

Coupling PV, EV and residual hydropower to reduce environmental impact of earth dam construction: a model and a case study

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1 Introduction

The construction of earth dams requires to supply to and to handle at the construction site a very large amount of material, with an order of magnitude of millions of cubic meters.

Usually, diesel dumpers are utilized to transport large volumes from far quarries or borrow areas. This implies a negative environmental impact due to gas emissions, disturbance to inhabited areas if any, impacts on traffic and on the existing road network.

In this context the paper presents a model implemented to evaluate the replacement of conventional diesel lorries with electric vehicles powered by a PV power plant. The PV power plant is supposed to be placed on the ground during the construction phases of the dam and to be finally transferred on the reservoir surface. The impact of gas emissions and, partially, on disturbance of the anthropic environment, will be significantly reduced.

The model is aimed to optimize the size of the PV plant taking into account all the relevant constraints, both on ground and floating (backup energy supply from the grid during cloud days, radiation profile during the year, space available on the ground and on the lake surface, recharge time of the dumper's fleet, impact of the variation of water level in the lake, safety issues, hybridization with the mini hydro system designed in the plant, etc.).

In the model it is also included the hybridization with the hydropower exploitation of both the ecological flow released and of the water flow feeding the water supply network.

The integration of Battery Energy Storage Solutions (BESS) to optimize both PV production and energy quality, has been evaluated in the model.

A case study related to a real project is used to show and highlight the main issues to be solved in this kind of systems, both from the technical and economical point of view.

In the paper is reported the multi-criteria analysis carried out to compare diesel-fueled and electric vehicles alternatives and to outline the gathered benefits.

Blufi project in brief

1.1 The project and the dam

The Blufi Dam project (Sicily) started in the '70s of the 20th century. To date, only the reinforced concrete works have been completed: the intake tower, the spillway and the outlet works, including the stilling basin.

Two years ago, it was decided to update the original design so that the feasibility study for the final construction of the dam is ongoing.

The main features of the dam are:

• Type	Embankment dam
• Height	68 m
• Impounded volume (at Max NOL)	28 Mm ³
• Maximum Normal Operation Level (Max NOL)	609,10 m a.s.l.
• Minimum Normal Operation Level (Min NOL)	585,60 m a.s.l.
• Design flood	1239 m ³ /s
• Maximum flood level	611,40 m a.s.l.
• Lake surface at Max NOL	1,34 km ²
• Lake surface at Min NOL	0,58 km ²
• Dam total volume	5 Mm ³
• Main use of water	Drinking water supply

The completion project already involves the installation of two mini-hydro power stations to exploit both the energy of the water delivered to the aqueduct and the ecological flow released downstream of the dam for a 1,3 MW total installed capacity. The mini-hydro power stations connection to the mains is of the same order of the power connection needed in dam construction phase. The main features of the mini-hydro plants are:

• Plant on the drinking water line	
○ Turbine	1 Francis vertical
○ Rated flow	1,01 m ³ /s
○ Minimum flow rate	0,25 m ³ /s
○ Maximum net head	34 m
○ Minimum net head	26 m
○ Installed power	308 kW
○ Expected production	1,2 GWh/year
• Plant on the Ecological Flow	
○ First unit	1 Francis vertical
▪ Rated flow	2,2 m ³ /s
▪ Minimum flow rate	0,52 m ³ /s
▪ Maximum net head	70 m
▪ Minimum net head	42,1 m
▪ Installed power	1015 kW
○ Second unit	PAT (Pump As Turbine)
▪ Rated flow	0,108 m ³ /s
▪ Minimum flow rate	0,065 m ³ /s
▪ Maximum net head	72 m
▪ Minimum net head	27 m
▪ Installed power	75 kW
○ Expected production (Francis + PAT)	1 GWh/year

The most innovative aspect of the project currently under development, anyway, pertains with the will to use electric trucks for dam construction, fed by a photovoltaic power plant located at the construction site, to dramatically reduce the CO₂ emissions without increasing or, even better, reducing the construction costs.

Once construction has been completed and the reservoir filled, the photovoltaic power plant will be moved in the reservoir to continue its life as a FPV plant. It will be electrically integrated with the mini-hydro plants, the dam electrical distribution system and with possible battery energy storage system (BESS) or with other devices to improve frequency and regulation features.

1.2 Volumes of materials involved in the construction of the dam

The dam holds approximately 5 million cubic meters. The construction materials for the embankment almost all come from quarries located at a certain distance from the construction site.

The roads to be traveled are mostly secondary, with significant differences in height, and pass through inhabited areas.

