Agrivoltaics and Aquavoltaics

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Agrivoltaics and aquavoltaics combine renewable energy production with agriculture and aquaculture. Agrivoltaics involves placing solar panels on farmland, while aquavoltaics integrates photovoltaic systems with water bodies and aquaculture. Benefits include dual land use, which allows farmers to produce clean energy while maintaining agricultural practices. They diversify renewable energy sources and reduce dependence on fossil fuels and greenhouse gas emissions. Solar panels in agrivoltaics provide shade, protect crops, reduce water needs, and increase yields. Challenges include high initial costs and limited accessibility, especially for small farmers. Integration with existing systems requires careful planning, considering irrigation, soil moisture, and crop or fish production. Maintenance and cleaning present additional challenges due to dust, debris, and algae. Policy and regulatory frameworks must support implementation, including incentives, grid integration, land use regulations, and conservation.

Keywords: agrivoltaics ; aquavoltaics ; Croatia ; water evaporation

1. Introduction

1.1. Agricultural Production and Climate Changes

Climate change poses a growing threat in the 21st century. It is a challenge to all humanity, affecting all aspects of the environment and the economy while threatening the sustainable development of society. Climate change affects the frequency and intensity of extreme weather events (extreme rainfall, floods and flash floods, erosion, storms, droughts, heat waves, and fires) and causes gradual climate change (increase in air, soil, and water surface temperatures, sea level rise, ocean acidification, and expansion of drylands) [1].

The agricultural sector is especially vulnerable to the profound impacts of climate change because of its dependence on weather [2]. Expected impacts on the agricultural sector include: (i) changes in growing seasons of arable crops, with a focus on crops and oilseeds (e.g., corn, sugar beets, soybeans, etc.); (ii) lower yields of all types of crops; and (iii) greater dependence on water. Extreme weather events such as droughts and hail led to average losses of 76 million euros per year in Croatia between 2000 and 2007, equivalent to 0.6% of national GDP [3]. Climate changes affect the duration/length of the vegetative period of agricultural crops and lead to lower yields. Frequent droughts will lead to a higher demand for irrigation water. A longer growing season will also allow for the cultivation of some new crops and varieties. On the other hand, more frequent flooding and stagnation of surface water will reduce or eliminate yields.

Agriculture faces the challenge of producing sufficient food, feed, and fiber to meet increasing demand under conditions of a changing climate and the depletion of natural resources [4]. A rise in temperature beyond the optimum becomes a major concern since most agricultural crops are directly dependent on climatic conditions. Shifts in acreage, length of growing season, winter hardiness potential, frost and hail events, lower yields, and food quality are some of the most obvious consequences of global warming trends [5]. Observations show an increase in the frequency and duration of warm weather extremes [6]. Warming tends to result in lower yields as plants accelerate their annual development and yield less. In general, both winter and summer crops exhibit advanced growth, anthesis, and maturity stages in response to higher temperatures, and the duration of the crop growth cycle is predicted to decrease [7].

Agricultural intensification also suggests that agriculture will have higher energy demands. As part of the global energy transition, fossil fuels are being replaced by renewable energy. The installed capacity of PV power plants around the world and the amount of energy they generate continue to grow almost exponentially, and the cost of electricity for new projects has already reached minimum levels in many countries compared to other generation methods [8][9].

Renewables are expected to overtake coal in electricity generation in the second half of the 2020s, and by 2050, renewables will account for 50% of global electricity generation. In agriculture, solar energy can dry hay, heat water, build more efficient greenhouses, provide energy for buildings and equipment that are away from residential power lines, etc. Mandatory use of energy supply measures in all sectors will increase the role of RES [10][11].

Croatia is located in a sensitive area of Europe, as a transition zone between Central Europe and the Mediterranean, where the trend of increasing average annual air temperature is present throughout Croatia. In Croatia, extreme weather events such as droughts and hail have resulted in average losses of EUR 76 million per year from 2000 to 2007, or 0.6% of national GDP [3]. In the field of low-carbon development in the Republic of Croatia, major changes are planned in the near future. Power plants that run on fossil fuels will be replaced by renewable energy sources, and the development will move towards decentralization of electricity generation. Consumers (households and institutions) will also be energy producers, and energy exchange will take place at the local level. Energy producers and energy storage will be interconnected by advanced grids. In the Proposal for the Strategy of Low Carbon Development of the Republic of Croatia until 2030 with a view to 2050 [12], the Government of the Republic of Croatia has emphasized the need to build facilities that use renewable energy sources for electricity and/or heat production, such as solar power plants. The aim of the strategy is to initiate changes in Croatian society that will contribute to the reduction of greenhouse gas emissions and enable the decoupling of economic growth from greenhouse gas emissions.

