Integration between green power generation, energy storage and smart grids in the context of e-mobility

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Abstract. In the manuscript is considered the integration between green energy production, charging infrastructure availability and development and the consumer behavior for e-mobility charging. The optimization of time for charging of electric vehicles is important for the balance of demand and energy availability, with regard the on-peak periods of solar power generation or with the balance of energy storage capacities. This can assure the energy system stability and reduction of external and non-ecological energy sources.

1 Introduction

Decarbonization plans lead to accelerated adoption and use of e-mobility. The plans of electric vehicles manufacturers are to increase their number. This leads to rapid increase of energy consumption. In order the electrification to make ecological sense, it is necessary to synchronize models for the production of renewable and clean electricity, its transportation, eventual storage and the charging behavior of e-mobility users. Therein lie the challenges related to grid capacity, charging devices, infrastructure, charging times, energy management, energy demand versus produced energy quantities. The stability of the system is subjected to probations related to the peaks of production demand and loss of produced but not consumed electricity.

1.1.Energy demand

Along with industry and agriculture, transportation is a major source of greenhouse gas emissions and a consumer of energy, which also generates emissions. According to EC data [1] transport generates about 5% of EU GDP and about 25% of CO2 emissions. The current EU target for passenger car manufacturers is 95g CO2/km. Newly produced personal transport vehicles must reach a zero-pollution value by 2030. This means that after this date, no cars will be produced that emit greenhouse gases. In the field of energy production,

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the trends that the EU is aiming for are to increase the target for renewable sources in the EU's energy mix to 100%. The uptake of renewable fuels such as hydrogen in industry and transport is encouraged. The above targets mean that with the current development of technologies for powering of road, rail, ship and air transport, and with an optimistic forecast for the achievement of the Green Deal targets, the main available technology by 2030 should be electric power. And indeed, the use of electric powered vehicles is on the rise. Cars using electric power – Battery Electric Vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) are steadily penetrating the EU market (Figure 1) [2]. There is a constant and sustainable increase in their number every year – from 700 in 2010 to about 550 thousand in 2019 (3.5% of new registrations). In 2020, the number of registered new electric vehicles increased to 11% of all new registered passenger cars. Battery EVs make up 6% of total new car registrations, and plug-in hybrid electric cars make up 5%.

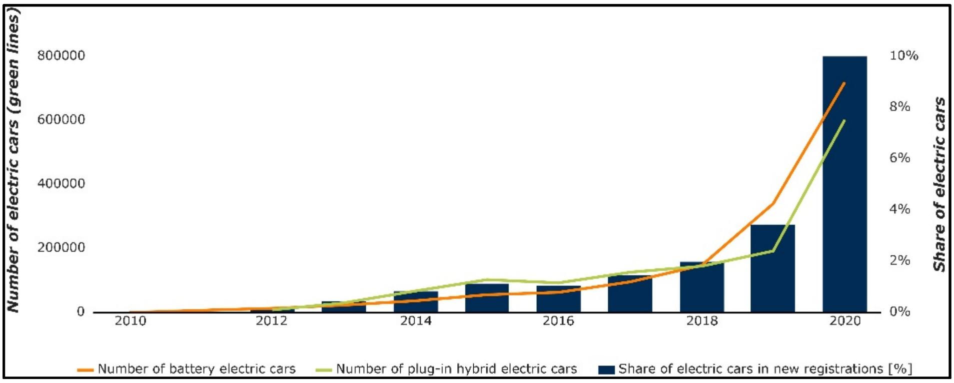

Fig. 1. Electric Vehicles registered in EU-27, Iceland, Norway and the United Kingdom.

1.2 Electric mobility (E-mobility)

Under the Green Deal, 13 million low-emission or zero-emission personal EVs are planned in the EU by 2025. In its 2020 Strategy for Sustainable and Smart Mobility [3], the EC sets milestone target of a minimum of 30 million zero-emission vehicles by 2030, and the car fleet to consist of fully zero-emission vehicles by 2050. Currently, electric vehicles registered in the EU are around 2 million.

According to The European Automobile Manufacturers' Association (ACEA) [4], in 2021, of all passenger cars produced, 10% were fully electric, battery-powered, 25.1% were hybrids, and 52.8% were with LPG (petrol, diesel or gas). How can the energy infrastructure absorb this increase in electricity consumption? On Figure 2 we can observe the total electricity consumption in Bulgaria.