Part of the materials must be placed in temporary storage, to be treated or simply to be deposited and then reloaded and transported to the laying site, given that the supply times and those of the relative positioning of the product are not always synchronous.

Additionally, there are the materials needed to reprofile the reservoir banks, and the subsequent blankets for their stabilization, given that these are fine-grained slopes that are subject to superficial landslides, if not protected. Finally, the volumes of the foundation excavations of the dam, cutoff and cofferdam are added: they are removed and positioned for profiling the banks of the reservoir and for the creation of fills at the base of the upstream and downstream facings of the dam.

The volume of vegetable soil to be used for the landscaping at the end of the works is not negligible, too. It's expected to move over 7 million cubic meters of material on site, which on trucks, not compacted, is equivalent to at least 8.8 million cubic meters. the volumes combined with the distances to travel, round trip, for 10 m³ trucks in bulk, give over almost 900,000 trips for 82 million kilometers.

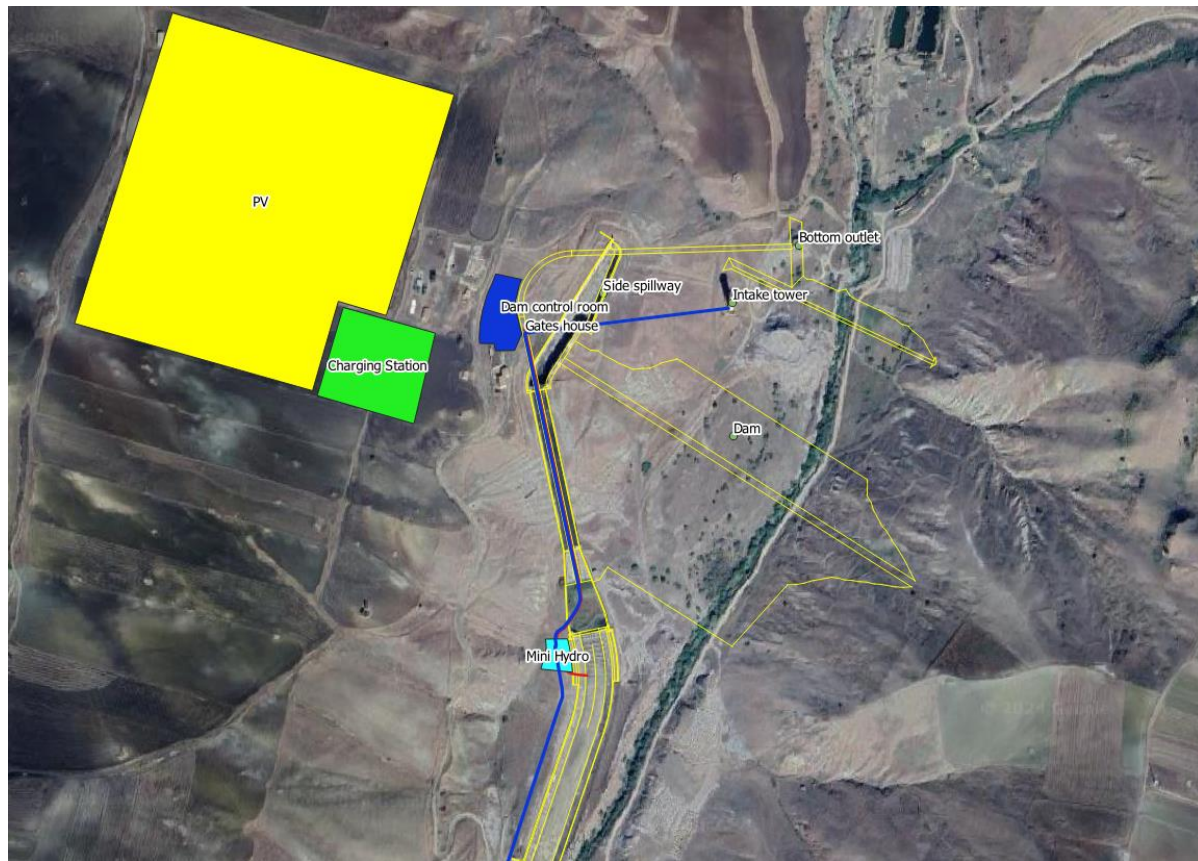


Figure 1 – Layout during the construction phases

2 FPV at the Blufi site

2.1 FPVs on reservoirs in general

FPV planning is a consistent portion of the energy transition. The fundamental motivation of this process is the containment (or reduction) of the global warming produced by human activity through the GHGs (greenhouse gases). Human activity to produce energy converts significant masses of carbon in the gaseous (trapped underground), solid or liquid state, into volatile compounds which are dispersed in the atmosphere. This produces a variation of the GHG balance in the atmosphere and induces a global warming.