The intensive use of solar energy (photovoltaics) in agriculture and freshwater aquaculture could make a significant contribution to avoiding or reducing potential damage from climate change. The combination of photovoltaics and agriculture or aquaculture, i.e., agrivoltaics (AgriPV) and aquavoltaics (AquaPV), creates a novel link between energy and food (land or water) that potentially benefits both parties. Agrivoltaics and aquavoltaics are emerging approaches that aim to combine agriculture/aquaculture and solar energy production in the same location on the land [13][14]. According to published statistics, the annual GHG emissions of all aquaculture operations worldwide (260 million t CO_2-eq/year) are rather small compared to those of cattle (3000 million t) or pig (800 million t) farming [15]. To meet the growing demand for aquatic food for a world population of 10 billion in 2050 [16], energy consumption and greenhouse gas emissions from the aquaculture industry are likely to increase significantly in the coming decades. In this regard, PV-integrated aquaculture systems with simultaneous production of food and electricity would be an important contribution to sustainable land use and climate change mitigation. By promoting intensive synergies between solar energy projects and the agriculture and aquaculture sectors, multiplier effects such as physical protection of certain crops (e.g., vineyards, olive groves, and pastures) from certain extreme weather events (heat waves, extreme rainfall) can be achieved, which would have a positive impact on yield levels and product quality. In addition to the impact on crop and fish production, the implementation of AgriPV and AquaPV increases the profitability of agriculture and aquaculture by generating additional revenue through energy production [14][17].

1.2. Use of Solar Energy in the Agricultural Sector

Climate changes in turn triggered the development of projects based on renewable energy sources (RES), with particular interest in photovoltaic systems, including the use of photovoltaic systems in the agriculture sector (agrivoltaics) [18]. To reduce its greenhouse gas emissions, the EU has decreed that 40% of energy consumption must come from renewable resources by 2030. Photovoltaics are expected to reach 16% of global electricity generation in 2050, but given climate change, it should be 30 to 100 TW before 2050 [19]. There is no internationally unified definition of agrivoltaics as such. The term “agrivoltaic” was firstly proposed in 1982, which combines electricity generation and crop planting on the same farmland. The word agrivoltaics is a neologism based on “agri” for agriculture and “voltaics” for photovoltaics [20]. “Agricultural photovoltaics (agrivoltaics) is the combined use of one and the same area of land for agricultural production as the primary use, and for electricity production by means of a PV system as a secondary use. The dual use of the land not only leads to increased ecological and economic land use efficiency, but in practice can also lead to positive synergy effects between agricultural production and the agrivoltaic system” [20]. Agrivoltaics is also known as agrophotovoltaics, solar sharing, farming photovoltaics (PV), AgriPV, or solar farming.

Numerous studies have shown that it is possible to combine photovoltaics (PV) with agricultural production, enabling PV development on a larger scale while protecting agricultural crops and maintaining yield [21][22][23][24]. The first advantage of AgriPV is the area productivity in winter, when agricultural production is not possible in the fields. This land productivity refers to the generation of electricity. Many studies indicate that it is possible to increase crop yields under PV systems [25][26].

This is possible because agrivoltaics create a modified microclimate beneath modules by altering air temperature, relative humidity, wind speed, wind direction, and soil moisture [27]. Agrivoltaics protects crops from both excess solar energy and stormy weather, such as hail [1]. Agrivoltaics also offers more efficient use of water, which may help reduce water consumption [22] and stabilize yield in dry years [28]. This is of particular interest in drylands where unfavorable growing conditions such as excessive sunlight, high temperatures, and severe droughts (water shortages) are predominant.

When trying to describe the challenges associated with AgriPV, the term solar sharing is probably the most descriptive. Sharing solar resources to produce food and energy simultaneously means that the design of the PV system cannot always follow a standard approach of orienting panels to optimize energy production, and that system design may conflict with optimized food production [26][29]. Therefore, the system must be adapted to the local climate, crop type, or land shape [30].