Consumption for the last 9 years has moved within small limits and increased smoothly. Currently, transport is the largest gross consumer of energy of all sectors of the Bulgarian economy, overtaking even industry. We can imagine what it would mean to replace even a fraction of this annual energy consumption from transport with electricity, and how this would affect energy capacities.

In Figure 2, the total energy consumption by sector can be analysed. The "Transport" sector has an absolute advantage in energy consumption compared to other sectors. This means that here are also the biggest challenges to the goals of the European Green Pact in Bulgaria.

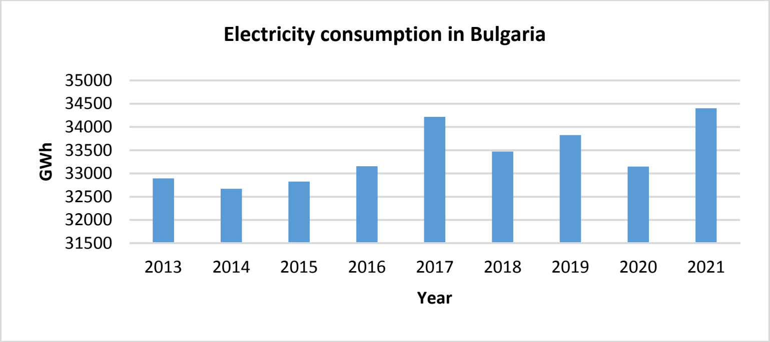

Fig. 2. Total consumed electric energy in Bulgaria during the period 2013 – 2021, according to official statistical data.

Transport, as one of the major energy consumers, also has the greatest potential for transition from fossil fuels to energy produced by Renewable Energy Sources (RES). Sea and air transport in the EU and Bulgaria can hardly be electrified at the moment. Urban transport, as well as railways, have a high level of use of electrical energy, unlike automobiles. Efforts to reduce direct emissions of greenhouse gases and to electrify the drive of these vehicles should also be focused on road transport. In 2019, transport generated almost 30% of CO2 emissions and 23% of direct energy emissions [5], distributed mainly in heavy goods transport, shipping, and aviation. In reality, the technologies to electrify passenger cars, light-duty vehicles, through the use of fully electric (BEV) and hybrid (PHEV) vehicles are currently possible and available. A particularly important point is not just the introduction of newly produced EVs, but their drive with clean energy produced by renewable energy sources. Otherwise, we would simply get a shift in the place of production of CO2 emissions from where cars are driven to places where electricity is produced. Therefore, the sources from which the electrical energy used to drive the EVs is produced are extremely important for ecological purposes (Figure 3).

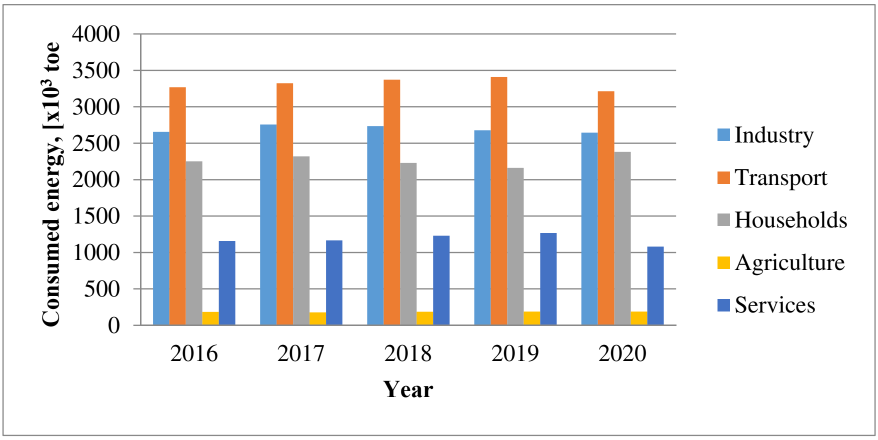

Fig. 3. Total amount of consumed energy by economy sectors, [x10^3 tones oil equivalent].

The model of the TransportPLAN Scenario Tool, CEESA [6], created by scientists at Aalborg University in 2012, allows to trace different scenarios for the development of the Bulgarian transport plan. The model has dynamic labels and allows for more in-depth analysis. In the analysis, it is possible to select a predefined or user-defined scenario. It is also possible to include or exclude international air and sea transport. It is applicable to both passenger and freight transport. According to the Smart Energy Europe Plan for Bulgaria, the scenario for the transport sector is shown in Figure 4.