Concurrent factors are the reduction of forests, the mobilization of carbon from the permafrost induced by the warming of the atmosphere, the melting of glaciers, the warming directly produced by exothermic processes, mainly the exhaust of internal combustion engines and refrigeration processes, dumping areas of wastes, livestock and agroindustrial processes.

The sector of dams and artificial reservoirs plays an important role in this complex scheme which sees many scientific sectors engaged simultaneously and in synergy. The impact of artificial reservoirs (and of FPV systems which are a growing reality), is supposed to be positive and decisive.

The impact factors are both FPV on the environment and of the environment on the FPV.

The impacts are very different from case to case, in quality and consistency. They depend on the conditions in which the plant is supposed to be built.

It should primarily be considered that there are strong differences depending on the proportion of the water surface that is occupied by the floating islands. Small surfaces undergo strongly conditioning impacts for the admissibility of an FPV system, while for large artificial lakes it is much easier to reconcile all the components and interests.

The primary impacts of the environment on FPVs are the environmental stresses on the structure. It can be listed:

- the corrosion of materials
- degradation produced by solar radiation
- the wind which acts directly on the islands by lifting them or causing them to drift, or which insists on the individual components, stressing the supports and structures
- the waves, which modify the buoyancy structure making them more vulnerable to the action of concomitant winds, and which transmit stresses to the structures and anchorages
- the currents, variable, which influence the structure of the islands, and which determine prevailing stresses on the anchorages
- the floating bodies that collide with the islands
- the materials carried by the wind that settle on the panels
- lightning and improbable meteorites
- aquatic animals and birds that gnaw, nest and litter
- falling rocks from the shores of the lake
- landslides and mudslides that may affect structures or anchorages
- the sedimentation of solids in the reservoir, which is an impact of the environment on the works.

The impact of FPVs on the natural environment, imagining the artificial lake as an acquired natural element, is above all the reduction of solar radiation to the water body, which has numerous induced effects, such as:

- less warming of the lake
- consequent impoverishment of the aquatic biosphere, which is beneficial when the lake tends to be eutrophic
- reduction of evaporation, due to less exposure to wind and solar reduction. The reduction of evaporation is a benefit for the conservation of water resources, in some cases even very important. It produces less cooling of the lake water; therefore, it is of opposite and compensatory sign with respect to the reduction in temperature due to less solar radiation
- reduction of CH₄ and CO₂ emissions, greenhouse gases which are often, but not always, emitted from water surfaces, especially when warm and poorly oxygenated waters allow anaerobic bacteria to prevail and determine marsh-like eutrophic conditions
- upheaval of the thermocline and the limitations resulting from the production of greenhouse gases from the seabed, of opposite sign compared to the previous point
- suffering of the riparian ecosystem as a result of the impoverishment of the aquatic ecosystem
- variations in the lake microclimate due to less evaporation, less fog but greater temperature changes, less contribution of humidity to the riparian vegetation.

It is reiterated that these impacts have strongly different consistencies depending on the size of the liquid surface, the portion occupied by the plants, the conformation of the shores and surrounding outcrops, the depth of the lake, the

windiness of the places and the speed of water exchange produced by the balance of inflows and outflows into the reservoir.

Applicable remedies are ladders or elevators for fish, oxygenation by mills, jets, blowing, the removal of vegetation or vegetable layers and organic soils in the reservoir and other measures that are evaluated and sized not only for FPVs, but more generally for the correct management of the artificial reservoir.

The panels have an impact on the landscape and are unusual and antagonistic effect if compared with a free water expanse.

These places are a capital for the well-being of the population and induce important direct economic returns with tourism and recreational activities and with the indirect benefits attributable to the landscape and to individual and collective psychological well-being.

The insertions of the FPV on water surfaces must consider:

- fishing
- nautical sports
- riverside and lakeside transports
- requirements of the plant for the maintenance of the reservoir, such as the need for dredging of the sediment and maintenance of the inlets of the bottom outlets and of the intakes.

Another impact on nature, less evident on the sites but very important in general, is the production of waste implicit in the end of life of the plants. The panels have a variable useful life, which is getting longer thanks to sector studies. By now the life of the panels is about 20 years, but it is true that at 40 years of life they still generate non-negligible percentages of the installed W_p .

However, the waste is millions of tons of siliceous materials that are difficult to degrade in nature.

The disposal of the panels must also be associated with the dismissal of the support structures and anchors, and of the electrical material, that can be recovered, and therefore in the design of the FPVs the predisposition for recycling is a key factor.

