises. To achieve this profit via DSM could be problematic for a householder. To achieve self-consumption of 100% using the same consumption pattern but with storage, the storage cost needs to be </= £103.34/2344 = £0.044/kWh, at present unfeasible at the household level. Peacock [32] writes that storage costs for a Tesla Powerwall 2 domestic storage battery are AU$0.155(£0.08)/kWh. The unit is rated at 5kW continuous with storage of 13.5kWh.

A KPMG report [33] estimates that PV generation costs will fall by 25% between 2018 and 2028. In the favourable case PV LCOE would fall to £0.09/kWh in 2028, the corresponding PV annualised repayment falling to £340.50. A Bloomberg report predicts that by 2028 Li-Ion battery costs will fall to $100/kWh from the present $176/kWh [34]. If costs of domestic storage fall in the same proportion, they would become £0.045/kWh. Assuming that grid power costs and export tariff rates remain at present levels, with present consumption patterns without storage one achieves break-even. With 100% self-consumption via storage a profit of £111.36 would be obtained.

3.2 Neighbourhood and micro-grids

Orehounig et al [35] examined a Swiss mountainous neighbourhood scenario with 29 buildings of differing ages and types connected as an energy hub. Depending on the RES mix used, including decentralised and RES such as PV and small hydro, together with district heating systems, building and district conversion approaches as well as energy storage at neighbourhood level, EA between 64 % and 92 % were obtainable, using a time-dependent buildings energy demand model. De Coninck et al [36] modelled integrating hydronic, thermal and electrical networks at both single building and local levels for zero-energy buildings in Brussels. Self-consumption rates of about 26 % were achievable, although connected feeder voltage fluctuations and potential transformer overload were problematic. Baetens et al [37] modelled a neighbourhood comprising 33 zero energy buildings (using adequate PV and heat pumps) in Brussels, applying DSM to reduce PV requirements. Thermal energy storage was effective to balance PV production, reducing losses and producing a net energy saving at neighbourhood level. Rae and Bradley [6] examined EA in sustainable communities through small-scale RES noting that a shift towards increased DG raises social and technical challenges, but also a range of social, financial and economic benefits. These authors identified DSM as needing further research, coupled with necessary enabling social, political and regulatory environments.

Some studies deal with the combination of PV and BSS. Lawder et al's [38] model-based study of Micro Grids (MGs) in the United States found that the combination is desirable for high levels of EA. But expensive BSS is often underused because of seasonal fluctuations. Four different shapes of demand curve were studied: trapezoidal, parabolic, constant and sinusoidal. The generation source was adequate to provide the daily energy required. Study parameters were the ratio between BSS and PV Capacities, and the ratio between the Maximum Power Demand and Maximum PV output (MDMP). The results suggested that as battery capacity rises, autonomy will rise, but only until the power demanded exceeds the combined capacity of the solar array and battery. The shape of the MG demand curve affects autonomy and battery use. When demand exceeded PV output, battery use was at the maximum with the parabola load, about 60% with the trapezoidal, whereas it reached the peak for the constant and sinusoidal load in proximity of MDMP=0.5. Autonomy and battery use could not normally be maximized simultaneously. Luthander et al [39] simulated over one year 21 Swedish detached single family homes with 108.9kWp PV, using a shared grid connection, 18 of which homes were equipped with BESS. Higher self-consumption was achieved via centralized storage rather than one BESS per house, a 50% reduction in PV curtailment being observed with reduced losses. Increased revenue was obtainable from shared rather than individual BESS. The annual PV generation was 107,000kWh, total consumption was 305,000kWh, and self-consumption with a common meter without storage was 62060 kWh (58%). Swedish domestic power prices as at December 2018 were €0.142/kWh (£0.122/kWh) [40]. To achieve adequate PV 311kWp installed capacity would be needed, ignoring losses, with associated annual storage of 243,000kWh.

For each house to have its own storage one could assume the Tesla Powerwall storage cost of £0.08/kWh [32], giving annual storage costs of £19440. To provide 311kWp PV with separate installations per household would cost £572240 at an assumed UK price of £1840/kWp [28]. Assuming i=2% [30] and a lifetime for the PV installation of 20 years, the CRF=0.0617 giving a levelised annual cost of the PV installation of £572240 *0.0617 = £35307. Adding to this figure the annual cost of storage, £19440, gives a total cost for an autonomous electrical supply of £54747. Savings on grid imported power would be 305,000 kWh at £0.122 = £37307.

Autonomy is thus uneconomic for an individual household. With a shared PV installation, costs per kWh would be reduced by avoiding duplication in electronics and control systems. An average community level production cost of £84/MWh was estimated in the Lazard levelised cost of energy 2018 [31] resulting in an annual cost for 305MWh of £25620 (€29448). Commercial and industrial level storage is estimated to cost £0.044/kWh [4], giving an annual cost of storage of £10692 (€12290). Total annual costs of providing autonomy could be estimated at £36312 (€41738) with an associated saving in grid power costs of £37210 (€42770). Autonomy appears economically feasible at the community level.

3.3 Districts and aggregation across different scales

The scope for moving towards EA for districts in Austria, German and England respectively using biomass, wind and PV RES has been analysed.

Killinger et al [41] chose four regions in Germany, with diverse RES (including wind and PV). Regional EA was optimised in terms of economics, environmental sustainability and security of supply, with the best mix of wind and PV to support regional electricity demand. The optimal mix of wind and solar PV differs significantly for determined energy policy goals. Schmidt et al [42] found for an Austrian region that full EA in the electricity and heating sectors would significantly increase biomass production and require full use of all roof-top PV potential, posing higher costs and competing with food production for land use. In contrast Jenssen et al [43] found that heat and power demand can be covered with limited land use for biomass production and at relatively low cost. Burgess et al [44] examined three different land-use scenarios; and they found real limits to meeting energy demands for transport (only up to a third) and heat (just over half), even with a high yielding crop. McKenna et al [7] modelled aggregation across various scales in Germany (from individual buildings, to neighbourhoods and districts) to find the economics of EA, minimising total lifetime energy costs. Resources included Micro-Combined Heat and Power (MCHP), PV, thermal storage, BESS and boilers. The total annual cost per household fell and the optimal degree of EA rose as the number of households increased, from 30.0% for one household to 96.1% for 1000. Above 560 households it was economically advantageous for a district to be fully autonomous. With lower battery costs the maximization of in-house consumption will become economically attractive.

Dang et al [45] described simulating a French district including residential and commercial buildings. To reduce transformer overload an Energy Management System (EMS) used available EVs via V2G. An economics layer was added in order to compute the electricity costs, establishing the most economic level of contracted power with the grid. As a result the duration of transformer overloads fell by 70%, average power during overload by 71 % and electricity costs by 17%.

At the district level, the economics of EA are becoming favourable. Xcel Energy in Colorado has bid to supply solar-plus-energy storage at prices as low as $36 per megawatt-hour [46]. This turns PV into a dispatchable source of generation at a lower cost than the $41/MWh minimum LCOE for a Combined Gas Cycle Plant. At a large enough scale the LCOE for PV plus storage is now competitive with fossil fuel powered generation, suggesting that PV based EA will become economically viable.

3.4 Summary of important results from studies reviewed

Table 3 shows some of the most frequently cited studies on EA. They have different scales and system set-ups in their empirical applied or simulated nature. Those studies are not fully transparent on their economics, such as investment costs or subsidies, or return on investment. None appears to be concerned with CO_2 emission, the focus projects such as the EU Interreg North Sea Region SEEV4-City project [47].