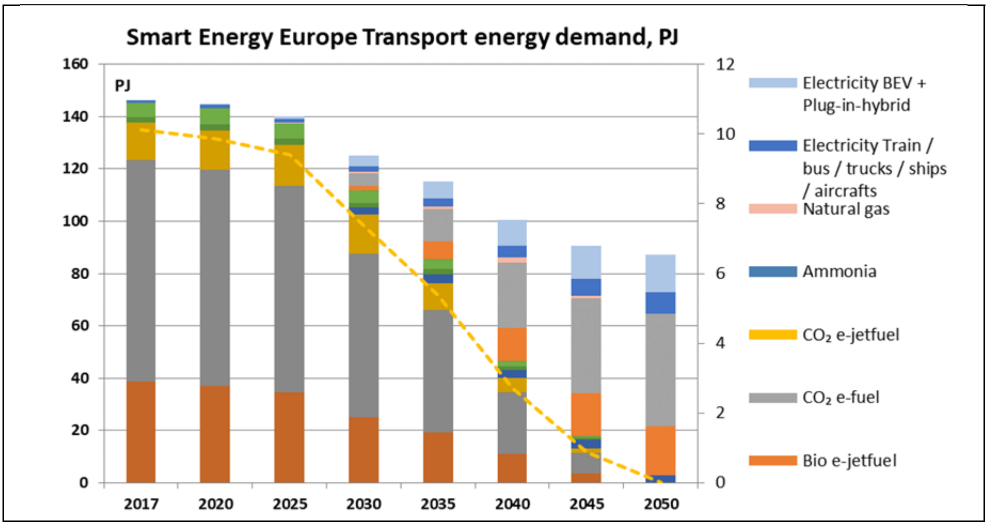

Fig. 4. Scenario of transport sector development in Bulgaria for the period 2017-2050.

1.3 EU planned production capacity of Li-ion batteries

A look over the planned EV battery capacity and therefore the demand of electricity load show the following picture. The total demand of lithium-ion battery from BEV and PHEV in the EU is expected to reach 112 GWh in 2023 and 176 GWh in 2025. Most of this demand will be generated from BEVs (91 GWh in 2023 and 148 GWh in 2025). PHEVs have much smaller batteries and will represent only17 GWh of the total demand in 2023 and 23 GWh in 2025. [7]. The forecasts show the average increase of BEVs battery capacity from 50 kWh in 2024 up to approximately 60 kWh in 2025 (+23%). The driving range of such vehicles also increases to more than 50 km.

Most countries in the EU, including Bulgaria, are facing the following dilemma - the popularization of electric vehicles is troubled by a lack of charging infrastructure. Investments in charging infrastructure seek more security regarding the implementation and usage of this technology by electric vehicles. One problem, which is not typical for Bulgaria only, is that the different EU countries fail enough in achieving pan-European coordination. A significant success in this direction is the promotion by the EU of a single EU standard used for charging points (CP) for electric vehicles.

According to the 2014 AFID Directive, a large proportion of charging stations in the EU are of the Type 2 AC charging standard [3]. The standard, popularly known as CCS, is established as sustainable in DC charging. According to EAFO, there has been around a 2-fold increase in CCS EV charging stations (from 26% in 2014 to 51% in 2020) since introducing the directives in 2014.

The growth of the charging network is irreversible and significant, but the chargers locations are irregularly distributed, there are no minimum requirements in terms of infrastructure. This is typical not only for Bulgaria, but also for the entire EU. It is planned to install 1 million charging stations by the end of 2025, and the goal is still far from its fulfilment. A single road map for e-mobility is also missing. The use of the same EV in different EU countries is also hampered by the lack of integrated payment systems and price calculation related to the consumption of the charged electrical energy.

In 2016, the EU created a low-emission mobility strategy [8]. Its ultimate goal is to make recharging an EV as easy or comparably easy as a vehicle with a regular fuel tank. The idea is to travel similarly simply and without difficulty in the territory of the entire EU. Charging of the main number of EVs takes place at home, office or working place, so publicly accessible CP are necessary and should be available for charging on longer journeys over long distances [9].

