Ground-mounted vs floating photovoltaic (PV) power plant: a trade-off using game theory in utility-scale PV power plant investment decision making

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Abstract. The development of a renewable energy power plant in Indonesia will increase rapidly in the future in line with the long-term electricity policy to achieve the renewable energy target of 23% by 2025. One type of renewable energy power plant that will be highly developed is the Photovoltaic (PV) power plant, both built on the ground or floating type. Floating PV power plants do not require large amounts of land. However, the construction of a floating PV requires a floater system along with mooring and anchoring, which costs up to 20-30% of the project cost. This paper aims to optimize and simulate the critical factors so that investors and utility companies can make a decision whether to build a PV power plant on land or floating in a used mine area. Critical factors that affected the PV power plant development are analyzed using Critical Success Factor Analysis. Furthermore, the analysis is carried out using Game Theory to obtain optimal decisions. Based on the analysis, if the other critical factors are assumed to be the same, the construction of a floating PV Power Plant in a typically used mining area will provide optimal commercial value at a depth of reservoir of fewer than 60 meters. If the depth of the reservoir is more than 60 meters, the ground mounted PV will provide a more optimal commercial value.

1. Introduction
Bloomberg predicts that wind and solar power plants will make up almost 50% of world electricity in 2050 – “50 by 50” and help put the power sector on track for 2 degrees to at least 2030 [1].

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*Figure 1 Energy Outlook 1970-2050. Source: Bloomberg BNEF*
A 12TW expansion of generating capacity requires about $13.3 trillion of new investment between now and 2050 – 77% of which goes to renewables [1]. Also, the Government of Indonesia through the National Energy General Plan has targeted a mix of renewable energy reaching 23% by 2025.

Photovoltaic (PV) energy is one of the promising renewable energies in the world due to its ubiquity and sustainability. However, the installation of solar panels on the ground can cause some problems, especially in countries where there is not enough space for installation. As an alternative, floating PV, with advantages in terms of efficiency and environment, has attracted attention, particularly about installing large-scale floating PV for dam lakes and reservoirs. [2]

The main factor that determines the floater cost as well as the mooring and anchoring costs is the depth of the reservoir. The construction of a floating PLTS requires a floater system along with mooring and anchoring, which costs up to 20-30% of the project cost as stipulated in the picture below.

![Cost Structure of Floating PV](image)

**Figure 2** Cost Structure of Floating PV [3]

On the other hand, there are a lot of opportunities to build a PV power plant in the used mining area in Indonesia. The potential area is in the waste dump area for a grounded PV power plant or in the water void for floating power plants as shown in Figure 3.

![Typical Waste Dump and Water Void in Used Mining Area](image)

**Figure 3** Typical Waste Dump and Water Void in Used Mining Area [4]
PV power plant investor is required to decide whether to develop a ground-mounted PV power plant or floating PV power plant in a used mining area. If it is developed in a water void, the waste dump area requires to be reclaimed. If it is developed, the water void should be reclaimed and dumped.

Refer to the condition above, this paper will optimize and simulate the critical factors so that investor and utility company can make optimum investment decision making in terms of PV power plant development.

2. Method

2.1. Critical Success Factor Analysis

Rockart defined CSFs as: "The limited number of areas in which results if they are satisfactory, will ensure successful competitive performance for the organization. They are the few key areas where things must go right for the business to flourish. If results in these areas are not adequate, the organization's efforts for the period will be less than desired." [5].

Rockart identified four main types of CSFs: [5]:

1. **Industry factors** result from the specific characteristics of your industry. These are the things that you must do to remain competitive within your sector. For example, a tech start-up might identify innovation as a CSF.
2. **Environmental factors** result from macro-environmental influences on your organization: the business climate, the economy, your competitors, and technological advancements, for example. A PEST Analysis can help you to understand environmental factors better.
3. **Strategic factors** result from the specific competitive strategy that your organization follows. This could include the way your organization chooses to position and market itself, and whether it’s a high-volume, low-cost producer, or a low-volume, high-cost one.
4. **Temporal factors** result from the organization's internal changes and growth and are usually short-lived. Specific barriers, challenges, directions, and influences will determine these CSFs. For example, a rapidly expanding business might have a CSF of increasing its international sales.

2.2. Game Theory

According to Kelly: “Game Theory is the theory of independent and interdependent decision making. It is concerned with decision making in an organization where the outcome depends on the decision of two or more autonomous players, one of which may be nature itself, and where no single decision-maker has full control over outcomes." [6]

There are three categories of games namely games of skill, games of chance, and games of strategy.

1. Games of skill are one-player games whose defining property is the existence of a single player who has complete control over all the outcomes.
2. Games of chance are one-player games against nature. Unlike games of skill, the player does not control the outcomes completely and strategic selections do not lead inexorably to certain outcomes. The outcomes of a game of chance depend partly on the player’s choices and partly on nature, who is a second player. Games of chance are further categorized as either involving risk or involving uncertainty.
3. Games of strategy are games involving two or more players, not including nature, each of whom has partial control over the outcomes. In a way, since the players cannot assign probabilities to each other’s choices, games of strategy are games involving uncertainty. They can be sub-divided into two-player games and multi-player games.

The classification of games is shown in the picture below.
2.3. **Framework of Thinking**

Based on the background, problems, and study of the concepts above, the framework of thinking is arranged as shown in the figure below.

