Energy Policy and Challenges to The Sustainable Development of PV Generation in Bulgaria and Environmental Consequences

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***Abstract*— In connection with the plan for decarbonisation of the energy sector in the Republic of Bulgaria and decommissioning of coal-fired power plants by 2030, the construction of new RES capacities needs to be accelerated. 7GW of photovoltaic plants are planned to be commissioned by 2030. This will lead to changes in the electricity market - fluctuations in the price of electricity on a daily basis, including zero and negative values. In order to achieve financial sustainability of PV, it is necessary to implement technical solutions for electrical energy storage (EES) in order to use (sell) at the optimal time of the day. The installation and operation of EES reduces the positive environmental impact of PV generation in terms of generation and recycling of waste, including hazardous waste.**

This paper is dedicated to an overview of the energy strategies of Bulgaria and estimation the environmental impact from the recycling of PV plant components in Bulgaria.

Keywords*— *energy policy, decarbonisation, renewables, sustainability of PV generation, recycling of waste PV plant components

I. Introduction

All forecasts are clear that the world's electricity needs will only grow, which means an increase in primary source generation capacity - hydro, wind, solar and nuclear. Natural gas is seen as a transitional fuel until the full decarbonsation of electricity generation. Biomass and waste-to-energy fuel systems have a non-significant share in the energy mix. The EU's free electricity market creates "market competition" between taxed and subsidised generation. This should lead to the “natural” economic collapse of TPPs and their decommissioning due to “natural economic logic”. All electricity should be produced from renewable energy sources and solar energy has the greatest potential in Bulgaria. This paper focuses on the sustainable development of photovoltaic (PV) power generation in Bulgaria and its environmental impacts.

II. Structure of the Energy System of Bulgaria

The structure of the generation capacity in Bulgaria by 2022 is shown in Figure 1 [3]. The main fossil generation capacities are 35% Thermal Power Plants (TPPs) + 9% Combined Heat and Power (CHPs) + 4% Factory TPPs - a total of 41%. Nuclear Power Plant (NPP) has a relative share of 15%. The oldest renewable technology Hydro Power Plants (HPPs) has a large relative share of 24%.

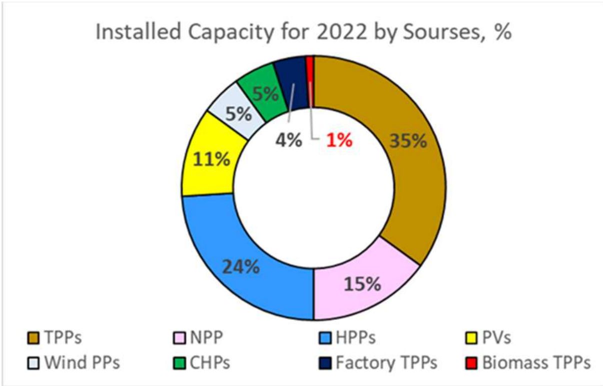

Figure 1

Current renewable technologies with the highest growth in recent decades Photovoltaics (PVs) and Wind PPs reached 11% and 5% respectively. At first glance, it seems that installed capacity from renewables (excluding nuclear) is significant at around 40%.

Looking at their relative share in the energy mix for 2022 Figure 2 [3], the picture changes sharply.

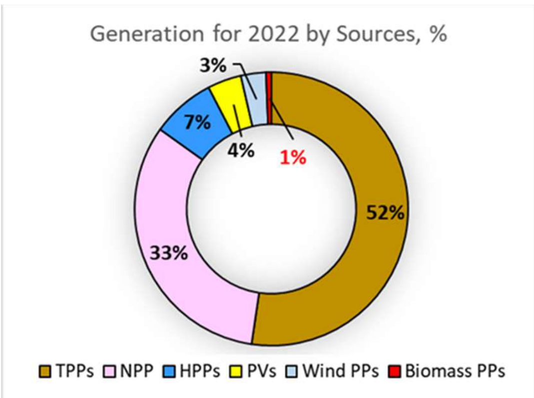

Figure 2

Current renewables (PV+Wind) together with HPP provide 14% of the energy mix. Water resources in the territory of Bulgaria are largely exploited. Onshore wind resource is also largely utilized. The prospects are in PVs, Wind offshore and NPP. NPP has been built and then demolished for 30 years with zero result. It does not look realistic that new nuclear units will come on line in the next 10 years. Building offshore wind farms is a serious technical challenge and hardly achievable in the short term.