In 2020, charging in 75% of cases takes place at the consumer's home, and the trend is to increase charging at publicly accessible CP (Table 1). Compared to traditional vehicles, the EVs have a shorter range per charge and require more frequent charging. The charging time depends on the vehicle battery and the power of the charging point. Depending on their capacity, charging stations are slow, normal, fast and super-fast.

Table 1. Types of public charging types, power and time for charging.

Speed and type of charging station	Power, kW	Time for full charge, h
Slow (single phase alternating current (AC)	3-7 kW	7-16 h
Normal (three-phase alternating current (AC)	11-22 kW	2-4 h
Fast (direct current (DC)	50-100 kW	30-40 min
Superfast (Direct Current (DC)	>100 kW	<20 min

Where is Bulgaria on e-mobility map? Each particular country in the EU has the freedom to develop and implement its own policy in the field of alternative energy sources, according to EU legislation. It can be realized through tax reductions or subsidies for the purchase of EVs, as well as for the construction of charging infrastructure. How uneven the distribution of infrastructure is and where Bulgaria is on this map can be seen in Figure 5. There are serious differences between EU countries.

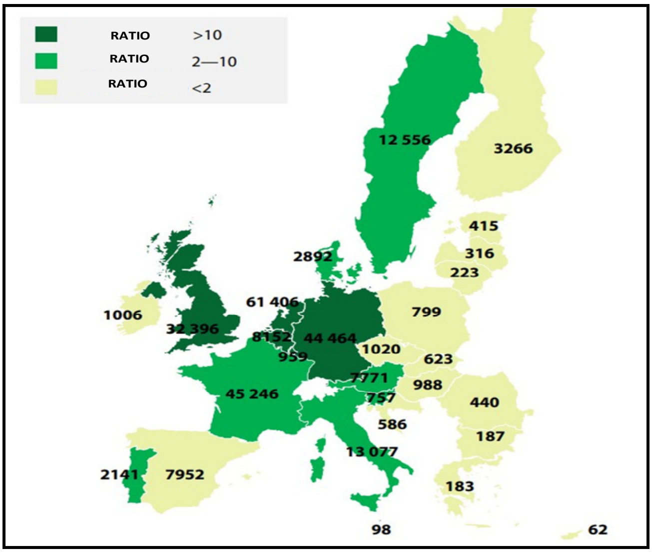

Fig. 5. Total amount of public CP and the ration of the CP to 100 km^2 land area.

Western and Northern Europe have the highest density, while Eastern Europe has the lowest density of public CP. The rate of achievement of the objectives is currently not very high. As in Figure 6, in 4 years, the number of charging stations that are must be constructed are 4 times more than those available in 2020. Green energy is still 38% of the energy mix in 2020, but difficulties lie ahead mainly due to the lack of enough critical infrastructure to bring this energy to consumers [10]. The decarbonization of energy and transport brings with it the need and corresponding challenges for both energy production and infrastructure.

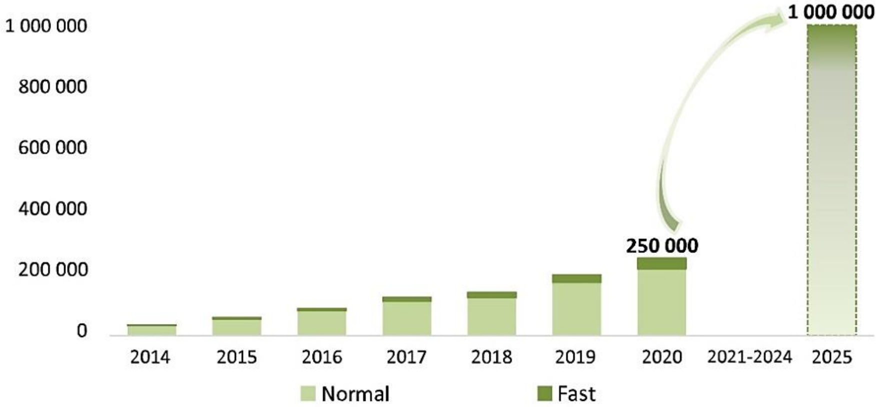

Fig. 6. Charging points (EU-27, together with the UK) and planned in the Green pact.