![Framework of Thinking](image)

*Figure 5 Framework of Thinking*

3. **Results and Discussions**

3.1. **Critical Success Factor Analysis**

According to the International Finance Corporation, some factors affected the PV Power Plant development. [7]

Those factors are land, PV module, Mounting Structure, Power Conditioning Unit/Inverters, Grid Connection, Preliminary and Operating Expenses, Civil and General Work, and Developer Fee.

Those factors above can be classified according to CSF analysis as stipulated in the table below.
| Table 1 Mapping of PV Critical Success Factor |
|---------------------------------------------|
| Factor                                      | Classification |
| Land                                        | Environmental factor |
| PV Modules                                  | Industry factor |
| Mounting structure                          | Industry factor |
| Power conditioning unit/inverter            | Industry factor |
| Grid connection                             | Environmental factor |
| Preliminary and operation expenses          | Industry factor |
| Civil and general work                      | Industry factor |
| Developer fee                                | Temporal factor |

To determine the critical success factor, a sensitivity analysis is conveyed and the result is shown in the picture as follows.

![Sensitivity Analysis](image)

**Figure 6 Sensitivity Analysis on Factors of PV Development**

Based on the analysis, the critical success factor for PV Power Plant development is mounting structure, PV module, and land.

3.2. *Assessment of Reclamation Cost*
According to Ebran, the reclamation cost for used mining areas in Indonesia is $9,730/ha. [8] If it is developed in a water void, the waste dump area requires to be reclaimed. If it is developed, the water void should be reclaimed and dumped.

3.3. *Game Theory*
Games of chance are one-player games against nature, but ones in which the single player is not deciding the conditions of certainty. In other words, nature affects the outcomes resulting from the player’s choices in an unpredictable way. The situation on PV power plant decision making for utility-scale is suited with games of chance condition. The condition of the depth of site location is involving uncertainty. The player cannot assign probabilities to nature’s moves. To prepare the pay-off matrix in terms of monetary values, the Internal Rate of Return (IRR) is calculated based on the strategy, investor, and natural condition.
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|                              | Floating PV                                                                 | Land-based PV                                                                 |
|------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Array configuration          | Modular design on “flat” water surface                                       | Design must accommodate terrain constraints or requires leveling             |
|                              | Limited tilt due to wind load considerations imply a lower                  | Flexible row spacing                                                        |
|                              | energy yield in high-latitude regions                                        | May consist of large tables of PV panels                                     |
|                              | Row spacing determined by floating structure                                 |                                                                              |
|                              | Consists of floating islands                                                 |                                                                              |
| Mounting and support structures | Floating platform structure                                                  | Flees and racks structure                                                    |
|                              | Anchoring and mooring system is essential                                    | Mounting structure experience forces from winds, snow, waves, and water     |
|                              | Need to provide maintenance walkway                                          | currents                                                                     |
|                              | Floating platform experiences forces from winds, snow, waves, and water     | Easier to implement tracking                                                 |
|                              | currents                                                                      | Potentially more susceptible to resonance effects                            |
| Electrical equipment and     | Electrical equipment may be placed on floats or on shore                    | String inverters and electrical boxes may be placed under PV modules        |
| cables                       | Cables mainly routed on floats                                               | Cables are placed in conduits above ground or buried underground            |
|                              | Potential need for higher protection standards and test                      |                                                                              |
|                              | certifications                                                                |                                                                              |
| Safety                       | Platform design needs to consider more risks for personnel                  | Safety relatively well established                                           |
|                              | performing O&M                                                               |                                                                              |
|                              | High humidity environment leads to lower insulation                         |                                                                              |
|                              | resistance and increased risks of electrical leakage                        |                                                                              |
|                              | Proper cable management is important to accommodate                        |                                                                              |
|                              | constant movement that may otherwise lead to cable                          |                                                                              |
|                              | damage and fire risk                                                         |                                                                              |

**Figure 7** Comparison of Floating and Land-based PV in terms of Design [9]

The comparison of the design shows that there is a lot of difference in terms of mounting and support structure that affected the estimation of the project cost. For floating PV, mounting and support structure is depending on the depth of the reservoir. The value of each critical success factor refers to the IRENA assumption as follows. [10]

**Figure 8** System Cost for Residential, Commercial, Utility-Scale PV
A financial model is prepared to create the pay-off matrix. The pay-off matrix is shown in the table below. Based on the analysis, if the land price is assumed to be the same, the construction of a floating PV Power Plant will provide IRR at a depth of a reservoir of fewer than 60 meters. If the depth of the reservoir is more than 60 meters, the onshore PV will provide a more optimal commercial value.

Table 2 Pay-off Matrix

| Strategy | Depth |
|----------|-------|
|          | 0     | 20    | 40    | 60    | 80    | 100   |
| On Shore | 13.45%| 13.45%| 13.45%| 13.45%| 13.45%| 13.45%|
| Floating | 23.15%| 18.35%| 15.40%| 13.52%| 10.31%| 7.40% |

4. Conclusions

Conclusion of this study are the critical success factor for PV power plant development is mounting structure, PV module, and land. If the land price is assumed to be the same, the construction of a floating PV Power Plant will provide IRR at a depth of a reservoir of fewer than 60 meters. If the depth of the reservoir is more than 60 meters, the onshore PV will provide a more optimal commercial value.

Actions that can be recommended are: In the future, the decision making by game theory can also be applied in residential and commercial PV power plant development. An investor needs to mitigate the risk not only for design or technical aspects but also for the non-technical such as permitting & licensing risk.

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