The containment of these aspects is evolving and constitutes one of the pillars for the sustainability of this important energy source.

Another impact aspect is constituted by the potential of the floating islands to interfere in their construction, operation, in possible accidents and in the process of decommissioning, with the dam systems and with its safety.

The management of FPVs, and PV in general, has a minimal carbon footprint but the production of panels has a not negligible footprint, requiring energy. Research are on their way and the energy consumption for panel production is under quick reduction. Nevertheless, this factor should be considered in the environmental analysis.

The impact of floating structures on GHG production from the reservoir essentially depends on the limitation of the free liquid surface.

By limiting the surface area exposed to solar radiation and wind, floating islands limit:

- evaporation (consider that water vapor is also a greenhouse gas)
- lake water heating
- the oxygenation of the lake water is reduced
- the transfer of greenhouse gases from the lake to the atmosphere is reduced.

The impact is therefore positive, at least in general. It absolutely depends on the surface occupied by the floating islands with respect to the surface of the lake.

The inhibition of solar radiation has a reductive effect in respect of aquatic life in general. The resulting contraction of the ecosystem (especially a function of the extension of the islands and of the complementary

environmental conditions, such as the speed of water exchange and its temperature) can produce unexpected effects that are not easy to predict, strongly depending on the particular situations that characterize each different reservoir.

Complex ecosystems are stable, for example the aquatic fauna that feeds on algae and microorganisms tends to limit eutrophication, which occurs only when specific equilibrium thresholds are exceeded; therefore, the negative impact possibly produced on the macrofauna could produce a blooming of the microfauna and favor anaerobic reactions and the formation of methane, reducing or canceling the benefit induced by the limitation of the free surface.

This eventuality is not probable but cannot be excluded, and the only way to evaluate it is to study the potential environmental evolution with suitable specialized studies. This is marginal for cold, deep lakes where islands occupy limited surfaces, but becomes increasingly important for shallow, warm waters where islands occupy significant surface area.

2.2 FPV issues at Blufi site

The reservoir purpose is water supply. Water level oscillations are consequent to the inflow and outflow balance. The Maximum Normal Operation Level is 609,10 m, and the reservoir surface varies from 1,34 km² (at Max NOL) to 0,58 km² (at Min NOL).

At the minimum retention level the FPV system surface is between 17 and 34% of the of the whole reservoir area, while at the maximum level is between 7 and 15%.

Reservoir oscillation affects public uses of the lake surface. Direct use of the lake is possible but with important limitations, for safety and to avoid pollution. The eligible portion is the one far from the dam and the intake devices and the spillway. A floating barrier is planned. The barrier prevents accidental impacts, including those caused by logs and floating debris as well as boats.

Furthermore, the FPV islands are planned near the dam, albeit at a safe distance from the upstream face. The system does not inhibit the aquatic environment and fishing and does not interfere with the maintenance of the bottom drain.

3 The model

3.1 General remarks

The model proposed is aimed to evaluate the feasibility of the construction of a dam using electric trucks fed by photovoltaic power plant instead of diesel trucks in terms of overall cost and emissions reduction.

The parameter chosen to compare the costs in the various scenarios is the cost per kilometer travelled by the trucks. The same model suggests also various possible solutions to be applied and evaluated to optimize the size of the charging station, the PV plant, the site connection with the mains and site internal grid.

Further, it involves also the integration of the mini-hydro production with PV plant once the dam is completed and in service.

The model is directly applied to a case study for sake of clarity.

3.2 The steps of the model

The model has some essential steps that can be resumed as it follows:

- a) statement of the general constraints, that are valid for all the scenarios.
- b) definition of the basic scenarios with the calculation of their cost per kilometer travelled and the calculation of their impact on CO2 emission. Each scenario can have further constraints:
 - scenario 1: traditional construction with diesel trucks
 - scenario 2: construction with electric trucks fed by the grid only
 - scenario 3: construction with electric trucks fed by a dedicated photovoltaic power systemThe scenarios shall be compared among them to correctly address the final choice.
- c) integration of construction site loads and mini-hydro with photovoltaic power plant and eventual BESS and further refining

3.3 General constraints

There are some constraints that are applicable in any of the above-mentioned scenarios, and they are for instance:

- volume of dam construction material to be moved from the quarry to the site within 5 years, that is about 5 million of cubic meters
- path between the site and the quarry is about 150 kilometers long
- working time: it is expected to work from Monday to Sunday (bank holiday excluded) while the activity at site should be limited for instance from 05:00 and 19:00 for safety reasons
- type of truck to be used is determined by the activity and by the road and their maintenance conditions
- traffic limitations that do not allow to circulate large group of trucks without causing traffic jams

4 Scenarios

4.1 Scenario 1: traditional construction with diesel trucks

The diesel trucks involved in this scenario are essentially a rugged version of the typical 6 x 4 dumper for building construction sites.