PV technology with all its imperfections has the greatest capacity for new generating power.

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III. Energy Strategies of Bulgaria

In connection with the GHG mitigation initiatives taken by the EU, Bulgaria had to prepare its own development plan, including for the energy sector. As a result, in 2022 a document with the loud title "Integrated Energy and Climate Plan of the Republic of Bulgaria 2021 - 2030, version 5.1" was prepared and proposed for approval by the EC [1]. After the change of the political conjuncture, a new document was prepared in 2023 called "Strategic vision for the development of the electricity sector of the Republic of Bulgaria 2023-2053" [2]. Table 1 compares some of the priorities in the two documents.

TABLE I.

Energy strategies of Bulgaria		
Sector	***Integrated Plan 2021 - 2030 (2022)***	***Strategic Vision 2023-2053 (2023)***
Coal power	Decommissioning by 2038	Decommissioning by 2030
Nuclear Energy	2000MW without exact commissioning date	New 2000MW by 2035 and another 2000MW by 2045
Reneuables	New 3GW by 2026, of which 1.4 GW with energy storage for 4h at 30% of capacity	New 7GW PV and 2GW Wind by 2030 New 12GW PV and 4GW Wind by 2050
HPPs	No specific data on new capacities	New 870MW by 2030 and 1270MW by 2050
Hydrogen	20 MW hydrogen plant by 2030	1 GW electrolyzers by 2030 with 90 000 t/y hydrogen production
Energy storage	New batteries with 6000MWh capacity	New batteries with 600MWh capacity, expansion of Chaira Pumped storage HPP by 2030, new 1GW PSHPP by 2035, 1.5GW seasonal energy storage systems by 2035

The 2022 Integrated Plan [1] is a huge document with specifics on just the 2038 coal sector decommissioning deadline, new 3GW renewable capacity with a fractional energy storage system, and an unrealistic new electric Battery Energy Storage System (BESS) with a storage capacity of 6000MWh.

The 2023 Strategic Vision [2] envisages a reduction in the timeframe for decommissioning coal plants by 2030 and the commissioning of colossal 9GW of renewable capacity by 2030 and 16GW by 2050, large 870MW of hydro capacity by 2030 and 1270MW by 2050. Commissioning of 2 nuclear units of 1000MW by 2035 and two more of 1000MW by 2045 - total 4000MW. 1GW of hydrogen generation by 2030 and a much more modest 600MWh BESS. Reaching around 2GW of PSHPP capacity and unspecified 1.5GW seasonal energy storage systems by 2050. A comparative chart of planned installed capacities in the two documents is shown in Figure 3.

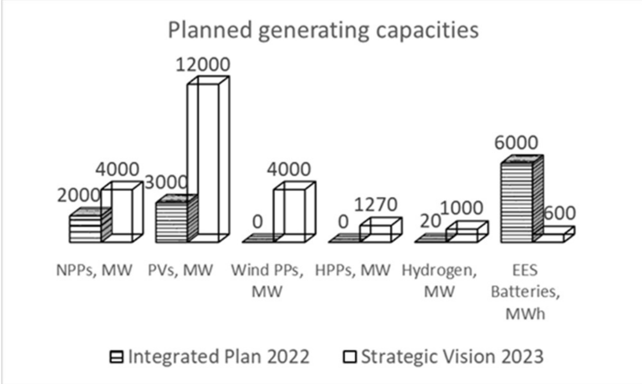

Figure 3

Considering that about 2GW of private PV, approximately 1GW of onshore wind farms and dozens of private flow-through micro-hydro plants have been installed for more than 30 years with a minimal share in the energy mix, the extremely ambitious large-scale projects envisaged in the Strategic Vision 2023 [2] do not seem realistic. It is about legitimising the utilisation of EU funds.

The most realistic in the short term is to build new PV capacities with electric batteries to store part of the energy.

IV. Opportunities for Sustainable Development of Photovoltaic Generation

There has been a visible increase in PV capacity in Bulgaria in the last three years, while the previous 7 years have been static. Within the EU, the increase has been steady, with the trend changing towards faster growth after 2017 Figure 4 [4].