AgriPV, as a concept or approach, includes a variety of different technologies defined by a specific way of combining agriculture and PV [20]. A closer look at the diversity of AgriPV solutions can be made using the framework recently proposed by some authors [31]. The first line of distinction is defined by whether the modules are installed in the open field or on the roof. Totally opaque roofs may be associated with agricultural buildings, even indoor agriculture, but there is no direct interaction between PV systems (other than electricity use) and agricultural activity. Aquaculture and horticulture can also be combined with ground-mounted PV or greenhouse systems. Open-space systems can be further differentiated by growing crops between rows of the modules (inter-space PV) or under modules that have a greater vertical distance (overhead PV). These systems can be fixed tilt, single-axis tracking, or dual-axis tracking. Since compatibility with agricultural machinery is a key planning criterion for AgriPV, interspatial photovoltaics are expected to focus primarily on grassland farming, fodder production, and grazing, while ground-mounted systems can accommodate a wider variety of stable food crops on arable land as well as horticulture, including perennial crops, permanent crops, and specialty crops [20].

2. Agricultural Potentials of Croatia for Application of AgriPV

The Republic of Croatia is divided into the Adriatic region and Continental Croatia. The territory of Continental Croatia includes central Croatia, Slavonia, and Baranja. Central Croatia is a slightly hilly region covered with vineyards, meadows, and forests and crossed by river courses. Slavonia is located in the far east of Croatia and is characterized by vast plains and large amounts of arable crops, the so-called green treasury. In the Adriatic region, permanent grasslands prevail, and plant production includes mostly viticulture and olive growing as the most important branches of this area, but also the production of Mediterranean fruits and vegetables. The Republic of Croatia covers a surface of 56,594 km^2, which is divided into: forests and bushes cover about 35%, agricultural land about 27%, urban areas 9%, inland waters 1%, and others 29% (**Figure 1**). According to the Croatian Bureau of Statistics [32], total agricultural land used in the period from 2010 to 2019 on average was around 1,477,000 ha, and main field crops—cereals, industrial plants, and fodder crops—were sown on about 675,000 ha (46%).

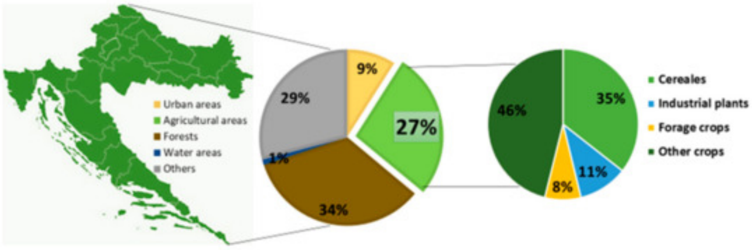

Figure 1. Land use in the Republic of Croatia Reproduced with permission from [32].

The agricultural farms of the Republic of Croatia are characterized by a large number of different production and economic entities. According to [32], the largest number of agricultural farms are small farms. Of the total number of farms, 14.1% have no agricultural land in use, while 59.7% use up to 3 ha of agricultural land. Of the total number of agricultural holdings, only 6% of holdings use more than 20 ha of agricultural land [33]. According to [34], of the total number of agricultural holdings (143,927), most of them (39%) have less than 2 ha, 30% have from 2 to 4.9 ha, and 15% have from 5 to 9.9 ha. The lowest number of agricultural holdings have over 100 ha (1%) (**Figure 2**).

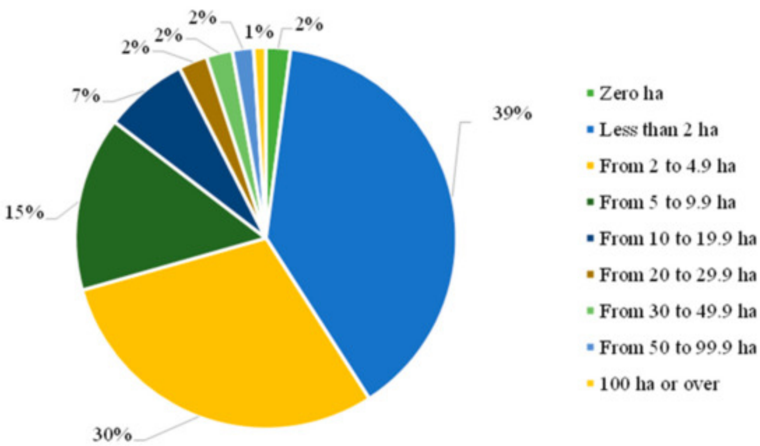

Figure 2. Agricultural land of family farms in Croatia in 2020 Reproduced with permission from [34].