About 120 trucks will run about 54 million kilometers. The duty cycle of each truck involves two rounds trip from the site to the quarry and it must be arranged taking in consideration the general limitation stated in the previous paragraph.

At this point a costs & revenues table can be written- It is worthy that all these trucks can be refueled in local tank station and therefore the infrastructures for this case are limited to a parking area at site.

Costs	Revenues
diesel trucks	diesel trucks reselling after the construction
fuel	
diesel trucks consumables and maintenance costs	
drivers' salaries for 120 trucks	

The sum of the costs and of the revenue duly actualized year by year and divided by the kilometers travelled gives the cost of the kilometer travelled.

The emissions can be calculated using fuel consumption already calculated and other parameters as stated in the relevant standards.

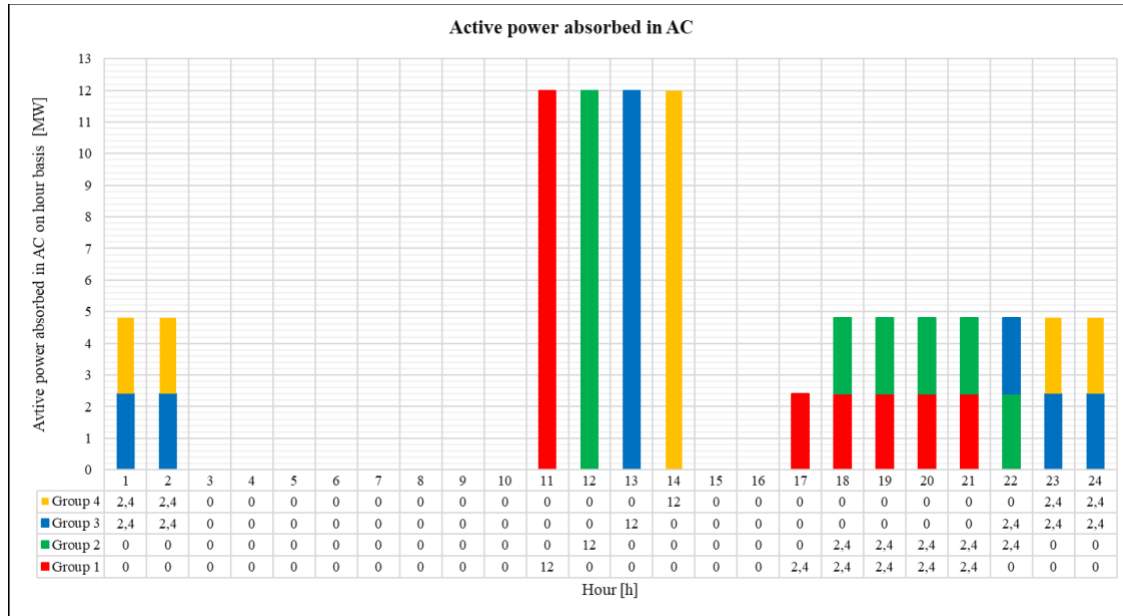
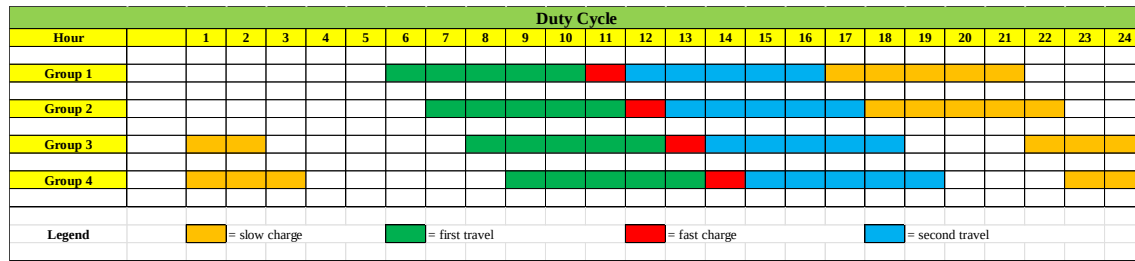
4.2 Scenario 2: construction with electric trucks fed by the grid only.