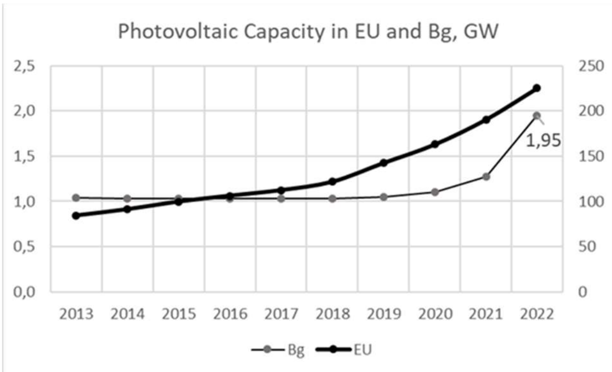

Figure 4

The sustainable development of PV capacities in Bulgaria is determined by the capabilities of PV technology, climatic conditions and the electricity market. The cost of the panels themselves and the cost/rent of the solar park site are important. Other factors that will become very significant in the near future are the operational lifetime, the cost of recycling the waste from PV systems after decommissioning and the recultivation of affected sites.

V. Technology Capabilities

A. Basic PV Panel Types

The current dominant PV technology is represented by the various types of crystalline silicon (c-Si) material. They include mono-, multi- and heterojunction silicon with various grades of efficiency [7].

The other important thin-film product is cadmium telluride (CdTe), although not as efficient as the best c-Si modules. The Copper Indium (Gallium) Sulphides and Selenides, overall generally referred to as CIS and CIGS depending on whether gallium is not or is included in the composition are used too. Amorphous silicon (a-Si) for its low energy conversion efficiency covers minimal market share [7].

The choice of one or another type of PV technology for deployment on the territory of Bulgaria depends on many factors, but in connection with the expected in the near future large quantities of waste PV components and the need for recycling, probably abroad, it is reasonable to take into account how easily recyclable are the selected.

B. Lifecycle of PV Modules and Degradation

The PV warranties are decades long - typically 80% of power after 25 years. A median degradation for x-Si technologies is in the 0,5-0,6 %/year range with mean degradation in the 0,8–0,9 %/year range. [7].

A diagram illustrating the effect of degradation and its impact on the actual generation over the lifetime of the PV systems fed to the consumers/grid is shown in Figure 5 [6].

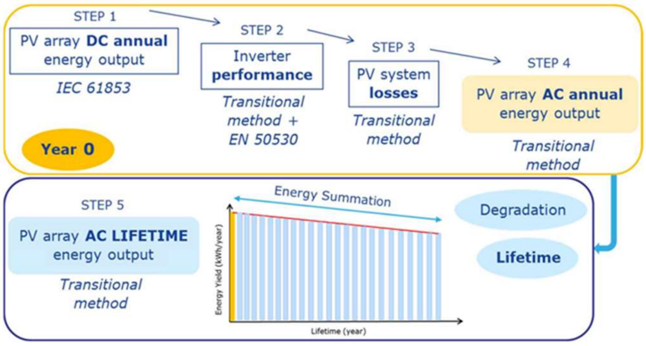

Figure 5

C. Mode of Pperation and Yield of PV Generating Capacities

The inconstant generation of PV power is its biggest disadvantage due to its dependence on the primary energy source - solar radiation. An illustration of the non-uniformity of generation on a diurnal basis is shown in Figure 6 for the highest generation day in 2022 [3].

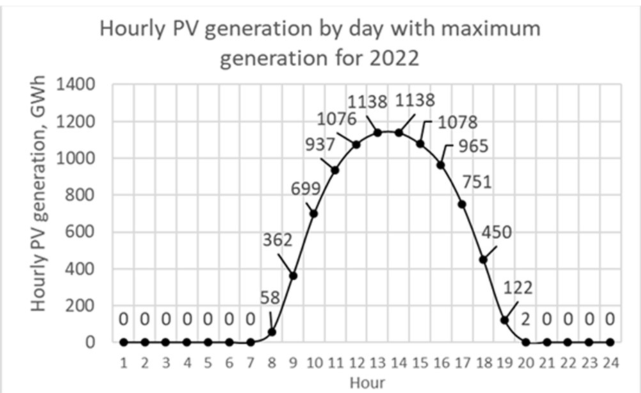

Figure 6

The average monthly (seasonal) yield from PV generating capacity depends on the average monthly solar radiation - for example, the Sofia city Figure 7 [5].