2 Charging behaviour of e-mobility users

The increase of EVs' number generates higher demand for charging electricity. The growing energy charging requirements projects higher load on the electricity generation and supply infrastructure. Such a load growth is a significant challenge to balance grid loads in the future. The adoption of EVs in recent years has created challenges to the utilities as the electricity demand by EVs is mostly during peak hours. Additionally, EVs will be connected to the charging facilities for a long time without being charged. The load shifting potential of EVs may be subsequently used to relieve challenges to the grid system. Considering charging behaviour for EV planning is critical due to the unpredictability of EV access [11]. Such uncertainties would impact on sustainable EV charging scheduling. Smart charging of EVs can resolve the challenges for the grids by shifting the charging load to a low charging demand period. This will decrease necessary investments for EV charging equipment and to reduce charging costs. Most EV charging sessions are in residential areas, commercial areas, public parking and workplaces. Due to the longer vehicle stay time in comparison with the charging time, EV supply infrastructure is occupied longer than needed or EVs are connected to the grid without being charged. That causes lower rate of utilization. The entire process of charging is popular as charging transaction. There are 3 parameters of the charging transaction: connection time, charging time and charging power. Many EV users plug in and leave the EVs for longer period at public EV charging facilities. The time can depend on the period while EVs stay at such parking facilities without charging.

The electric tariffs in general could be 2 kinds: 1. Flat and 2. Time of use. A flat rate is constant during the day and the electricity price is the same. A Time of use tariff varies within a day and depends on seasons and days. During the specific period electricity prices are different. High prices periods are result of higher electricity demand and are known as called “on peak periods”. The periods of lower demand and therefore lower prices are called “off peak periods.” According to the research in [11, 12] the clustered data points for different value of Clustering EV charging behavior is visualized on Figure 7.

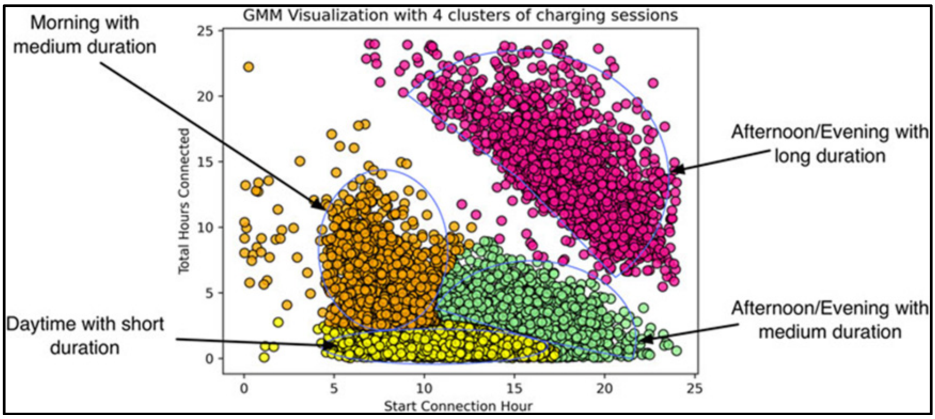

Fig. 7. Visualization 4 clusters of charging sessions.

Clusters of charging transactions can be found based on 2 variables: starting time of charging transaction and the total connection time. Based on these two variables, there are 4 clusters:

1. Day time with short duration (day charging sessions, average duration of 1.5 h.)
2. Morning time with medium duration (morning sessions, average duration of 8.5 h)
3. Afternoon/Evening time with long duration (afternoon or evening start, av. duration of 4.5 h.)
4. Afternoon/evening time with medium duration (afternoon or evening start, av. duration of 15 h).

Depending on the on peak and off-peak periods could be developed the following charging strategies:

1. Immediate charging strategy – instant EV charge. The EV is plugged in when it comes to a charge station and begins the charge session immediately. The EV is continuously charging the battery until it is full or unplugged by the driver.
2. Distributed slot strategy - the charging period is limited to shorter time sessions and distributed during the entire connection slot. That strategy has advantages for larger fleets, with no urgent need to charge.
3. Deferred strategy - the charging scheme dependent on time of use rates and EV user’s schedule. That means, a charging session is delayed to the off-peak time period. Deferred strategy can selectively connect the vehicle at lower time of use. It can be used for long-term vehicle stay. This strategy maximizes the cost reduction for EV users during the grid peak demand.
4. Smart and flexible charging - the energy usage and best time ratio play main role in scheduling for an optimal solution. If an EV consumer starts a session, the prediction of inactivity time ratio and electricity consumption can affect in positive way the programming of charging slot schedule.