In this scenario there are further constraints that are for instance:

- the electric truck type, that shall be as far as possible equivalent to the diesel truck
- the electric truck autonomy is limited to about 300 kilometers
- only one charging station to be located at site is planned
- the fast charges and slow charges shall be distributed in the time to avoid high absorption peaks, that inevitably rise the connection and electrical network cost.

In this case about 160 electrical trucks shall be used and each truck shall be recharged between the first and the second travel with a fast recharge and with a slow recharge during the night. In this case the power absorption of the charging station is limited at 12 MW, and the power connection and the internal grid can be designed around this value.

To respect all the constraints, the trucks can be divided in 4 groups composed by 40 trucks each. The first group departs from the site at 5:00 in the morning (solar time), while the other groups will follow shifted by one hour one from the other.



Each truck is expected to be equipped with lifting hook to take and release rapidly the containers, that can be filled and emptied independently from truck presence in the loading/unloading area at site or at the quarry.

The costs & revenues table can be written as it follows:

Costs	Revenues
price difference to buy electric truck	electric trucks reselling after the construction
electrical trucks consumables and maintenance costs	charging station reselling after the construction
drivers' salaries for 160 trucks	
electrical energy absorbed from the national grid	
12 MW charging station	
12 MW power connection to the national grid	
MV and LV network to sustain the charging station	

The sum of the costs and of the revenue duly actualized year by year and divided by the kilometers travelled gives the cost of the kilometer travelled.

The emissions are reduced compared to the previous scenario, but it shall be considered that each MWh absorbed from the Italian national grid is energy obtained by a mix of renewable and not renewable power sources. Said in other words, this energy is not fully green, and it must be considered a certain amount of emission due to the percentage of energy from not renewable source.

4.3 Scenario 3: construction with electric trucks fed by a dedicated photovoltaic power system.

This scenario involves the installation of a PV plant of suitable size on ground, that after the dam completion and reservoir filling (about 5 years after), it is transferred in the basin and transformed in a floating photovoltaic power plant for grid service. The expected life of the photovoltaic power station is up to 25 years.

The introduction of photovoltaic power plant to charge the electric trucks has four fundamental targets:

- to minimize the emissions directly feeding the charging station with solar energy
- to minimize the exchange of power with the national grid during the construction phase
- to minimize the cost of electricity during the construction phase
- to maximize the revenues during the operation period.

It is worthy to note that the introduction of photovoltaic power plant significantly increases the cost of electrical structure, but it offers the possibility to sell the exceeding production to the mains and – in somehow – to contribute to the project cost reduction as well.

This scenario brings additional constraints:

- all the electrical charges or at least most of them shall be done during daytime and planned in the most favorable hours as far as possible
- the maximum water surface occupied by photovoltaic power plant shall be between 17% and 34% of the basin surface at minimum level, that in this case means a surface between 10 ha and 20 ha
- the maximum land occupied by photovoltaic power plant during the construction period shall be limited. It is reasonable to use more or less the same limitations used for the floating PV
- the floating structure shall be not a dangerous for dam safety. This means that photovoltaic platforms on which panels are fixed shall be safely moored to rivers and/or reservoir bottom and far away from the dam and critical structures like the spillway, the intake, and the bottom outlet. Protection measures shall be taken to avoid that parts of photovoltaic platform accidentally detached can block or clog those critical structures
- to minimize the peaks of power exchange with the national grid
- the connection to the national grid shall be capable to feed the charging station absorbing all the power from mains, to avoid an unwanted stop of the construction during dark days.
- the PV plant shall be taken in operation for all its expected life because the revenues from energy sales to the national grids greatly contributes to the reduction of the cost of the kilometer travelled

The scenario it is quite complicate, and more alternatives shall be studied to select the best ones for further development.

In facts, it shall be considered that:

- the irradiation to the ground changes during the day and during the year due to the solar path variation
- the hourly distribution of the energy captured by the photovoltaic panels changes also because of the inclination angle to the ground (tilt angle) and inclination angle to South (azimuth angle) chosen for panels installation.

Here below the sun paths calculated for Blufi area.