This indicates that fragmentation of farms is still great in Croatia, where the average of commercial farms is about 8.5 ha and the average of all farms is only 2.9 ha, which can be a limiting factor in the wider application of AgriPV projects. About 55–60% of used agricultural land belongs to the category of arable land and gardens, which occupies more than 850,000 ha (**Figure 3**), followed by perennial grass areas (about 540,000 ha). Other crops—vegetables, orchards, olive groves, and vineyards—occupy about 6% of agricultural land (about 80,000 ha) [32].

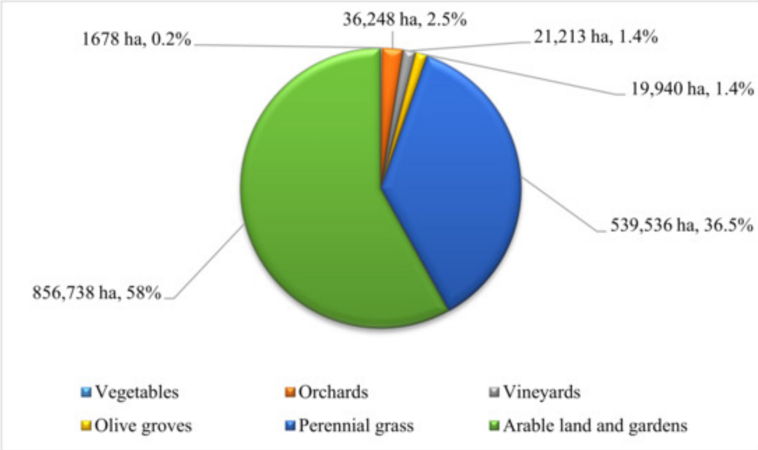

Figure 3. Area (ha) and share (%) of agricultural land by category in 2021, reproduced with permission from [32].

In the last decade, of the total agricultural area used, about 70% was located in the continental and about 30% in the Adriatic parts of Croatia (**Figure 4**).

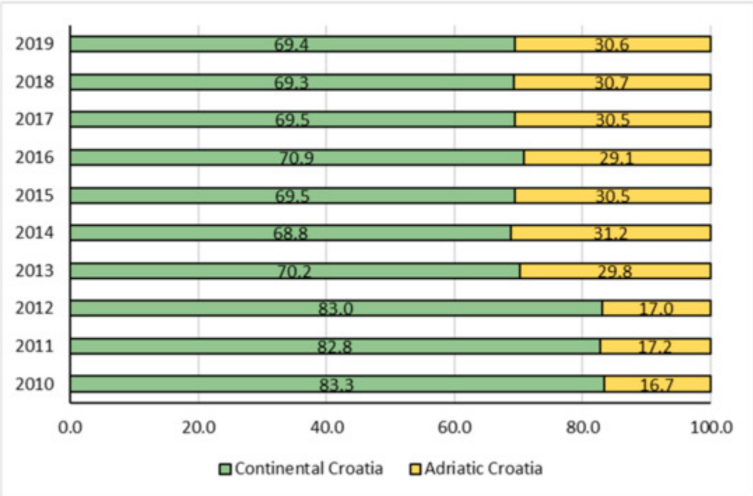

Figure 4. Share of used agricultural area for Continental and Adriatic Croatia from 2010 to 2019, reproduced with permission from [32].

The analysis of the advantages and limitations for the application of AgriPV projects for certain types of cultivated species considering different researches, the applicable case studies and examples of similar corresponding projects, and the conclusion about the applicability of AgriPV projects for certain types of crops in Croatia are given.