3 Can energy storage impact the balance

To assure the relevant energy demand during on-peak moments there is a need of a smart grid secured with the respective storage of energy. Electricity storage can also be viewed differently as transformation from one form to another. It can be not only in a classical battery form [13]. The storage of energy can be built in different ways and for many years. The methods can include:

- Pumping Hydro Storages - the kinetic energy of water is stored by its pumping to the higher part of the dam when the electricity generation is cheapest.
- Usage of compressed air as ES;
- Electrochemical method of ES like. Vanadium Redox Flow Batteries (VRFBs) and Reversible Solid Oxide Cells (rSOC);
- Electromechanically stored energy;
- Liquefied air;
- In electric power batteries storage (NiCd, Li-ion, NaS, Lead-Acid)
- Storage of thermal power;
- Hydrogen production storage.

The comparative analysis of the various technical methods of energy storage and its subsequent conversion into electricity shows that the pumped storage hydroelectric power plants (PHS) are the most economically efficient compared to the other applied technologies. It should be noted that constructing such a repository is a difficult and time-consuming process, which is a prerequisite for their economic expediency [13]. For example, suppose one considers the option of preserving primary energy as an independent economic entity. In that case, several factors will have to be taken into account, such as the type of primary energy carrier (water, solar or wind energy, etc.), the capacity of generators, substations, power lines, and so-called All of them together form the so-called energy storage power plants (ESP). Their main tasks are reduced to meeting energy needs, as well as their role in balancing the supply and uneven production of electricity from renewable sources (RES). The profitability of such a particular entity is the subject of analysis in UK and EU companies. The RES produced electricity is increasing, but along with this the costs for its production are also increasing. The conclusions for such entities cannot offer competitive enough energy prices. That’s why they must be subsidized because of their insecure independent economic existence. From an economic point of view, they can provide additional capacity of already generated electricity at the specific on-peak demand and moment of electricity deficit, even at a higher cost.

The same research team investigated the "spare capacity vs. profitability" trade-off in a large ESP and how to reach "optimally sized capacity". According to [13], the net present value (NPV) optimal storage capacity is lower than the size optimal capacity. There is no economic sustainability for ESP technologies without subsidies. An ESP can exist only as a working energy storage and as a load-following installation and diverts electrical energy from off-peak periods to on-peak periods.

A major problem facing RES is the inconsistency of their production and the mismatch between demand and generation. For example, photovoltaic plants generate the largest amount of electricity around noon, and the highest demand is between 7 and 9 p.m. and between 9 and 11 a.m. These problems can be solved with the help of distributed energy networks, in which renewable energy plays a significant role, and in some cases, their share is 100%. This necessitates the use of various energy storage (ES) technologies and the distribution between capacity and power [14]. The distribution between capacity and power, along with flexible energy storage, is based mostly on vanadium redox flow batteries and reversible solid oxide cells. For micro-grids with a low level of interconnection, power and capacity are very important characteristics to achieve higher cost-effectiveness and flexibility. Still, the economic performance of RES storage cannot be successful in terms of the monetary value of the stored energy. The authors state, it is possible for the EU to improve its performance and capacity within micro-grids, both technically and economically.

RES (solar, biogas, water, and wind energy) can be more reliable if they are connected to larger grids and therefore their costs can be significantly reduced. Using periodic data over 36 years (1980–2015) [15, 16] assess the impact of low-cost energy storage on highly reliable electric systems using only RES. RES status can shift from expensive to low-cost storage if it can perform as seasonal ES or filling variable renewable energy generation and hourly peak demand. CAPEX of energy storage technologies significantly improves their technical characteristics and parameters. ES technologies bring benefits to both network operators and electricity traders, and the ultimate goal is to ensure the energy needs of the end customer (consumers) with a very high level of energy security and a full load of production capacities. This is a prerequisite for increasing the role of the EU from an economic and technical point of view for electrical grids.

Energy storage at a competitive price can prove that electricity from RES is sufficiently cost-competitive with that from fossil fuels. According to [17], energy storage is recommended to cost up to USD 20 per kWh for a 100% solar and wind energy mix to make sense. This is quite a long way for Li-Ion batteries, which cost around 175 USD per kWh. Energy storage makes sense at a cost of $10 to $20/kWh from a solar/wind mix to be competitive with baseload from a NPP or natural gas plant providing up to $5 per kWh. These scenarios can be valid if ES matches demand 100% of the time. If this storage is equal to up to 5% of the time, it can operate at a cost of 150 USD per kWh. In addition, Li-Ion batteries could soon reach USD 150 per kWh. The PHS and Compressed Air Storage with backup power to lift water or compress air can be used to power the turbine and generate electricity on demand. They also have meaningful price of 20 USD per kWh. The disadvantages of such systems are that they take up a lot of space and require special geological conditions.