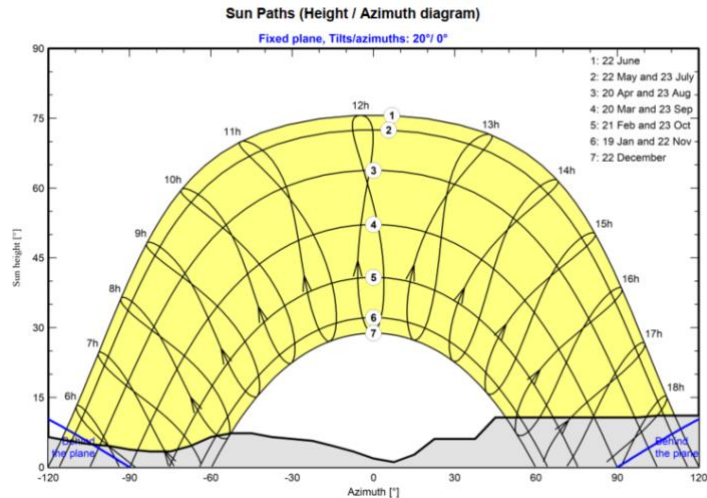
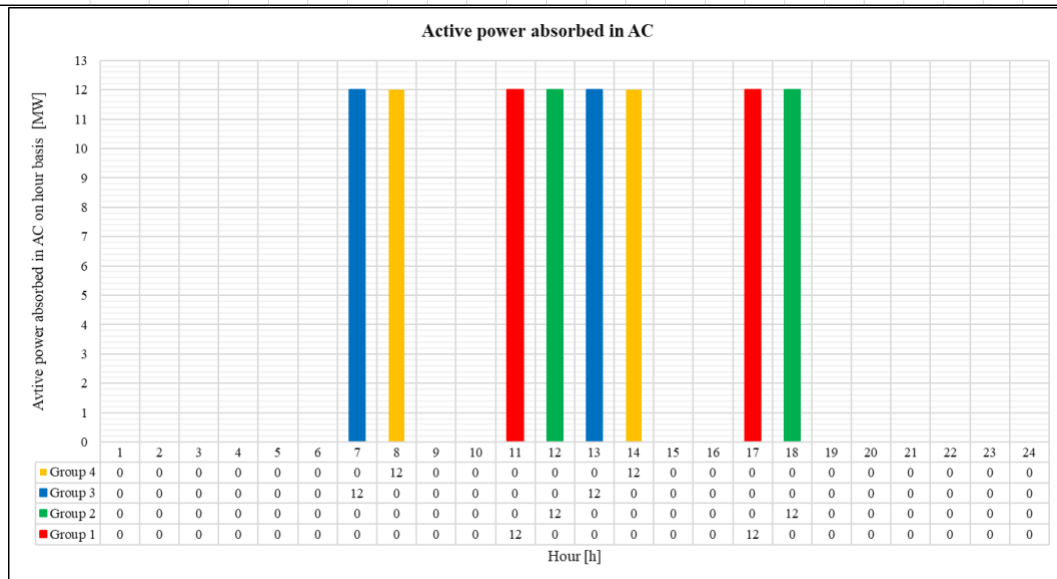
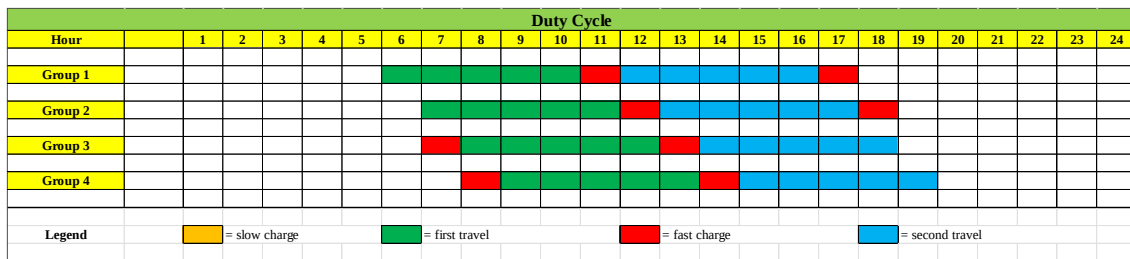


Figure 2 – Sun paths

Further, the needs during the construction phase are different from the ones in the operation phase. In facts, during the construction phase is important to warranty as far as possible:

- a constant power production during the year to minimize the consequences of grid fault to the construction activity,
- a quite flat day production in the light-time to charge the trucks during the day only - as represented in the duty cycle here below – and use therefore mostly cheap and self-produced green energy.



From the other side, the need during the operation phase is to maximize the revenues from the production.

Therefore, it is recommended to study two different arrangements of the photovoltaic panels in terms of tilt and azimuth angles.

For each alternative of the scenario, the costs & revenues table can be written as it follows:

Costs	Revenues
price difference to buy electric truck instead of diesel trucks	electrical energy delivered to the national grid
electrical trucks consumables and maintenance costs	electric trucks reselling after the construction
drivers' salaries for 160 trucks	charging station reselling after the construction
electrical energy absorbed from the national grid	
12 MW charging station	
xx MW power connection to the national grid	
yy MW photovoltaic power station	
transfer of the photovoltaic power station from ground to the reservoir and mooring structures	
MV and LV network to sustain the charging station and photovoltaic power plant connection	

For each alternative, the sum of the costs and of the revenue duly actualized year by year and divided by the kilometers travelled gives the cost of the kilometer travelled.