Unfortunately, there is still no legislation on AgriPV in Croatia. But, there is some slight movement in this area, as the Croatian government issued two legal documents on 28 June 2023: the Regulation on the Promotion of Electricity Production from Renewable Energy Sources and High-Efficiency Combined Heat and Power (OG 70/2023) and the Regulation on the Criteria for Conducting a Public Tender for the Granting of an Energy Permit and the Conditions for Granting an Energy Permit (OG 70/2023). In these documents, AgriPV (the term Agrosolar is used in the documents) is defined as a solar power plant located on an area designated as agricultural land by the land use plan of any level and on which the establishment of permanent agricultural plantations is registered in the Agricultural Land Use Records (ARKOD) or on which, in addition to the existing area, farms, greenhouses, or greenhouses with the installation of an agrosolar power plant achieve the objectives of the development of agricultural activity while maintaining the purpose of agricultural land, except in the National Park and Natural Park. These two documents are the only official legal documents that mention or define AgriPV in Croatia. Croatia has considerable solar energy potential due to its geographical location and climate. The country receives a considerable amount of sunlight throughout the year, which makes it suitable for solar energy production. The southern regions, especially Dalmatia, have the highest solar potential as they experience more direct sunlight. The use of photovoltaics is steadily increasing in Croatia. The government has also introduced various incentives and support programs to encourage the use of solar energy. However, the overall solar energy capacity in Croatia is still relatively modest compared to other European countries.

3. Aquavoltaics

Considering the title of the review article, this subsection provides a somewhat more detailed overview of the definition of aquavoltaics, its uses, benefits, and challenges, with an addition on the structure of freshwater aquaculture (cyprinids) in Croatia.

Aquavoltaics, or AquaPV, is a concept combining electricity production with aquaculture. The goal of AquaPV is the efficient use of water for both food and energy generation. While solar panels above the water or on its surface provide electrical energy, the aquatic organisms living within the water below provide a sustainable food source. AquaPVs floating on the water body can lessen water losses by preventing evaporation by up to 70–85% due to covering the water [35]. Aquavoltaics technology enables electricity to be generated and aquaculture to be carried out in the same area, significantly improving overall productivity per unit area compared to conventional land use [17]. These systems withstand fluctuating water levels; however, they are not commonly designed to operate while resting on the bottom if the body of water is drained [36]. The AquaPV approach aims to maintain parameters such as water and air temperature, light availability, water pH, dissolved oxygen (DO), feeding system, and predator pressure and improve the system by exploiting synergies between the aquaculture and PV systems. Cultured species have different requirements, confirming the need for variation in essential parameters as a function of species type and farming systems. The integration of photovoltaic technology with aquaculture creates synergies as aquatic farming can benefit from module shading effects when temperatures are high, while modules' efficiency values are enhanced at the same time due to the proximity to cool water environments [37]. Aquaculture systems are characterized by a very high energy input, mainly due to their need for an artificial oxygen supply. Electric power generation using floating, elevated, or other forms of PV module integration offers the possibility to substitute fossil-based energy sources without the occupation of additional land. To maximize the productivity of aquavoltaic systems, the coverage of PV modules and the mounting of the whole system require careful consideration [37]. Common benefits from these installations were a reduction in water evaporation from the reservoir/pond [38][39] and decreased algal growth (due to the reduction in sunlight penetration within the water body) [40]. Also, electrical yields were slightly improved in most reported cases, probably because of the cooling benefit offered by the underlying water surface, as illustrated in some papers [41] while testing a PV panel that was in direct contact with water (**Figure 5**). According to [42], the high humidity conditions under aquavoltaics operation can reduce the lifespan of photovoltaic modules. Additionally, advancements in photovoltaic technology, such as longer lifespans and higher power output rates, can improve the economic and environmental efficiency of the system.

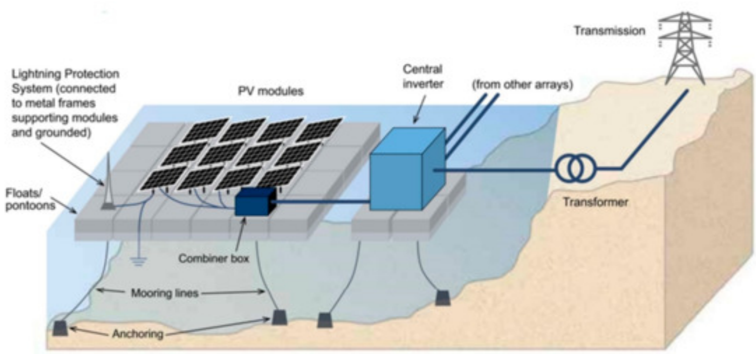

Figure 5. Schematic representation of a typical large-scale FPV (Reproduced with permission from source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore).