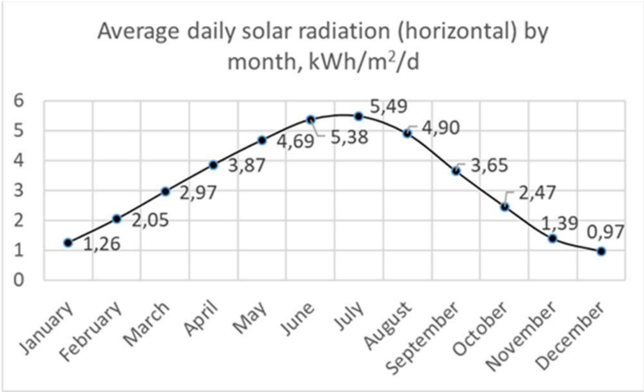

Figure 7

In the periods of the most intense sunshine in Bulgaria, PV generates a large part of the mix - for 27.07.2023 as much as 38% Figure 8 [3].

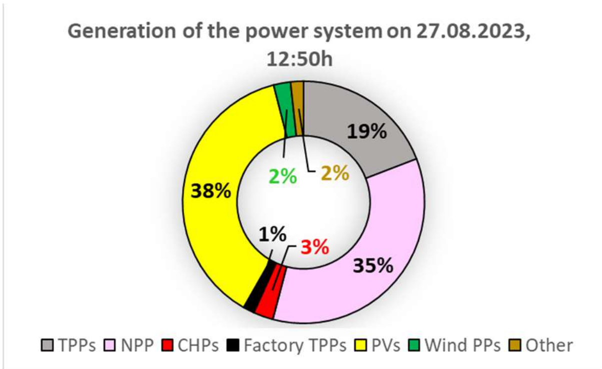

Figure 8

D. Low Energy Market Prices During Peak PV Generation Periods

To achieve sustainable development of the PV sector, it must be economically viable. Unfortunately, PV generation has the largest share in periods of low electricity price Figure 9 [3], which without subsidies or guaranteed feed-in tariffs can reduce revenues and make PV projects unprofitable.

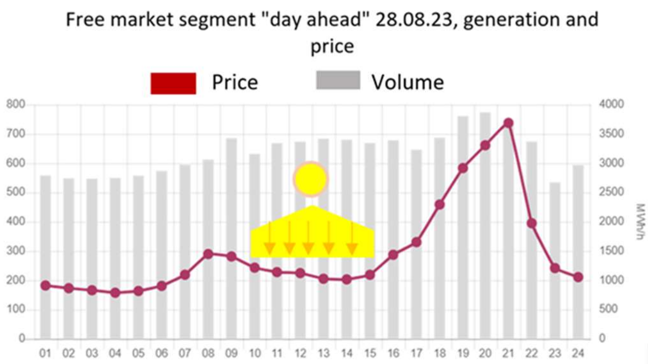

Figure 9

Partial market participation in periods of high electricity prices can be achieved by integrating an energy storage system, but these are additional investments and currently in Bulgaria investors prefer not to make them, relying on preferential prices for PV electricity. Usually, Energy Storage

Systems (ESS) are based on electro-chemical energy sources - electric batteries.

E. PV Energy Storage Batteries

The batteries used in PV systems, are mainly of two rechargeable types: lead-acid and lithium-ion. They can be described by a capacity. The capacity can be defined in two ways:

- the current capacity in ampere-hour (Ah) that can be drawn from the battery fully charged;
- the power capacity in watt-hour (Wh), which would be calculated as the product of the current capacity and the nominal voltage [7].

The battery capacity mainly depends on the charging/discharging current rate applied, the battery temperature and the ageing rate of the battery. This in turn depends on the operating conditions [7].