Table 3 Summary of important results from studies reviewed

Authors	Study reference	Comodi et al (2015)	Milan et al (2012)	Luthander et al (2016)	McKenna et al (2017)
System description	Scale	Single building 6 apartments	Single house	Neighbourhood 21 houses	District 1000 houses
System dimensions	kW	20 PV	10 PV	108.9 PV	Not stated
Components	Type	PV, storage, solar thermal, HP	PV , HP	PV Storage	MCHP,PV, storage thermal/electrical, boilers
Electricity demand	kWh	Not stated	5300	305000	4474495
Investment	€	32740	53300	417380	Not stated
Electricity price	€/kWh	0.138/0.129	Not stated	0.109	0.29
Subsidy	€/kWh	Not stated	Not stated	Not stated	0.1
Return on Investment	Years	Not stated	Not stated	10	Not stated
Total Cost of Ownership	€	Not stated	37200 (loss)	-10320 (profit)	Not stated
EA / self-consumption	Percentage	60	100	58/100	100
CO2 emission	…	Not stated	Not stated	Not stated	Not stated
Reference electricity price	€/kWh	None specified	None specified	None specified	None specified
Country	Detailed location in the study reference	Italy	Denmark	Sweden	Germany

4. Deployment and applications

EA is enhanced by using ESS to support RES. This section presents the applications of various ESS to EA, both stationary and as part of an EV battery pack. EA studies of PV and wind turbines, the two most widely adopted RES for distribution networks, are also presented. In addition, regional and national renewable energy policies are discussed with regard to their promotion of EA. Smart energy management, centralised and decentralised, is presented with its applications to EA.

4.1 Applications of various forms of energy storage to energy autonomy

According to Barbour et al [48] pumped hydro is the most developed ESS with 150GW, 99% of global capacity of 150GW. Super Capacitor and hydrogen based energy storage technology are still at the R & D stage. Li-Ion batteries are enjoying massive market expansion with the rising deployment of EVs and BESS. The price for Li-Ion battery packs is forecast to drop below \$100/kWh by 2028 [34]. According to Ibrahim and Ilinca [49] there is a rank order for energy storage capability and power output; Electrochemical batteries: Flow batteries: Large Compressed Air Energy Storage (CAES): Pumped Hydro.

Sundararagavan and Baker summarised the component cost of various ESS in US\$/kWh [50] including: lead-acid (300), sodium–sulphur (534), nickel–cadmium (1197), and lithium-ion batteries (1500), superconducting magnetic energy storage (10000), electrochemical capacitors (30000), flywheels (1000), flow batteries (400), pumped hydro (12) and CAES (10). Cost estimates concern grid services with a grid connected wind farm, including load shifting, frequency support, and power quality support. In practice only the flow and Li-Ion batteries are competitive for general purpose energy storage in the absence of favourable geological conditions, Li-Ion technology being the cheapest at present [4].

LCOE for Li-Ion battery storage is US\$0.187 /kWh [46]. Assuming that the chief cost in Li-Ion storage is battery degradation, and since [51] the Li-Ion battery price in 2018 was US\$176/kWh, an estimate of the useful battery lifetime can be obtained: US\$176/US\$0.187 = 941 full charge/discharge cycles. Li-Ion storage costs including capital and depreciation are now as low as \$124/MWh at the wholesale level (400MWh); \$171/MWh at the transmission and distribution scale (60MWh); and \$492 at the commercial and industrial scale (2MWh) [4].

Després et al [52] modelled ESS enabling large amounts of RES to be grid connected to the whole European power network. The European grid relies on software known as EUCAD (European Unit Commitment and Dispatch) which allows for the effects of ESS. The work links the two types of software, allowing long and short term prediction. The types of storage modelled include Li-Ion batteries pumped-hydro storage, CAES and EVs. The developed system includes continental grid connections and demand response. Ghofrani et al [53] reported further modelling work on utility scale wind integration with ESS. A genetic algorithm (GA)-based approach is used together with power flow analysis to place and size storage by minimizing the sum of operation and interrupted-load costs. Brekken et al [54] studied a zinc-bromine flow battery-based BESS to facilitate grid connection of wind farms. ESS at the RES location could provide equalisation. The authors discuss methods for choosing the optimum battery size and control regime. Control via an artificial neural network (ANN) gives better results than those obtained via more basic control systems.

Several authors have examined CAES in conjunction with wind generation to provide reliable baseload power [55-57]. CAES has a rapid enough response time to carry out energy arbitrage. Fertig and Apt [55] maintained that the economically optimum size for the expander may be at present high at 17-24GW [55]. Madlener and Latz [56] used a profit maximising algorithm and modelling to study the economics of a German wind farm of 100 MW capacity. Unless there is a market where hourly contracts are traded the system must be subsidised. A centralized CAES plant is more economic than a wind power/ integrated CAES plant. Diabatic CAES is more profitable than the adiabatic form. Zunft et al [57] discussed the European "AA-CAES" Project, again finding that Grid integration of the variable RES output may be an issue. CAES offers the necessary energy storage at high efficiency, with possible economic value.

Suul et al [58] examined variable speed pumped storage for its potential to level power fluctuations and provide frequency control using wind power in an isolated grid. ESS for the Faroe Islands enables absorption of more RES in the system. Muyeen et al [59] simulated an energy capacitor system (ECS) to level the output of combined variable-speed wind turbines connected to the grid through a fully controlled frequency converter. The ECS comprised an inverter, fuzzy logic controlled buck/boost converter, and an electric double layer capacitor (EDLC) bank. Castillo and Gayme [60] surveyed grid-scale ESS to facilitate RES grid connection in the context of relevant regulatory changes. Ummels et al [61] considered energy storage to enable the integration of large amounts of wind power in a Dutch environment; including pumped hydro accumulation storage (PAC), underground PAC, CAES and CHP. The economics improve as more wind power is installed. Speidel and Bräunl [62] examined ESS via Li-Ion batteries for PV. They examined various RES, energy storage, grid connected and off-grid systems and described a case study using the University of Western Australiaʹs off-grid “Future Farm” with a 10 kW PV and a 20 kWh BESS.

EVs may be used to facilitate integration of RES. Soares et al [63] modelled the electric power system in North-East Brazil to optimise the use of future wind farms. Combining variable output wind generation with conventional generation, nuclear and river hydropower can result in disequilibrium between supply and demand. PHEVs could be used to restore equilibrium. Andersen et al [64] proposed (2009) using EVs as distributed BSS to level fluctuating RES. They discussed V2G together with distributed power generation and recommended that Artificial Intelligence (AI) should be used to create virtual power plants from distributed sources. In 2011, there was interest in applying this model in Israel, Denmark, Australia, and the United States (the Bay Area cities and Hawaii). Robledo et al [65] studied hydrogen fuel cell electric vehicles (FCEV) for power generation and mobility. An FCEV could be used via V2G as a local energy source and could reduce the yearly grid importation of electricity by 71%, assisting in achieving a net zero-energy building target. The procedure might become economic if at the pump hydrogen prices reach 8.24 €/kg. Hoarau and Perez [66] reviewed the interaction between PV and EVs; they pose separate challenges for power grids; in conjunction they could decrease the overall burden. EVs could use PV to charge; PV systems could use EV V2G to enhance self-consumption. The synergy depends on technical as well as economic factors and was found at scales from single households to whole territories. Haddadian et al [67] examined strategies for integration of RES into the grid, without compromising infrastructure security. These authors demonstrated the merits of a proposed optimization model via numerical case studies. RES in conjunction with EV fleets could reduce power system peak demands, minimizing costs, wind energy curtailment, and fossil fuel backup generation. Iacobucci et al [68] showed via modelling that shared autonomous electric vehicles (SAEVs) may transform EVs into a mobility service, control their charging and assist in decarbonising transport. The SAEVs would provide storage to help RES integration. Richardson [69] reviewed EVs, the grid, and the integration of RES, finding that EVs can reduce RES curtailment. Mwasilu et al [70] concluded that EV integration into the energy market can level grid energy fluctuations. Schuller et al [71] evaluated the degree to which EVs can charge from RES. A mixed-integer optimization problem minimized the amount of conventional generation required. The usage of RES can be more than doubled as compared to uncoordinated charging. Chellaswamy and Ramesh [72] reviewed EV charging systems. A new charging system is proposed using wind and PV with a wind duct to improve wind output.