Several projects and studies are carried out to verify positive and negative aspects in terms of ecosystems and the technical and economic feasibility of dual use in aquavoltaics:

- *Cooling*

Regardless of the system design, several aspects must be considered when integrating PV modules into aquaculture systems. It is well known that the efficiency of PV modules decreases with increasing temperatures. In the AquaPV approach, a positive cooling effect can be achieved by both water and increased wind speeds. Thanks to the cooling effect, increases of ~10–15% in PV output can be achieved compared to fixed ground-mounted solar systems [43]. The cooling effect of water on solar cells, which favors higher energy conversion efficiency, is considered one of the main advantages of FPVs [44]. The magnitude of this effect depends on the orientation and the amount of contact of the module with the water. The greatest improvement was found for floating, tracking, cooling, and concentrating (FTCC) systems [17].

- *Light*

In waters exposed to the sun, photosynthesis allows the growth of organic matter, including algae. These algae are generally not desirable in water reservoirs because they can obstruct pumping and filtration systems and require costly chemical treatment to control the problem. Installing FPVs shades the water and reduces photosynthesis. This reduces the formation of algal blooms and reduces chemical and operational costs. Aquavoltaic systems provide shade on the water surface of the pond, and the blocked light is absorbed by solar cells and converted into usable energy. If uncontrolled, an increase in shading decreases, and general plant life and microbial density are reduced, affecting the entire food chain down to the fish intended for breeding [45]. Typically, fish are either more active in light and less active in darkness or vice versa [46], and this can be altered by daily changes in factors such as temperature or oxygen [47]. The growth of aquatic organisms is linked to light, but it is not unique because species vary in their growth conditions. Fish and larvae, for example, must be reared in specific light ranges depending on the species and stage of development [46]. Light-emitting diodes (LEDs) can be installed on the underside of the pontoon structures in the aquavoltaic system, powered by the PV portion of the system, to affect the photoperiod of aquatic life. This design provides the “aquaculturist” with a powerful tool to increase and further optimize production for specific aquatic species [17]. This needs to be tested further, and the effects of energy conversion need to be considered. Another alternative is to rotate or move the plant around the water body in which it is located. This action would limit the amount of natural light shading that a given water area experiences [45]. A change to the pontoon structure itself could increase the distance between the modules that make up a facility. This change would allow a controlled amount of light to penetrate the water below. This approach does reduce the efficiency per unit area of the array because the density of the solar modules is lower, but if the area is not a constraint, this is an insignificant drawback [48].

- *Land use and evaporation*

PV systems floating on water do not occupy habitable land and can be deployed in degraded environments and reduce land-use conflicts [49][50][51], as can dual-use infrastructure, such as reservoirs, where evaporation can also be reduced [52][53]. One of the most important synergistic effects resulting from coupling PV systems with aquaculture is saving water. In aquaculture systems where high water flow rates are observed, the prevention of water loss is a great benefit from both economic and ecological points of view. FPVs save water by reducing evaporation and improving water security in arid areas while being flexible for use in various water bodies such as fishponds, drinking water reservoirs, etc. Because the system acts like a protective blanket over the water, FPVs can reduce water evaporation by up to 33% for natural lakes and ponds and up to 50% for man-made facilities [54]. Some authors noted that water loss from reservoirs could be reduced by as much as 70–85% with FPV [17][35]. Especially in the context of climate change, where dry periods are becoming more frequent, reducing evaporation is a major achievement [39].

- *Maintenance*

Another advantage related to proximity to water emerges when considering pollution effects. First, particles are washed off the module surface more regularly. Soiling of the surface of PV modules can also occur from other sources, such as bird droppings or biofouling [17]. Biofouling describes the colonization of organisms such as algae on PV surfaces, which can affect not only the modules but also mounting systems and cables. According to some of the authors [17], one of the biggest unknowns is the interaction of FPVs with aquatic organisms and the potential for biofouling to occur. Mechanical stress would also be high due to increased wind speeds and waves, especially during stormy conditions [37]. Stable anchoring is essential to compensate for lateral forces [38], while flexible mounting of PV modules offers the advantage of floating with the waves and protecting the system from external forces. Depending on the location, maintenance of the system may be more difficult, as work must be performed from boats or from the movable pontoons. However, because accessibility is difficult, vandalism and theft can be expected to decrease [3]. On the other hand, floating systems do not require thousands of metal frames to be attached to the ground, which means that a panel array can be constructed more quickly. In addition, decommissioning a floating system is much easier and less expensive.