In this case, the emissions are minimal and limited to the quote of electricity done with not renewable power sources.

5 Comparison between the scenarios

At the end all the scenarios shall be compared, and one shall be chosen for further development. A table like the following should be a useful tool. The table could be filled with marks and/or numeric values depending on the specific purpose.

Here below the situation found for Blufi project in terms of marks: the scenario 3 and its alternatives offer can be considered the best.

Scenario	1 Diesel trucks	2 Electric trucks	3 Electric trucks and PV
Cost per km travelled	Medium	High/Very high	Medium/Low
Emissions	High	Medium	Low/Very Low

It clearly appears that the third scenario can be an appreciable alternative to the traditional construction method based on diesel trucks.

6 Integration of construction site loads and mini-hydro with photovoltaic power plant and eventual BESS and further refining

The scenario 3, that involves electrical trucks fed by a dedicated photovoltaic power station, is the most suitable to be developed in Blufi project case.

The alternative chosen shall be implemented integrating - from electrical point of view - all the equipment already supplied during the construction and during the operation in a unique modular electric scheme in which components are added or removed as needed. The size and the type of the components can be refined and optimized in this view. The heart of the system is composed by the main MV power control center and its connections with the national grid, that are strategically placed in the site. It makes sense to place the control room based on SCADA and the telecommunication devices in the same area. In Blufi project the area chosen is on the right side of the dam, because this position is barycentric and because from this position it is possible to directly watch the reservoir, the dam, and the construction site.

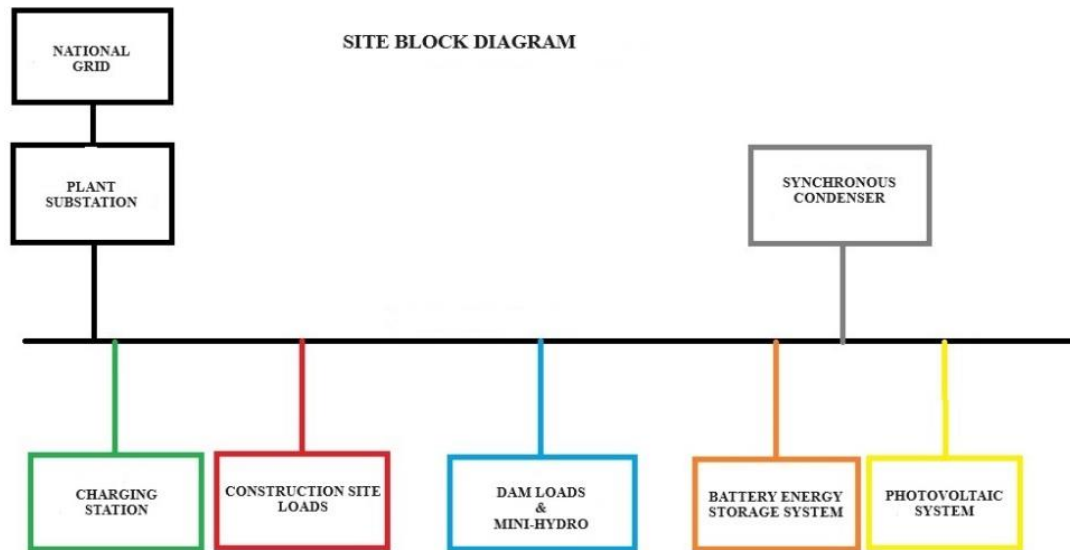


Figure 3 – Site Block Diagram

In this scheme:

- the main MV power control center and its connections with the national grid shall be always present
- the construction site PCC and the charging station are present only in the construction phase
- the photovoltaic power station at site is present in the construction site and it is transformed in the operation phase
- the mini-hydro and dam loads are present in operation phase only
- BESS and synchronous condenser are installed if needed.

It is worthy to note that BESS can be evaluated and sized for several functions, such as:

- to supply part of the energy during morning or afternoon for fast charges in dark months
- grid services for frequency regulation
- emergency power supply to the dam in case of blackout.

7 Conclusions

The model proposed, duly applied to Blufi project, show that is possible to build a similar dam in Italy using electric trucks feed by a dedicated photovoltaic power plant and that it is possible integrate the already mentioned photovoltaic power plant in the final civil and electrical structure of the dam keeping the correct precautions.

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