4.2 Renewable energy resources for energy autonomy

This section discusses PV and wind energy in terms of profitability across different countries and under different support strategies; highlighting the potential benefits when PV and wind power combine with ESS. This shows the conditions under which the addition of storage becomes profitable.

The International Renewable Energy Agency [73] gave 2015 Global LCOE prices per kWh: Solar PV US$ 0.13, onshore wind US$ 0.07, offshore wind US$ 0.18. Their projections for 2025 were: Solar PV US$ 0.06, onshore wind US$ 0.05, offshore wind US$ 0.12. Table 4 summarises these results. According to Carbon Tracker, the 'think tank' [74] the capacity-weighted operating cost of US coal fired electricity generation is in the range US$ 0.04/0.05 /kWh, as at 2018 and tending to rise. According to Lazard [31], Solar PV generation costs are low in 2019 but decrease substantially with installation size; the figures per MWh LCOE are: Rooftop Residential $160-$267; Commercial and Industrial rooftop $81-$170; community level PV $73-$145; Utility scale Silicon crystalline $40-$46. The US Energy Information Administration [75] (2019) finds that by 2023 the LCOE for onshore wind and solar PV will both be lower than that for coal fired power generation. Fossil fuelled generation will become less justifiable because of the resulting environmental problems.

Table 4 2015 and estimated 2025 costs of Wind and PV generation from [73]

Reference Date	Solar PV US$/kWh	Onshore Wind US$/kWh	Offshore Wind US$/kWh
2015	0.13	0.07	0.18
2025	0.06	0.05	0.12

4.3 Applications involving PV systems

As at 2010, global support for RES led to their extensive deployment and adoption. Especially for PV, countries like Germany and Spain were pioneers in introducing FiT, Germany became the current leader in terms of PV capacity per capita according to López Prol [76]. Recently FiT support has declined but so has PV cost, making it economically competitive. Grid parity is the capability to supply electricity at a cost comparable to that of grid electricity. Lorenzi and Santos Silva [24] argued in 2011 that as electricity prices rise and PV costs decrease grid parity will be achieved in Europe. In 2016 Merei et al [77] found that installation of PV reduced electricity costs via self-consumption in Aachen.

PV profitability of PV depends on the national support system and the scale. In Germany policies were stable and supportive, but in Spain erratic policy changes caused a diffusion bubble and a subsequent profitability bubble leading to the collapse of the support system in 2012 according to López Prol [76]. Spain has good solar irradiance but has restrictive PV self-consumption regulations which render it uneconomic. Germany has more EA than Spain. There are other incentive systems including a dynamic net billing scheme [78]. In the UK Jones et al [79] predicted that battery-less PV systems will become economic by 2020 without FiT.

The International Energy Agency in 2015 [80] suggested that in some countries grid parity has not been yet achieved. In such cases supporting policies can contribute towards increasing installations and therefore energy autonomy.

Energy generated from RES must be consumed locally; excessive generation can cause reverse power flow and inefficient operation of the electricity grid. According to Hubera et al [81] integrating RES, especially wind and solar, can require increased flexibility from the backup generation system. ESS can store the excess energy and provide for electricity demand when there is scarcity of RES generation. This increases the self-sufficiency and self-consumption of the overall system, as defined in Section 2. Luthander at al [8] show the feasibility of increasing self-consumption by 13–24% with storage of 0.5–1 kW h per installed kW PV power.

Installing BESS may be uneconomic. Anuphappharadorn et al [82] evaluated the cost of energy (COE), benefit cost ratio (BCR), and simple net present value (SNPV) for PV systems equipped with BESS in Thailand. The results show that the COE, BCR, and SNPV using Li-Ion battery are 0.13, 34.93 baht/kWh and 145,927 baht, respectively. The corresponding figures for a lead-acid battery are 0.19, 23.30 baht/kWh and 89,143 baht, respectively. The synergy between PV and BESS can create environmental benefits. In a particular installation, the combination lowered CO_2 emissions by 17% [79]. Li-Ion batteries are an efficient and reliable storage solution, but their economic viability should be studied on a case-by-case approach. Naumann et al [83] argued in 2015 that profitability of PV and BESS systems in Germany would be reached in the near future. Merei et al [77] found that the use of batteries to increase self-consumption as of 2016 is uneconomic for commercial application in Germany. A PV/BESS combination could reduce electricity costs further once battery costs fall below 200 €/kWh. Uddin et al [27] analysed the profitability of PV and BESS in the UK, concluding that installation of the battery gives no economic benefit and may even cause a loss to the householder. However, Jones et al [79] found that battery costs must fall to £334/kWh or else extra revenue from providing ancillary services is required. It is clear that the economic viability of PV and ESS depend on the technology with investment costs still too high in the majority of countries to stimulate wide adoption.

4.4 Applications involving wind energy conversion systems

Along with PV, wind has become a popular RES. Between 2000 and 2006 wind energy formed a significant source of power with almost 74 000 MW installed worldwide at the end of this period [84]. Australia established a National Electricity Market in 1999 and an early renewable energy target scheme in 2001 [85].

The variability of wind speed brings challenges which affect the achievable degree of EA. Wind power is concentrated more in certain areas [86] and wind power penetration in power systems can cause an energy surplus [87], most likely in off peak periods. Available pumped-hydro resources are insufficient to level the generation total; curtailment causes economic loss. DeCesaro et al [88] argued that successful penetration of large-scale wind power will necessitate changes in the planning and operation of power grids together with more accurate weather forecasting.

Weber [89] examined liquidity in the spot and intra-day markets in France, Germany, Scandinavia, Spain and UK. Sufficient liquidity is important with wind power, a fluctuating RES. The requirements for flexibility owing to wind fluctuation at a transnational power system are lower than for regional systems, especially at high levels of wind penetration [81]. Liu et al [90] modelled the potential of the Chinese electrical energy network to accept wind power and other fluctuating RES. The maximum degree of wind integration possible was 26%; barriers to further penetration were identified. Milligan and Kirby [91] found that it was necessary to consider the fluctuation induced increase in power system operating costs to determine the true cost of wind power. Wind-farm energy income depends on matching its uncertain time varying output with the uncertain regional half hourly market price [85]. Bitar et al [92] confirmed this, noting that reserves are used to increase the reliability of tenders. An accurate forecasting model can reduce uncertainty. González-Aparicio and Zucker [93] studied the Spanish electricity market and used clustering techniques and time series analysis to find the likely wind power forecasting errors. Zhou and Francois [94] described the support of wind power with Hydrogen and Super Capacitor storage. The system could give predictable power outputs, as well as providing grid ancillary services. ESS can avoid the need for wind energy curtailment [87] but the returns do not currently justify the investment. Zafirakis et al [95] considered this problem, employing a socioeconomic cost-benefit model which allows for investment subsidies and FiTs. There are advantages in using pumped hydro and CAES to satisfy peak demand, and these techniques may prove cost-effective if larger "socially just" FiTs are applied. Moura and De Almeida [96] addressed the issue of wind energy fluctuation via ESS, alternative sources of generation and DSM. Large-scale integration of wind energy brings technical and economic challenges. ESS has been proposed to facilitate wind power integration. Although the technical feasibility of such solutions is clear, the economic assessment should be in line with operating conditions and regulatory frameworks.

4.5 Centralized and decentralized control

Zhu et al [97] obtained an optimum EV charging policy for the use of fluctuating RES in charging EVs by modelling RES output, and the number of charging EVs and their battery states. Simulation results show improved service availability for EVs in MGs powered by RES. Kamankesh and Agelidis [98] presented similar results using ANN controlled V2G from a modelled grid-connected MG incorporating PV, Fuel Cells, Micro and Wind Turbines.

Yu and Li [99] developed a 'flexible-possibilistic stochastic programming' (FPSP) method for managing a city scale (Beijing) energy system to reduce costs and harmful emissions, allowing for the effects of RES and EVs. The introduction of EVs reduces SO2, NOx and inhalable particles (PM10) by 7.9%, 10.8% and 9.1%, respectively. In contrast, Timmers and Achten

[100] noted the correlation between vehicle weight and non-exhaust PM emissions. Diesel Particulate Filters are installed in new Diesel vehicles; EVs weigh more than their ICE counterparts. Total PM10 emissions from EVs were found to equal those of modern ICEVs and PM2.5 emissions were only 1-3% lower.