Manufacturers normally provide a static durability value for a reference temperature of 20°C. Working temperature could be higher and, thus reducing considerably the expected lifetime of the batteries. Number of cycles and depth of discharge (DoD) could be considered for the definition of the functional parameter for batteries. The battery capacity depends on discharge current C10 or C100 Ah, i.e. the capacity is different when discharging the battery in 10 or 100 hours respectively. [7].

Since it is well known that batteries have a much shorter lifetime than PV panels, the amount of electric battery waste to be recycled in Bulgaria in the future could be significant depending on the type of battery chemistry chosen, for which we are not prepared at this stage.

VI. Recycling of PV and BESS Waste After the End of Life of the Parks

A. Recycling of PV Module Waste

According to International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) by 2030, the projected waste PV modules will amount to 1.7 – 8 million tons and 60 – 80 million tons by 2050 in Europe. The EU WEEE directive requires 85% by mass of waste PV modules shall be recovered and 80% shall be prepared for re-use and recycled [8].

Currently, the dedicated recycling of both crystalline-Si PV modules and non-silicon modules is not feasible at a commercial scale with some limited exceptions. Silicon recycling from the end of life of PV modules is in theory possible. Today Silicon recycling is not done because it isn't economically viable. Hyper pure polysilicon from quartzite would still be required and cannot be fully substituted by recycled silicon. This is because of the dopants and impurities that are likely to be present in a PV module silicon waste stream [8].

There are research initiatives in the area of PV eco-design aim at reducing resource consumption in PV production, increasing material/value recovery in PV recycling, and using recycled raw materials in new PV Modules. The module has no encapsulation material, no soldering and no lamination requirement. Therefore, components can be recovered for further recycling or reuse [8].

The life cycle of PV modules and the most commonly applied after-treatment methods are shown in Figure 10 and 11 [9]. In the EU, only recycling to clean material for use or usable energy with minimal waste for landfill or disposal is permissible.

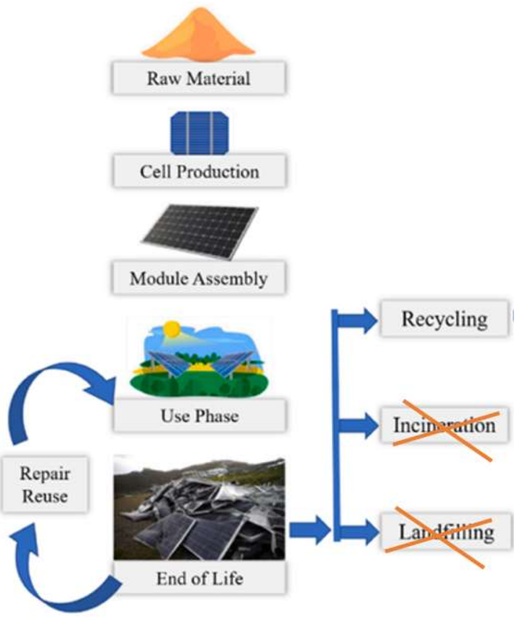

Figure 10

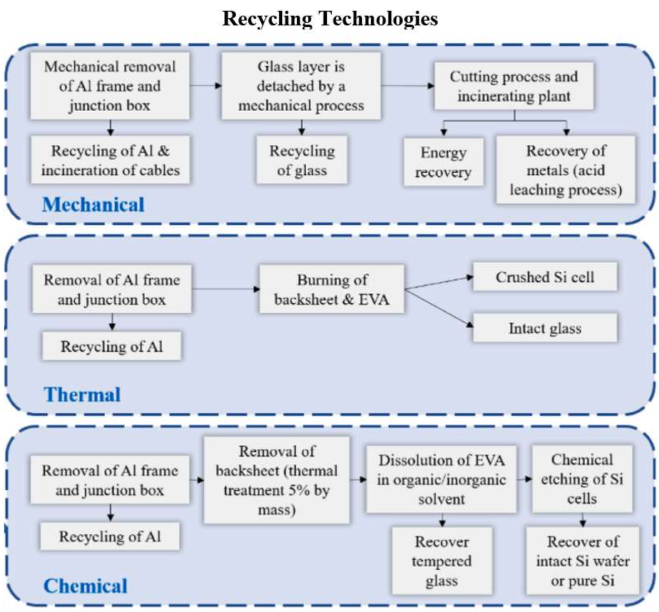

Figure 11

As mentioned above, recycling of PV modules is unprofitable. To make economic sense on an industrial scale, a shift to manufacturing modules specifically designed for easy and cost-effective recycling i.e. eco-modules is needed. Another option is to subsidise recycling by imposing additional charges already at the installation stage, which will reduce the profitability of the PV plant itself.