- *Material availability*

Material requirements for PV are likely to increase substantially to limit warming to well below 2 °C, but PV materials are widely available, have possible substitutes, and can be recycled [18][55]. The main materials for PV are silicon, copper, glass, aluminum, and silver, with silicon being the most expensive and glass the most important by mass at 70%. None of these materials are considered critical or potentially in short supply [56]. FPVs are compatible with the existing hydropower and electric infrastructure, which supports diversifying the energy supply and its resilience. The lack of supporting policies and development roadmaps by governments could hinder FPVs’ sustainable growth [50]. There is scarce research on the socio-environmental impacts of FPV farms. [57] reflected on three key socio-environmental impacts of FPVs: job creation, non-occupation of habitable land, and improving water security in water-scarce regions. The addition of floating modules will most likely increase the difficulty of tending the aquaculture system, and the aquatic life may slow or disrupt the maintenance of the PV modules. After a typical useful life of 30 years, PV modules can be recycled to prevent environmental pollution from the toxic materials they contain, reuse valuable materials, and avoid the accumulation of waste (**Figure 6**).

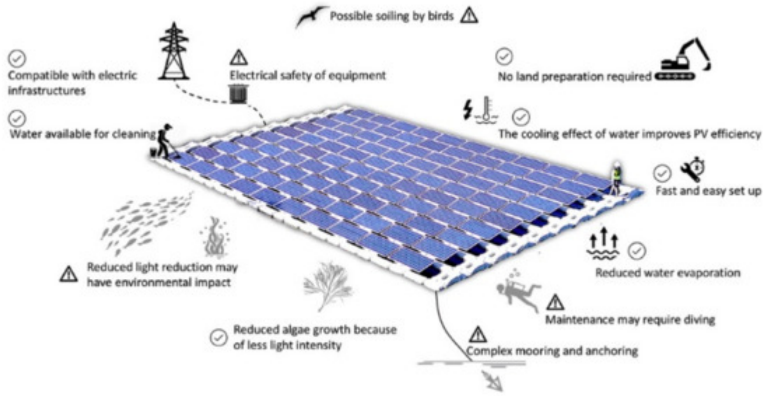

Figure 6. Benefits and challenges of floating solar panels Reproduced with permission from [50].

- *Structure of Freshwater (Cyprinid) Aquaculture in Croatia*

In Croatia, cyprinid species are traditionally farmed in carp ponds, which usually cover several hundred hectares, with five carp ponds having an area of over 1000 ha. The total area of carp ponds in Croatia is currently 14,081.49 ha, while the production area in 2021 was 12,539 ha [58], preliminary data).

Most carp ponds are located along larger river basins in the lowlands and the continental area of the Republic of Croatia, where the continental climate prevails. Continental Croatia has a temperate continental climate, and throughout the whole year it is in a circulation zone of mid-latitudes, where the atmospheric conditions are very variable. They are characterized by a diversity of weather situations with frequent and intense exchanges during the year. These are caused by moving systems of low or high air pressure, often resembling vortices hundreds and thousands of kilometers in diameter. The climate of continental Croatia is modified by the maritime influence of the Mediterranean, which is stronger in the area south of the Sava River than in the north and weakens towards the east. Cultivation of cyprinids in Croatia mostly involves controlled rearing of common carp (*Cyprinus carpio*) in monoculture or polyculture with other species, the most common of which are Grass carp (*Ctenopharyngodon idella*), bighead carp (*Hypophthalmichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), catfish (*Silurus glanis*), perch (*Sander lucioperca*), pike (*Esox lucius*), and tench (*Tinca tinca*). The production is mostly semi-intensive, where, in addition to the natural food produced in the pond by biological processes and whose production is stimulated by agrotechnical measures (fertilization, etc.), the fish are also fed additional feed, usually cereals (corn, wheat, rye, and barley). The production cycle in carp farming usually lasts three years [58], preliminary data.

According to [59] the analysis of spatial capacities and conditions for the use of the potential of renewable energy sources in the Republic of Croatia, as well as the considered criteria for determining the vulnerability of an area to the energy potential of the sun, encourages the development of the possibility of establishing hybrid photovoltaic systems and aquaculture. Mainly because of their symbiotic relationships, which include increasing the efficiency of energy conversion due to cooling and cleaning the surfaces of the PV modules, reducing the evaporation rate of the water surface, improving the growth rate of fish through integrated designs with PV-powered pumps to control oxygen levels, etc. [17].

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