RES tend to be intermittent; hence their output tends not to be dispatchable. Zhang et al [101] proposed a Markov decision process algorithm (MDP) to alleviate this difficulty in a MG with random RES output and vehicle driving patterns. The MDP could 'learn', giving a system whose performance improved with experience. Rahbari et al [102] combined RES and EVs allowing for fluctuating energy usage. They used a Genetic algorithm /Fuzzy logic based controller to optimise power flow with a large number of EVs. Divshali et al [103] discussed a related problem, voltage stability in Smart Grids (SG) containing RESs, EVs, and ESSs. They describe a multi-agent transactive energy management system (TEMS) maximising profit for the participants whilst maintaining voltage levels within statutory limits allowing for the fluctuating RES output. Nguyen et al [104] addressed the problem of fluctuating RES output with a new controller which measured the power balance in a system via its frequency deviation, achieving power balance via V2G.

Attia et al [105] suggested that SGs will require real time information, via IT and communication technologies, on the behaviour of the system components, to permit operation with intermittent RES and fluctuating loads. Their SG architecture included generation, transmission, distribution, loads, SG and cyber-security managers, together with their intercommunication. EVs are treated as prosumers. The result was to delay network reinforcement, maximising RES uptake, minimising pollution. Suganya et al [106] noted that random location of PHEVs and RES in distribution systems may cause system overload, unnecessary losses, and a poor voltage profile. They described a strategic placement method, and proposed an ANN based energy management framework to cope with the necessary scheduling requirements. Kamalinia et al [107] considered the problem of integrating large amounts of wind energy using hydro and natural gas backup and presented an algorithm for optimum, flexible allocation of the backup systems. The reliability criteria included the loss of load expectation (LOLE) and load curtailment limits.

5. Renewable energy policies to promote energy autonomy

In order to integrate fluctuating RES into the grid and match supply and demand, storage and/or self-consumption can be helpful.

The EU's Renewable Energy Directive 2018/2001 [108] includes policies to promote EA. Article 21 (renewable self-consumers) and Article 22 (renewable energy communities) propose:

- To ensure that consumers are entitled to become renewables self-consumers.
- To ensure renewables self-consumers and renewable energy communities are entitled to: (i) the generation, consumption, storage and selling of excess renewable electricity; (ii) the installation and operation of electricity storage systems for self-consumption, and; (iii) to maintain rights and obligations as final consumer.
- No charges or fees for self-generated electricity produced in installations up to 30 kW installed capacity.

- To ensure renewable self-consumers located in the same building are permitted to arrange sharing of renewable energy produced on their site or sites between themselves without charges, fees, levies and taxes.

The EU Directive on Energy Efficiency (2012/27/EU) [109] makes no direct reference to EA or self-sufficiency. According to Article 1, moderation of energy demand is one of the five dimensions of the Energy Union Strategy established by the 2015 Commission Communication entitled ‘A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy’. Improving energy efficiency will improve energy security by reducing dependence on energy imports from outside the EU; thus energy efficiency is to be treated as an energy source in its own right.

In the EU’s “Clean Energy for all Europeans” package [110] there is also no direct reference to EA or self-sufficiency. This policy package applies to the five dimensions of the Energy Union, closely related and mutually reinforcing:

(a) energy security;
(b) internal energy market;
(c) energy efficiency;
(d) decarbonisation; and
(e) research, innovation and competitiveness.

‘Energy Security’ requires national objectives with regard to: increasing the diversification of energy sources and supply from third countries, the purpose of which may be to reduce energy import dependency; increasing the flexibility of the national energy system; addressing constrained or interrupted supply of an energy source, for the purpose of improving the resilience of regional and national energy systems, including a timeframe for when the objectives should be met.

All EU Member States must draw up every 3 years National Energy Efficiency Action Plans under the EU Energy Efficiency Directive [111], setting out their estimated energy consumption, planned energy efficiency measures, and the expected improvements. They must also report annually on the progress achieved towards their national energy efficiency targets, and outline how they will meet the renewable energy and energy efficiency targets for 2030 in a 10-year National Energy & Climate Plan, to be submitted by 31 December 2019 [112].

Colmenar-Santos [113] argued for the creation of new Spanish national energy policies for the economic creation of large scale systems of distributed generation.

A French initiative to encourage electrical self-consumption, in June 2019 [114], called for tenders for renewable facilities for self-consumption for installations between 100 kW and 1 MW. This is open to consumers in the industrial, tertiary and agricultural sectors who can participate in the solar energy sector. A target is 450 MW of self-consumption projects. In July 2017 the French Government published details of its new initiative to combat climate change [115]. Ecological transition contracts (ETC) were introduced to support the ecological transformation of the territories/regions of France. ETCs concern energy transition, building renovation, developing short supply chains and sustainable agriculture, the circular economy, sustainable mobility, and the fight against artificial environments for crops. The State will enter into contracts with these territories on a voluntary basis to give them the means to contribute to the national objectives and net job creation and social opportunities.

The French co-constructed ecological transition contracts [116] aim to:

- demonstrate that ecology is a driving force of the economy, and develop local employment through the ecological transition (structuring of sectors, development of new training).
- act with all actors in the territory, public as well as private, to translate the ecological transition in appropriate forms.
- support industrial reconversion of a territory (vocational training, redevelopment of sites).

Each territory will rely on its ecological transition contract to develop its strategic ecological transition, according to its specificities and needs: renewable energies, energy efficiency, mobility, rurality and agriculture, circular economy, construction and urban planning and biodiversity. Set up at the level of one or more intercommunalities they are co-built from local projects through the mobilization of the actors of the territories: communities, companies, associations and citizens. A particular French ETC with EA is described [117] for the Briançonnais county whose 37 communes are working on EA, food, travel and a zero waste policy. The ETC is one of 20 to be agreed with the State. The region enjoys plentiful sunshine and has hydroelectric resources. In 2011 local people created a company to bring together communities, businesses and citizens, supported by the local distribution company. In 2015 Greater Briançon received a state subsidy.

In the Dutch 2018 Draft Integrated National Energy and Climate Plan 2021-2030 [118] EA requires the encouragement of storage, noting that consumers can respond to real-time rates because of the increase in smart meters, 'whether or not through the use of aggregators. In addition, any obstacles to storage will be removed. The transition to electric cars might be able to contribute to this'. RES self-consumption is to be encouraged: until 2023, PV energy used by small-consumer connections (3x30A) and fed back into the grid is deducted from the energy purchased from the grid, (the netting scheme) [118,119]. Between 2023 and 2030 the scheme will be gradually phased out, encouraging self-consumption.

The UK's House of Commons Energy and Climate Change Committee recommended in 2016 that attention be given to encouraging storage and DSM, both key drivers for EA [120]. In October 2018 UK agency Innovate UK awarded £1.5m to a consortium led by Cenin Renewables to investigate the decentralization of, inter alia, power and energy generation in the Bridgend area [121].

6. Challenges and opportunities

This section discusses technical, economic, social and political matters along the pathway to energy autonomy. One of the most promising possibilities for economic energy supply is the use of EV batteries, appropriately aggregated, to store energy from RES when in surplus, releasing it when needed (V2G/V2H/V2B). EV batteries suffer degradation in use, so their price and lifetime determine storage cost, one of the primary technical challenges for V2G [122]. Automotive useful lifetime is defined as a capacity fade to 80% of the initial value according to IEC 62660-1 and ISO 12405-1 Standards. EV battery costs have fallen dramatically over the last few years [123,124]. Bloomberg NEF [51] predicted very large investments in EV battery technology and production capacity at scale, leading to price reductions for both automotive and stationary storage batteries; prices have fallen by 79% since 2010. Bloomberg NEF expect that 1,291GW of new battery capacity will be added by 2050, some 40% of which will be 'behind-the-meter'. Bloomberg anticipates a price of $70/kWh by 2030 for stationary applications. The volume-weighted average price of a lithium-ion battery pack is $176/kWh, the fall in price resulting from improved technology, especially in higher cell energy density. The report speaks of selling price but there is ambiguity and the quoted price series might possibly refer to production costs. Performing an exponential extrapolation of the price series in constant 2018 US$ suggests that the price of EV batteries may well fall to below $100/kWh by 2021. Once EV batteries fall to such low price levels, barriers to increasing EA will fall. This revolution in battery prices should be quantified. EVs for energy storage can overcome many of the limitations impeding adoption of EA. The costs of storage for larger scales are considerably lower than for smaller scales.