In some PV panel manufacturing countries, the manufacturer is obliged to take care of the recycling of PV modules at the end of their life. This forces manufacturers to look for a solution to the problem themselves, i.e. to switch to the production of cost-effective recyclable eco-panels.

Unfortunately, most of the PV panels for the parks in Bulgaria are imported from non-EU countries and this elegant approach is not feasible. A solution will probably be sought to export the waste outside the country for recycling in specialised plants in PV panel producing countries in the EU. Apart from a complex logistical task, recycling abroad would be too expensive. There is a risk that waste from PV parks in Bulgaria would simply be buried. The operational lifetime of the first large PV parks will expire in the next 5-8 years. There is a risk that new unregulated landfills for e-waste from them will appear, and why not develop again the trade in foreign waste for disposal on our territory. We will soon find out.

B. *Recycling of Waste Electric Batteries*

The recyclability of electric batteries depends on their chemistry. Lead-acid batteries are currently recyclable. In some countries, new lead-acid batteries are produced only from recycled material after appropriate purification.

Recycling of lead acid (LA) batteries is possible, the process is routine and up to 98 % of the constituent materials are recyclable. But recycling LA batteries is "dirty business". It can lead to long-term complex environmental pollution and lead accumulation in the body tissues and blood of people who are directly or indirectly exposed. Lead is toxic to humans and animals but tends to accumulate in plants, thence in herbivores and ultimately in predators and humans. The higher up the food chain a creature is, the higher the levels of accumulated lead [10].

The main routes of lead exposure and absorption are inhalation, ingestion and, to a much lesser extent, dermal contact. Inhalation of fumes and dust is the primary route of exposure for people working with lead [10].

Despite the environmental and health risks, lead-acid batteries can be recycled in Bulgarian plants, probably with the necessary expansion of battery plants and respecting safety and environmental requirements.

If the Lithium Batteries (LiB) chemistry is chosen for the EES in Bulgaria, the recycling problem is currently unsolvable. In Bulgaria, it is unlikely that in the foreseeable future LB will be recycled. The hope is to achieve an economically positive technological breakthrough on an industrial scale in the coming years. The nearest recycling destination is expected to be EU county in which there is production of lithium bat-teries. Bulgaria is expected to organize the safe collection, storage and transportation of the batteries to the recycling point, which is no small challenge. And is expected to be expensive.

From a safety point of view, the concentration of large volumes of lithium batteries for storage and transport is unacceptable due to the risk of explosions and fires. It is likely that special “dry” transport containers capable of withstanding a potential explosion, storage in inert media, etc. will be obligatory.

VII. Environmental Impact on Land and Recultivation

At the end of a PV park's operational life, there are several scenarios.

1/ Replacement of panels with new ones after inspection and partial repair of damaged/corroded metal structures and other equipment i.e. new PV park on the same site. This is the most logical scenario.

2/ The company operating the park is obliged to dismantle the panels, metal structures, drive systems and all electrical and other equipment and take care of its recycling. Thereafter to carry out site reclamation as per approved design. This is the optimal scenario.

3/ Sell what can be sold for second hand use and let everything else remain on site unattended and unguarded. The site in question will then become an unregulated dumping ground for e-waste and all other waste.

Which scenario will happen depends on the rules laid down by law, but most of all on the control of their implementation.

VIII. Conclusions

The chaotic planning and management of the Bulgarian energy sector in the last 30 years does not foresee the realisation of the colossal energy capacities planned in the two "strategic documents" - nuclear, pumped storage and even hydrogen generation. Most likely is the expansion of PV parks with partial energy storage.

In the coming years, huge volumes of hazardous waste will be generated from PV panels and rechargeable lithium batteries (LiB), which cannot be recycled locally. It remains to be seen whether civilised, environmentally sound and safe methods will be implemented for collecting, storing and transporting this waste to recycling locations, or whether we will create hundreds of new unregulated landfills across our territory.

Acknowledgment

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