4 Optimize the management of ES for integration of EV usage

Storage systems and power plants exist and work alongside the charging facilities, responding to consumer needs and behavior. Optimal storage management is crucial for proper integration with the smart grid and charging infrastructure. Along with the economic impact, there are some risks arising with ES technologies. They are planned to play a role in demand management and system load planning. For utility purposes such as EV charging, the operator receives a demand request to provide power with varying requirements and duration. The controller must manage the limited capacity. The goal is to develop an ES management algorithm, minimizing long-term network operating costs [17]. The price is a function of the current grid consumption. Any additional power at increased demand is more expensive. The algorithm can adaptively provide and schedule charge and discharge cycles for energy storage equipment. The algorithm is meant to be optimal when the charge and discharge capacity increases. It is assumed that a certain amount of energy must always be provided, and this is performed by programming. The optimal model can be extended and complicated by including a renewable source to charge the ES device.

5 Supplement the demand of energy storage devices to the E-mobility

The entry of ES devices helps to change the energy mix from different sources. Key sources in this case are wind, biogas, sun, geothermal energy, and waves. E-mobility should benefit from the deployment of new ES facilities. In transport, the use of PHEV is growing by leaps and bounds. PHEVs, EVs and railways could make ES solutions key. The most important aspects for network configurations [18] are the determination of the scale and size of the ES, selection of the type and control of the ES. For example, in Australia, a significant amount of ES equipment in micro-grids consists of hybrid systems with at least two types of ES devices.

Hybrid ES is a concept combining at least 2 different ES together, e.g. g. super capacitor and battery combination. Transportation and e-mobility are typical large energy consumers and therefore an area that accelerates the deployment of hybrid energy storage systems (HESS) (Table 2).

There are 2 key characteristics of HESS: specific energy and specific power. Specific energy corresponds to the amount of energy stored and released over an extended period. Specific power represents the ability to load the capacity of the device when delivering energy to the end user.

HESS suitably combines the stability and the speed of energy of ES devices. Thus, energy and power are effectively combined in their symmetrical user. The study of such systems attracts more attention on the technologies of battery management systems (BMS), power conversion systems (PCS), energy management systems (EMS), but also on planning and control techniques [19]. This leads to significant symmetry as well as HESS implementation experience.

The digitization of production processes in recent years has been characterized by a continuous increase in devices that turn modern electrical networks into smart ones. Almost every single device at every single level from primary production to the final consumer is networked and can exchange information with other devices. This generates large volumes of databases that require a lot of computing power for their processing and storage.. The importance of reliable, flexible, and clean energy is increasing. Industry 4.0 emphasizes digital technologies and total connectivity on the Internet of Things (IoT). The economic share of the transport business is also growing, with more than 5% of the EU countries' GDP. A transition from road and air to rail transport is planned, which will improve the state of the environment and reduce CO2 emissions. Many additional benefits will be generated such as reduced dependence on imported energy suppliers or reduced congestion as well as health problems [10]. Digitization, innovation, and the intensive use of e-mobility will establish the ES supporting energy management of the three main components of the energy grid: production, transmission, and distribution of energy.

Table 2. Comparison of energy parameters between batteries and super capacitors.

Energy Parameter of ES equipment	Supercapacitor	Battery
Service life	5	2
Energy density	1	5
Power density	5	Low
Charging time	4	2

Rating scale: 1- low; 5 high.

6 Conclusion

There is an increase in industrial and consumer demand for electricity. It was generated by traditional industries and the increasing share of e-mobility. The decarbonization of industry and energy production requires accelerating the invention of RES. Solar power seems still very erratic and unreliable, and so the balance of energy smart grids with consumer behavior is increasingly important. The use of adaptive ES provides several opportunities to improve energy efficiency. They refer both to storing excess amounts of electrical energy due to overproduction or insufficient demand and to offering the stored energy in case of shortages or provision of peak consumption. In this way, the consumption, and energy supplies will be planned and the operation of the electrical networks will be better balanced. The economic effect of the introduction of the EU will increase in the coming years and will upgrade and optimize the existing and newly developed energy infrastructure.

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