If consumers practise EA, they lower their Grid power consumption. Network costs tend to be added to consumers' power bills. Thus increasing EA decreases the contribution towards the maintenance of the Grid system from EA adopters, leaving more of the costs to be borne by the remainder of consumers. By increasing their degree of local EA they reduce their imports from medium and high voltage electricity networks, hence they contribute less to the overall network costs [1]. The effect of a single household adopting EA is low but if EA became very widespread [125] there would be substantial extra costs for non-EA consumers. Other challenges include the costs and opportunities of investment together with social and reputational factors. A reduced need for energy transmission and distribution from central networks has environmental benefits in reduced environmental impacts of this infrastructure and required technology [126]. This will only be seen by continued movement along the pathway to achieve energy autonomy with systemic and practical efforts at local and regional levels [127].

7. Conclusions

The IPCC report of October 2018 [128] highlights the need to limit Global Warming to 1.5^0 C. This means a 'climate emergency'. Humankind must reduce CO_2 emissions. The August 2019 IPCC report [129] notes continuing degradation of agricultural land through human activities, the problem becoming more severe as climate change becomes more serious. EA can help to reduce CO_2 normally associated with DG, which often includes PV and BSS. Having a RES (PV) system already gives some degree of self-sufficiency but this paper emphasizes that two key ways to increase energy autonomy are through a storage system and/or with the adoption of DSM. Use of storage adds to energy costs since its provision is expensive. Some significant investments are necessary, but the higher the investment in storage capacity the higher is the achieved grid independency. The components of a PV and Li-Ion battery storage system have now become sufficiently affordable that 100% EA is becoming economically viable for a consumer at neighbourhood and district scales, even if at the household level the relevant prices must fall further. The same argument applies to the achieved CO_2 emission reduction. The larger the scale for EA, the less the generation cost for PV and the lower the storage costs, which are expected to decrease with time. The degree of achievable grid autonomy depends also on the shape of the load curve for various times of day and seasons. This also is contingent on the scale of the system: the higher the number of elements of consumption and generation involved, the higher the achieved self-consumption.

This relationship is linear in an initial phase; a proportional increase in the grid investments increases with the number of households. But this reaches a saturation point after an optimal number. Moreover, the right time-scale is essential for a correct evaluation of EA, because a long interval will lead to inaccurate calculations whereas shorter intervals will require more calculations. The same applies to the billing period: if instantaneous billing is adopted then the compensation of the lack of PV generation in winter with the overproduction in summer with net metering is not considered. Finally, DSM is an economic way to achieve higher EA, and when it is paired with a battery system even higher autonomy is achieved. If there is already a high level of EA, diminishing returns apply requiring considerable investment. There must be a coherent definition for EA in order to calculate this parameter within an Operational Pilot or for a monitored implementation. EA helps reduce CO_2 emissions. They both depend on the energy produced by RES. This offers clear savings in CO_2 emissions compared to fossil fuel technologies. In the EU a Guarantee of origin is a certificate issued by a RES generator warranting that 1MWh of electricity has been generated from renewable sources. A consumer will buy the certificate thus demonstrating that the energy used originates from RES. Encouragingly RES are making rapid progress [130] reports that in 2018 the RES supply of Guarantees of Origin reached almost 600TWh and demand exceeded 500TWh.

Acknowledgements: This work was supported by the EU–Interreg North Sea Region programme's Smart, clean Energy and Electric Vehicles for the City (SEEV4-City) project. We thank Geoff O'Brien, Bert Herteleer, Jan Cappelle, Xuewu Dai, Aymeric Buatois, Chris Rimmer and Mousa Marzband.

References:

[1] Mc Kenna, R., 2018, The double-edged sword of decentralized energy autonomy. *Energy Policy* **113**, 747-750.
[2] Department for Business, Energy and Industrial Strategy, 2019, Average variable unit costs and fixed costs for electricity for UK regions 2018. Available online: https://www.gov.uk/government/collections/domestic-energy-prices (Accessed 17/7/2019).
[3] GreenBusinessWatch UK Domestic Solar Panel Costs and Returns 2019. Available online at: https://greenbusinesswatch.co.uk/uk-domestic-solar-panel-costs-and-returns-2019 (Accessed 17/7/2019).
[4] Lazard LCOS analysis November 2018. Available online: https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf (Accessed 17/7/2019).
[5] Dubarry, M., Devie, A. and McKenzie, K., 2017, Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis. *Journal of Power Sources* **358**, 39-49.
[6] Rae, C. and Bradley, F., 2012, Energy autonomy in sustainable communities—a review of key issues. *Renewable and Sustainable Energy Reviews* **16**(9), 6497-6506.
[7] McKenna, R., Merkel, E. and Fichtner, W., 2017, Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects. *Applied Energy* **189**, 800-815.
[8] Luthander, R., Widén, J., Nilsson, D. and Palm, J., 2015, Photovoltaic self-consumption in buildings: A review. *Applied Energy*, **142,** 80–94.

[9] Nicolosi, M., Mills, A. and Wiser, R., 2010, The Importance of High Temporal Resolution in Modelling Renewable Energy Penetration Scenarios. 9th Conference on Applied Infrastructure Research, TU Berlin.

[10] Warren, C.R. and McFadyen, M., 2010, Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. *Land Use Policy*, **27**(2), 204–213.

[11] Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P.A, Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K. and Hvelplund, F.K., 2015, Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Applied Energy*, **145**, 139-154.

[12] Østergaard, P.A., 2009, Reviewing optimisation criteria for energy systems analyses of renewable energy integration. *Energy*, **34**(9), 1236-1245.

[13] Comodi, G., Giantomassi, A., Severini, M., Squartini, S., Ferracuti, F., Fonti, A., Cesarini, D.N., Morodo, M. and Polonara, F., 2015, Multi-apartment residential microgrid with electrical and thermal storage devices: experimental analysis and simulation of energy management strategies. *Applied Energy*, **137**, 854–866.

[14] Milan, C., Bojesen, C. and Nielsen, M., 2012, A cost optimization model for 100% renewable residential energy supply systems. *Energy*, **48**(1), 118–127.

[15] Akter, M.N., Mahmud, M.A. and Oo, A.M.T., 2017, Comprehensive economic evaluations of a residential building with solar photovoltaic and battery energy storage systems: An Australian case study. *Energy and Buildings*, **138,** 332-346.

[16] Weniger, J., Tjden, T. and Quaschning, V., 2013, Sizing of residential PV battery systems. *Energy Procedia*, **46**, 78–87.

[17] Quoilin, S., Kavvadias, K., Mercier, A, Pappone, I. and Zucker, A., 2016, Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Applied Energy*, **182**, 58-67.

[18] Mulder, G., De Ridder, F.D. and Six, D., 2010, Electricity storage for grid-connected household dwellings with PV panels. *Solar Energy*, **84**(7), 1284-1293.

[19] Santos, J.M., Moura, P.S. and De Almeida, A.T., 2014, Technical and economic impact of residential electricity storage at local and grid level for Portugal. *Applied Energy*, **128**(1), 254-264.

[20] Hassan, A.S., Cipcigan, L. and Jenkins, N., 2017, Optimal battery storage operation for PV systems with tariff incentives. *Applied Energy*, **203**, 422-441.

[21] Mariaud, A., Acha, S., Ekins-Daukes, N., Shah, N. and Markides, C.N., 2017, Integrated optimisation of photovoltaic and battery storage systems for UK commercial buildings. *Applied Energy*, **199**, 466-478.

[22] Widén, J., Wäckelgård, E. and Lund, P.D., 2009, Options for improving the load matching capability of distributed photovoltaics: methodology and application to high latitude data. *Solar Energy*, **83**, 1953–66.

[23] Mesarić, P. and Krajcar, S., 2015, Home demand side management integrated with electric vehicles and renewable energy sources. *Energy & Buildings*, **108**, 1-9.

[24] Castillo-Cagigal, M., Caamaño-Martín, E., Matallanas, E., Masa-Bote, D., Gutiérrez, A., Monasterio-Huelin, F. and Jiménez-Leube, J., 2011, PV self-consumption optimization with storage and Active DSM for the residential sector. *Solar Energy*, **85**(9), 2338-2348.

[25] Lorenzi, G. and Santos Silva, C.A., 2016, Comparing demand response and battery storage to optimize self-consumption in PV systems. *Applied Energy*, **180**, 524-535.

[26] Vieira, F.M., Moura, P.S. and De Almeida, A.T., 2017, Energy storage system for self-consumption of photovoltaic energy in residential zero energy buildings. *Renewable Energy*, **103**, 308-320.

[27] Uddin, K., Gough, R., Radcliffe, J., Marco, J. and Jennings, P., 2017, Techno-economic analysis of the viability of residential photovoltaic systems using lithium-ion batteries for energy storage in the United Kingdom. *Applied Energy*, **206**, 12-21.

[28] UK Government statistics on solar PV cost data. Available online: https://www.gov.uk/government/statistics/solar-pv-cost-data (Accessed 17/7/2019).

[29] Cost of financing UK Solar PV. Available online at: https://www.solarguide.co.uk/solar-pv-finance#/ (Accessed 17/5/2019).

[30] Cost of remortgage below 2% for home improvements. Available online: shttps://www.thisismoney.co.uk/money/mortgageshome/article-6640285/How-use-mortgage-finance-home-improvements.html (Accessed 17/7/2019).

[31] Lazard levelised cost of energy 2018. Available online: https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf (Accessed 17/7/2019).

[32] Storage costs of Tesla Powerwall 2 domestic storage battery. Available online: https://www.solarquotes.com.au/blog/powerwall-2-warranty (Accessed 17/7/2019).

[33] Trends in PV generation costs. Available online: http://www.r-e-a.net/upload/uk-solar-beyond-subsidy-the-transition.pdf (Accessed 17/7/2019).

[34] Curry, C., 2017, Lithium-ion Battery Costs and Market, Bloomberg New Energy Finance. Available online: https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf (Accessed 17/7/2019).

[35] Orehounig, K., Evins, R. and Dorer, V., 2015, Integration of decentralized energy systems in neighbourhoods using the energy hub approach. *Applied Energy*, **154**, 277–89.

[36] De Coninck, R., Baetens, R., Saelens, D., Woyte, A. and Helsen, L., 2014, Rule-based demand side management of domestic hot water production with heat pumps in zero energy neighbourhoods. *Journal of Building Performance Simulation*, **7**(4), 271-288.

[37] Baetens, R., De Coninck, R., Van Roy, J., Verbruggen, B., Driesen, J., Helsen, L. and Saelens, D., 2012, Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation. *Applied Energy*, **96**, 74–83.

[38] Lawder, M.T., Viswanathan, V. and Subramanian, V.R., 2015, Balancing autonomy and utilization of solar power and battery storage for demand based microgrids. *Journal of Power Sources*, **279**, 645-655.

[39] Luthander, R., Widén, J., Munkhammar, J. and Lingfors, D., 2016, Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment. *Energy*, **112**, 221-231.

[40] Swedish domestic power prices as at December 2018. Available online: https://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/price-trends-in-the-energy-sector/energy-prices-on-natural-gas-and-electricity/pong/tables-and-graphs/average-prices-by-half-year-2007/prices-on-electricity-for-household-consumers-2007/ (Accessed 15/7/2019).

[41] Killinger, S., Mainzer, K., McKenna, R., Kreifels, N. and Fichtner, W., 2015, A regional optimisation of renewable energy supply from wind and photovoltaics with respect to three key energy-political objectives. *Energy*, **84**, 563-574.

[42] Schmidt, J., Schönhart, M., Biberacher, M., Guggenberger, T., Hausl, S., Kalt, G., Leduc, S., Schardinger, I. and Schmid, E., 2012, Regional energy autarky: potentials, costs and consequences for an Austrian region. *Energy Policy*, **47**, 211–221.

[43] Jenssen, T., König, A. and Eltrop, L., 2014, Bioenergy villages in Germany: bringing a low carbon energy supply for rural areas into practice. *Renewable Energy*, **61**, 74–80.

[44] Burgess, P.J., Casado, M.R., Gavu, J., Mead, A., Cockerill, T., Lord, R., Van der Horst, D. and Howard, D.C., 2012, A framework for reviewing the trade-offs between, renewable energy, food, feed and wood production at a local level. *Renewable Sustainable Energy Reviews*, **16**(1), 129–42.

[45] Dang, X.L., Petit, M. and Codani, P., 2015, Energy optimization in an eco-district with electric vehicles smart charging. PowerTech IEEE, Eindhoven.

[46] Greentechmedia levelised cost of energy for lithium ion batteries. Available online: https://www.greentechmedia.com/articles/read/report-levelized-cost-of-energy-for-lithium-ion-batteries-bnef#gs.prpbh4 (Accessed 15/7/2019).

[47] EU Interreg North Sea Region State of the Art Summary Report-SEEV4 City. https://www.seev4-city.eu/wp-content/uploads/2018/08/20180124_State-of-the-art-Summary-Report-SEEV4-City.pdf

[48] Barbour, E., Wilson, I.A., Radcliffe, J., Ding, Y. and Li, Y., 2016, A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, **61**, 421-432.

[49] Ibrahim, H. and Ilinca, A., 2013, Techno-Economic Analysis of Different Storage Technologies In: Energy Storage - Technologies and Applications 2013, edited by A. F. Zobaa. *IntechOpen*. Available online: https://www.intechopen.com/books/energy-storage-technologies-and-applications/techno-economic-analysis-of-different-energy-storage-technologies (Accessed 15/7/2019).

[50] Sundararagavan, S. and Baker, E., 2012, Evaluating energy storage technologies for wind power integration. *Solar Energy*, **86**(9), 2707-2717.

[51] Bloomberg NEF's New Energy Outlook (NEO) 2018. Available online: https://www.facebook.com/BloombergNEF/videos/our-2018-battery-price-survey-has-found-that-the-volume-weighted-average-price-o/2243145969343197/ (Accessed 16/7/2019).

[52] Després, J., Mima, S., Kitous, A., Criqui, P., Hadjsaid, N. and Noirot, I., 2017, Storage as a flexibility option in power systems with high shares of variable renewable energy sources: a POLES-based analysis. *Energy Economics*, **64**, 638-650.

[53] Ghofrani, M., Arabali, A., Etezadi-Amoli, M. and Fadali, M.S., 2013, Energy Storage Application for Performance Enhancement of Wind Integration. *IEEE Transactions on Power Systems*, **28**(4), 4803-4811.

[54] Brekken, T.K.A., Yokochi, A., Von Jouanne, A., Yen, Z.Z, Hapke, H.M. and Halamay, D.A., 2011, Optimal Energy Storage Sizing and Control for Wind Power Applications. *IEEE Transactions on Sustainable Energy*, **2**(1), 69-77.

[55] Fertig, E. and Apt, J., 2011, Economics of compressed air energy storage to integrate wind power: A case study in ERCOT. *Energy Policy*, **39**(5), 2330-2342.

[56] Madlener, R. and Latz, J., 2013, Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power. *Applied Energy*, **101**(C), 299-309.

[57] Zunft, S., Jakiel, C., Koller, M. and Bullough, C., 2006, Adiabatic Compressed Air Energy Storage for the Grid Integration of Wind Power. Proceedings of the Sixth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Windfarms, Delft: 346-351.

[58] Suul, J., Uhlen, K. and Undeland, T., 2008, Variable speed pumped storage hydropower for integration of wind energy in isolated grids: case description and control strategies. Nordic Workshop on Power and Industrial Electronics; Espoo.

[59] Muyeen, S.M., Takahashi, R., Murata, T. and Tamura, J., 2009, Integration of an Energy Capacitor System with a Variable-Speed Wind Generator. *IEEE Transactions on Energy Conversion*, **24** (3), 740-749.

[60] Castillo, A. and Gayme, D.F., 2014, Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management*, **87**, 885-894.

[61] Ummels, B.C., Pelgrum, E. and Kling, W.L., 2008, Integration of large-scale wind power and use of energy storage in The Netherlands' electricity supply. *IET Renewable Power Generation*, **2**(1), 34-46.

[62] Speidel, S. and Bräunl, T., 2016, Leaving the grid. The effect of combining home energy storage with renewable energy generation. *Renewable and Sustainable Energy Reviews*, **60**, 1213-1224.

[63] Soares, B., Borba, M.C., Szklo, A. and Schaeffer, R., 2012, Plug-in hybrid electric vehicles as a way to maximize the integration of variable renewable energy in power systems: The case of wind generation in north-eastern Brazil. *Energy*, **37**(1), 469-481.

[64] Andersen, P.H., Mathews, J.A. and Rask, M., 2009, Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles. *Energy Policy*, **37**(7), 2481-2486.

[65] Robledo, C.B., Oldenbroek, V., Abbruzzese, F. and Van Wijk, A.J.M., 2018, Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building. *Applied Energy*, **215**, 615-629.

[66] Hoarau, Q. and Perez, Y., 2018, Interactions between electric mobility and photovoltaic generation: A review. *Renewable and Sustainable Energy Reviews*, **94**, 510-522.

[67] Haddadian, G., Khalili, N., Khodayar, M. and Shahidehpour, M., 2016, Optimal coordination of variable renewable resources and electric vehicles as distributed storage for energy sustainability. *Sustainable Energy, Grids and Networks*, **6**, 14-24.

[68] Iacobucci, R., McLellan, B. and Tezuka, T., 2018, The Synergies of Shared Autonomous Electric Vehicles with Renewable Energy in a Virtual Power Plant and Microgrid. *Energies*, **11**(8), 2016.

[69] Richardson, D.B., 2013, Electric vehicles and the electric grid: A review of modelling approaches, impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews*, **19**, 247-254.

[70] Mwasilu, F., Justo, J.J., Kim, E.K., Do, T.D. and Jung, J.W., 2014, Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. *Renewable and Sustainable Energy Reviews*, **34**, 501-516.

[71] Schuller, A., Flath, C.M. and Gottwalt, S., 2015, Quantifying load flexibility of electric vehicles for renewable energy integration. *Applied Energy*, **151**, 335-344.

[72] Chellaswamy, C. and Ramesh, R., 2017, Future renewable energy option for recharging full electric vehicles. *Renewable and Sustainable Energy Reviews*, **76**, 824-838.

[73] International Renewable Energy Agency 2016. The Power to Change: Solar and Wind Cost Reduction Potential to 2025. Available online: https://www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025 (Accessed 16/7/2019).

[74] Understanding the operating costs of coal power: US example.2018. Available online: https://www.carbontracker.org/reports/understanding-operating-cost-coal-fired-power-us-example/ (Accessed 17July 2019).

[75] US Energy Information Administration 2019 Levelized Cost and Levelized Avoided Cost of New Generation Resources, Annual Energy Outlook. 2019. Available online: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf (Accessed 16/7/2019).

[76] López Prol, J., 2018, Regulation, profitability and diffusion of photovoltaic grid-connected systems: A comparative analysis of Germany and Spain. *Renewable and Sustainable Energy Reviews*, **91**, 1170-1181.

[77] Merei, G., Moshövel, J., Magnora, D. and Sauer, D.U., 2016, Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications. *Applied Energy*, **168**, 171-178.

[78] López Prol, J. and Steininger, K.W., 2017, Photovoltaic self-consumption regulation in Spain: Profitability analysis and alternative regulation schemes. *Energy Policy*, **108**, 742-754.

[79] Jones, C., Peshev, V., Gilbert, P. and Mander, S., 2017, Battery storage for post-incentive PV uptake? A financial and life cycle carbon assessment of a non-domestic building. *Journal of Cleaner Production*, **167**, 447-458.

[80] International Energy Agency 2015. Projected Costs Of Generating Electricity. Available online: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf (Accessed 16/7/2019).

[81] Hubera, M., Dimkovab, D. and Hamacher, T., 2014, Integration of wind and solar power in Europe: Assessment of flexibility requirement, *Energy*, **69**, 236-246.

[82] Anuphappharadorn, S., Sukchai, S., Sirisamphanwong, C. and Ketjoy, N., 2014, Comparison the Economic Analysis of the Battery between Lithium-ion and Lead-acid in PV Stand-alone Application. *Energy Procedia*, **56**, 352-358.

[83] Naumann, M., Karl, R.C., Truong, C.N., Jossen, A. and Hesse, H.C., 2015, Lithium-ion Battery Cost Analysis in PV-household Application. *Energy Procedia*, **73**, 37-47.

[84] Smith, J.C., Milligan, M.R., DeMeo, E.A. and Parsons, B., 2007, Utility Wind Integration and Operating Impact. State of the Art. *IEEE Transactions on Power Systems*, **22**(3), 900-908.

[85] MacGill, I., 2010, Electricity market design for facilitating the integration of wind energy: Experience and prospects with the Australian National Electricity Market. *Energy Policy*, **38**(7), 3180-3191.

[86] Söder, L., Hofmann, L., Orths, A., Holttinen, H., Wan, Y.H. and Tuohy, A., 2007, Experience from Wind Integration in Some High Penetration Areas. *IEEE Transactions on Energy Conversion*, **22**(1), 4-12.

[87] Faias, S., De Sousa, J., Reis, F.S. and Castro, R., 2012, Assessment and Optimization of Wind Energy Integration into the Power Systems: Application to the Portuguese System. *IEEE Transactions on Sustainable Energy*, **3**(4), 627-635.

[88] DeCesaro, J., Porter, K. and Milligan, M., 2009, Wind Energy and Power System Operations: A Review of Wind Integration Studies to Date. *The Electricity Journal*, **22**(10), 34-43.

[89] Weber, C., 2010, Adequate intraday market design to enable the integration of wind energy into the European power systems. *Energy Policy*, **38**(7), 3155-3163.

[90] Liu, W., Lund, H. and Mathiesen, B.V., 2011, Large-scale integration of wind power into the existing Chinese energy system. *Energy*, **36**(8), 4753-4760.

[91] Milligan, M. and Kirby, B., 2009, Calculating Wind Integration Costs: Separating Wind Energy Value from Integration Cost Impacts. NREL Technical Report 2009 NREL/TP-550-46275. Available online: http://www.consultkirby.com/files/NREL-TP-550 46275_Calculating_Wind_Inegration_Costs.pdf (Accessed 18/7/2019).

[92] Bitar, E.Y., Rajagopal, R., Khargonekar, P., Poolla, K. and Varaiya, P., 2012, Bringing Wind Energy to Market. *IEEE Transactions on Power Systems*, **27**(3), 1225-1235.

[93] González-Aparicio, I. and Zucker, A., 2015, Impact of wind power uncertainty forecasting on the market integration of wind energy in Spain. *Applied Energy*, **159**, 334-349.

[94] Zhou, T. and Francois, B., 2011, Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration. *IEEE Transactions on Industrial Electronics*, **58**(1), 95-104.

[95] Zafirakis, D., Chalvatzis, K.J., Baiocchi, G. and Daskalakis, G., 2013, Modelling of financial incentives for investments in energy storage systems that promote the large-scale integration of wind energy. *Applied Energy*, **105**, 138-154.

[96] Moura, P.S. and De Almeida, A.T., 2010, The role of demand-side management in the grid integration of wind power. *Applied Energy*, **87**(8), 2581-2588.

[97] Zhu, L., Yu, F.R., Ning, B. and Tang, T., 2013, Optimal Charging Control for Plug-in Electric Vehicles in Smart Microgrids Fueled by Renewable Energy Sources. *International Journal of Green Energy*, **10**(9), 924-943.

[98] Kamankesh, H. and Agelidis, V.G., 2007, A sufficient stochastic framework for optimal operation of micro-grids considering high penetration of renewable energy sources and electric vehicles. *Journal of Intelligent and Fuzzy Systems*, **32**(1), 373-387.

[99] Yu, L. and Li, Y.P., 2019, A flexible-possibilistic stochastic programming method for planning municipal-scale energy system through introducing renewable energies and electric vehicles. *Journal of Cleaner Production*, **207**, 772-787.

[100] Timmers, V.R.J.H. and Achten, P.A.J., 2016, Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment* **134**, 10-17

[101] Zhang, K., Li, J., He, Z. and Yan, W., 2018, Microgrid energy dispatching for industrial zones with renewable generations and electric vehicles via stochastic optimization and learning. *Physica A: Statistical Mechanics and its Applications*, **501**, 356-369.

[102] Rahbari, O., Vafaeipour, M., Omar, N., Rosen, M.A., Hegazy, O., Timmermans, J.M., Heibati, S. and Van der Bossche, P., 2017, An optimal versatile control approach for plug-in electric vehicles to integrate renewable energy sources and smart grids. *Energy*, **134**, 1053-1067.

[103] Divshali, P.H., Choi, B.J. and Liang, H., 2017, Multi-agent transactive energy management system considering high levels of renewable energy source and electric vehicles. *IET Generation, Transmission & Distribution*, **11**(15), 3713-3721.

[104] Nguyen, H., Zhang, C.S. and Zhang, J., 2016, Dynamic Demand Control of Electric Vehicles to Support Power Grid with High Penetration Level of Renewable Energy. *IEEE Transactions on Transportation Electrification*, **2**(1), 66-75.

[105] Attia, M., Sedjelmaci, H., Senouci, S.M. and El-Hassane, E.H., 2016, Game model to optimally combine electric vehicles with green and non-green sources into an end-to-end smart grid architecture. *Journal of Network and Computer Applications*, **72**, 1-13.

[106] Suganya, S., Raja, C., Srinivasan, D. and Venkatesh, P., 2018, Smart utilization of renewable energy sources in a microgrid system integrated with plug-in hybrid electric vehicles. *International Journal of Energy Research*, **42**(3), 1210-1224.

[107] Kamalinia, S., Wu, L. and Shahidehpour, M., 2014, Stochastic Midterm Coordination of Hydro and Natural Gas Flexibilities for Wind Energy Integration. *IEEE Transactions on Sustainable Energy*, **5**(4), 1070–1079.

[108] EU Renewable Energy Directive 2018/2001. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN (Accessed 18/7/2019).

[109] EU 2012 Energy Efficiency Directive (2012/27/EU). Available online: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive (Accessed 18/7/2019).

[110] Clean energy for all Europeans. Available online: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans (Accessed 18/7/2019).

[111] EU National Energy Efficiency Action Plans. Available online: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive/national-energy-efficiency-action-plans (Accessed 18/7/2019).

[112] EU National Energy & Climate plans. Available online: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans (Accessed 18 July 2019).

[113] Colmenar-Santos, A., Campíñez-Romero, S., Pérez-Molina, C. and Castro-Gil, M., 2012, Profitability analysis of grid-connected photovoltaic facilities for household electricity self-sufficiency. *Energy Policy*, **51**, 749-764.

[114] French initiative to encourage electrical self-consumption June 2019. Available online: https://translate.googleusercontent.com/translate_c?depth=1&hl=en&prev=search&rurl=translate.google.com&sl=fr&sp=nmt4&u=https://www.actu-environnement.com/ae/news/francois-de-rugy-relance-appel-offres-autoconsommation-solaire-industrie-tertiaire-agricole-33642.php4&xid=17259,15700022,15700186,15700190,15700256,15700259&usg=ALkJrhgaSJSawg6QZu2Oj7uHaAj5rkm3zg (Accessed 18/7/2019).

[115] French Climate Plan 1 Planet 1 plan. Available online: https://www.tresor.economie.gouv.fr/Articles/6d47bddb-1d14-4597-8878-785ab59fc529/files/3d3c0615-0213-46b2-bb67-63956440d6ca (Accessed 18/7/2019).

[116] French ecological transition contracts. Available online: https://www.ecologique-solidaire.gouv.fr/contrat-transition-ecologique (Accessed 18/7/2019).
[117] French CTE involving EA. Available online: https://translate.google.com/translate?hl=en&sl=fr&u=https://www.actu-environnement.com/ae/news/Pays-Brianconnais-territoire-signe-un-contrat-pour-accompagner-transition-ecologique-32142.php4&prev=search (Accessed 18/7/2019).
[118] NECP, Draft Integrated National Energy and Climate Plan 2021-2030, The Netherlands, 2018. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/netherlands_draftnecp_en.pdf.pdf (Accessed 18/7/2019).
[119] Rijksoverheid. (2019, April 26). Salderingsregeling verlengd tot 2023. Available online: https://www.rijksoverheid.nl/actueel/nieuws/2019/04/26/salderingsregeling-verlengd-tot-2023 (Accessed 18/7/2019).
[120] UK House of Commons Energy and Climate Change Committee 2016. Available online: https://publications.parliament.uk/pa/cm201617/cmselect/cmenergy/705/705.pdf (Accessed 18/7/2019).
[121] UK Governmental funding agency Innovate UK proposal. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/778375/Smart_Local_Energy_Systems_Concepts_and_Designs_-_Competition_Results.pdf (Accessed 18/7/2019).
[122] Lance, N., De Rubens, G.Z., Kester, J. and Sovacool, B.J., 2019, *Vehicle-to-Grid. A Socio-Technical Transition beyond Electric Mobility*, London: Palgrave Macmillan.
[123] Boston Consulting Group. *Batteries for Electric Cars. January 2010. Challenges, Opportunities, and the Outlook to 2020*. Available online: https://www.bcg.com/documents/file36615.pdf (Accessed 18/7/2019).
[124] After electric cars, what more will it take for batteries to change the face of energy? From *The Economist* 12th August 2017 print edition. Available online at: https://www.economist.com/briefing/2017/08/12/after-electric-cars-what-more-will-it-take-for-batteries-to-change-the-face-of-energy (Accessed 18/7/2019).
[125] Jägemann, C., Hagspiel, S. and Lindenberger, D., 2013, The economic inefficiency of grid parity: The case of German photovoltaics. EWI Working Paper No 13/19. Available online: https://www.econstor.eu/handle/10419/92970 (Accessed 18/7/2019).
[126] Delfino, F., Bracco, S. and Pampararo, F., 2015, Key performance indicators in assessing new technology for electricity transmission and distribution networks, In: J-L. Bessede (Ed) *Eco-Friendly Innovations in Electricity Transmission and Distribution Networks*, (Cambridge: Woodhead Publishing), pp. 47-63.
[127] Lopez, F., Pellegrino, M. and Coutard, O. (eds), 2019, *Local energy autonomy: spaces, scales, politics*. Wiley: London.
[128] October 2018 IPCC Report. Available online: https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/ (Accessed 18/7/2019).
[129] August 2019 IPCC report. Available online: https://www.ipcc.ch/report/srccl/ (Accessed 08/8/2019)
[130] The European market for renewable energy reaches new heights. Available online https://www.eqmagpro.com/the-european-market-for-renewable-energy-reaches-new-heights/ (Accessed 27/08/2019)